From Particle to Cosmos on the Net

A Reference Work on the Particles, the Earth, the Sky and the Vacuum.Net

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First edition, 16 October 2026. Version 1.0.

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How to read this book

This book tells, in one volume, the parts of the world that lie below the atom, at the size of the Earth, and beyond it in the sky. It tells them with the measured cases: the masses, sizes, lifetimes, dates and counts.

Part I, *Below the Nucleus*, runs through light, the electron, the quarks and nucleons, the neutrinos, the carriers of the forces, the Higgs, antimatter, the measured constants, the measured vacuum and the lifetimes of the unstable. Part II, *The Earth*, tells the planet itself from its making to now. Part III, *The Sky*, tells the universe from its first moments to the galaxies of now.

Each part opens with the few basics of the net it needs. The unit of length of the ladder is half the inverse of the Rydberg constant of hydrogen. Some lengths of the electron and the atom therefore stand on the ladder as identities of its units, and the text says so where they appear.

Through the whole history runs one set of forms, the forms of the Vacuum.Net. What closes stays. The form lasts while its carriers are replaced.

The residue of one depth becomes the alphabet of the next. A new kind of union opens once and is then filled many times. Reading keeps the relations and drops the rest.

Where a form shows in the history, the text names it in a sentence or two, and the history goes on. The forms are read in the history. They are described beside it, not as its cause; a reading is called a reading.

The ladder. Every size and every time in the book has a position on one scale. The position of a length is log base 3 of the length over 4.558816×10^{-8} m. The position of a time is log base 3 of the time over 1.520655×10^{-16} s.

One year is 3.15576×10^{7} s. An age is placed as the time from then to now. The day sits at 43.50, the year at 48.87.

Chapter 36 sets the lengths, durations and ages of the catalogue in order on one ladder: 2,407 positions.

Self-contained. Every number stands in the text with its unit, and every calculation is shown. The numbers in square brackets point to the list of sources at the end of the book. The reader needs nothing else to follow the text.

The catalogue. Every case told in the book is also a row in the catalogue: 7,035 cases with their values, positions, forms and sources. The catalogue is held in the MAZE.

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Part I — Below the Nucleus

1. Light

Light is the first thing below the nucleus that people measured. They timed it across the orbit of the Earth before they knew what it was. Three centuries later its speed became the definition of the metre.

This chapter follows light in the order it was measured. First comes its speed, from the moons of Jupiter to the laser.

Then come its portions: the photon that ejects an electron, recoils from it and arrives one at a time. Then its bounds, its spectrum, its turning into matter and its scattering on itself, and last its extremes.

The book reads this history beside the net. The net is a strand that touches itself; where its form shows in the measured world, the text says so in a sentence and goes on. The basics are introduced here once, where the history first needs them, and the later chapters refer back.

The finite speed of light, 1676–1729

On 22 August 1676 Cassini told the Paris Academy that light seemed to take ten to eleven minutes to cross the half-diameter of the Earth’s orbit [3][4]. On 9 November 1676 an eclipse of Jupiter’s moon Io was observed to be 10 minutes late [4]. A short anonymous paper, “Démonstration touchant le mouvement de la lumière”, appeared in the *Journal des sçavans* on 7 December 1676 [4].

Rømer’s own figure became 22 minutes for the full diameter of the orbit [3][4]. That is 1,320 s, at time position 39.69. Across two astronomical units of $1.495978707 \times 10^{11}$ m it gives $2 \times 1.495978707 \times 10^{11}$ m / 1,320 s = 2.27×10^{8} m/s, 24 % below today’s value.

The position of a time needs the ladder of the net, and the ladder comes in here. Every size and every time has a position: the logarithm to base 3 of the size over $S_0 = 4.558816 \times 10^{-8}$ m, or of the time over $T_0 = 1.520655 \times 10^{-16}$ s [26]. One step up is a factor 3; the day sits at 43.50 and the year at 48.87.

The two units are those of Larson’s natural system, taken over in the net texts [26]. They come from the light of hydrogen, as the section on the units below shows. Positions are given to two decimals, as coordinates; sizes and times smaller than the units have negative positions.

The light time across the full orbit is $2 \times 1.495978707 \times 10^{11}$ m / 299,792,458 m/s = 998 s, or 16.6 minutes. Its position is 39.44. Rømer’s 1,320 s sits 0.25 positions above it.

Huygens turned Rømer’s timing into a speed of 220,000 km/s, 27 % below the present value [3]. In 1729 Bradley found the speed from the aberration of starlight. Light travels 10,210 times faster than the Earth in its orbit, and from the Sun it takes 8 minutes 12 seconds [3].

Bradley’s 492 s sits at position 38.80. The modern Sun–Earth light time is $1.495978707 \times 10^{11}$ m / 299,792,458 m/s = 499 s, or 8 minutes 19 seconds, at 38.81. Bradley’s time was 1.4 % short.

Light measured on Earth, 1849–1950

In 1849 Fizeau sent light through a toothed wheel from Suresnes to Montmartre and back [5]. The baseline was 8,633 m, at size position 23.64. The wheel had 720 notches; the light was eclipsed at 12.6 rotations per second and visible again at 25.2 [5].

At the eclipse the wheel turns half a notch while the light travels out and back. That half notch takes $1 / (2 \times 720 \times 12.6\ \mathrm{s^{-1}}) = 5.51 \times 10^{-5}$ s, at time position 24.23. The speed is $2 \times 8{,}633$ m $\times 2 \times 720 \times 12.6\ \mathrm{s^{-1}} = 313{,}274{,}304$ m/s, 4.5 % high [5]; another account rounds it to 315,000 km/s [3].

Cornu repeated the toothed-wheel run and found 300,400 km/s, 0.2 % high [5]. In 1862 Foucault used a rotating mirror and found 298,000 km/s, 0.6 % low [3]. The error had fallen from tens of percent to below one percent.

Michelson's rotating mirror of 1879 gave 299,864 ± 51 km/s in air [6]. The published result, corrected to vacuum, was 299,910 ± 50 km/s, 0.04 % high [6]. In 1883 he found 299,853 ± 60 km/s [6].

In 1887 Michelson and Morley looked for the motion of the Earth through an aether. The result was null [6]. Michelson received the Nobel Prize in Physics in 1907 [6].

At Mount Wilson in 1926 Michelson measured 299,796 ± 4 km/s [6][3]. That is 3.5 km/s above the present value, inside one standard error.

The last run, by Michelson, Pease and Pearson, used a vacuum tube one mile long (1,609 m, position 22.11). It was published after his death: 299,774 ± 11 km/s, 18.5 km/s low, 1.7 standard errors [6].

In 1950 Essen used a cavity resonator. He found 299,792.5 ± 3.0 km/s [3]. That is 42 m/s above the present value, a relative difference of 1.4×10^{-7}.

Before these measurements the speed had been computed once from the properties of a medium. In 1861 Maxwell found 193,088 miles per second from the elastic constants of his medium, and his paper itself quotes 195,647 [28]. With one mile = 1,609.344 m these are 310,745 km/s and 314,863 km/s, 3.7 % and 5.0 % above the present value.

The net texts take up Maxwell's route. Maxwell wrote $c^2 = 1/(K\mu)$, with K and μ as properties of the medium; the textbook later froze them into the universal ε_0 and μ_0 [28]. Here the form is context (form 14): the net texts read K and μ as state functions of the local vacuum [28].

The laser and the definition, 1972–1983

In 1972 Evenson and his group at the National Bureau of Standards measured both the frequency and the wavelength of a laser. Their product gave c = 299,792,456.2 ± 1.1 m/s [3]. That is 1.8 m/s below the value that followed, 1.6 standard errors.

From then on the uncertainty lay in the metre itself. In 1983 the 17th General Conference on Weights and Measures defined the metre as the length of the path travelled by light in vacuum in 1/299,792,458 of a second [3]. The speed of light became 299,792,458 m/s exactly [1].

Length and frequency are now tied by c alone. The inverse metre–hertz relationship is 299,792,458 Hz, exact [1]. A length is a time multiplied by 299,792,458 m/s.

Year	Who	Method	Value	Against c
1676	Rømer	Io eclipses	22 min across the orbit (2.27×10^8 m/s)	−24 %
1676–1690	Huygens	from Rømer	220,000 km/s	−27 %
1729	Bradley	aberration	10,210 × Earth's orbital speed; 8 min 12 s from the Sun	−1.4 % in time
1849	Fizeau	toothed wheel, 8,633 m	313,274 km/s	+4.5 %
after 1849	Cornu	toothed wheel	300,400 km/s	+0.2 %
1862	Foucault	rotating mirror	298,000 km/s	−0.6 %
1879	Michelson	rotating mirror	299,910 ± 50 km/s	+0.04 %
1883	Michelson	rotating mirror	299,853 ± 60 km/s	+0.02 %
1926	Michelson	Mount Wilson	299,796 ± 4 km/s	$+1.2 \times 10^{-5}$
1935	Michelson, Pease, Pearson	one-mile vacuum tube	299,774 ± 11 km/s	-6.2×10^{-5}
1950	Essen	cavity resonator	299,792.5 ± 3.0 km/s	$+1.4 \times 10^{-7}$

1972	Evenson et al.	laser frequency × wavelength	299,792,456.2 ± 1.1 m/s	-6.0×10^{-9}
1983	CGPM	definition	299,792,458 m/s exact	0

Over 296 years the error fell in steps tied to method [3][5][6]. Astronomical timing gave tens of percent, mechanical chopping of light a few percent, rotating mirrors 10^{-4} to 10^{-5}. Microwave cavities gave 10^{-7} and laser frequency chains 10^{-9}.

Light in portions, 1887–1931

In 1887 Hertz saw ultraviolet light change an electric spark [11]. Hallwachs and Lenard studied the effect from 1886 to 1902 [11]. In 1902 Lenard found that the energy of each emitted electron was independent of the intensity of the light [11].

In 1905 Einstein published “On a Heuristic Viewpoint Concerning the Emission and Transformation of Light” [11]. It treated light as arriving in portions. Millikan tested it in “A Direct Determination of ‘h’” (1914) and “A Direct Photoelectric Determination of Planck’s ‘h’” (1916) [11].

Einstein received the Nobel Prize of 1921 “for his discovery of the law of the photoelectric effect” [11]. Millikan received the prize of 1923 for his work on the elementary charge and on the photoelectric effect [11]. The constant in the energy of a portion, Planck’s h, is now exact: $6.62607015 \times 10^{-34}$ J s [1][2].

In 1923 Compton scattered X-rays of about 17 keV off light elements [12]. The scattered rays came out with longer wavelengths, as if each portion had struck one electron and recoiled. His paper, “A Quantum Theory of the Scattering of X-Rays by Light Elements”, appeared in *Physical Review* 21(5):483–502 [12].

The scale of the shift is the Compton wavelength of the electron, $h/(m_e c) = 2.42631023538(76) \times 10^{-12}$ m, at position −8.96 [1]. At 180° the shift is twice that, 4.85 pm. For 17 keV X-rays, of wavelength 1.2398×10^{-6} eV m / 17,000 eV = 72.9 pm (position −5.86), that is a change of 6.7 %.

The Compton wavelength is the first electron length in this book, and it is an identity of the units. S_0 is half the inverse Rydberg constant, $S_0 = 1/(2R)$ [26], and $R\infty = \alpha^2 m_e c/(2h)$ [1]. So $\lambda\_C / S_0 = \alpha^2$ exactly: 2.42631 pm / 45.5634 nm = $5.32514 \times 10^{-5} = (7.2973525643 \times 10^{-3})^2$.

The position of λ_C is therefore $2 \log_3 \alpha = -8.96$, for either Rydberg constant. The same holds for the Bohr radius, $a_0 = (\alpha/2\pi) \cdot S_0$, at $\log_3(\alpha/2\pi) = -6.15$, and the classical orbit time of hydrogen equals T_0.

The net texts place the two lengths at −8.96 and −6.15 [30], and the orbit time at the unit of time [29]. These electron positions follow from the choice of unit and from α; chapter 2 meets them again.

Bothe and Geiger, and Compton and Simon, checked single scattering events in coincidence [12]. Momentum was conserved in each event, which ruled out the BKS theory [12]. Compton received the Nobel Prize in 1927 [12].

The low-energy limit of photon–electron scattering is the Thomson cross section, $6.6524587051(62) \times 10^{-29}$ m² [1]. The PDG table, still on the 2018 values, gives 0.66524587321(60) barn [13]. On 18 December 1926 G. N. Lewis named the portion the photon, in a letter to *Nature* [9].

In 1931 Raman and Bhagavantam showed that the photon carries spin angular momentum $\pm\hbar$, independent of its frequency [9]. Light now had energy, momentum and spin in portions. Each was measured through an electron that was ejected, recoiled or changed state.

In the net, the photon is the first row of the table of strand, winding, knot and mesh. In the words of the net’s main text: “One ratio, one directed stretch, one photon on an open path.” [26]

The strand on an open path is the free photon. A strand that returns on itself in phase is

a winding, which is what physics calls energy. Windings that hold each other in three directions form a knot, which is mass [26].

Mass, charge and lifetime of the photon

Every measured property of the photon apart from its speed and spin is a bound. The Particle Data Group gives a mass below 1×10^{-18} eV [7]. In kilograms that is $1 \times 10^{-18} \times 1.602176634 \times 10^{-19}\ \mathrm{J} / c^2 = 1.78 \times 10^{-54}$ kg, less than 2×10^{-24} of the electron's mass.

The limit comes from magnetohydrodynamics of the solar wind, a method extended to the radius of Pluto's orbit (Ryutov 2007) [8]. The largest laboratory gives the tightest accepted bound. The PDG lists further limits that it does not use for its average [8].

Study	Method	Mass limit
Ryutov 2007 (used)	solar-wind MHD to Pluto's orbit	$< 1 \times 10^{-18}$ eV
Wang 2023	fast-radio-burst dispersion (68 % CL)	$< 2.1 \times 10^{-15}$ eV
Bonetti 2017	repeating FRB 121102, frequency-dependent delays	$< 2.2 \times 10^{-14}$ eV
Bonetti 2016	FRB 150418, at the initially reported redshift	$< 1.8 \times 10^{-14}$ eV
Retinò 2016	Ampère's law in the solar wind, Cluster spacecraft	$< 1.9 \times 10^{-15}$ eV
Egorov 2014	lensed quasar positions (95 % CL)	$< 2.3 \times 10^{-9}$ eV
Tu 2006	torque on a rotating magnetized toroid	$< 1 \times 10^{-19}$ eV (frequentist 1.2×10^{-19})
Adelberger 2007	Proca galactic field	$< 1 \times 10^{-26}$ eV
Füllekrug 2004	speed of 5–50 Hz radiation in the atmosphere, called questionable	$< 2 \times 10^{-16}$ eV

The bounds differ by seventeen orders of magnitude.

The galactic-field bound of Adelberger holds only for a Proca photon; for a photon with a Higgs-type mass "no limit feasible" [8]. An encyclopaedia page cites a galactic vector-potential bound of 3×10^{-27} eV and a Coulomb-law bound of about 10^{-14} eV (Williams et al. 1971) [9]. It gives a PDG value of 1.07×10^{-27} eV; the PDG summary table gives 1×10^{-18} eV [9][7].

The charge of the photon is bounded below 1×10^{-35} e for a single charge, from the isotropy of the cosmic microwave background (Caprini 2005) [7][8]. For mixed charges the bound is 1×10^{-46} e, from a VLBI search for an Aharonov–Bohm phase shift (Altschul 2007) [7][8]. A laboratory deflection of laser light gives 8.5×10^{-17} e (Semertzidis 2003) [8].

The PDG lists the photon as stable [7]. For a massive photon a lifetime above 10^{18} years is quoted (Heeck 2013) [9]. That is 3.16×10^{25} s, at time position 86.60.

Charge brings in the first basic of the net, the trit. Every crossing of the strand holds one of three values: +1, 0 or −1; the strand passes in one sense, in the other, or not at all [26]. The net texts write charge in this three-valued register, as the scalar residue of non-closure [28].

Three trits in a row form a window. A window is closed when its three values add to zero, counted in threes; of the 27 possible windows, 9 are closed [32]. Three of the closed ones hold one value three times, the form of a crystal; six hold all three values, so the content changes while the window stays closed, the form of metabolism.

What closes, stays; an open window carries tension [26]. Read on this register, the electron and the positron stand at −1 and +1. The photon, at less than 10^{-35} e, reads as 0.

Single photons, 1909–2018

In 1909 G. I. Taylor built a double-slit interference pattern from light so faint that the photons arrived one at a time [9]. The pattern formed from single arrivals.

In 1977 H. J. Kimble, M. Dagenais and L. Mandel observed photon antibunching in resonance fluorescence [14][9].

Antibunching means that one emitting atom never sends two photons at once. After each emission the atom must be excited again before it emits the next. In 1986 P. Grangier, G. Roger and A. Aspect reported evidence for a photon anticorrelation effect on a beam splitter, single-photon interference with one portion at a time [15].

This is the form never loaded twice (form 5). A closure cannot load twice in succession without first discharging; the net writes it $\Psi^2 = 0$ [31]. The single emitter shows the same order: excite, emit, excite again.

A single photon can make a rod of the human retina answer [34]. The eye counts single portions. The detector of the oldest light measurements is a counter of photons.

The time an electron takes to leave a surface after a photon strikes it has been measured. It is about 100 as in a solid (Cavalieri et al. 2007), 20 as (Schultze et al. 2010) and 45 as (Ossiander et al. 2018), with 1 as = 10^{-18} s [11]. The positions are −0.38, −1.85 and −1.11: all of them shorter than the unit T_0 = 152 as.

Year	Who	Measured	Value	Position
1909	Taylor	interference from single arrivals	—	—
1977	Kimble, Dagenais, Mandel	photon antibunching	—	—
1986	Grangier, Roger, Aspect	anticorrelation on a beam splitter	—	—
2007	Cavalieri et al.	photoemission delay	about 100 as	−0.38
2010	Schultze et al.	photoemission delay	20 as	−1.85
2018	Ossiander et al.	absolute photoemission timing	45 as	−1.11

The spectrum

The spectrum is one quantity, the wavelength, listed in decades. Each decade down in wavelength is a decade up in photon energy, $E = hc/\lambda$ with $hc = 1.2398 \times 10^{-6}$ eV m [1]. The named bands are conventions; their lower-frequency edges are listed below [10].

Because $S_0 = c \cdot T_0$, a wavelength and its period have the same position. The table gives one position for both.

Band (lower-frequency edge)	Wavelength	Frequency	Photon energy	Position
Gamma	10 pm	30 EHz	124 keV	−7.67
Hard X-ray	100 pm	3 EHz	12.4 keV	−5.57
Soft X-ray	10 nm	30 PHz	124 eV	−1.38
Extreme ultraviolet	121 nm	3 PHz	10.2 eV	0.89
Near ultraviolet	400 nm	750 THz	3.1 eV	1.98
Visible, red end	700 nm	480 THz	1.77 eV	2.49
Near infrared	1 µm	300 THz	1.24 eV	2.81
Mid infrared	10 µm	30 THz	124 meV	4.91
Far infrared	100 µm	3 THz	12.4 meV	7.00
Far infrared, lower edge	1 mm	300 GHz	1.24 meV	9.10
Microwave EHF	1 cm	30 GHz	124 µeV	11.19

Microwave SHF	10 cm	3 GHz	12.4 µeV	13.29
Microwave UHF	1 m	300 MHz	1.24 µeV	15.39
Radio VHF	10 m	30 MHz	124 neV	17.48
Radio HF	100 m	3 MHz	12.4 neV	19.58
Radio MF	1 km	300 kHz	1.24 neV	21.67
Radio LF	10 km	30 kHz	124 peV	23.77
Radio VLF	100 km	3 kHz	12.4 peV	25.87
Band 3	1,000 km	300 Hz	1.24 peV	27.96
Band 2	10,000 km	30 Hz	124 feV	30.06
Band 1	100,000 km	3 Hz	12.4 feV	32.15

Gamma rays have no defined lower limit to their wavelength, and long waves can be indefinitely long [10]. Astronomy uses the range from 2.4×10^{23} Hz, the frequency of 1 GeV gamma rays, down to about 1 kHz [10]. Below that, the plasma of the ionized interstellar gas stops the waves; 1 kHz has a wavelength of 300 km, at 26.87.

Visible light runs from 400 nm to 700 nm, positions 1.98 to 2.49 [10]. That is $\log_{10}(700/400) = 0.24$ of one decade, half a step on the ladder. Each step of the ladder is a factor 3, 0.48 of a decade.

The measured spectrum runs from 3 Hz to the 2.5 PeV photons of the last section. Their frequency is $E/h = 2.5 \times 10^{15} \times 1.602176634 \times 10^{-19}$ J / $6.62607015 \times 10^{-34}$ J s = 6.0×10^{29} Hz. That is 29.3 decades, from position −29.27 to 32.15: 61.42 steps of the ladder.

The laws of thermal radiation have exact constants since 2019 [1]. The Stefan–Boltzmann constant is $5.670374419 \times 10^{-8}$ W m^{-2} K^{-4}; the first radiation constant $3.741771852 \times 10^{-16}$ W m^2. Wien's displacement constants are $2.897771955 \times 10^{-3}$ m K for the wavelength and $5.878925757 \times 10^{10}$ Hz K^{-1} for the frequency.

The spectrum has the form of the same winding at every depth (form 13). One relation, $E = hc/\lambda$, holds unchanged over 61 positions of the ladder, from 4.96×10^{-22} m to 10^8 m. The ladder below zero is a count of steps, not a floor: position 0 is a measuring rod, chosen the way the metre is chosen [30].

The units of the ladder: the light of hydrogen

The two units of the ladder are lengths and times of hydrogen's light. T_0 is half the period of the Rydberg frequency, and $S_0 = c \cdot T_0 = 1/(2R)$ [26]. The Rydberg constant R_∞ is 10,973,731.568157(12) m^{-1} [1].

Larson's unit uses the Rydberg constant of hydrogen itself. That is $R_H = R_\infty/(1 + m_e/m_p) = 10{,}973{,}731.57\ \text{m}^{-1} / (1 + 1/1836.15) = 10{,}967{,}758\ \text{m}^{-1}$ [1]. Then $S_0 = 1/(2R_H) = 45.588$ nm and $T_0 = 1/(2R_H\, c) = 1.520658 \times 10^{-16}$ s, which agrees with Larson's 1.520655×10^{-16} s to 2 parts in a million.

With R_∞ instead, $S_0 = 45.5634$ nm and $T_0 = 1.519830 \times 10^{-16}$ s; both values circulate in the net texts [26][29]. They differ by 0.054 %, the ratio of the electron's mass to the proton's. On the ladder that is 0.0005 positions, invisible at two decimals.

The shortest wavelength of the Lyman series of hydrogen, the Lyman limit, is $1/R_H = 91.18$ nm, at position 0.63. S_0 is half of it. The unit of the ladder is a wavelength of hydrogen's light, cut in two.

Some lines of hydrogen therefore fall on whole positions as identities. The Balmer line Hδ, from level 6 to level 2, has $1/\lambda = R_H(1/4 - 1/36) = (2/9)R_H$, so $\lambda = 9/(2R_H) = 9 \cdot S_0$ [29]. Computed, it is 410.2935 nm against 9×45.58816 nm = 410.2934 nm, at position 2.00.

The same unit fixes the electron lengths named in the Compton section. $\lambda_C = \alpha^2 \cdot S_0$ and $a_0 = (\alpha/2\pi) \cdot S_0$ are identities of the Rydberg unit, not findings. The classical orbit time of the electron in hydrogen, $2\pi a_0/(\alpha c) = 1.519830 \times 10^{-16}$ s, is T_0 itself.

Light into matter, 1932–2021

In 1932 Carl Anderson found the positron in cosmic rays [17]. Pair production was first observed in Patrick Blackett's counter-controlled cloud chamber [16]. A photon near a nucleus turned into an electron and a positron.

The threshold is twice the electron's rest energy. With $m_e c^2$ = 0.51099895069(16) MeV [1], $2m_e c^2$ = 1.02199790138 MeV = 1.637×10^{-13} J. A photon at that energy has a wavelength of 1.2132 pm, position −9.59 [16]; that is λ_C/2, one factor 2 below the Compton wavelength.

The cross-section grows roughly as the square of the atomic number of the nucleus nearby [16]. Above the MeV scale pair production is the dominant interaction of photons with matter [16]. Light becomes matter wherever it carries more than 1.022 MeV near a charge.

In 1997 the E-144 experiment at SLAC, by D. L. Burke and colleagues, reported "Positron Production in Multiphoton Light-by-Light Scattering" [18]. Several photons together made a pair, the multiphoton form of the Breit–Wheeler process [18]. The net texts record it as matter made from light on light [33].

In 2021 the STAR collaboration at RHIC measured the Breit–Wheeler process, matter and antimatter from the collision of two photons [19]. Gold nuclei passed each other at √s_NN = 200 GeV without touching, and their fields supplied linearly polarized photons. STAR counted 6,085 exclusive electron–positron pairs, with a cos 4Δφ modulation of (16.8 ± 2.5) %, 6.7 standard errors from zero [19].

Here the net needs its second basic, the ring. A strand that returns on itself in phase is a winding [26]. A ring of trits can close with all three values only at lengths 3, 6, 9 and so on, since the values must add to zero in threes.

The count of nested rings is the depth. An address in the net is a depth plus a number in balanced ternary [26]. In the books on life, depth 3 is the first ring that stays closed while all its values change, and at depth 6 that ring divides into two closed rings of three.

Below the nucleus the winding is the photon on a closed loop [26]. The net texts take the electron from Williamson and van der Mark (1997): a photon confined to a double loop, a torus [26][27]. In the net texts the electron–positron pair is the smallest knot, formed from windings alone [33].

Every knot made from light has appeared with its mirror. In Blackett's chamber, at SLAC and at STAR the electron came with a positron [16][18][19]. The net texts record that no measurement has produced a knot without its mirror [33]; here the form is the mirror, with the positron the electron reversed.

Year	Experiment	Process	Measured
1932	Anderson	positron in cosmic rays	discovery
after 1932	Blackett	pair production in a counter-controlled cloud chamber	observation
1997	SLAC E-144	several photons on one electron → e^+e^-	positrons
2021	STAR, Au+Au at 200 GeV	$\gamma\gamma \to e^+e^-$ (Breit–Wheeler)	6,085 pairs; cos 4Δφ = 16.8 ± 2.5 %

Light on light, 2017–2019

Two photons can also scatter off each other and stay photons. In 2017 the ATLAS collaboration at the LHC reported evidence for this light-by-light scattering in lead–lead collisions at 5.02 TeV per nucleon pair [20]. With 480 μb^{-1} of data, 13 candidate events were seen against an expected background of 2.6 ± 0.7 [20].

The measured cross-section was 70 ± 24 (statistical) ± 17 (systematic) nb [20]. It held for photons of E_T > 3 GeV, |η| < 2.4, pair mass above 6 GeV, pair transverse momentum below 2 GeV and acoplanarity below 0.01. It agreed with the Standard Model [20].

In 2019 ATLAS observed the process with 1.73 nb⁻¹, 3.6 times the earlier data [21]. There were 59 candidate events against a background of 12 ± 3, a significance of 8.2 standard deviations [21]. The cross-section was 78 ± 13 (stat) ± 7 (syst) ± 3 (lumi) nb [21].

The counts are small: 13, then 59 events. Both runs used the fields of heavy ions passing without contact, where the nuclear charge supplies a dense flux of nearly real photons [20][21]. Light on light is measured only where fields are extreme; chapter 9 returns to it with the measured vacuum.

Year	Experiment	Data	Events	Background	Cross-section
2017	ATLAS, Pb+Pb	480 μb⁻¹	13	2.6 ± 0.7	70 ± 24 ± 17 nb
2019	ATLAS, Pb+Pb	1.73 nb⁻¹	59	12 ± 3	78 ± 13 ± 7 ± 3 nb

The extremes: the hottest photons and the photon bath

In 2021 the LHAASO observatory in China reported photons up to 1.4 PeV [22]. They came from 12 ultrahigh-energy gamma-ray sources in the Galaxy, each above seven standard deviations, with more than 530 photons above 100 TeV [22]. A photon of 1.4 PeV has a wavelength of 8.86×10^{-22} m, at position −28.74.

In 2024 LHAASO reported a gamma-ray bubble in Cygnus X spanning at least 100 square degrees, with 2 photons above 1 PeV in its core [23]. The press release of the institute gave the highest energy as 2.5 PeV [24].

That photon carries $2.5 \times 10^{15} \times 1.602176634 \times 10^{-19}$ J = 4.0×10^{-4} J. Its wavelength is 1.2398×10^{-6} eV m / 2.5×10^{15} eV = 4.96×10^{-22} m, at position −29.27.

The same release names cosmic-ray particles with energies up to 20 PeV, and a break in their spectrum, the knee, near 1 PeV [24]. The array has 5,216 electromagnetic particle detectors, 1,188 muon detectors and 18 wide-angle Cherenkov telescopes [24]. The hottest photons are rare and come from a few places in the Galactic plane.

The coldest photons are the most numerous. The cosmic microwave background has a temperature of 2.7255(6) K and holds 410.73(27) photons per cubic centimetre, 4.107×10^8 per cubic metre [25]. Its energy density is $4.645(4) \times 10^{-34}$ g cm⁻³, about 0.260 eV cm⁻³ [25].

The mean energy per photon is 0.260 / 410.73 = 6.33×10^{-4} eV. By Wien’s law the spectrum peaks at $2.897771955 \times 10^{-3}$ m K / 2.7255 K = 1.063 mm, at position 9.15. The photon share of the cosmic density is $\Omega_\gamma = 5.38(15) \times 10^{-5}$ [25].

The baryon-to-photon ratio from the synthesis of the first nuclei is $\eta = 6.04(12) \times 10^{-10}$ [25]. That is 1 / 6.04×10^{-10} = 1.66×10^9 photons for each baryon. The background also shows the motion of the Sun: a dipole of 3.3621(10) mK, a velocity of 369.82(11) km/s towards galactic longitude 264.021° and latitude 48.253° [25].

The measured photon energies span from 6.33×10^{-4} eV to 2.5×10^{15} eV, a factor of 3.9×10^{18}. The photons in flight outnumber the baryons by more than a billion to one. In the net they are the open strand between closures.

Quantity	Value	Position
Highest photon energy, 2021	1.4 PeV (λ = 8.86×10^{-22} m)	−28.74
Highest photon energy, 2024	2.5 PeV (λ = 4.96×10^{-22} m)	−29.27
Sources above 7σ beyond 100 TeV, 2021	12	—
Photons above 100 TeV, 2021	more than 530	—
Photons above 1 PeV in the Cygnus core, 2024	2	—
CMB temperature	2.7255(6) K	—
CMB peak wavelength	1.063 mm	9.15
CMB photon density	410.73(27) cm⁻³	—
CMB energy density	0.260 eV cm⁻³	—
Mean CMB photon energy	6.33×10^{-4} eV	—
Photons per baryon	1.66×10^9	—

What this part of the history shows

Light was measured long before it was understood. Its speed went from 24 % low in 1676 to an exact number in 1983. Each gain in precision came with a new method, until the measurement was limited by the metre and the number was fixed.

The speed first entered physics as a modulus of a medium. Maxwell's 1861 figure, 3.7 % high, came from the elastic constants of his medium. The form is context (form 14): the textbook later froze those constants, and the net reads them again as states of the local vacuum.

The photon is the open strand, the first row of the net texts' table. Each of its portions was measured where it met an electron. The electron was ejected in the photoelectric effect, recoiled in Compton's X-rays and was excited in the single emitter.

The single emitter gives one photon at a time. After each emission it must be excited again, as the antibunching of 1977 and the anticorrelation of 1986 showed. That order, load, discharge, load again, is the form never loaded twice (form 5).

Read on the register of charge, the photon stands at zero, with a measured charge below 10^{-35} e. Its mass is below 10^{-18} eV, less than 2×10^{-24} of the electron's mass. Every measured property of the open strand apart from speed and spin is a bound.

The spectrum shows the same form at every depth (form 13). $E = hc/\lambda$ holds from 3 Hz to 6×10^{29} Hz, over 61 positions of the ladder. Visible light takes half a step of it, at positions 1.98 to 2.49.

The units of the ladder come from hydrogen's light. $S_0 = 1/(2R)$ is half the Lyman limit, $H\delta = 9 \cdot S_0$ sits at position 2.00, and the Compton wavelength sits at $2 \log_3 \alpha = -8.96$. These are identities of the unit, stated as such; they set the ruler on which the rest of the book is read.

Light becomes matter above 1.022 MeV, and always as a pair. Blackett's chamber, SLAC E-144 and the 6,085 pairs at STAR each gave an electron with a positron. Here the form is the mirror: no knot made from light appeared without its reversed twin.

Light also scatters on light, in 13 and then 59 events at the LHC. At the cold end, 411 photons fill every cubic centimetre of space, 1.66×10^9 for each baryon. The open strand is everywhere; the closures it joins are few.

2. The Electron

The electron was the first particle found below the atom. It was found in a glass tube in 1897, as a ray that carried charge. Within thirty years it had a charge, a mass, a spin and a place in every atom.

Today it is the most precisely measured particle there is. Its magnetic moment is known to 1.3 parts in 10^{13}. Its mass is known to 3 parts in 10^{10}, and no decay of it has ever been seen.

This chapter follows the electron from the cathode tube to the trapped single electron of 2023. It then follows its two heavier copies, the muon and the tau, and the atom it makes with the proton. In chapter 1 the electron was the partner that measured light; here it is measured itself.

The particle of the cathode rays, 1897–1925

In 1897 J. J. Thomson measured the ratio of charge to mass of cathode rays [17]. By 1899 he had shown that this ratio was independent of the material of the cathode [17]. The rays were one kind of particle, the same in every metal.

Robert Millikan then measured the charge itself. His oil-drop method used an electric field to stop a charged droplet of oil from falling [17].

In 1925 Goudsmit and Uhlenbeck proposed that the electron, besides the angular momentum of its orbit, has an angular momentum of its own [17]. This is its spin.

The net texts take the electron as a photon closed on itself. Following Williamson and van der Mark (1997), the electron is light confined to a double loop, a torus [27][26]. In the net's words it is "a winding that must turn twice before it meets itself." [55]

The net texts read the two turns as the spin. A strand returns to its initial state after a rotation of 4π, 720°, and not after 2π; spin one half is the label of that return [27]. The orientation states of a winding form the unit quaternions, which cover each rotation twice [27][28].

Mass and charge today

The CODATA 2022 adjustment gives the electron's mass as $m_e = 9.1093837139(28) \times 10^{-31}$ kg [1]. Its rest energy is $m_e c^2 = 0.51099895069(16)$ MeV [1]. The relative uncertainty is 3.1×10^{-10}.

The tables of the Particle Data Group of 2024 still carry the CODATA 2018 values: 0.51099895000(15) MeV and $9.1093837015(28) \times 10^{-31}$ kg [35][13]. From 2018 to 2022 the value rose by 6.9×10^{-10} MeV. That is 1.35×10^{-9} of the mass and 4.6 of the 2018 standard uncertainties.

The proton is 1836.152673426(32) times heavier than the electron [1]. The inverse ratio is $5.446170214889(94) \times 10^{-4}$ [1]. The charge is $e = 1.602176634 \times 10^{-19}$ C, exact since the redefinition of the SI in 2019 [1].

The ratio of charge to mass that Thomson measured is now $e/m_e = -1.75882000838(55) \times 10^{11}$ C kg^{-1} [1]. The positron carries the same charge with the opposite sign. The sum of the two charges is below 4×10^{-8} of e, at 90 % confidence [35].

Read on the register of chapter 1, the electron and the positron stand at −1 and +1. The net texts give a charge and its opposite the same address, mirrored trit by trit [27]. The measured equality to 4 parts in 10^{8} shows that mirror; chapter 7 follows it through antimatter.

Quantity	CODATA 2022	PDG 2024 (CODATA 2018)
m_e	$9.1093837139(28) \times 10^{-31}$ kg	$9.1093837015(28) \times 10^{-31}$ kg

$m_e c^2$	0.51099895069(16) MeV	0.51099895000(15) MeV
m_p/m_e	1836.152673426(32)	—
e	$1.602176634 \times 10^{-19}$ C, exact	same
e/m_e	$-1.75882000838(55) \times 10^{11}$ C/kg	—
q(e⁺) + q(e⁻)	—	$< 4 \times 10^{-8}$ e (90 % CL)

An electron that does not decay

No decay of the electron has been seen. The lower bound on its mean life is 6.6×10^{28} years at 90 % confidence, from the Borexino detector in 2015 [35][36]. The bound is two orders of magnitude better than the one before it [36].

Borexino looked for an electron turning into a neutrino and a single photon of fixed energy [36]. By the balance of energy that photon would carry $m_e c^2/2 = 255.5$ keV. The line was absent.

In seconds the bound is $6.6 \times 10^{28} \times 3.15576 \times 10^{7}$ s $= 2.08 \times 10^{36}$ s. Its time position is 109.27. Borexino set the bound as a test of the conservation of electric charge [36].

The electron has the form of what closes, stays (form 1). A closed winding keeps its form while it lasts, and this one has lasted beyond every bound set. Its heavier copies, the muon and the tau, decay within microseconds and femtoseconds.

The size of the electron

Every measurement of the electron’s size is an upper limit. A single electron held in a Penning trap gives an upper limit on its radius of 10^{-22} m (Dehmelt 1988) [17][37]. That is position −30.72.

The uncertainty relation in energy, applied to collider data, gives an upper bound of 10^{-18} m [17]. That is position −22.34. The two limits differ by four orders of magnitude; the first rests on a model that ties the magnetic anomaly to a radius, the second on collision energies.

Even the larger bound is 10^{-18} m / 8.4075×10^{-16} m = 0.0012 of the proton’s charge radius. The proton sits at −16.21 [1]. The electron is at least six positions smaller.

The lengths usually tied to the electron are built from its mass and charge. They are the classical electron radius, the reduced Compton wavelength, the Compton wavelength and the Bohr radius. Each step between the first, second and fourth is a factor α.

Length	Value	Position	Definition
Penning-trap limit	$< 10^{-22}$ m	−30.72	upper limit
Uncertainty-relation limit	$< 10^{-18}$ m	−22.34	upper limit
Proton charge radius	0.84075(64) fm	−16.21	measured
Classical radius r_e	2.8179403205(13) fm	−15.11	$e^2/(4\pi\varepsilon_0 m_e c^2)$
Reduced Compton wavelength ƛ_C	0.38615926744(12) pm	−10.63	$\hbar/(m_e c)$
Compton wavelength λ_C	2.42631023538(76) pm	−8.96	$h/(m_e c)$
Bohr radius a_0	52.9177210544(82) pm	−6.15	$\hbar/(\alpha m_e c)$

The values are those of CODATA 2022 [1]. The 2018 values in the PDG tables are r_e = 2.8179403262(13) fm and $a_0 = 0.529177210903(80) \times 10^{-10}$ m [13]. The classical radius is not a measure of the structure of the electron [17].

The steps are exact. $\alpha^2 a_0 = (7.2973525643 \times 10^{-3})^2 \times 52.9177210544$ pm = 2.817940320 fm = r_e. $\alpha\, a_0 = 0.3861592674$ pm = ƛ_C; on the ladder each step is $\log_3(1/\alpha) = 4.48$ positions.

These electron lengths are identities of the ladder’s units, as chapter 1 set out. With $S_0 = 1/(2R\infty)$, $\lambda\text{_C} = \alpha^2 \cdot S_0$ and $a_0 = (\alpha/2\pi) \cdot S_0$; the net texts place the two at −8.96 and

−6.15 [30]. Computed, $\lambda_C/S_0 = 5.3251354 \times 10^{-5} = \alpha^2$, and $a_0/S_0 = 0.00116141 = \alpha/2\pi$.

The classical radius follows in the same way, $r_e = (\alpha^3/2\pi)\cdot S_0$, at $\log_3(\alpha^3/2\pi) = -15.11$. So the positions −15.11, −10.63, −8.96 and −6.15 are α written on the ladder. The proton at −16.21 and the limits at −22.34 and −30.72 are measured placements.

The magnetic moment, 1987–2023

The electron’s magnetic moment is the most precisely measured property of any elementary particle. It is written g/2, in units of the Bohr magneton. Dirac’s equation gives exactly 1; the measured value is larger by an anomaly $a_e = g/2 - 1$.

In 2008 D. Hanneke, S. Fogwell and G. Gabrielse measured g/2 = 1.00115965218073(28), to 0.28 parts per trillion [39]. Their uncertainty was 2.7 times smaller than that of 2006 and 15 times smaller than that of 1987 [39].

In 2023 X. Fan, T. G. Myers, B. A. D. Sukra and Gabrielse held one electron in a Penning trap at low temperature, a quantum cyclotron [38]. They measured g/2 = 1.00115965218059(13), to 0.13 parts per trillion, 2.2 times more precise than 2008 [38]. The new value lies 1.4×10^{-13} below the old one, 0.45 combined standard errors.

The anomaly is $a_e = 1.15965218059(13) \times 10^{-3}$ [38]. On the anomaly alone the uncertainty is $0.13 \times 10^{-12} / 1.1597 \times 10^{-3} = 1.1 \times 10^{-10}$. CODATA 2022 gives $a_e = 1.15965218046(18) \times 10^{-3}$ and g = −2.00231930436092(36) [1].

The PDG gives $a_e = (1159.65218062 \pm 0.00000012) \times 10^{-6}$ [35]. The Bohr magneton is $\mu_B = 9.2740100657(29) \times 10^{-24}$ J T⁻¹ [1]. The electron’s magnetic moment is $-9.2847646917(29) \times 10^{-24}$ J T⁻¹, and its gyromagnetic ratio $1.76085962784(55) \times 10^{11}$ s⁻¹ T⁻¹ [1].

Read as the remainder of form 11, the anomaly is what is left over Dirac’s 1: 1.16×10^{-3}. The net texts say of α that its tuning is exact only at the renormalization fixed point, leaving a residue [58].

Year	Who	g/2	Relative uncertainty
2008	Hanneke, Fogwell, Gabrielse	1.00115965218073(28)	2.8×10^{-13}
2023	Fan, Myers, Sukra, Gabrielse	1.00115965218059(13)	1.3×10^{-13}
2022	CODATA, a_e	$1.15965218046(18) \times 10^{-3}$	1.6×10^{-10} of a_e

The electric dipole moment

A charge displaced from the centre of a particle would give it an electric dipole moment. For the electron none has been seen. The PDG bound is $|d_e| < 0.041 \times 10^{-28}$ e cm = 4.1×10^{-30} e cm, at 90 % confidence [35].

In SI lengths that is 4.1×10^{-32} e m. As a displacement of one charge it is 4.1×10^{-32} m / 8.4075×10^{-16} m = 4.9×10^{-17} of the proton’s radius. The electron is round to that degree.

The bound comes from JILA in 2023, by T. S. Roussy, J. Ye, E. A. Cornell and colleagues [40]. They held electrons inside molecular ions, the most precise measurement of its kind [40]. Their result is consistent with zero and lowered the earlier bound by a factor of about 2.4 [40].

The fine-structure constant α

The constant α ties the electron’s charge to light. CODATA 2022 gives $\alpha = 7.2973525643(11) \times 10^{-3}$ and $\alpha^{-1} = 137.035999177(21)$, a relative uncertainty of 1.5×10^{-10} [1]. The 2018 value was $\alpha^{-1} = 137.035999084(21)$; the step to 2022 was 9.3 ×

10^{-8}, 4.4 of the 2018 standard uncertainties [13].

α is measured in two independent ways. One is the recoil of an atom that absorbs a photon, which gives h/m for the atom. The other is the electron's magnetic anomaly, turned into α by the theory of quantum electrodynamics.

In 2008 the anomaly of Hanneke and colleagues gave $\alpha^{-1} = 137.035999084(51)$, to 0.37 parts per billion [39]. In 2018 R. H. Parker, C. Yu, W. Zhong, B. Estey and H. Müller at Berkeley measured caesium recoil [41]. They found $\alpha = 1/137.035999046(27)$, to 2.0×10^{-10}, in a 2.5σ tension with the electron anomaly [41].

In 2020 L. Morel, Z. Yao, P. Cladé and S. Guellati-Khélifa in Paris measured rubidium recoil [42]. They found $\alpha^{-1} = 137.035999206(11)$, to 81 parts per trillion [42]. It differs by more than five standard deviations from the caesium value [42].

In 2023 the anomaly of Fan and colleagues gave $\alpha^{-1} = 137.035999166(15)$, to 0.11 parts per billion [38]. Its uncertainty is ten times smaller than the disagreement between the measured values [38]. It lies between the two atoms.

Year	Source	Method	α^{-1}	Relative uncertainty
2008	Hanneke et al.	electron g − 2 + QED	137.035999084(51)	3.7×10^{-10}
2018	Parker et al.	caesium recoil	137.035999046(27)	2.0×10^{-10}
2020	Morel et al.	rubidium recoil	137.035999206(11)	8.1×10^{-11}
2023	Fan et al.	electron g − 2 + QED	137.035999166(15)	1.1×10^{-10}
2018	CODATA	adjustment	137.035999084(21)	1.5×10^{-10}
2022	CODATA	adjustment	137.035999177(21)	1.5×10^{-10}

The differences follow from the table. Rubidium minus caesium is 160×10^{-9} in α^{-1}; with the combined uncertainty of 29×10^{-9} that is 5.5σ. The 2023 anomaly value lies 40×10^{-9} below rubidium (2.1σ) and 120×10^{-9} above caesium (3.9σ); CODATA 2022 lies 11×10^{-9} above it.

The change in α moved the lengths built on it. The PDG 2018 reduced Compton wavelength is $3.8615926796(12) \times 10^{-13}$ m [13]. The 2022 value is 5.2×10^{-22} m smaller, 4.3 of the 2018 uncertainties [1].

α also changes with the energy at which it is measured. At low energy it is 1/137.036; at a momentum transfer near the W mass the PDG gives about 1/128 [13]. An encyclopaedia page gives about 1/127 near 90 GeV [57].

The running of α has the form of context (form 14). The same constant takes another value in other surroundings, here at a higher energy. The net texts hold α stiff against any state change reachable on Earth, while the effective coupling moves [56].

The heavier electrons: muon and tau

The muon has the electron's charge and spin and 206.7682827(46) times its mass [1]. Its rest energy is 105.6583755(23) MeV, or $1.883531627(42) \times 10^{-28}$ kg, the same in CODATA 2022 and the PDG [1][35]. Computed, 105.6583755 / 0.51099895069 = 206.768283.

The muon's Compton wavelength is $1.173444110(26) \times 10^{-14}$ m, at position −13.81 [1]. Its mean life is 2.1969811(22) μs, at time position 21.29 [35]. In 2013 the MuLan experiment measured 2,196,980.3(2.2) ps, to 1.0 part per million, thirty times more precise than earlier experiments [45].

From that lifetime MuLan gave the Fermi constant of the weak force, $G_F = 1.1663787(6) \times 10^{-5}$ GeV^{-2}, to 0.5 parts per million [45]. The muon's electric dipole moment is below 1.8×10^{-19} e cm at 95 % confidence [35]. That is 4.4×10^{10} times the electron's bound.

The muon's magnetic anomaly was measured at Fermilab, with the final result in 2025

[43]. All runs combined give $a_\mu = 1.165920705(148) \times 10^{-3}$, to 127 parts per billion [43]. The runs of 2020–2023 alone give $1.165920710(162) \times 10^{-3}$, and the world average is $1.165920715(145) \times 10^{-3}$, to 124 parts per billion [43].

Before the final release the PDG gave $a_\mu = (11659205.9 \pm 2.2) \times 10^{-10}$, and CODATA 2022 gave $1.16592062(41) \times 10^{-3}$ [35][1]. In 2025 the Muon g − 2 Theory Initiative gave the Standard Model value $116{,}592{,}033(62) \times 10^{-11}$, to 530 parts per billion [44]. Its leading hadronic part came from a lattice average at about 0.9 %, because the data-driven evaluations conflict [44].

The difference between experiment and theory is $38(63) \times 10^{-11}$, with no tension at the present precision [44]. With the Fermilab number alone it is $116{,}592{,}070.5 - 116{,}592{,}033 = 37.5 \times 10^{-11}$ against a combined 63.7×10^{-11}, 0.6σ. The theory uncertainty, 62×10^{-11}, is 4.2 times the experimental one, 14.8×10^{-11}.

The muon anomaly exceeds the electron's by $1.16592062 \times 10^{-3} - 1.159652180 \times 10^{-3} = 6.27 \times 10^{-6}$. That is 0.54 % [1]. The remainder over Dirac's 1 is almost the same for both.

The tau is heavier still. The PDG gives $m_\tau = 1776.93 \pm 0.09$ MeV and a mean life of $(290.3 \pm 0.5) \times 10^{-15}$ s, with $c\tau = 87.03$ μm [35]. The life sits at time position 6.88, and cτ at size position 6.88, the same number because $S_0 = c \cdot T_0$.

CODATA 2022 gives $m_\tau c^2 = 1776.86(12)$ MeV, $3.16754(21) \times 10^{-27}$ kg, and $m_\tau/m_e = 3477.23(23)$ [1]. The PDG and CODATA values differ by 0.07 MeV, inside their errors. In 2023 Belle II measured 1777.09 ± 0.08 (stat) ± 0.11 (syst) MeV from 175 million tau pairs, 190 fb^{-1} at 10.579 GeV, the most precise to date [46].

Belle II used the kinematic edge of the pseudomass in the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ [46]. Its value lies 0.16 MeV above the PDG average. For the tau the PDG gives the dipole moment $\mathrm{Re}(d_\tau)$ between -0.185 and 0.061×10^{-16} e cm and the anomaly a_τ between -0.057 and 0.024, at 95 % confidence [35].

	Electron	**Muon**	**Tau**
Mass	0.51099895069(16) MeV	105.6583755(23) MeV	1776.86(12) MeV (CODATA); 1776.93(9) MeV (PDG)
Mass / m_e	1	206.7682827(46)	3477.23(23)
Mean life	> 6.6×10^{28} years (position 109.27)	2.1969811(22) μs (position 21.29)	290.3(5) fs (position 6.88)
Anomaly a	$1.15965218046(18) \times 10^{-3}$	$1.165920705(148) \times 10^{-3}$	−0.057 to 0.024
Dipole moment	< 4.1×10^{-30} e cm	< 1.8×10^{-19} e cm	Re −1.85 to 0.61 × 10^{-17} e cm

The three charged leptons have the same charge and the same spin. Their masses stand as 1 : 206.77 : 3477.2, and their lives fall from beyond 10^{28} years to 2.2 μs to 290 fs. Read in the forms of the net, they are one form at three depths (form 13), carried at three masses.

The heavy carriers decay and the electron lasts. Read as form and carrier (form 3), the form stays while its heavier carriers live 2.2 μs and 290 fs. The precision of every quantity falls from electron to tau, with the shorter lives.

Hydrogen, 1947–2026

The electron and the proton make hydrogen, the most precisely measured bound system. In 1947 Lamb and Retherford measured with microwaves that the $2S_{1/2}$ level lies about 1,000 MHz, 0.03 cm^{-1}, above $2P_{1/2}$ [47]. Two levels of the same principal number were found apart.

The observed shift is given as 1,057 MHz [47]. Its energy is h × 1,057 MHz = 7.00×10^{-25} J = 4.37×10^{-6} eV. Its period, 1/(1,057 MHz) = 9.46×10^{-10} s, sits at time position 14.24.

In the same year Bethe was the first to calculate the shift, in "The Electromagnetic Shift

of Energy Levels” [47]. Read like the electron’s anomaly, the Lamb shift is a small remainder of 4.37×10^{-6} eV between two levels of one shell (form 11). Chapter 9 returns to it as a measurement of the vacuum.

In 2019 N. Bezginov, E. A. Hessels and colleagues at York University measured the $2S_{1/2}(f = 0)$ to $2P_{1/2}(f = 1)$ interval [48]. They found 909.8717(32) MHz, to 3.5×10^{-6}, and a proton radius of 0.833(10) fm [48]. The 909.87 MHz is one hyperfine component; the 1,057 MHz is the centroid.

In 2011 C. G. Parthey and colleagues at Garching measured the 1S–2S transition [49]. The frequency of the hyperfine centroid is 2,466,061,413,187,035(10) Hz, a fractional uncertainty of 4.2×10^{-15} [49]. The excitation is by two photons.

The 1S–2S wavelength is c/f = 121.567 nm, at position 0.89; each of the two photons is at 243.13 nm, position 1.52. The period $1/f = 4.055 \times 10^{-16}$ s also sits at 0.89. It stands at the edge of the extreme ultraviolet band of chapter 1, 121 nm at 0.89.

In 2026 L. Maisenbacher and colleagues measured the 2S–6P transition at 730,690,248,610.79(48) kHz [50]. They found a proton radius of 0.8406(15) fm, at least 2.5 times more precise than other hydrogen determinations [50]. The bound-state corrections of quantum electrodynamics were tested to 0.5 parts per million, and the Standard Model to 0.7 parts per trillion [50].

The 2S–6P line has a wavelength of c/f = 410.287 nm, at position 2.00. It is the Balmer line Hδ, which chapter 1 placed at $9 \cdot S_0$ as an identity of the unit. The measured line lies 1.6×10^{-5} below 9×45.58816 nm = 410.2934 nm.

From 1S–2S and 2S–6P together the paper gives $R\infty$ = 10,973,731.568152(14) m^{-1}, to 1.3×10^{-12} [50]. CODATA 2022 gives 10,973,731.568157(12) m^{-1}, to 1.1×10^{-12} [1]. The difference, -5×10^{-6} m^{-1}, is 0.27 combined standard errors.

The Rydberg frequency is $R\infty c = 3.2898419602500(36) \times 10^{15}$ Hz and its energy $R\infty hc$ = 13.605693122990(15) eV [1]. The PDG, on the 2018 values, gives 13.605693122994(26) eV [13]. The Hartree energy, twice the Rydberg energy, is $27.211386245981(30)$ eV $= 4.3597447222060(48) \times 10^{-18}$ J [1].

The atomic unit of time is $2.4188843265864(26) \times 10^{-17}$ s, at position −1.67 [1]. Computed, $1/(4\pi R\infty c) = 2.4188843 \times 10^{-17}$ s equals it. With $T_0 = 1/(2R\infty c)$ the ratio is then 2π exactly: 1.519830×10^{-16} s / $2.4188843 \times 10^{-17}$ s = 6.28319, another identity of the unit.

Year	Measurement	Value	Relative uncertainty	Position
1947	Lamb shift, Lamb and Retherford	about 1,000 MHz; centroid 1,057 MHz	—	14.24 (period)
2011	1S–2S, Parthey et al.	2,466,061,413,187,035(10) Hz	4.2×10^{-15}	0.89
2019	$2S_{1/2}(f=0)$–$2P_{1/2}(f=1)$, Bezginov et al.	909.8717(32) MHz	3.5×10^{-6}	14.38 (period)
2022	$R\infty$, CODATA	10,973,731.568157(12) m^{-1}	1.1×10^{-12}	—
2026	2S–6P, Maisenbacher et al.	730,690,248,610.79(48) kHz	6.6×10^{-13}	2.00
2026	$R\infty$ from 1S–2S and 2S–6P	10,973,731.568152(14) m^{-1}	1.3×10^{-12}	—

The proton seen by the muon, 2010–2026

Two numbers enter every hydrogen line: the Rydberg constant and the radius of the proton. Before 2010 hydrogen spectroscopy and electron scattering gave 0.8768(69) fm [51]. Electron–proton scattering alone gave about 0.8775(5) fm (Sick and Trautmann 2014) [54].

In 2010 R. Pohl and colleagues at the Paul Scherrer Institute measured muonic

hydrogen [51]. A muon replaces the electron and orbits 207 times closer, at $a_0/206.77 = 2.56 \times 10^{-13}$ m (position −11.01), so its 2S level feels the proton's size far more. Laser spectroscopy of the 2S–2P transition gave $r_p = 0.84184(67)$ fm, 5.0 standard deviations from the CODATA value [51].

The step was $0.8768 - 0.84184 = 0.035$ fm, a radius 4.0 % smaller. With the combined uncertainty the difference is $(0.8768 - 0.84184) / \sqrt{(0.0069^2 + 0.00067^2)} = 5.04\sigma$. The muon saw a smaller proton.

In 2013 A. Antognini and colleagues measured two 2S–2P transitions in muonic hydrogen, at 54,611.16(1.05) GHz and 49,881.35(65) GHz [52]. They found $r_E = 0.84087(39)$ fm, 1.7 times as precise as 2010 and about 7σ from CODATA 2010 [52]. They also gave a Zemach radius of 1.082(37) fm and a magnetic radius of 0.87(6) fm [52].

Then the electron measurements moved. In 2019 the hydrogen Lamb shift of Bezginov and colleagues gave 0.833(10) fm [48].

The same year the PRad experiment at Jefferson Lab scattered electrons at very low momentum transfer. It found 0.831 ± 0.007 (stat) ± 0.012 (syst) fm, 2.7 standard deviations below the average of earlier electron–proton experiments [53].

CODATA 2022 recommends 0.84075(64) fm, 0.13 % below the muonic value of 2010 [1]. The PDG gives 0.8409 ± 0.0004 fm [54]. Within CODATA 2022 the electronic hydrogen and deuterium data alone give 0.8529(13) fm and the muonic Lamb shifts 0.84060(66) fm [2].

In 2026 the hydrogen 2S–6P line gave 0.8406(15) fm [50]. The value of 2006 lay 0.036 fm higher, 5.2 of its own uncertainties above the value now recommended. The proton radius sits at position −16.21.

Year	Method	r_p	Source
before 2010	electronic hydrogen and e–p scattering (CODATA)	0.8768(69) fm	[51]
2010	muonic hydrogen 2S–2P, Pohl et al.	0.84184(67) fm	[51]
2013	muonic hydrogen, two transitions, Antognini et al.	0.84087(39) fm	[52]
2014	e–p scattering, Sick and Trautmann	about 0.8775(5) fm	[54]
2019	hydrogen Lamb shift, Bezginov et al.	0.833(10) fm	[48]
2019	e–p scattering, PRad	0.831 ± 0.007 ± 0.012 fm	[53]
2022	CODATA, all data	0.84075(64) fm	[1]
2022	CODATA, electronic data only	0.8529(13) fm	[2]
2022	CODATA, muonic data only	0.84060(66) fm	[2]
2024	PDG	0.8409(4) fm	[54]
2026	hydrogen 2S–6P, Maisenbacher et al.	0.8406(15) fm	[50]

Read in the forms of the net, the muonic atom is the electronic atom at another depth (form 13). The same bound form, with the muon in place of the electron, sits 4.85 positions lower on the ladder. It measured the proton first, and the electron measurements followed it.

The precision of the electron's world

The most precise numbers in this part of physics are frequencies of hydrogen and the magnetic moment of one trapped electron. Each is a count of cycles against a caesium

clock, or a ratio of two frequencies of the same electron. Quantities that need a step of theory are known 10^3 to 10^8 times less well.

Rank	Quantity	Relative uncertainty	Year	Source
1	Hydrogen 1S–2S frequency	4.2×10^{-15}	2011	[49]
2	Electron g/2	1.3×10^{-13} (1.1×10^{-10} on a_e)	2023	[38]
3	Hydrogen 2S–6P frequency	6.6×10^{-13} (Standard Model test 0.7 ppt)	2026	[50]
4	R∞, CODATA 2022	1.1×10^{-12}	2024	[1]
5	α from rubidium recoil	8.1×10^{-11}	2020	[42]
6	α from electron g − 2 and QED	1.1×10^{-10}	2023	[38]
7	α from caesium recoil	2.0×10^{-10}	2018	[41]
8	m_e, CODATA 2022	3.1×10^{-10}	2024	[1]
9	Muon anomaly a_μ	1.27×10^{-7}	2025	[43]
10	Bound-state QED corrections in hydrogen	5×10^{-7}	2026	[50]
11	Muon anomaly, theory	5.3×10^{-7}	2025	[44]
12	Muon lifetime	1.0×10^{-6}	2013	[45]
13	Hydrogen Lamb shift, one component	3.5×10^{-6}	2019	[48]

The questions opened between 2010 and 2020 had different outcomes by 2026. The proton radius moved to the muonic value. The muon anomaly agreed with theory once the hadronic input changed; the two atom-recoil values of α still differ by 5.5σ.

Order of events

Year	Event
1897–1899	Thomson: cathode-ray particle, e/m independent of the cathode
1925	Goudsmit and Uhlenbeck: spin
1947	Lamb and Retherford: the 2S–2P shift; Bethe’s calculation
1988	Dehmelt: radius limit from one trapped electron
2008	Hanneke et al.: g/2 to 0.28 ppt
2010	Pohl et al.: muonic proton radius 0.84184 fm, 5σ
2011	Parthey et al.: 1S–2S to 4.2×10^{-15}
2013	MuLan: muon life to 1 ppm; Antognini et al.: 0.84087 fm
2015	Borexino: electron mean life > 6.6×10^{28} years
2018	Parker et al.: α from caesium
2019	Bezginov et al.: hydrogen Lamb shift; PRad: 0.831 fm
2020	Morel et al.: α from rubidium, more than 5σ from caesium
2023	Fan et al.: g/2 to 0.13 ppt; JILA: dipole bound 2.4 times lower; Belle II: tau mass
2024	CODATA 2022 values released
2025	Fermilab: final muon anomaly to 127 ppb; Theory Initiative: no tension
2026	Maisenbacher et al.: hydrogen 2S–6P, 0.7 ppt test

What this part of the history shows

The electron was found as one kind of particle in every metal, in 1897. Since then it has never been seen to decay: its life exceeds 6.6×10^{28} years, position 109.27. It has the form of what closes, stays (form 1).

The net texts take the electron as light closed on a double loop, a winding that turns twice before it meets itself. They read spin one half as the label of the strand's return after 4π, 720°.

Every measured size of the electron is an upper limit, 10^{-18} m and 10^{-22} m. The lengths tied to it, r_e, ƛ_C, λ_C and a_0, stand in steps of α at −15.11, −10.63, −8.96 and −6.15. They are identities of the units S_0 and T_0, which come from hydrogen's own light.

The magnetic moment is Dirac's 1 plus $1.15965218059(13) \times 10^{-3}$. The Lamb shift is a 1,057 MHz split between the 2S and 2P levels of hydrogen. Both read as the remainder of form 11: each leaves a small amount over a closed value.

α is measured to 8×10^{-11} and yet its two atomic routes differ by 5.5σ. It runs from 1/137 at low energy to about 1/128 near the W mass. The running has the form of context (form 14): the same constant in other surroundings takes another value.

The electron, the muon and the tau share charge and spin at masses 1 : 206.77 : 3477.2. Their lives run from beyond 10^{28} years to 2.2 μs to 290 fs. Read in the forms of the net, this is one form at three depths (form 13), whose heavy carriers decay while the electron lasts (form 3).

The muonic atom reads as hydrogen 4.85 positions lower. In 2010 it gave a proton radius 4 % smaller than the electron's, at 5σ. By 2026 electron measurements stood at 0.8406 fm, and the recommended value at 0.84075 fm, position −16.21.

The positron's charge equals minus the electron's to 4 parts in 10^8. Read on the register of chapter 1, they stand at −1 and +1, the mirror of one address. Chapter 7 follows that mirror into antimatter.

3. Quarks, Proton and Neutron

The atom has a centre. Its nucleus is about 27,000 to 60,000 times smaller than the atom around it [85].

The nucleus holds two kinds of particle, the proton and the neutron. Each of them is made of quarks, which have never been seen alone.

This chapter tells how that inner world was found and measured. It runs from the nucleus (1911) and the neutron (1932) through the quark model (1964) and the six quarks (1968–1995). It then follows the proton and the neutron as they are measured today, the nuclei they build, the hadrons, and the hot plasma of free quarks and gluons made since 2000.

The sizes in this chapter lie between 0.84 fm (the proton's charge radius, position −16.21) and 11.7 fm (the diameter of the uranium nucleus, −13.81). The times run from 4.6×10^{-25} s (the top quark, −17.85) to 878 s (the free neutron, 39.32). The proton itself has never been seen to decay; its limit lies beyond 7.6×10^{41} s (120.93).

From the nucleus to the quark model (1911–1964)

The atomic nucleus was discovered in 1911 [85]. The neutron followed in 1932 [85]. From then on the nucleus was a cluster of protons and neutrons, held within a few femtometres.

In 1964 Murray Gell-Mann and George Zweig independently proposed that these particles are built of smaller ones, the quarks [60]. In the model the quarks carry fractions of the elementary charge e. Up, charm and top carry +2/3 e; down, strange and bottom carry −1/3 e [60].

The number of supposed flavours grew. In 1970 Glashow, Iliopoulos and Maiani presented the GIM mechanism, the proposal of a fourth quark, charm [60].

In 1973 the count reached the present six, with the work of Kobayashi and Maskawa [60]. "There are six types, known as flavors, of quarks" [60].

The quarks are seen, one by one (1968–1995)

The first evidence came from scattering. In 1968 deep inelastic scattering of electrons on protons at the Stanford Linear Accelerator Center (SLAC) revealed objects inside the proton [60]. The paper appeared on 20 October 1969 [61].

"The objects that were observed at SLAC would later be identified as up and down quarks" [60]. The same scattering experiments also gave indirect evidence for the strange quark [60].

Charm appeared in November 1974. Two teams found the same heavy particle almost at once, one at Brookhaven and one at SLAC [60]. The Brookhaven paper, "Experimental Observation of a Heavy Particle J", is dated 2 December 1974 [62].

The particle is the J/ψ, a bound pair of a charm quark and its antiquark. Its mass is 3,096.900 ± 0.006 MeV and its width 92.6 ± 1.7 keV [101]. From $\tau = \hbar/\Gamma$ its life is 7.11×10^{-21} s, position −9.08.

The bottom quark followed in 1977. A team at Fermilab led by Leon Lederman found a resonance at 9.5 GeV in dimuon pairs from 400 GeV proton collisions with nuclei [60] [63]. The paper is dated 1 August 1977 [63].

The resonance is the ϒ, a bound bottom–antibottom pair. Its ground state today weighs 9,460.40 ± 0.10 MeV, width 54.02 ± 1.25 keV [108]. Its life is 1.22×10^{-20} s, position −8.59.

The top quark came last, in 1995. The CDF and DØ teams at Fermilab reported it in two papers dated 3 April 1995 [60][64][65].

The top quark was not found as a bound pair. “The only exception is the top quark, which may decay before it hadronizes” [60].

Order	Quark	Year	Signal	Paper
1–2	u, d	1968 (publ. 20 Oct 1969)	deep inelastic e–p scattering, SLAC	[61]
3	s	indirect, SLAC	same experiments	[60]
4	c	Nov 1974 (publ. 2 Dec 1974)	J/ψ at Brookhaven and SLAC	[62]
5	b	1977 (publ. 1 Aug 1977)	ϒ at 9.5 GeV, Fermilab	[63]
6	t	1995 (publ. 3 Apr 1995)	CDF and DØ, Fermilab	[64][65]

The quarks were seen in order of rising mass. The gaps between first sightings were 6, 3 and 18 years. Twice two teams found the same quark at once: charm in November 1974, top on 3 April 1995.

The six masses as measured now

The Particle Data Group gives the six masses in its 2024 tables [59]. Light quarks are quoted in the MS-bar scheme at a scale of 2 GeV.

“The c- and b-quark masses are the MS masses renormalized at the MS mass” [59]. “The t-quark mass is extracted from event kinematics” [59].

Quark	Charge (e)	Mass (PDG 2024)	Scheme	Reduced Compton length ħc/mc²	Position
u	+2/3	2.16 ± 0.07 MeV	MS-bar, 2 GeV	9.14×10^{-14} m	−11.94
d	−1/3	4.70 ± 0.07 MeV	MS-bar, 2 GeV	4.20×10^{-14} m	−12.65
s	−1/3	93.5 ± 0.8 MeV	MS-bar, 2 GeV	2.11×10^{-15} m	−15.37
c	+2/3	1.2730 ± 0.0046 GeV	MS-bar at m_c	1.55×10^{-16} m	−17.75
b	−1/3	4.183 ± 0.007 GeV	MS-bar at m_b	4.72×10^{-17} m	−18.83
t	+2/3	172.57 ± 0.29 GeV	direct (kinematics)	1.14×10^{-18} m	−22.22

The lengths in the table are computed as ħc/(mc²) with ħc = 0.1973269804 GeV fm. They place each quoted mass on the ladder. The top quark’s length lies 10.28 positions below the up quark’s.

The top mass has three PDG entries [59]. Direct measurement gives 172.57 ± 0.29 GeV. The pole mass from the cross section gives 172.4 ± 0.7 GeV.

The MS-bar mass from the cross section gives 162.5 (+2.1/−1.5) GeV. An older Tevatron combination, quoted in a footnote, gave 173.2 ± 0.9 GeV [59]. The top–antitop mass difference is −0.15 ± 0.20 GeV [59].

The ratios are measured more tightly than some of the masses [59]. The up-to-down ratio is m_u/m_d = 0.462 ± 0.020. The strange-to-down ratio lies between 17 and 22.

The mean light mass is $\bar{m}$ = (m_u + m_d)/2 = 3.49 ± 0.07 MeV, and m_s/$\bar{m}$ = 27.33 (+0.18/−0.14). The difference m_b − m_c is 3.45 ± 0.05 GeV.

Within each charge family the steps are large. For +2/3: up 2.16 MeV, charm 1,273 MeV, top 172,570 MeV. Charm is 589 times up; top is 136 times charm.

For −1/3: down 4.70 MeV, strange 93.5 MeV, bottom 4,183 MeV. Strange is 19.9 times down; bottom is 44.7 times strange. Top over up is 172,570/2.16 = 7.99×10^4, a ratio of

mixed schemes, good to its order of magnitude.

The top quark’s short life

The top quark’s full width is $\Gamma_t = 1.42\ (+0.19/-0.15)$ GeV [59]. Its life is $\tau = \hbar/\Gamma = 6.582 \times 10^{-25}$ GeV s / 1.42 GeV $= 4.64 \times 10^{-25}$ s, position −17.85. The width errors give a range from 4.09×10^{-25} s (−17.96) to 5.18×10^{-25} s (−17.75).

The top decays almost always to a W boson and a bottom quark [59]. The ratio $\Gamma(Wb)/\Gamma(Wq)$, summed over q = b, s, d, is 0.957 ± 0.034.

The decay fractions are e ν_e b (11.10 ± 0.30) %, μ ν_μ b (11.40 ± 0.20) %, τ ν_τ b (10.7 ± 0.5) % and q $\bar{q}$ b (66.5 ± 1.4) %. The W bosons from top decay have helicity fractions $F_0 = 0.693 \pm 0.013$, $F_- = 0.315 \pm 0.010$ and $F_+ = -0.005 \pm 0.007$.

Searches for more

No fourth generation has been found [59]. A heavier b′ is excluded below 1,390 GeV if it decays to Zb, below 1,350 GeV if to Wt and below 1,570 GeV if to Hb. Electron–positron data exclude any b′ below 46.0 GeV; a quasi-stable b′ is excluded below 190 GeV.

A heavier t′ of charge 2/3 is excluded below 1,280 GeV (to Zt), 1,295 GeV (to Wb), 1,310 GeV (singlet) and 1,350 GeV (doublet). A t′ of charge 5/3 is excluded below 1,460 GeV. All limits are at 95 % confidence.

Free quarks have been sought since 1977. “All searches since 1977 have had negative results” [59].

The strong coupling and confinement

Quarks are held together by the strong force. Its coupling is quoted at the mass of the Z boson, 91 GeV. “It has become standard practice to quote the value of αs at a given scale (typically the mass of the Z boson, mZ)” [66].

The PDG 2024 value is $\alpha_s(m_Z) = 0.1180 \pm 0.0009$ [13]. The relative uncertainty is $0.0009/0.1180 = 7.6 \times 10^{-3}$.

The coupling changes with the energy of the probe. “For momentum transfers in the 0.1–1 TeV range, αs ~ 0.1” [66]. At low momentum transfer it grows.

“Most evidence points to a moderately large coupling, typically of value 1-3” [67]. Between the TeV range and the scale of the proton, the same coupling takes values from about 0.1 to about 1–3.

Read in the forms of the net, this is context (form 14, chapter 1): the same rule takes other values in other surroundings. The PDG names the scale with every number it gives.

Confinement is “the phenomenon that color-charged particles (such as quarks and gluons) cannot be isolated” [67]. “The confinement scale or QCD scale is the scale at which the perturbatively defined strong coupling constant diverges” [67]. No free quark has been found in any search since 1977 [59].

The charges of the bound states are whole. The proton’s charge plus the electron’s charge is zero to $|q_p + q_e|/e < 1 \times 10^{-21}$ [69].

The neutron’s charge is $(-0.2 \pm 0.8) \times 10^{-21}$ e [69]. The thirds of the quarks never show outside.

Counted in thirds of e, an up quark carries +2 and a down quark −1. The proton (two up, one down) carries $+2 + 2 - 1 = +3$.

The neutron (one up, two down) carries $+2 - 1 - 1 = 0$. Every hadron in this chapter carries a whole number of e: its thirds add to a multiple of three.

As a reading, this has the form of the closed window of chapter 1, where three values add to zero, counted in threes. Counted in threes, +2 is the same as −1, since $2 - 3 =$

−1. Every quark then counts as −1 and every antiquark, with −2 or +1 thirds, as +1.

Read this way, three quarks give (−1, −1, −1): sum −3, which counts as 0 in threes, the closed window that holds one value three times. A quark with an antiquark and a rest gives (−1, +1, 0), sum 0. One quark alone, (−1, 0, 0), sums to −1 and does not close.

The Maxwell text of the net names charge a three-valued register of +1, 0 and −1 [28].

The temperature at which hadrons dissolve

Lattice QCD computes where bound quarks give way to a plasma. With two light flavours and a strange quark, at physical pion and kaon masses and in the continuum limit, the crossover lies at $T_c(0) = 156.5 \pm 1.5$ MeV [70].

In kelvin that is $156.5 \text{ MeV} \times 1.16045 \times 10^{10} \text{ K/MeV} = 1.82 \times 10^{12}$ K. The curvature of the transition line in baryon chemical potential is $\kappa_2^B = 0.012(4)$, with $\kappa_4^B = 0.000(4)$ [70].

At chemical freeze-out the boundary "coincides with the lines of constant energy density of 0.42(6) GeV/fm³ and constant entropy density of 3.7(5) fm⁻³" [70]. Older lattice work gave higher values.

In 2008 "Lattice QCD predicts a phase transition to quark gluon plasma at ~ 170 MeV" [71], which is 1.97×10^{12} K. An encyclopaedia page gives about 175 MeV (2.03×10^{12} K) for older lattice work [68].

The Hagedorn temperature, read from the growth of hadron spectra, lies close to the crossover. One source gives "approximately 130–140 MeV per particle", about 2×10^{12} K [67].

Another gives 150 MeV per particle, above 1.66×10^{12} K [68]. In kelvin, 130–150 MeV is $1.51–1.74 \times 10^{12}$ K.

The proton measured

The proton's mass is known to 3 parts in 10^{10}. The PDG 2024 value is $m_p = 938.272\,088\,16(29)$ MeV/c² $= 1.672\,621\,923\,69(51) \times 10^{-27}$ kg [13].

In other units it is 1.007 276 466 621(53) u and 1,836.152 673 43(11) electron masses [13]. Its reduced Compton length $\hbar c/(m_p c^2)$ is 0.2103 fm, position −17.47.

Its charge equals the electron's in size to better than 1 part in 10^{21}: $|q_p + q_e|/e < 1 \times 10^{-21}$ [69]. Proton and antiproton charges agree to $|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}$ (90 % CL) [69]. Antimatter is the subject of chapter 7.

The magnetic moment is $\mu_p = 2.792\,847\,3446 \pm 0.000\,000\,0008$ nuclear magnetons [69]. The antiproton moment agrees: $(\mu_p + \mu_{\bar{p}})/\mu_p = (0.002 \pm 0.004) \times 10^{-6}$ [69]. No electric dipole moment has been seen; the limit is 2.1×10^{-25} e cm [69].

The proton's electric polarizability is $\alpha_E = (11.2 \pm 0.4) \times 10^{-4}$ fm³ and its magnetic polarizability $\beta_M = (2.5 \pm 0.4) \times 10^{-4}$ fm³ [69].

The proton's size (before 2010 to 2026)

Before 2010 two methods agreed on a radius near 0.877 fm. Hydrogen spectroscopy gave 0.8768(69) fm and electron–proton scattering 0.8775(5) fm [72].

The accepted value was "about 0.877 fm" [72]. On the ladder 0.8768 fm sits at −16.17.

In 2010 a team at the Paul Scherrer Institute measured the Lamb shift in muonic hydrogen. A muon replaces the electron and orbits 207 times closer, so the 2S level feels the proton's size far more.

The result was $r_p = 0.841\,84(67)$ fm, "which differs by 5.0 standard deviations from the CODATA value of 0.8768(69) fm" [51]. The check is $(0.8768 - 0.84184)/\sqrt{0.0069^2 + 0.00067^2} = 5.04\ \sigma$.

In 2013 the same method, with two 2S–2P transitions, gave r_E = 0.840 87(39) fm [52]. The transition frequencies were 54,611.16(1.05) GHz for $2S_{1/2}(F=0)$–$2P_{3/2}(F=1)$ and 49,881.35(65) GHz [52].

The Zemach radius came out as 1.082(37) fm (−15.98) and the magnetic radius as 0.87(6) fm (−16.18) [52]. The abstract states a difference of about 7 σ from the CODATA 2010 value [52].

The step from 0.8768 fm to 0.84087 fm is 0.0359 fm, 4.1 % of the old value. It is 5.2 times the old spectroscopic error. On the ladder the proton moved from −16.17 to −16.21, a shift of 0.04 positions.

Electronic hydrogen then moved too. In 2017 a 2S–4P measurement in hydrogen gave a radius “~5% smaller than the previously accepted spectroscopic values” [72]. In 2019 the hydrogen Lamb shift gave 0.833 fm (−16.22) [72].

In the same year the PRad experiment at Jefferson Lab scattered electrons at very low momentum transfer [53]. It gave r_p = 0.831 ± 0.007 (stat) ± 0.012 (syst) fm, position −16.22, “2.7 standard deviations smaller than the average of all e–p experimental results” [53].

The present values cluster. PDG 2024 gives 0.8409 ± 0.0004 fm from electronic data and 0.840 87 ± 0.000 39 fm from the muonic Lamb shift [69]. CODATA 2022 gives 0.840 75(64) fm [1].

In 2026 hydrogen 2s–6p spectroscopy gave 0.8406(15) fm [72]. All four sit at −16.21.

One tension remains in the CODATA analysis. Electronic hydrogen and deuterium data alone give 0.8529(13) fm (−16.20); the muonic Lamb shifts give 0.840 60(66) fm [107]. The difference is 2.8 σ.

“The proton radius ‘puzzle’ is not yet over” [107]. The proton’s magnetic radius, in the PDG, is 0.851 ± 0.026 fm (−16.20) [69].

Year	Method	r_p (fm)	Position	Source
before 2010	hydrogen spectroscopy	0.8768(69)	−16.17	[72][51]
before 2010	e–p scattering	0.8775(5)	−16.17	[72]
2010	muonic H 2S–2P	0.841 84(67)	−16.21	[51]
2013	muonic H, two lines	0.840 87(39)	−16.21	[52]
2017	H 2S–4P	“~5% smaller”	—	[72]
2019	H Lamb shift	0.833	−16.22	[72]
2019	PRad, low-Q^2 e–p	0.831 ± 0.014	−16.22	[53]
2022	CODATA 2022	0.840 75(64)	−16.21	[1][107]
2024	PDG	0.8409(4)	−16.21	[69]
2026	H 2s–6p	0.8406(15)	−16.21	[72]

The proton is a measured size on the ladder. The electron’s lengths in chapter 2 are fixed by α and the unit; the proton’s position is not.

The net’s Heat Beneath text takes it as the lower end of its span, from layer −16 at the proton to layer 71 at the observable universe [30]. That is 71 − (−16) + 1 = 88 layers.

The proton’s spin (1988–2007)

In 1988 the European Muon Collaboration at CERN scattered polarized muons on polarized protons [74]. It measured the spin asymmetry and the structure function g_1. This measurement began the line of work known as the proton spin crisis.

In 2007 HERMES at DESY fixed the quark share [75]. It used 27.6 GeV polarized positrons on polarized hydrogen and deuterium gas, over $0.0041 \le x \le 0.9$ and $0.18 \le Q^2 \le 20$ GeV². The flavour-singlet axial charge came out as $a_0 = 0.330 \pm 0.011$ (theo.) ± 0.025 (exp.) ± 0.028 (evol.) at $Q^2 = 5$ GeV² [75].

With the errors added in quadrature that is 0.330 ± 0.039. The quarks’ spins carry about one third of the proton’s spin.

COMPASS at CERN measured the gluons' part from deuteron data of 2002–2004 [76]. The first moment of the gluon spin is "of the order of 0.2 - 0.3 in absolute value" at Q^2 = 3 $(GeV/c)^2$ [76]. The fits allow two solutions, one with the gluon share positive and one negative [76].

Where the proton's mass sits (2008–2018)

"More than 99% of the mass of the visible universe is made up of protons and neutrons" [77]. "Both particles are much heavier than their quark and gluon constituents" [77]. The three valence quarks of the proton weigh $2m_u + m_d = 2 \times 2.16 + 4.70 = 9.02$ MeV.

That is 0.96 % of 938.27 MeV. For the neutron, $m_u + 2m_d = 11.56$ MeV, 1.23 % of 939.57 MeV.

In 2008 lattice QCD computed the light hadron masses from first principles [77]. It used pion masses down to 190 MeV, lattices about four times the inverse pion mass, and three lattice spacings. "Our results completely agree with experimental observations" [77].

In 2018 a lattice calculation split the proton's mass into its parts [78]. It used the MS-bar scheme at 2 GeV, with the physical pion mass included. The quark energy gives 33(4)(4) %, the gluon field energy 37(5)(4) %, a quarter of the trace anomaly 23(1)(1) %, and the quark-mass term 9(2)(1) % [78].

The four add to 102 %, within their errors. The 9 % term includes the strange quark's share in the sea.

The proton is mostly the energy of what moves and binds inside it. The net's vdef text states the matching form in one line: "A knot is what current physics calls mass" [26].

Read as a knot, the proton has less than 1 % of its mass in its three valence quarks. The rest is motion, field and the trace anomaly.

Does the proton decay? (1996–2018)

Super-Kamiokande watched a large tank of water from April 1996 to May 2018 [73]. Its fiducial volume was enlarged from 22.5 to 27.2 kilotons.

The total exposure was 450 kiloton-years, 0.45 megaton-years. For the decay to a positron and a neutral pion it found zero candidates; for a muon and a neutral pion, one, "consistent with the atmospheric neutrino background" [73].

The limits are $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ years and $\tau/B(p \to \mu^+\pi^0) > 1.6 \times 10^{34}$ years, at 90 % confidence [73]. With one year = 3.15576×10^7 s, 2.4×10^{34} years is 7.57×10^{41} s, position 120.93. The $\mu^+\pi^0$ limit is 5.05×10^{41} s, position 120.56.

The PDG 2024 lists limits for other channels, all at 90 % confidence [69]. The table gives them in years and their positions.

Channel	Limit (years)	Limit (s)	Position
$e^+e^+e^-$	$> 3.4 \times 10^{34}$	$> 1.07 \times 10^{42}$	121.24
$e^+\pi^0$	$> 2.4 \times 10^{34}$	$> 7.57 \times 10^{41}$	120.93
$\mu^+\pi^0$	$> 1.6 \times 10^{34}$	$> 5.05 \times 10^{41}$	120.56
$e^+\eta$	$> 1.0 \times 10^{34}$	$> 3.16 \times 10^{41}$	120.13
$\bar{\nu}K^+$	$> 5.9 \times 10^{33}$	$> 1.86 \times 10^{41}$	119.65
$\mu^+\eta$	$> 4.7 \times 10^{33}$	$> 1.48 \times 10^{41}$	119.44
e^+K^0	$> 1.0 \times 10^{33}$	$> 3.16 \times 10^{40}$	118.04
$e^+\gamma$	$> 6.7 \times 10^{32}$	$> 2.11 \times 10^{40}$	117.67
$\bar{\nu}\pi^+$	$> 3.9 \times 10^{32}$	$> 1.23 \times 10^{40}$	117.18
invisible	$> 9 \times 10^{29}$	$> 2.84 \times 10^{37}$	111.65

The $e^+\pi^0$ limit lies 81.61 positions above the free neutron's life (39.32). In decades it lies 38.9 orders of magnitude beyond the 878 s of the neutron.

The neutron

The neutron's mass is $m_n = 939.565\,420\,52(54)$ MeV/c² = 1.008 664 915 95(49) u [13]. Its reduced Compton length is 0.2100 fm, position −17.47.

The neutron is heavier than the proton by $m_n - m_p = 1.293\,3324 \pm 0.000\,0005$ MeV [69]. From the two masses, 939.565 420 52 − 938.272 088 16 = 1.293 332 36 MeV, the same value.

The difference is small. "The measured mass difference is only 0.14% of the average of the two masses" [79]. The check is 1.29333/939.92 = 0.138 %.

In 2015 lattice QCD with electromagnetism computed the splitting "with an accuracy of 300 kilo-electron volts, which is greater than 0 by 5 standard deviations" [79]. It "results from the competition between electromagnetic and mass isospin breaking effects" [79].

The free neutron decays to a proton. The energy of the decay is the neutron's mass less a hydrogen atom's: 1.293 332 36 − 0.510 998 95 = 0.782 333 MeV, with the electron mass of CODATA 2022 [1].

How long the free neutron lives

The PDG 2024 average mean life is 878.4 ± 0.5 s [69]. That is 14.64 minutes, position 39.32.

Two methods give two answers. The beam method counts the protons from decays in a neutron beam.

At NIST a 2005 result of 886.3 ± 1.2 ± 3.2 s was renormalised in 2013 with a directly measured neutron-monitor efficiency, precision 0.057 % [80]. "The updated lifetime is $\tau_n = (887.7 \pm 1.2\ [\text{stat}] \pm 1.9\ [\text{syst}])$ s" [80]. Position 39.33.

The bottle method stores ultracold neutrons and counts those left after a holding time. The UCNτ magneto-gravitational trap at LANSCE counted about 38 million surviving neutrons in 2017–2018 [81]. It gave $\tau_n = 877.75 \pm 0.28\ (\text{stat})\ {}^{+0.22}_{-0.16}\ (\text{syst})$ s, position 39.32 [81].

Beam minus bottle is 887.7 − 877.75 = 9.95 s. With the beam errors combined, $\sqrt{1.2^2 + 1.9^2} = 2.25$ s, the gap is 4.4 σ. On the ladder the two values differ by 0.01 positions.

Method	Year	τ_n (s)	Position	Source
beam (NIST), original	2005	886.3 ± 1.2 ± 3.2	39.33	[80]
beam (NIST), renormalised	2013	887.7 ± 1.2 ± 1.9	39.33	[80]
bottle (UCNτ)	2021	877.75 ± 0.28 +0.22/−0.16	39.32	[81]
PDG average	2024	878.4 ± 0.5	39.32	[69]

What the neutron does not show

The neutron's electric dipole moment was measured at PSI with ultracold neutrons and a mercury-199 co-magnetometer [82]. The analysis was blinded and done by two groups.

It gave $d_n = (0.0 \pm 1.1\ (\text{stat}) \pm 0.2\ (\text{sys})) \times 10^{-26}$ e cm [82]. The PDG limit is 1.8×10^{-26} e cm at 90 % confidence [69].

Its magnetic moment is $\mu_n = -1.913\,0427 \pm 0.000\,0005$ nuclear magnetons [69]. The ratio to the proton's is −1.913 0427/2.792 8473 = −0.685.

Its mean-square charge radius is negative, $\langle r^2 \rangle = -0.1155 \pm 0.0017$ fm² [69]. Its polarizabilities are $\alpha_E = (11.8 \pm 1.1) \times 10^{-4}$ fm³ and $\beta_M = (3.7 \pm 1.2) \times 10^{-4}$ fm³ [69].

The free neutron decays. Bound in a nucleus it holds: the deuteron, one proton with one neutron, is stable (next section).

Free, it lives 878 s. Read as context (form 14), the same neutron shows no decay in one surrounding and lives a quarter of an hour in another.

Nucleons bound: the deuteron and the nuclei

Two nucleons

The deuteron, one proton and one neutron, has mass m_d = 1,875.612 942 57(57) MeV/c² [13]. Its binding energy is the mass lost in the union: 938.272 088 16 + 939.565 420 52 − 1,875.612 942 57 = 2.224 566 MeV. That is 1.112 283 MeV per nucleon.

A tabulated value from older masses gives 2.22452 MeV and 1.11226 MeV per nucleon [83]. The two differ by 0.05 keV.

The deuteron is one of only five stable nuclides with an odd number of protons and an odd number of neutrons: “deuterium, lithium-6, boron-10, nitrogen-14, tantalum-180m” [84].

Size

Nuclear radius grows with the cube root of the mass number A: r = r₀A^(1/3), with “r0 = 1.25 fm” that “varies by 0.2 fm, depending on the nucleus in question” [85]. The length r₀ = 1.25 fm sits at −15.85. Measured diameters run “in the range of 1.70 fm” for hydrogen, a single proton, “to about 11.7 fm for uranium” [85].

On the ladder that is −15.57 to −13.81. The atom is larger than its nucleus “by a factor of about 27,000” for uranium “to about 60,000” for hydrogen; the footnoted values are 26,634 and 60,250 [85].

A	Example	r = 1.25 fm × A^(1/3)	Position
1	proton	1.25 fm	−15.85
2	deuteron	1.57 fm	−15.64
4	helium-4	1.98 fm	−15.43
16	oxygen-16	3.15 fm	−15.01
56	iron-56	4.78 fm	−14.63
62	nickel-62	4.95 fm	−14.60
208	lead-208	7.41 fm	−14.23
238	uranium-238	7.75 fm	−14.19
294	oganesson-294	8.31 fm	−14.12

From A = 1 to A = 294 the radius grows by a factor 6.65 and climbs 1.72 positions. Each tripling of the radius is one position; each 27-fold rise in A is one position.

Binding

Binding per nucleon rises from the deuteron’s 1.11 MeV to a flat peak in the iron group [83]. “Nickel-62 is the most tightly bound nucleus in terms of binding energy per nucleon” [83]. Its value is 8.7948 MeV; iron-58 has 8.7925 MeV and iron-56 8.7906 MeV [83].

The three lie within 0.0042 MeV of each other. The current mass evaluation is AME2020 [86].

Closed shells (1948–1963)

Some numbers of protons or neutrons bind more strongly than their neighbours. Maria Goeppert Mayer gave evidence for closed shells in 1948 and their spin–orbit explanation in 1949–1950 [87].

Wigner coined the term magic number; Mayer and Jensen shared the 1963 Nobel Prize [87]. “The seven most widely recognized magic numbers as of 2019 are 2, 8, 20, 28, 50, 82, and 126” [87].

Nuclei magic in both counts are listed: helium-4, helium-10, oxygen-16, oxygen-28, calcium-40, calcium-48, nickel-48, nickel-56, nickel-78, tin-100, tin-132 and lead-208 [87]. Oxygen-28 “is not regarded as doubly magic” [87]. Further closures are predicted at 114, 122, 124 and 164 protons and at 184, 196, 236 and 318 neutrons, with 228 and

308 in newer calculations [87].

Read in the forms of the net, closed shells show what closes, stays (form 1). A full shell binds more strongly than an open one.

How many nuclei

The NUBASE2020 evaluation "contains recommended properties for the ground state of 3340 nuclides" [88]. It adds "1938 excited isomeric (T1/2≥100 ns) states" and information on 218 unobserved ground states and 45 unobserved isomers [88]. The isomer limit, 100 ns, is position 18.48.

Of these, 251 nuclides in 80 elements "have not been shown to decay using current equipment" [84]. That is 251/3,340 = 7.5 % of the evaluated ground states. Of the 251, 150 are even–even (60 %), five are odd–odd, and by subtraction 96 have odd mass number [84].

Nuclei with an even count of protons and an even count of neutrons make 60 % of the stable ones. Nuclei odd in both make five.

Primordial nuclides number 286, the 251 stable plus about 35 long-lived radioactive ones [84][89]. About 339 occur naturally; a table on the same subject gives about 347 [84][89]. "987 are stable or have a half-life longer than one hour" [89].

One hour is position 40.61. Tin has the most stable isotopes of any element, ten [89]. Technetium (43) and promethium (61) have no stable nuclide; stability ends after lead (82) [84].

The heaviest element (2002–2016)

Oganesson, element 118, is the last of the table [90]. It was first made in 2002 at the Joint Institute for Nuclear Research in Dubna, by "collisions of californium-249 atoms and calcium-48 ions" [90].

The discovery was announced on 9 October 2006 [90][91]. "A total of three (possibly four) nuclei" have been made [90].

Oganesson-294 has a half-life of 0.7 ms, position 26.54; a calculated value of 0.89 ms (26.76) is also given [90]. IUPAC approved the name in November 2016 [90]. Its radius from $r_0 A^{(1/3)}$ is 8.3 fm, position −14.12.

The hadron spectrum

A quark bound with an antiquark makes a meson, such as the J/ψ ($c\bar{c}$). Three quarks make a baryon, such as the proton. The PDG lists states from the pion at 135 MeV to bottom hadrons above 10 GeV.

The light mesons

The pions are the lightest hadrons [92]. The charged pion weighs 139.570 39 ± 0.000 18 MeV and lives $(2.6033 \pm 0.0005) \times 10^{-8}$ s, position 17.26. The neutral pion weighs 134.9768 ± 0.0005 MeV and lives $(8.43 \pm 0.13) \times 10^{-17}$ s, position −0.54.

The charged pion is 0.149 of a proton; the proton is 6.95 neutral pions. The charged pion lives 3.09×10^{8} times longer than the neutral one.

The kaons follow [92]. The charged kaon weighs 493.677 ± 0.015 MeV and lives $(1.2380 \pm 0.0020) \times 10^{-8}$ s, position 16.58. The two neutral kaons live $(0.8954 \pm 0.0004) \times 10^{-10}$ s (K^0_S, 12.09) and $(5.116 \pm 0.021) \times 10^{-8}$ s (K^0_L, 17.87).

Their lives differ by a factor 571. The η weighs 547.862 ± 0.017 MeV [92].

Resonances

Some hadrons are known only by their widths. Their lives are as short as the time light takes to cross a proton: 1.70 fm / c = 5.67×10^{-24} s, position −15.57. The time position

equals the size position, because the unit of space is c times the unit of time.

The ρ(770)⁰ has mass 775.26 ± 0.23 MeV and width 147.4 ± 0.8 MeV [92]. Its life, ħ/Γ, is 4.47 × 10⁻²⁴ s, position −15.79.

The Δ(1232) has a width of “114 to 120 (≈ 117) MeV” [69]. Its life is 5.63 × 10⁻²⁴ s, position −15.58.

The ground states and the resonances stand apart on the time axis. The charged pions, the kaons and most hyperons live 10⁻¹⁰ to 10⁻⁸ s; the ρ and Δ live 5 × 10⁻²⁴ s. Read in the words of the net’s text on the Bethe ansatz, what returns onto itself in phase persists, and what does not close scatters [55].

The strange baryons

The hyperons are the strange baryons [69]. All but one live near 10⁻¹⁰ s.

Baryon	Mass (MeV)	Mean life (s)	Position
Λ	1,115.683 ± 0.006	(2.617 ± 0.010) × 10⁻¹⁰	13.07
Σ⁺	1,189.37 ± 0.07	(0.8018 ± 0.0026) × 10⁻¹⁰	11.99
Σ⁰	1,192.642 ± 0.024	(7.4 ± 0.7) × 10⁻²⁰	−6.94
Σ⁻	1,197.449 ± 0.029	(1.479 ± 0.011) × 10⁻¹⁰	12.55
Ξ⁰	1,314.86 ± 0.20	(2.90 ± 0.09) × 10⁻¹⁰	13.16
Ξ⁻	1,321.71 ± 0.07	(1.639 ± 0.015) × 10⁻¹⁰	12.64
Ω⁻	1,672.45 ± 0.29	(0.821 ± 0.011) × 10⁻¹⁰	12.01

Six of them lie between positions 11.99 and 13.16. The Σ⁰ is the exception: it lives 1.08 × 10⁹ times shorter than the Σ⁺.

Charm and bottom

The heavy-flavour hadrons were measured after 1974 and 1977 [108].

Hadron	Content	Mass (MeV)	Life	Position
D⁰	charm meson	1,864.84 ± 0.05	(410.3 ± 1.0) × 10⁻¹⁵ s	7.19
Λ_c⁺	charm baryon	2,286.46 ± 0.14	202.6 ± 1.0 fs	6.55
J/ψ(1S)	$c\bar{c}$	3,096.900 ± 0.006	Γ 92.6 keV → 7.11 × 10⁻²¹ s	−9.08
B⁰	bottom meson	5,279.63 ± 0.20	1.517 ± 0.004 ps	8.38
B⁰_s	bottom-strange meson	5,366.93 ± 0.10	1.520 ± 0.005 ps	8.38
Λ_b⁰	bottom baryon	5,619.60 ± 0.17	1.471 ± 0.009 ps	8.35
Ω_b⁻	bottom baryon	6,045.8 ± 0.8	1.64 (+0.18/−0.17) ps	8.45
B_c±	bottom-charm meson	6,274.47 ± 0.32	0.510 ± 0.009 ps	7.39
ϒ(1S)	$b\bar{b}$	9,460.40 ± 0.10	Γ 54.02 keV → 1.22 × 10⁻²⁰ s	−8.59
ϒ(4S)	$b\bar{b}$	10,579.4 ± 1.2	Γ 20.5 MeV → 3.21 × 10⁻²³ s	−13.99

The four bottom hadrons with one b quark live 1.47 to 1.64 ps, positions 8.35 to 8.45. Mesons and baryons alike: the B⁰ (1.517 ps), the B⁰_s (1.520 ps) and the Λ_b⁰ (1.471 ps) agree within 3.3 %.

With light partners, the bottom quark keeps its own time in meson and baryon alike. Read as form 4, the letter and the word: the letter keeps what the word does not supply.

The ϒ(4S) is 380 times wider than the ϒ(1S): 20.5 MeV against 54.02 keV. It is the source of B-meson pairs; Belle used 152 million of its $B\bar{B}$ events [96]. Its mass exceeds two B⁰ masses, 2 × 5,279.63 = 10,559.3 MeV, by 20.1 MeV.

Counting the measurements

The PDG 2024 edition rests on 2,717 new measurements from 869 papers and 46,838 earlier measurements from 12,909 papers [93]. In total that is 49,555 measurements from 13,778 papers.

The particles are grouped in “six categories”: gauge and Higgs bosons, leptons, quarks, mesons, baryons and searches [93]. The edition holds 120 reviews, 97 in volume 1 and 23 in volume 2 [94].

Since 2010 the Large Hadron Collider has added new hadrons. “So far 75 hadrons have been discovered at the LHC, of which 67 by LHCb” [95].

The other LHC experiments found 8. The latest entries in that list are dated 6 June 2024 [95].

Exotic hadrons (2003–2023)

Every hadron so far in this chapter holds a quark with an antiquark or three quarks. In 2003 Belle found a narrow state of another kind [96]. In 152 million $B\bar{B}$ events at the $\Upsilon(4S)$, it saw a peak at 3,872.0 ± 0.6 (stat) ± 0.5 (syst) MeV, “very near the M_D + M_D* mass threshold” [96].

The significance was “in excess of 10 sigma” [96]. The state is now named χ_c1(3872).

In 2015 LHCb found two states consistent with pentaquarks, of content $c\bar{c}uud$, in decays of the Λ_b^0 to J/ψ, a kaon and a proton [97]. The data were 3 fb⁻¹ at 7 and 8 TeV. $P_c(4380)^+$ has mass 4,380 ± 8 ± 29 MeV and width 205 ± 18 ± 86 MeV.

$P_c(4450)^+$ has mass 4,449.8 ± 1.7 ± 2.5 MeV and width 39 ± 5 ± 19 MeV. “The significance of each of these resonances is more than 9 standard deviations” [97]. The preferred spins were 3/2 and 5/2, of opposite parity [97].

From their widths the two lives are 3.21×10^{-24} s ($P_c(4380)^+$, −16.09) and 1.69×10^{-23} s ($P_c(4450)^+$, −14.58).

In 2019 LHCb returned with a Λ_b^0 sample “an order of magnitude larger” [98]. A new narrow state, $P_c(4312)^+$, appeared at 7.3 σ. The 2015 $P_c(4450)^+$ split into two, $P_c(4440)^+$ and $P_c(4457)^+$, at 5.4 σ [98].

The masses are 4,312 (+7/−1), 4,440 (+4/−5) and 4,457 (+4/−2) MeV [95]. The narrow peaks lie close to the $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds [98].

In 2021 LHCb found a doubly charmed four-quark state, T_{cc}^+, with content $cc\,\bar{u}\,\bar{d}$ [99]. It is “a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons” lying “just below the $D^{*+}D^0$ mass threshold” [99].

“The near threshold mass together with a strikingly narrow width reveals the resonance nature of the state” [99].

The LHC list holds further four- and five-quark states [95]:

State	Content	Mass (MeV)	Year
$T_{c\bar{c}c\bar{c}}(6900)$	$c\bar{c}c\bar{c}$	6,905 ± 13	2020
$T_{cs0}(2900)^0$	—	2,866 ± 7	2020
$T_{cs1}(2900)^0$	—	2,904 ± 5	2020
$T_{c\bar{s}1}(4000)^+$	—	4,003 (+7/−15)	2021
$T_{c\bar{s}1}(4220)^+$	—	4,220 (+50/−40)	2021
$T_{\bar{c}s0}(2900)^0$	—	2,892 ± 21	2022
$T_{\bar{c}s0}(2900)^{++}$	—	2,921 ± 25	2022
$P_{c\bar{c}s}(4338)^0$	$c\bar{c}uds$	4,338.2 ± 0.8	2022
$T_{c\bar{c}c\bar{c}}(6600)$	$c\bar{c}c\bar{c}$	6,552 ± 16	2023
$T_{c\bar{c}s1}(4000)^0$	—	3,991 (+14/−20)	2023

The X(3872), the three narrow pentaquarks and the T_{cc}^+ all sit close to a threshold, where two ordinary hadrons could just form. Most of the exotic states contain a charm–anticharm pair or two charm quarks. Almost all were found by one experiment, LHCb.

Their charges are whole. A tetraquark holds two quarks and two antiquarks: quarks less antiquarks is 0.

A pentaquark holds four quarks and one antiquark: quarks less antiquarks is 3. The number of quarks less the number of antiquarks is a multiple of three in every hadron whose content this chapter gives.

The new kind opened once, in 2003, and has since filled many times. The pentaquark opened in 2015, resolved into three in 2019, and gained a strange member in 2022. Read as form 6: a new kind of union opens once; then the opened depth fills many times.

Glueball candidates

A glueball would be a hadron of gluons alone. None has been established. The PDG lists two scalar candidates without calling them glueballs [92].

The $f_0(1500)$ has a Breit–Wigner mass of 1,522 ± 25 MeV and a pole at √s = (1,430–1,530) − i(40–90) MeV. The $f_0(1710)$ has 1,733 (+8/−7) MeV and a pole at (1,680–1,820) − i(50–180) MeV.

In 2024 BESIII studied (10,087 ± 44) × 10^6 J/ψ decays [100]. It fixed the spin and parity of the X(2370) as 0^{-+} “for the first time”, at more than 11.7 σ.

The mass is 2,395 ± 11 (stat) (+26/−94) (syst) MeV and the width 188 (+18/−17) (stat) (+124/−33) (syst) MeV [100]. The product branching fraction is (1.31 ± 0.22 (+2.85/−0.84)) × 10^{-5} [100].

Mass and spin–parity are “consistent with the predictions of the lightest pseudoscalar glueball” [100]. The state weighs 2.55 proton masses.

Its life from the width is 3.50 × 10^{-24} s, position −16.01. In the PDG charm–anticharm table the X(2370) and the X(1835) appear only as names of J/ψ decay channels [101].

Quark–gluon plasma (2000–2019)

Above the crossover temperature the hadrons dissolve into a plasma of quarks and gluons. Heavy nuclei collided at high energy make it for an instant.

On 10 February 2000 CERN announced “evidence for a new state of matter” from lead–lead collisions at the SPS [68]. In 2005 the Relativistic Heavy Ion Collider at Brookhaven (RHIC) reported “something like a liquid”, a “perfect” liquid [68]. On 26 November 2010 CERN reported “the first direct observation of jet quenching” [68].

How hot

PHENIX measured direct photons in central gold–gold collisions at √s_NN = 200 GeV [71]. The inverse slope of the photon excess is T = 221 ± 19 (stat) ± 19 (syst) MeV, that is 221 ± 27 MeV or 2.56 × 10^{12} K [71]. “Hydrodynamical models with initial temperatures ranging from 300–600 MeV at times of ~ 0.6 - 0.15 fm/c after the collision are in qualitative agreement with the data” [71].

The temperatures 300–600 MeV are 3.48–6.96 × 10^{12} K. The times 0.6 and 0.15 fm/c are 2.00 × 10^{-24} s (−16.52) and 5.00 × 10^{-25} s (−17.78). The earliest of them lies 0.07 positions from the life of the top quark (−17.85).

Brookhaven’s press release of 15 February 2010 gave “about 4 trillion degrees Celsius”, “about 250,000 times hotter than the center of the Sun” [102]. 4 × 10^{12} K is 345 MeV. The matter “flows with almost no frictional resistance, or viscosity” [102].

At the LHC, ALICE measured direct photons in lead–lead collisions at √s_NN = 2.76 TeV, 0–20 % centrality, 0.9 < p_T < 2.1 GeV/c [103]. The inverse slope is 297 ± 12 (stat) ± 41 (syst) MeV, that is 297 ± 43 MeV or 3.45 × 10^{12} K.

The direct-photon signal stands at 2.6 σ [103]. The paper gives an inverse slope, not a

temperature, since the blue-shift from the flow is not removed [103].

Both slopes lie above the 156.5 MeV crossover [70]. The energy density at the transition is “a little less than 1 GeV/fm3” in one account [68] and 0.42(6) GeV/fm³ along the freeze-out line in the lattice [70].

How it flows

A bound on the ratio of shear viscosity to entropy density was proposed in 2005 from string theory, η/s = ħ/(4πk_B) [104]. It holds “for a large class of strongly interacting quantum field theories whose dual description involves black holes” [104].

“This value may serve as a lower bound for a wide class of systems” [104]. In units of ħ/k_B it is 1/(4π) = 0.0796.

A Bayesian fit of models to RHIC and LHC data measured the ratio [105]. “The estimated minimum value is η/s = 0.085 (+0.026/−0.025) (posterior median and 90% uncertainty)”, “close to the conjectured lower bound of 1/4π ≃ 0.08” [105]. The difference from 1/(4π) is 0.005, inside the uncertainty.

“η/s likely increases slowly as a function of temperature” [105]. The published version appeared in 2019 [106].

An earlier fit found “a clear signal for a nonzero bulk viscosity” [105]. The JETSCAPE analysis of 2021 constrained both viscosities “at temperatures of ~150–350 MeV” [105].

Quantity	Value	Kelvin	Source
crossover T_c	156.5 ± 1.5 MeV	1.82 × 10¹² K	[70]
PHENIX photon slope	221 ± 27 MeV	2.56 × 10¹² K	[71]
initial T (hydrodynamics)	300–600 MeV	3.48–6.96 × 10¹² K	[71]
BNL press	“about 4 trillion degrees”	4 × 10¹² (345 MeV)	[102]
ALICE photon slope	297 ± 43 MeV	3.45 × 10¹² K	[103]
η/s minimum	0.085 (+0.026/−0.025)	—	[105]
reference 1/(4π)	0.0796	—	[104]

What this part of the history shows

What closes, stays. Read in the forms of the net, the proton shows no decay in 0.45 megaton-years of water; its $e^+\pi^0$ limit lies beyond 7.57 × 10⁴¹ s, position 120.93. The resonances ρ and Δ, known only by their widths, live 4.5–5.6 × 10⁻²⁴ s, at −15.79 to −15.58, 136.5 positions lower.

In the nuclei the same form shows as closed shells. The magic numbers 2, 8, 20, 28, 50, 82 and 126 bind most strongly, and twelve nuclei are listed as closed in both counts.

The closed window, as a reading. Counted in thirds of e, up is +2 and down −1; counted in threes, every quark is −1 and every antiquark +1. Three quarks read as (−1, −1, −1) and a quark with an antiquark as −1 + 1: the proton carries +3 thirds and the neutron 0.

One quark alone does not close, and none has been seen since 1977. The proton’s charge matches the electron’s to 1 part in 10²¹.

Mass as a knot. The proton weighs 938.27 MeV; its three valence quarks weigh 9.02 MeV, 0.96 %. The lattice splits the mass into quark energy 33 %, gluon field 37 %, trace anomaly 23 % and quark masses 9 %.

Context, as a reading. The strong coupling is 0.1180 at 91 GeV, about 0.1 at 0.1–1 TeV and 1–3 at low momentum. The neutron lives 878.4 s free (39.32) and shows no decay in the deuteron. Each value is read in its surroundings.

The letter and the word, as a reading. With light partners the bottom quark keeps its time: B^0 1.517 ps, B^0_s 1.520 ps, Λ_b^0 1.471 ps, Ω_b^- 1.64 ps, positions 8.35 to 8.45. Meson or baryon, the word changes and the letter’s time stays.

Opened once, filled many times, as a reading. The quarks were seen in order of rising mass: u and d in 1968, c in 1974, b in 1977, t in 1995. The LHC alone added 75 hadrons since 2010, 67 of them at LHCb. The exotic kind opened in 2003, and the pentaquark opened in 2015 and became three narrow states in 2019.

The nuclei. Of the 251 stable nuclides, 150 are even in both protons and neutrons and five are odd in both. The deuteron, one of those five, is bound by 2.2246 MeV, 1.1123 MeV per nucleon; the iron group holds 8.79 MeV per nucleon.

The ladder. The proton sits at −16.21, a measured size not fixed by the unit; the 4.1 % step of 2010 moved it by 0.04 positions. The nuclei span −15.85 (r_0) to −13.81 (uranium’s diameter), 2.04 positions for a factor of 9.4. The times run from −17.85 (top quark) to 39.32 (neutron), and the proton’s limit stands 81.6 positions higher still.

4. Neutrinos

The neutrino was proposed in 1930 and caught in 1956. It has no charge, and it passes through almost everything [30].

This chapter tells the neutrino's history from its proposal to the present. It runs from the reactor experiment of 1956 to the neutrinos of the Sun and the burst from a dying star in 1987. It follows the count of kinds at the Z boson, the discovery that neutrinos change kind, and the neutrinos of the Earth.

It ends with the limits on their mass, the sea of relic neutrinos left from the first second, and single neutrinos from other galaxies.

The neutrino's lengths cover a wide span of the ladder. The wavelength of a 220 PeV neutrino is 5.6×10^{-24} m (position −33.34). A relic neutrino of today has a wavelength of 7.3 mm (10.91).

If the lightest state has no mass, the heaviest weighs 50.1 meV. Written as a length $\hbar c/mc^2$, that mass lies at 3.94 µm, position 4.06, above the unit of the ladder.

A particle proposed (1930–1934)

The neutrino was proposed in 1930 [109]. In 1933 Fermi published a theory of beta decay that used it [109]. In 1934 Bethe and Peierls computed how rarely such a particle would interact [109].

The proposal came first; the measurement took twenty-six years. That interval, 26 years, sits at time position 51.84.

Caught at a reactor (1951–1956)

Cowan and Reines began work at Los Alamos in 1951 [109]. In 1953 they ran a first test at Hanford with a detector named "Herr Auge" [109]. Late in 1955 they moved to the Savannah River reactor [109].

The detector stood "11 m from the reactor and 12 m underground" [109]. These distances sit at positions 17.57 and 17.65. The flux of antineutrinos from the reactor was "5×10^{13} neutrinos per second per square centimeter" [109].

The target held "about 200 liters of water with about 40 kg of dissolved $CdCl_2$" [109]. It used two water tanks and 110 photomultipliers of five inches (127 mm) [109]. An antineutrino striking a proton in the water made a positron and a neutron, seen in delayed coincidence [109].

The rate was "about three neutrino interactions per hour" [109]. That is one event every 1,200 s, against 1.8×10^{17} antineutrinos per square centimetre per hour.

The measured cross section was 6.3×10^{-44} cm², against a prediction of about 6×10^{-44} cm² [109]. In SI units it is 6.3×10^{-48} m², or 6.3×10^{-20} barn. A disc of that area has a radius $\sqrt{(6.3 \times 10^{-48}\ \text{m}^2/\pi)} = 1.4 \times 10^{-24}$ m, position −34.60.

The paper, "Detection of the Free Neutrino: a Confirmation", appeared in *Science* on 20 July 1956 [110]. Reines received the Nobel Prize in 1995, 39 years later (position 52.21); Cowan had died in 1974, aged 54 [109].

Neutrinos from the Sun (1970–2020)

The Sun's core makes neutrinos in every branch of its fusion. They leave the Sun in 2.3 s (position 33.91), while its light takes 10^4 to 1.7×10^5 years to escape (57.25 to 59.83) [133]. Neutrinos carry about 2 % of the Sun's energy [133].

The chlorine deficit

The Homestake detector began measuring in 1970 [128]. It caught electron neutrinos by the reaction $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$.

Over 108 extractions it measured a production rate of 2.56 ± 0.16 (stat) ± 0.16 (syst) SNU [128]. The final paper appeared in 1998, 28 years after the start (position 51.90).

The measured rate was “around a third of the number predicted by the standard solar model” [120]. The shortfall became known as the solar neutrino problem [120].

Gallium and the pp flux

Gallium detectors measured the neutrinos of the proton–proton chain. SAGE measured a capture rate above 233 keV of 65.4 (+3.1/−3.0 stat) (+2.6/−2.8 syst) SNU over 168 extractions to December 2007 [129].

Combined with GALLEX/GNO the rate is 66.1 ± 3.1 SNU [129]. The pp flux at the Earth is $(6.0 \pm 0.8) \times 10^{10}$ cm^{-2} s^{-1} [129].

SNO: the total holds, the kind changes (2001–2002)

The Sudbury Neutrino Observatory used heavy water. In 2001 it measured the charged-current rate, from electron neutrinos [117]. The ^{8}B flux from it was 1.75 ± 0.07 (stat) +0.12/−0.11 (sys) ± 0.05 (theor) × 10^6 cm^{-2} s^{-1}.

The elastic-scattering rate measured by Super-Kamiokande gave 2.39 ± 0.34 (stat) +0.16/−0.14 (sys) × 10^6 cm^{-2} s^{-1} [117]. The difference stood at 3.3 σ. The total active ^{8}B flux came out as 5.44 ± 0.99 × 10^6 cm^{-2} s^{-1} [117].

In 2002 SNO measured the neutral current, which gives the total of all kinds [118]. The electron-type flux was 1.76 ± 0.05 (stat) ± 0.09 (syst) × 10^6 cm^{-2} s^{-1}.

The other kinds gave 3.41 ± 0.45 (+0.48/−0.45) × 10^6. The total was 5.09 (+0.44/−0.43)(+0.46/−0.43) × 10^6 cm^{-2} s^{-1}, consistent with solar models [118].

The non-electron part stood “5.3 standard deviations greater than zero” [118]. The electron share is 1.76/5.09 = 34.6 %. The Sun sends the full number; two thirds arrive as other kinds.

Read in the forms of the net, this is the metabolism of chapter 1 (form 1): the content changes while the window stays closed. The total flux holds at the solar value, 5.09 × 10^6 cm^{-2} s^{-1}, while its kind changes on the way.

Nobel Prizes followed in 2002, to Davis and Koshiba for solar and cosmic neutrinos, and in 2015, to Kajita and McDonald for oscillations [120].

Borexino: every branch (2007–2021)

Borexino at Gran Sasso, under 3,800 m water equivalent, held 278 t of liquid scintillator [120]. It took data from May 2007 to October 2021 [120]. In 2014 it measured the pp neutrinos directly in its spectrum [130].

Phase II ran 1,291.51 days (position 50.02) over 0.19–2.93 MeV [131]. Its rates per day per 100 t were pp 134 ± 10 (+6/−10), ^{7}Be 48.3 ± 1.1 (+0.4/−0.7) and pep 2.43 ± 0.36 (+0.15/−0.22) [131]. The ^{7}Be rate is known to 2.7 %; the CNO rate was below 8.1 per day per 100 t at 95 % confidence [131].

Phase III ran from July 2016 to February 2020, 1,072 days (49.85) with 71.3 t of fiducial mass [132]. It found neutrinos of the carbon–nitrogen–oxygen cycle at 7.2 (+3.0/−1.7) per day per 100 t [132].

The significance was 5.1 σ, and the flux 7.0 (+3.0/−2.0) × 10^8 cm^{-2} s^{-1} [132]. The CNO cycle gives “of the order of 1%” of the Sun’s energy [132].

Detector	Target	Period	Result	Source
Homestake	^{37}Cl, 108 runs	1970–1998	2.56 ± 0.16 ± 0.16 SNU, a third of the	[128][120]

			model	
SAGE + GALLEX/GNO	^{71}Ga	to 2007	66.1 ± 3.1 SNU; pp 6.0 × 10^{10} cm^{-2} s^{-1}	[129]
SNO (CC)	D_2O	2001	^{8}B ν_e 1.75 × 10^{6} cm^{-2} s^{-1}; 3.3 σ	[117]
SNO (NC)	D_2O	2002	^{8}B total 5.09 × 10^{6}; ν_e 34.6 %; 5.3 σ	[118]
Borexino II	scintillator	1,291.5 days	pp 134, ^{7}Be 48.3, pep 2.43 per day per 100 t	[131]
Borexino III	scintillator	2016–2020	CNO 7.0 × 10^{8} cm^{-2} s^{-1}; 5.1 σ	[132]

The fluxes at the Earth span from 6.0 × 10^{10} cm^{-2} s^{-1} (pp) to 5.09 × 10^{6} cm^{-2} s^{-1} (^{8}B), a factor of 1.2 × 10^{4}. CNO lies between, 86 times below pp and 138 times above ^{8}B. Every branch of solar fusion has now been seen in neutrinos: pp, ^{7}Be, pep, ^{8}B and CNO.

A star collapses: SN 1987A

In 1987 a burst of antineutrinos from a collapsing star reached the Earth at 07:35 UT [123]. Kamiokande-II counted 12, IMB 8 and Baksan 5, 25 in all [123].

They came “in a burst lasting less than 13 seconds” (position 35.49), two to three hours before the light [123]. Three hours is 1.08 × 10^{4} s, position 41.61.

The Mont Blanc detector saw 5 events about three hours earlier; they are “generally believed to not be associated” [123]. The Kamiokande paper, “Observation of a neutrino burst from the supernova SN1987A”, is dated 6 April 1987 [139].

The source lay about 51.4 kpc away, 168,000 light-years [123]. That is 1.59 × 10^{21} m, position 59.82.

Models estimate that the collapse sent out about 10^{58} neutrinos carrying 10^{46} J [123]. The spread of the arrival times limits the electron neutrino’s mass: “the rest mass of the electron neutrino is < 16 eV/c² at 95% confidence” [123].

The collapse released its energy in under 13 s. Read as rest and discharge (form 16), loading, holding and discharge, the 25 counted antineutrinos are the discharge seen at 1.59 × 10^{21} m.

How many kinds (1989–2025)

The Z boson decays to every kind of light neutrino. Its invisible width counts them. The four LEP experiments recorded 17 million Z decays; SLD added 600 thousand [111].

The final LEP analysis of 2006 gave: “The number of light neutrino species is determined to be 2.9840+/-0.0082” [111]. That is (3 − 2.9840)/0.0082 = 1.95 σ below three.

In 2020 an improved calculation of the Bhabha cross section, which sets the luminosity, lowered that cross section by about 0.048 % [112]. Its uncertainty fell from ±0.061 % to ±0.037 % [112].

The count moved “to N_ν = 2.9963 ± 0.0074” [112]. “The 20-years-old 2σ tension with the Standard Model is gone” [112]. The new value lies 0.50 σ from three.

The PDG 2025 summary gives N = 2.996 ± 0.007 from Standard Model fits to the LEP and SLC data [113]. The direct measurement of the invisible width gives 2.92 ± 0.05 [113].

The invisible width is Γ(inv) = 499.3 ± 1.5 MeV, (20.000 ± 0.055) % of all Z decays [113]. It is 5.945 times the width to one charged-lepton pair, 83.984 ± 0.086 MeV [113].

The early universe counts neutrinos too. The Standard Model expects N_eff = 3.044 [114].

Planck 2018 alone gives N_eff = 2.92 (+0.36/−0.37) at 95 % confidence [114]. Planck 2018 with ACT and DESI DR1 gives 2.86 ± 0.13 at 68 % [114].

An older summary gives Planck 3.15 ± 0.23 and an expected value near 3.046 [115]. The value 2.86 lies 1.4 σ below 3.044. Both counts, the Z and the early universe, agree with three kinds.

Method	Year	N	Source
Z lineshape, LEP	2006	2.9840 ± 0.0082	[111]
Z lineshape, revised luminosity	2020	2.9963 ± 0.0074	[112]
SM fit, PDG	2025	2.996 ± 0.007	[113]
direct invisible width, PDG	2025	2.92 ± 0.05	[113]
Planck 2018 (N_eff)	2018	2.92 (+0.36/−0.37), 95 %	[114]
Planck + ACT + DESI DR1 (N_eff)	2025	2.86 ± 0.13	[114]

Three light neutrinos stand beside three charged leptons (chapter 2). One Z decay in five goes to neutrinos.

Neutrinos change kind (1998–2012)

From the sky: atmospheric neutrinos (1998)

Super-Kamiokande watched atmospheric muon neutrinos [116]. After a 33.0 kiloton-year exposure, 535 days (position 49.22), it reported “Evidence for oscillation of atmospheric neutrinos” [116].

The allowed region was $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV², with $\sin^2 2\theta > 0.82$ at 90 % confidence [116]. The mixing is close to its largest possible value.

From reactors: the third angle (2012)

Daya Bay compared antineutrinos at near and far detectors from six reactors of 2.9 GW thermal each [119]. In 55 days (position 47.15) it collected 43,000 ton·GW·days.

The far-to-near ratio was R = 0.940 ± 0.011 ± 0.004 [119]. The far detector saw 6.0 % fewer antineutrinos than expected.

The result was $\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst), non-zero at “a significance of 5.2 standard deviations” [119]. Within fourteen years three sources had shown the change of kind: the air (1998), the Sun (2001–2002) and reactors (2012).

The angles and the splittings

Global fits now give three angles and two mass splittings. NuFIT 6.0 (2024) gives two variants, with and without the Super-Kamiokande atmospheric data [121]. The table gives the variant with those data, for the two possible orderings of the masses.

Parameter	Normal ordering	3σ range	Inverted ordering	3σ range
θ_{12}	33.68° (+0.73/−0.70)	31.63–35.95°	33.68° (+0.73/−0.70)	31.63–35.95°
$\sin^2\theta_{12}$	0.308 (+0.012/−0.011)	0.275–0.345	0.308 (+0.012/−0.011)	0.275–0.345
θ_{23}	43.3° (+1.0/−0.8)	41.3–49.9°	47.9° (+0.7/−0.9)	41.5–49.8°
$\sin^2\theta_{23}$	0.470 (+0.017/−0.013)	0.435–0.585	0.550 (+0.012/−0.015)	0.440–0.584
θ_{13}	8.56° ± 0.11	8.19–8.89°	8.59° ± 0.11	8.25–8.93°
$\sin^2\theta_{13}$	0.02215 (+0.00056/−0.00058)	0.02030–0.02388	0.02231 ± 0.00056	0.02060–0.02409
δ_CP	212° (+26/−41)	124–364°	274° (+22/−25)	201–335°
Δm^2_{21}	$7.49 \pm 0.19 \times 10^{-5}$ eV²	6.92–8.05	$7.49 \pm 0.19 \times 10^{-5}$ eV²	6.92–8.05

$\Delta m^2_{3\ell}$	+2.513 (+0.021/−0.019) × 10^{-3} eV²	2.451–2.578	−2.484 ± 0.020 × 10^{-3} eV²	−2.547 to −2.421

Without the atmospheric data the fit gives θ_{23} = 48.5° (+0.7/−0.9) in normal ordering and 48.6° in inverted [121]. Then θ_{13} = 8.52° (normal) and 8.58° (inverted), and δ_{CP} = 177° (+19/−20) (normal) and 285° (+25/−28) (inverted) [121]. The splitting $\Delta m^2_{3\ell}$ becomes +2.534 (+0.025/−0.023) × 10^{-3} and −2.510 (+0.024/−0.025) × 10^{-3} eV² [121].

The ordering is not settled. With the atmospheric data, “the global fit prefers normal ordering with $\Delta\chi^2 = 6.1$”; without them, the inverted ordering is slightly better, $\Delta\chi^2 = -0.6$ [121]. The 3σ relative precision of the well-known parameters is “about 13%, 8%, 15%, and 6%, respectively” [121].

In normal ordering the fit “is consistent with CP conservation within 1σ” [121]. In inverted ordering it favours $\delta_{CP} \approx 270°$ over CP conservation at more than 3.6 σ [121]. The angle θ_{23} “still suffers from the octant ambiguity” [121].

The PDG 2025 summary gives its own values [113]. They are $\sin^2\theta_{12} = 0.307 \pm 0.012$, $\Delta m^2_{21} = (7.50 \pm 0.19) \times 10^{-5}$ eV² and $\sin^2\theta_{13} = (2.16 \pm 0.06) \times 10^{-2}$. For θ_{23} it gives $\sin^2\theta_{23}$ = 0.534 (+0.015/−0.019) (normal) and 0.537 ± 0.020 (inverted).

The PDG splittings are $\Delta m^2_{32} = (2.451 \pm 0.026) \times 10^{-3}$ eV² (normal) and $(-2.527 \pm 0.034) \times 10^{-3}$ eV² (inverted) [113]. The phase is $\delta = 1.21\ (+0.19/-0.22)\ \pi$ rad, that is 218° [113]. NuFIT’s 0.470 for $\sin^2\theta_{23}$ and the PDG’s 0.534 lie on opposite sides of 45°.

The angles are 33.7°, 8.6° and 43–48°. θ_{23} lies within 1.7° to 3.6° of 45°, on one side or the other with the data set. The two splittings differ by $2.513 \times 10^{-3}/7.49 \times 10^{-5} = 33.6$. Δm^2_{21} is known to 2.5 %, $\Delta m^2_{3\ell}$ to 0.8 %.

If the lightest neutrino has no mass, the others follow from the splittings. In normal ordering $m_2 = \sqrt{(7.49 \times 10^{-5}\ \text{eV}^2)} = 8.65$ meV and $m_3 = \sqrt{(2.513 \times 10^{-3}\ \text{eV}^2)} = 50.1$ meV.

The sum is 58.8 meV. In inverted ordering the two heavy states weigh 49.8 and 50.6 meV, and the sum is 100.4 meV.

How heavy (1987–2025)

Direct limits

The first limit came from SN 1987A: below 16 eV at 95 % confidence, from the spread of arrival times [123]. Written as a length $\hbar c/mc^2$, 16 eV is 1.23×10^{-8} m, position −1.19.

The tritium experiments measure the end of the beta spectrum. The PDG 2025 summary gives $m < 0.8$ eV at 90 % confidence from tritium decay [113].

KATRIN tightened it with 36 million electrons in 259 measurement days, its first five campaigns [122]. That is six times the earlier statistics, and the limit fell by a factor of almost two.

KATRIN gives “an upper limit of $m_\nu < 0.45$ eV at 90 % confidence level” [122]. Its best fit for the squared mass is $m^2_\nu = -0.14\ (+0.13/-0.15)$ eV² [122].

As lengths, 0.8 eV is 0.25 µm (position 1.54) and 0.45 eV is 0.44 µm (2.06). The 259 days sit at position 48.56.

The neutrino’s magnetic moment is below 0.064×10^{-10} Bohr magnetons, at 90 % confidence, from solar and radiochemical data [113].

The sum, from the sky

Cosmology weighs the sum of the three masses, not one mass. The relation is $\Omega_\nu = \Sigma m_\nu/(93.12\ h^2\ \text{eV})$ [114]. The limits at 95 % confidence have fallen with each survey [114][124][125].

Data	Σm_ν limit (95 %)	Length $\hbar c/\Sigma mc^2$	Position	Source

WMAP	< 1.3 eV	0.152 μm	1.09	[114]
Planck 2018	< 0.26 eV	0.759 μm	2.56	[114]
Planck 2018 + lensing	< 0.24 eV	0.822 μm	2.63	[114]
Planck + ACT + SPT-3G	< 0.17 eV	1.16 μm	2.95	[114]
DESI 2024 (DR1 BAO) + CMB	< 0.072 eV	2.74 μm	3.73	[124]
Planck + ACT + DESI-DR1 (BAO + full shape)	< 0.071 eV	2.78 μm	3.74	[114]
Planck + ACT + DESI-DR2	< 0.077 eV	2.56 μm	3.67	[114]
DESI DR2 + CMB (ΛCDM)	< 0.064 eV	3.08 μm	3.84	[125]
PR4 + ACT + DESI-DR1 + Lyman-α	< 0.053 eV	3.72 μm	4.01	[114]
Planck + ACT + SPT-3G + DESI-DR2	< 0.048 eV	4.11 μm	4.10	[114]

The DESI 2024 result reads “$\Sigma m_\nu < 0.072$ (0.113) eV at 95% confidence” [124]. The same analysis gives $\Omega_m = 0.295 \pm 0.015$ from BAO alone and $H_0 = 68.52 \pm 0.62$ km s^{-1} Mpc^{-1} with BBN and the CMB acoustic scale [124]. With the CMB and lensing it gives $\Omega_m = 0.307 \pm 0.005$ and $H_0 = 67.97 \pm 0.38$ [124].

DESI DR2 gives $\Sigma m_\nu < 0.064$ eV “assuming ΛCDM” and < 0.16 eV in a model with evolving dark energy ($w_0 w_a$) [125]. That model is preferred over ΛCDM at 3.1 σ with the CMB, and at 2.8–4.2 σ with supernovae added [125]. In the same $w_0 w_a$ model the tightest combination gives < 0.186 eV [114].

The oscillations set a floor. “At the minimum level allowed by oscillations $\Sigma m_\nu \simeq 0.06$ eV” [114].

The floor is 58.8 meV in normal ordering and 100.4 meV in inverted. The tightest cosmological limit, 0.048 eV, lies below both floors; DESI DR2, 0.064 eV, lies between them.

As lengths, the floors sit at 3.36 μm (normal, position 3.91) and 1.97 μm (inverted, 3.43). The direct limit of KATRIN, 0.45 eV for one mass, and the cosmological 0.048–0.064 eV for the sum differ by a factor of 7 to 9.

The electron’s reduced Compton length is 3.86×10^{-13} m, at −10.63 (chapter 2). The heaviest neutrino state, at 50.1 meV in normal ordering, has its length at 3.94 μm, position 4.06. The electron is 1.02×10^7 times heavier; on the ladder the two lie 14.69 positions apart.

Neutrinoless double-beta decay

The 2020 review of two-neutrino double-beta decay gives the ten half-lives below, from 7×10^{18} to 2.2×10^{21} years [127]. Its recommended value for tellurium-128, 2.25×10^{24} years (position 99.91), lies beyond them [127].

Nucleus	Half-life (years)	Half-life (s)	Position
^{100}Mo	$7.06\ (+0.15/-0.13) \times 10^{18}$	2.23×10^{26}	88.38
^{150}Nd	$(9.34 \pm 0.65) \times 10^{18}$	2.95×10^{26}	88.63
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	7.26×10^{26}	89.45
^{116}Cd	$(2.69 \pm 0.09) \times 10^{19}$	8.49×10^{26}	89.59
^{48}Ca	$5.3\ (+1.2/-0.8) \times 10^{19}$	1.67×10^{27}	90.21
^{82}Se	$0.87\ (+0.02/-0.01) \times 10^{20}$	2.75×10^{27}	90.66
^{130}Te	$(7.91 \pm 0.21) \times 10^{20}$	2.50×10^{28}	92.67
^{76}Ge	$(1.88 \pm 0.08) \times 10^{21}$	5.93×10^{28}	93.46

^{238}U	$(2.0 \pm 0.6) \times 10^{21}$ (radiochemical)	6.31×10^{28}	93.52
^{136}Xe	$(2.18 \pm 0.05) \times 10^{21}$	6.88×10^{28}	93.59

The ten lie within 5.2 positions, from 88.38 to 93.59.

The neutrinoless form is the search for Majorana neutrinos, particles that are their own antiparticles [126]. It asks whether the neutrino is its own mirror (chapter 7). KamLAND-Zen searched with 745 kg of enriched xenon, an exposure of 2.1 ton-years of xenon-136 [126].

No such decay was seen. The half-life exceeds 3.8×10^{26} years at 90 % confidence, a limit 1.7 times better than before [126].

In seconds that is 1.20×10^{34} s, position 104.58. It is 2.75×10^{16} times the age of the universe, 13.797 ± 0.023 Gyr [25].

The limit on the effective Majorana mass is “in the range 28–122 meV” [126]. The range, a factor of 4.4, comes from different models of the nuclear matrix elements. The neutrinoless limit lies 1.74×10^{5} times beyond the measured two-neutrino half-life of the same nucleus, 11 positions higher.

Neutrinos from the Earth (2005–2025)

Antineutrinos come from the decay of uranium, thorium and potassium in the mantle and the crust [30]. A detector catches them by the reaction on protons that Cowan and Reines used.

That reaction needs 1.8 MeV [30]. The neutrinos of potassium stop at 1.3 MeV, below the threshold of every detector now in use [30].

A 2 MeV antineutrino has a wavelength hc/E = 0.62 pm, position −10.20 [30]. The 1.8 MeV threshold sits at −10.10 and the 1.3 MeV potassium end at −9.81. The parent half-lives are 4.47×10^{9} years for uranium-238 (69.10), 14.0×10^{9} years for thorium-232 (70.14) and 1.25×10^{9} years for potassium-40 (67.94) [150].

KamLAND and Borexino

In 2005 KamLAND in Japan [30] reported 152 antineutrino events in 749 days of live time (position 49.52) [134]. Between 4.5 and 54.2 of them were geoneutrinos. The power of uranium and thorium was below 60 TW [134].

In 2011 KamLAND had 841 candidates, 106 of them geoneutrinos [134][135]. Uranium-238 and thorium-232 “together generate 20.0 TW” [134].

Potassium-40, below detection, is “known to contribute 4 TW” [135]. “Heat from radioactive decay contributes about half” of the 44.2 ± 1.0 TW that the Earth loses [135].

In 2013 KamLAND counted 116 (+28/−27) events from uranium and thorium [136]. The geoneutrino flux at Kamioka is $3.4 \pm 0.8 \times 10^{6}$ cm^{-2} s^{-1}, with a chondritic thorium-to-uranium ratio [136].

Borexino in Italy [30] reported 9.9 geoneutrinos of 15 candidates in 537 days in 2010, rejecting the null hypothesis at 4.2 σ [134]. A central georeactor above 3 TW was excluded at 95 % confidence.

In 2013 it had 14.3 ± 4.4 in 1,353 days, with a mantle signal of 14.1 ± 8.1 TNU and a georeactor limit of 4.5 TW [134]. In 2015 it had 24 of 77 candidates in 2,056 days, and a radiogenic heat of 23–36 TW [134].

The full Borexino analysis of 2020 used 3,262.74 days (position 50.86) [137]. It counted about 52.6 geoneutrinos from uranium-238 and thorium-232 and a signal of about 47 TNU. The mantle gave about 21 TNU, converted to about 24.6 TW of mantle radiogenic heat [137].

The total radiogenic heat came out near 38 TW, with a convective Urey ratio near 0.78 [137]. The data stand in a 2.4 σ tension with the models of lowest heat-producing

content. A central georeactor above 2.4 TW is excluded at 95 % confidence [137].

The unit TNU is one event per year per 10^{32} free protons at full efficiency; 10^{6} cm^{-2} s^{-1} is 8.9 TNU for a thorium-to-uranium ratio of 4.0 [134].

Experiment	Year	Days	Geoneutrinos	Heat	Source
KamLAND	2005	749	4.5–54.2 of 152	U + Th < 60 TW	[134]
Borexino	2010	537	9.9 of 15	georeactor < 3 TW	[134]
KamLAND	2011	—	106 of 841	U + Th 20.0 TW; K 4 TW	[134][135]
KamLAND	2013	—	116 (+28/−27)	flux 3.4 × 10^{6} cm^{-2} s^{-1}	[136]
Borexino	2013	1,353	14.3 ± 4.4	georeactor < 4.5 TW	[134]
Borexino	2015	2,056	24 of 77	radiogenic 23–36 TW	[134]
Borexino	2020	3,262.74	about 52.6	radiogenic about 38 TW; georeactor < 2.4 TW	[137]

The Earth’s surface heat flow is 47 ± 2 TW from 38,347 measurements [138]. KamLAND’s 20.0 TW of uranium and thorium plus 4 TW of potassium is 54 % of 44.2 TW. Borexino’s 38 TW is 81 % of 47 TW; its mantle share is 65 % of its total.

New detectors followed: SNO+ in Canada, 0.8 kt, and JUNO in China, 20 kt [134][30]. The Heat Beneath text gives JUNO more than 20,000 tonnes of liquid, running since August 2025 [30]. Before it, only a few hundred geoneutrinos had been caught [30].

Read as form and carrier (form 3), the geoneutrino carries from one closure to the next. It leaves a decaying uranium or thorium nucleus and ends at a proton in a detector, binding nowhere on the way.

The oldest neutrinos: the relic background

They decoupled from matter at “temperatures T ~ 2 MeV” [114], “when the universe was just one second old” [115]. One second is position 33.15.

Their temperature today is “$T^0_\nu \simeq 1.7 \times 10^{-4}$ eV ≃ 1.9 K” [114]. It is set by the photon temperature: T_ν/T_γ = (4/11)^(1/3) = 0.714 [114]. With the CMB at 2.7255 ± 0.0006 K [25], T_ν = (4/11)^(1/3) × 2.7255 K = 1.945 K.

One fit of phase shifts in the CMB gave 1.96 ± 0.02 K, against 1.95 K expected [115]. Their energies today lie near 10^{-4} to 10^{-6} eV [115]. As wavelengths, hc/E, that is 1.24 cm to 1.24 m, positions 11.39 to 15.58; at 1.7 × 10^{-4} eV the wavelength is 7.3 mm (10.91).

There are 339.5 relic neutrinos and antineutrinos per cm³ today, all kinds together [114]. The simple count gives (3/11) × 410.73 = 112.0 per cm³ for each kind, 336.0 for three; the PDG value includes the correction to N_eff = 3.044. Photons number 410.73 per cm³ [25].

Their thermal energy, 1.7 × 10^{-4} eV, is 295 times below the 50.1 meV of the heaviest state. They have not been caught in any detector; the proposed PTOLEMY experiment aims at them [115].

Neutrinos from beyond the Galaxy (2013–2023)

The first PeV events (2013)

IceCube reported two events near a petaelectronvolt in 2013 [140]. Their energies were 1.04 ± 0.16 and 1.14 ± 0.17 PeV, in 615.9 days of live time (position 49.35) [140]. The

expected background was 0.082 ± 0.004 (stat) +0.041/−0.057 (syst); the excess stood at 2.8 σ, p = 2.9 × 10^{-3} [140].

The same year brought “Twenty-six additional events” above about 30 TeV, from May 2010 to May 2012 [141]. A purely atmospheric origin of the 28 was rejected at “the 4σ level” [141]. The wavelengths hc/E of these neutrinos run from 4.1 × 10^{-20} m at 30 TeV (−25.24) to 1.1 × 10^{-21} m at 1.14 PeV (−28.55).

A blazar (2017–2018)

On 22 September 2017 IceCube recorded a neutrino of “approximately 290 TeV”, IceCube-170922A [142]. It coincided with a gamma-ray flare of the blazar TXS 0506+056, observed with Fermi-LAT, MAGIC and thirteen other teams [142]. Its wavelength is 4.3 × 10^{-21} m, position −27.31.

An archival search of 9.5 years of data (position 50.92) then found an excess from the same direction between September 2014 and March 2015 [143]. It gave “3.5σ evidence for neutrino emission from the direction of TXS 0506+056” [143].

The blazar lies at redshift 0.3365 ± 0.0010, at a luminosity distance of about 1.75 Gpc, 5.7 billion light-years [144]. That is 5.4 × 10^{25} m, position 69.32; its gamma-ray flux varies by at least a factor of 1,000 [144].

A nearby galaxy and the Milky Way (2022–2023)

In 2022 IceCube found “an excess of 79 (+22/−20) neutrinos” from the active galaxy NGC 1068, in data of 2011–2020 [145]. The significance was 4.2 σ [145]. In 2023 it observed neutrinos from the plane of the Milky Way, “at the 4.5σ level of significance”, in ten years of data (position 50.97) [146].

The highest energy (2023)

On 13 February 2023, at 01:16:47 UTC, KM3NeT/ARCA recorded the event KM3-230213A [149]. The detector then had 21 detection lines, at a depth of 3,500 m (position 22.81), off Portopalo di Capo Passero, Sicily, at 36°16′N 16°06′E [149]. The muon carried 120 (+110/−60) PeV [149].

The estimated neutrino energy is 220 PeV, 0.035 J [149]. The check is 220 × 10^{15} eV × 1.602 176 634 × 10^{-19} J/eV = 0.0352 J.

It came in 0.6° above the horizon and is the “highest-energy neutrino event observed so far” [149]. The paper appeared in *Nature* on 12 February 2025 [147].

A companion analysis speaks of “hundreds of PeVs” [148]. For an E^{-2} spectrum it gives a flux normalisation of 7.5 × 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}, in 2.5–3 σ tension with the IceCube samples [148].

The event’s wavelength is 5.6 × 10^{-24} m, position −33.34; the muon’s 120 PeV corresponds to −32.79. The energy is 200 times that of the first PeV events and 759 times that of IceCube-170922A.

Event or source	Year	Energy	Significance	Source
two PeV events	2013	1.04, 1.14 PeV	2.8 σ	[140]
28 events above 30 TeV	2013	30 TeV – PeV	4 σ	[141]
IceCube-170922A, TXS 0506+056	2017	about 290 TeV	coincidence with flare	[142]
TXS 0506+056, 2014–2015 excess	2018	—	3.5 σ	[143]
NGC 1068	2022	79 events	4.2 σ	[145]
Galactic plane	2023	—	4.5 σ	[146]
KM3-230213A	2023	about 220 PeV	single event	[147][149]

The sky in neutrinos opened in 2013 with two events. Then it filled source by source: a blazar, a nearby galaxy, the Milky Way, and an event of 220 PeV. Read as form 6, the

sky in neutrinos was opened once and filled many times.

What this part of the history shows

What closes, stays, while the content changes, as a reading. The Sun’s ^{8}B neutrinos arrive with their total intact, 5.09×10^{6} cm^{-2} s^{-1}, but only 34.6 % as electron type. Reactor antineutrinos lose 6.0 % of their kind between near and far detectors. The total holds; the kind flows.

The carrier, as a reading. The neutrino binds to nothing on its way. A reactor flux of 5×10^{13} cm^{-2} s^{-1} gave three events per hour in 200 litres of water; the cross section was 6.3×10^{-44} cm^{2}. It leaves the Sun in 2.3 s (33.91), against 10^{4} to 1.7×10^{5} years for light, and passes from a decaying nucleus to a detector’s proton.

Rest and discharge, as a reading. SN 1987A released an estimated 10^{46} J in about 10^{58} neutrinos within 13 s (35.49). Three detectors counted 25 of them, two to three hours (41.61) before the light.

Three kinds. The Z width gives 2.9963 ± 0.0074 light neutrinos; the early universe gives N_eff = 2.86 ± 0.13 against 3.044 expected. Three neutrinos stand beside three charged leptons.

Opened once, filled many times, as a reading. The solar branches were seen one after another: pp, ^{7}Be, pep, ^{8}B, and CNO in 2020. The cosmic sky opened in 2013 with two PeV events and filled with a blazar (2017), NGC 1068 (2022), the Galactic plane (2023) and a 220 PeV event (2023).

The mirror, not seen. The two-neutrino double-beta decay of xenon-136 is measured at 2.18×10^{21} years (93.59). The neutrinoless form, the search for a neutrino that is its own mirror, gives a half-life above 3.8×10^{26} years (104.58).

The ladder. The heaviest neutrino state, at 50.1 meV if the lightest has none, has its mass length at 3.94 µm, position 4.06, 14.69 positions above the electron’s. The neutrinos met in this chapter span wavelengths from 5.6×10^{-24} m (−33.34) to 1.24 m (15.58), more than 48 positions. The limits on mass fell from 16 eV (1987) to 0.45 eV for one mass and 0.048 eV for the sum.

5. The Carriers of the Forces

Forces between particles are carried by particles. The photon carries the electromagnetic force; chapter 1 told its history as light.

The W and Z bosons carry the weak force, which turns one kind of quark or lepton into another. The gluon carries the strong force, which holds quarks together inside the proton and the neutron.

The three carriers differ in every measured way. The photon is listed as stable, and its mass is bounded below 1×10^{-18} eV.

The W and the Z weigh 80.37 and 91.19 GeV and live about 3×10^{-25} s. The gluon is listed with mass 0, and no gluon has ever been seen alone.

The history runs in this order. First the photon as carrier, with its bounds and its coupling. Then the weak force: beta decay, the broken mirror of parity in 1956, the broken mirror of CP in 1964, the W and Z in 1983, and the precise measurements that followed.

Then the mixing of the quarks, and the strong force with its coupling, its confinement and its candidate glueballs. The chapter ends with the times and lengths of all three carriers on the ladder of chapter 1.

The photon as carrier

G. N. Lewis gave the photon its name in a letter to *Nature* of 18 December 1926 [151]. In 1931 Raman and Bhagavantam verified its spin angular momentum of $\pm\hbar$, the same at every frequency [151]. The Particle Data Group lists its mean life as “Stable” [7].

Every other measured property of the photon is an upper bound. The PDG 2024 summary table gives $m_\gamma < 1 \times 10^{-18}$ eV [7]. In kilograms that is $1 \times 10^{-18} \times 1.602176634 \times 10^{-19}$ J / (299,792,458 m/s)$^2 = 1.78 \times 10^{-54}$ kg.

The limit rests on Ryutov’s 2007 analysis of the magnetohydrodynamics of the solar wind [8]. It “extends the method of RYUTOV 97 to the radius of Pluto’s orbit” [8]. Against the electron’s 0.511 MeV the bound is $1 \times 10^{-18} / 0.51099895 \times 10^{6} = 1.96 \times 10^{-24}$ of the electron mass.

The PDG photon listing holds other limits that it does not use for the average [8]. They are set out below, with the length each one implies.

A mass m corresponds to a length, the reduced Compton wavelength $\hbar c/(mc^2)$. With $\hbar c = 1.973269804 \times 10^{-7}$ eV m, a photon lighter than the bound has a reduced Compton wavelength longer than the length in the table.

Limit	Method	Bound	$\hbar c/(mc^2)$	Position	Source
Ryutov 2007 (PDG value)	solar-wind MHD to Pluto’s orbit	$< 1 \times 10^{-18}$ eV	$> 1.97 \times 10^{11}$ m	> 39.06	[7][8]
Tu 2006	torque on a rotating magnetized toroid	$< 1 \times 10^{-19}$ eV (frequentist 1.2×10^{-19})	$> 1.97 \times 10^{12}$ m	> 41.16	[8]
Füllekrug 2004	speed of 5–50 Hz radiation in the atmosphere, called “questionable”	$< 2 \times 10^{-16}$ eV	$> 9.87 \times 10^{8}$ m	> 34.24	[8]
Retinò 2016	Ampère’s law in the solar wind, Cluster spacecraft	$< 1.9 \times 10^{-15}$ eV	$> 1.04 \times 10^{8}$ m	> 32.19	[8]

Wang 2023	fast-radio-burst dispersion (68 % CL)	< 2.1 × 10⁻¹⁵ eV	> 9.40 × 10⁷ m	> 32.10	[8]
Bonetti 2016	FRB 150418, frequency-dependent delay	< 1.8 × 10⁻¹⁴ eV	> 1.10 × 10⁷ m	> 30.14	[8]
Bonetti 2017	repeating FRB 121102	< 2.2 × 10⁻¹⁴ eV	> 8.97 × 10⁶ m	> 29.96	[8]
Egorov 2014	lensed quasar positions (95 % CL)	< 2.3 × 10⁻⁹ eV	> 85.8 m	> 19.44	[8]
Adelberger 2007	Proca galactic magnetic field	< 1 × 10⁻²⁶ eV	> 1.97 × 10¹⁹ m	> 55.83	[8]

The PDG value gives a length of at least 1.97 × 10¹¹ m. With the astronomical unit of 1.495978707 × 10¹¹ m, that is 1.32 times the distance from the Earth to the Sun. Egorov’s lensing bound is “not competitive but obtained on cosmological distance scales” [8].

The galactic-field bound depends on a model. The listing states that “the very existence of the galactic field implies m < 10⁻²⁶ eV”, and that for a photon with a Higgs-type mass “no limit feasible” [8]. Wikipedia gives a mass “on the order of 10⁻⁵³ g” (Heeck 2013), a galactic vector-potential bound of 3 × 10⁻²⁷ eV, and a Coulomb-law bound of about 10⁻¹⁴ eV (Williams and colleagues, 1971) [151].

Wikipedia also quotes a PDG value of 1.07 × 10⁻²⁷ eV; the PDG 2024 summary table gives < 1 × 10⁻¹⁸ eV [7][151]. The limits span nine orders of magnitude, depending on whether a model of the galactic field is accepted.

The photon’s charge is bounded in two ways [7][8]. For a single charge, the isotropy of the cosmic microwave background gives q_γ < 1 × 10⁻³⁵ e (Caprini 2005). For a mixed charge, a VLBI search for an Aharonov–Bohm phase shift gives q_γ < 1 × 10⁻⁴⁶ e (Altschul 2007).

A laboratory laser-deflection experiment gives q_γ < 8.5 × 10⁻¹⁷ e (Semertzidis 2003) [8]. For a massive photon, Heeck (2013) gives a lifetime of more than 10¹⁸ years [151]. That is 1 × 10¹⁸ × 3.15576 × 10⁷ s = 3.16 × 10²⁵ s, position 86.60.

The strength of the electromagnetic coupling is the fine-structure constant. At zero momentum transfer it is α = 7.2973525643(11) × 10⁻³, or 1/137.036 [152]. Chapter 8 tells how it is measured.

The coupling is not the same at every energy. At a momentum transfer near the W mass, Q² ≈ m_W², the PDG gives α “~ 1/128” [152]. Wikipedia gives α ≈ 1/127 at about 90 GeV [153].

From 1/137.036 to 1/128 the coupling grows by 137.036/128 = 1.0706, that is by 7.1 %. The two values for high energy differ by 0.8 %.

Two photons carry no charge, yet they have been seen scattering off each other. ATLAS reported the evidence in 2017 from lead–lead collisions at 5.02 TeV per nucleon pair [20]. In 480 μb⁻¹ of data it counted 13 candidate events against an expected background of 2.6 ± 0.7.

The fiducial cross section was 70 ± 24 (stat.) ± 17 (syst.) nb, in agreement with Standard Model predictions [20]. In 2019 ATLAS observed the process in 1.73 nb⁻¹: 59 candidates against a background of 12 ± 3, a significance of 8.2 standard deviations [21].

The cross section was 78 ± 13 (stat.) ± 7 (syst.) ± 3 (lumi.) nb [21]. Chapter 9 sets these events among the measurements of the vacuum.

The weak force: beta decay and the broken mirrors

The weak force entered physics through beta decay. Fermi published his theory of beta decay in 1933, three years after the neutrino was proposed [109]. Chapter 4 tells how

the neutrino was caught in 1956.

In December 1956 C. S. Wu and her colleagues observed that beta decay tells left from right [155]. They cooled cobalt-60 nuclei to about 0.01 K and aligned their spins with a field of about 1 T, about 0.1 T at the nucleus inside the paramagnetic salt [155]. They followed the electrons for about a quarter of an hour as the crystal warmed: 900 s, position 39.34.

The electrons left preferentially opposite to the nuclear spin. The paper, “Experimental Test of Parity Conservation in Beta Decay”, appeared in *Physical Review* on 15 February 1957 [154]. It gave a lower limit of −0.7 for the asymmetry; corrected, the value was about −1, and later work gave −1.01 ± 0.02 [155].

An asymmetry of −1 is the largest possible. Just after New Year 1957, Garwin, Lederman and Weinrich confirmed the violation of parity in the decay of pions and muons [155]. Lee and Yang, who had proposed the test, received the Nobel Prize in 1957 [155].

The second mirror broke in 1964. Christenson, Cronin, Fitch and Turlay published “Evidence for the 2π Decay of the K_2^0 Meson” in *Physical Review Letters* on 27 July 1964 [156].

The long-lived neutral kaon was seen to decay, in a small fraction of cases, into two pions. Cronin and Fitch received the Nobel Prize in 1980 [157].

The size of the effect is now measured to better than one percent [113]. The branching ratio $K^0_L \to \pi^+\pi^-$ is $(1.967 \pm 0.010) \times 10^{-3}$. The amplitude ratio $|\eta_{+-}|$ is $(2.232 \pm 0.011) \times 10^{-3}$, and the CP parameter $|\varepsilon|$ is $(2.228 \pm 0.011) \times 10^{-3}$.

The two neutral kaons differ in mass by $m_{KL} - m_{KS} = (0.5293 \pm 0.0009) \times 10^{10}\ \hbar\ s^{-1} = (3.484 \pm 0.006) \times 10^{-12}$ MeV [113]. They differ in lifetime by a factor of 571 [113]. The K^0_L lives $(5.116 \pm 0.021) \times 10^{-8}$ s, position 17.87; the K^0_S lives $(0.8954 \pm 0.0004) \times 10^{-10}$ s, position 12.09.

A part of the violation is direct. This direct part is $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.66 \pm 0.23) \times 10^{-3}$ [113]. Its “final proof” came in 1999 from the KTeV and NA48 experiments [157].

In 2001 CP violation was found in B mesons, and there it is large. BaBar measured $\sin 2\beta = 0.59 \pm 0.14\ (\text{stat}) \pm 0.05\ (\text{syst})$ from 32 million $B\bar{B}$ pairs [158]. Belle measured the same quantity, which it calls $\sin 2\varphi_1$, as $0.99 \pm 0.14\ (\text{stat}) \pm 0.06\ (\text{syst})$ from 29.1 fb^{-1} [159].

The two first values differ by 0.40. With the errors combined in quadrature, $\sqrt{(0.14^2 + 0.05^2)}$ and $\sqrt{(0.14^2 + 0.06^2)}$, that is 1.9σ. The world average now is $\sin 2\beta = 0.709 \pm 0.011$ [160].

Charm followed: LHCb saw CP violation in D^0 decays in 2019, at 5.3σ [157]. In 2025 LHCb saw it in a baryon, the Λ_b, at 5.2σ [157]. The four systems were found in 1964, 2001, 2019 and 2025, over 61 years.

Year	System	Measured	Significance or value	Source
1956–57	^{60}Co beta decay (parity)	asymmetry	−0.7 (limit), later −1.01 ± 0.02	[154][155]
1957	pion and muon decay (parity)	confirmation	—	[155]
1964	$K^0_L \to 2\pi$ (CP)	discovery	today BR 1.967×10^{-3}	[156][113]
1999	kaons, direct CP	ε'/ε	$(1.66 \pm 0.23) \times 10^{-3}$	[157][113]
2001	B^0, BaBar	$\sin 2\beta$	$0.59 \pm 0.14 \pm 0.05$	[158]
2001	B^0, Belle	$\sin 2\varphi_1$	$0.99 \pm 0.14 \pm 0.06$	[159]
now	B^0, world average	$\sin 2\beta$	0.709 ± 0.011	[160]
2019	D^0, LHCb	CP violation	5.3σ	[157]
2025	Λ_b, LHCb	CP violation	5.2σ	[157]

The W and the Z

The carriers of the weak force were found at CERN in 1983. The UA1 and UA2 experiments at the SPS proton–antiproton collider saw the W clearly in January 1983 and the Z in May [161]. Rubbia and van der Meer received the Nobel Prize in 1984 [161].

The Z was then made in great numbers. The four LEP experiments recorded 17 million Z decays, and SLD recorded 600 thousand [111]. From the shape of the resonance came its mass, its width and the way that width divides.

The PDG 2025 values are these [113]. The total width is $\Gamma_Z = 2.4955 \pm 0.0023$ GeV. One charged-lepton pair takes $\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV; the hadrons take 1,744.4 ± 2.0 MeV; the invisible decays take 499.3 ± 1.5 MeV.

The parts add up: 3 × 83.984 + 499.3 + 1,744.4 = 2,495.7 MeV, against the total of 2,495.5 ± 2.3 MeV. The invisible share is (20.000 ± 0.055) % [113]. It is 499.3/83.984 = 5.945 times one charged-lepton width.

The invisible width counts the light neutrinos. LEP gave $N_\nu = 2.9840 \pm 0.0082$ in 2006 [111]. An improved calculation of the Bhabha cross section, which fixes the luminosity, moved it to 2.9963 ± 0.0074 in 2020 [112].

The PDG gives 2.996 ± 0.007 from Standard Model fits and 2.92 ± 0.05 from the direct invisible width [113]. Chapter 4 tells the neutrino side of this count.

The masses are now known to parts in 10^4 and 10^5. The PDG 2025 tables give $m_W = 80.3692 \pm 0.0133$ GeV and $m_Z = 91.1880 \pm 0.0020$ GeV [152][113].

The relative precisions are 1.7×10^{-4} for the W and 2.2×10^{-5} for the Z [152]. The PDG 2024 values are the same [7].

The W mass has its own history of measurements. In April 2022 the CDF collaboration at Fermilab gave 80,433 ± 9 MeV, from 4.2 million W candidates collected at the Tevatron [162][163]. The precision was 0.01 %; the Standard Model prediction quoted beside it was 80,357 ± 6 MeV [162].

The difference is 80,433 − 80,357 = 76 MeV. With $\sqrt{(9^2 + 6^2)} = 10.8$ MeV, that is 7.0σ. A phenomenology paper of the same year states “about 7σ deviations from the SM prediction” [164].

Two LHC measurements followed in 2024. ATLAS, re-analysing its 7 TeV data of 2011, gave 80,366.5 ± 9.8 (stat.) ± 12.5 (syst.) MeV = 80,366.5 ± 15.9 MeV [165].

An earlier ATLAS value from the same data, listed by Wikipedia, was 80,360 ± 16 MeV [161].

CMS, using W → μν decays in its 13 TeV data of 2016, gave 80,360.2 ± 9.9 MeV [166]. Wikipedia calls it “the most precise measurement to date” [161].

Measurement	Year	m_W (MeV)	Data	Source
CDF II	2022	80,433 ± 9	Tevatron, 4.2 million W	[162][163]
ATLAS	2023	80,360 ± 16	LHC 7 TeV, 2011	[161]
ATLAS	2024	80,366.5 ± 15.9	LHC 7 TeV, 2011	[165]
CMS	2024	80,360.2 ± 9.9	LHC 13 TeV, 2016, W → μν	[166]
PDG 2025 average	2025	80,369.2 ± 13.3	world average	[113]
Standard Model (as quoted by CDF)	2022	80,357 ± 6	calculation	[162]

CDF and CMS differ by 72.8 MeV. With $\sqrt{(9^2 + 9.9^2)} = 13.4$ MeV, that is 5.4σ. ATLAS and CMS differ by 6.3 MeV, and CMS lies 3.2 MeV above the Standard Model value CDF quoted.

The widths of the W come from three sources. The PDG 2025 gives $\Gamma_W = 2.14 \pm 0.05$ GeV, with a scale factor of 1.7 [113].

The PDG 2024 table gives 2.085 ± 0.042 GeV [7]. ATLAS measured 2,202 ± 32 (stat.) ± 34 (syst.) MeV = 2,202 ± 47 MeV [165].

A W decays to a charged lepton and a neutrino in one case out of three [113]. The branching ratios are eν (10.71 ± 0.16) %, μν (10.63 ± 0.15) %, τν (11.38 ± 0.21) %, and hadrons (67.41 ± 0.27) %. The three leptonic channels add to 32.72 %.

The τν channel lies 0.67 points above eν. With the errors combined in quadrature, $\sqrt{(0.16^2 + 0.21^2)} = 0.26$, that is 2.5σ.

A width Γ gives a lifetime $\tau = \hbar/\Gamma$, with $\hbar = 6.582119569 \times 10^{-25}$ GeV s. For the W, 2.14 GeV gives 3.08×10^{-25} s, position −18.22; 2.085 GeV gives 3.16×10^{-25} s, position −18.20.

For the Z, 2.4955 GeV gives 2.64×10^{-25} s, position −18.36. Wikipedia gives “a half-life of about 3×10^{-25} s” [161].

Both bosons are wide. Γ/m is 2.14/80.3692 = 0.0266 for the W and 2.4955/91.1880 = 0.0274 for the Z.

Their masses also give lengths. The reduced Compton wavelength $\hbar c/(mc^2)$ is 0.1973269804 GeV fm / 80.3692 GeV = 2.455×10^{-18} m for the W, position −21.52. For the Z it is 2.164×10^{-18} m, position −21.64.

The proton’s charge radius, 0.84075 fm, sits at −16.21. It is 0.84075×10^{-15} / 2.455×10^{-18} = 342 times the W length, 5.31 positions higher.

The heaviest quark decays through the W. The top quark lives 4.6×10^{-25} s, from its width of 1.42 (+0.19/−0.15) GeV, position −17.85 [59]. Its decays to W b make up $\Gamma(Wb)/\Gamma(Wq) = 0.957 \pm 0.034$ of those to W and a down-type quark [59].

The W from a top decay has a measured spin direction [59]. Its helicity fractions are $F_0 = 0.693 \pm 0.013$ (longitudinal), $F_- = 0.315 \pm 0.010$ (left-handed) and $F_+ = -0.005 \pm 0.007$ (right-handed). The right-handed share is zero within its error.

The strength of the weak force

The weak force is weak at low energy. Its strength there is the Fermi constant, measured through the lifetime of the muon. The PDG 2025 value is $G_F/(\hbar c)^3 = 1.1663785(6) \times 10^{-5}$ GeV^{-2}, with a relative uncertainty of 514 ppb [152].

The MuLan experiment reported the positive muon’s lifetime in 2013 as 2,196,980.3(2.2) ps, a precision of 1.0 ppm [45]. The result was “thirty times more precise than previous generations of lifetime experiments” [45]. From it MuLan gave $G_F = 1.1663787(6) \times 10^{-5}$ GeV^{-2}, to 0.5 ppm [45].

The PDG 2025 muon lifetime is $(2.1969811 \pm 0.0000022) \times 10^{-6}$ s, position 21.29 [113]. The Fermi constant and the W mass are measured independently and stand side by side.

The weak and electromagnetic couplings are joined by the weak mixing angle. In the MS-bar scheme at the Z mass, the PDG 2025 gives $\sin^2\theta(M_Z) = 0.23122(6)$ [152]. The PDG 2024 edition gave 0.23129(4) [13].

The angle can also be defined by the two masses. In this on-shell form, $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = 1 - (80.3692/91.1880)^2 = 0.22321$, with $m_W/m_Z = 0.88136$. The two schemes differ by 0.008; they are two definitions of one angle.

From the Fermi constant follows the energy scale of the weak force, the vacuum value of the Higgs field. At tree level it is v = (√2 G_F)^(−1/2) = 246.22 GeV. Chapter 6 tells its history.

The weak force sets the lifetimes of the particles that can decay only through it. They span from the top quark to the free neutron.

Particle	Mean life	Position	Source
top quark (from Γ = 1.42 GeV)	4.6×10^{-25} s	−17.85	[59]
τ lepton	$(290.3 \pm 0.5) \times 10^{-15}$ s	6.88	[113]

K^0_S	$(0.8954 \pm 0.0004) \times 10^{-10}$ s	12.09	[113]
π±	$(2.6033 \pm 0.0005) \times 10^{-8}$ s	17.26	[113]
K^0_L	$(5.116 \pm 0.021) \times 10^{-8}$ s	17.87	[113]
muon	$(2.1969811 \pm 0.0000022) \times 10^{-6}$ s	21.29	[113]
neutron	878.4 ± 0.5 s	39.32	[69]

The muon lives $2.1969811 \times 10^{-6} / 3.08 \times 10^{-25} = 7.1 \times 10^{18}$ times longer than the W. It lives 4.7×10^{18} times longer than the top quark. Between the top and the neutron lie 57.17 positions.

A decay through the electromagnetic force is much faster. The neutral pion decays into photons in $(8.43 \pm 0.13) \times 10^{-17}$ s, position −0.54 [113]. The charged pion, which can decay only weakly, lives $2.6033 \times 10^{-8} / 8.43 \times 10^{-17} = 3.09 \times 10^{8}$ times longer.

The mixing of the quarks

The W does not keep the quark families apart. It joins each quark of charge +2/3 to each of the three quarks of charge −1/3, each pair with its own strength. The strengths form a three-by-three table, the CKM matrix.

The direct measurements of its magnitudes are these, as collected by the PDG 2025 [160].

Element	Measured magnitude	Source
$\lvert V_{ud}\rvert$	0.97367 ± 0.00032	[160]
$\lvert V_{us}\rvert$	0.22431 ± 0.00085	[160]
$\lvert V_{ub}\rvert$	$(3.82 \pm 0.20) \times 10^{-3}$	[160]
$\lvert V_{cd}\rvert$	0.221 ± 0.004	[160]
$\lvert V_{cs}\rvert$	0.975 ± 0.006	[160]
$\lvert V_{cb}\rvert$	$(41.1 \pm 1.2) \times 10^{-3}$	[160]
$\lvert V_{td}\rvert$	$(8.6 \pm 0.2) \times 10^{-3}$	[160]
$\lvert V_{ts}\rvert$	$(41.5 \pm 0.9) \times 10^{-3}$	[160]
$\lvert V_{tb}\rvert$	1.010 ± 0.027	[160]

The global fit, which imposes that the table be unitary, gives the full matrix [160].

	d	s	b
u	0.97435 ± 0.00016	0.22501 ± 0.00068	0.003732 (+0.000090/−0.000085)
c	0.22487 ± 0.00068	0.97349 ± 0.00016	0.04183 (+0.00079/−0.00069)
t	0.00858 (+0.00019/−0.00017)	0.04111 (+0.00077/−0.00068)	0.999118 (+0.000029/−0.000034)

The matrix is written with four numbers, the Wolfenstein parameters [160]. They are $\lambda = 0.22501 \pm 0.00068$, $A = 0.826$ (+0.016/−0.015), $\bar{\rho} = 0.1591 \pm 0.0094$ and $\bar{\eta} = 0.3523$ (+0.0073/−0.0071).

The pattern is a ladder of powers. On the diagonal the magnitudes are 0.973 to 0.999.

One step off the diagonal stands $\lambda = 0.225$. Two steps off, $A\lambda^2 = 0.826 \times 0.22501^2 = 0.0418$, and the corners stand at 0.0037 to 0.0086, near $A\lambda^3 = 0.0094$.

CP violation in the quark sector has one measure, the Jarlskog invariant: $J = 3.12$ (+0.13/−0.12) $\times 10^{-5}$ [160]. The three angles of the unitarity triangle are measured too. From $\sin 2\beta = 0.709 \pm 0.011$ follows $\beta = \frac{1}{2} \arcsin 0.709 = 22.6°$; the PDG gives $\alpha = 84.1$ (+4.5/−3.8)° and $\gamma = 65.7 \pm 3.0°$ [160].

The three angles add to 84.1 + 22.6 + 65.7 = 172.4°, against 180°, with a combined error of about 5.4°. The direct first-row measurements add to $\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2 = 0.9984 \pm 0.0007$ [160].

The strong force and the gluon

The carrier of the strong force is the gluon. The PDG lists its mass as 0 [7]. It carries colour charge, and colour-charged particles have never been isolated: confinement is “the phenomenon that color-charged particles (such as quarks and gluons) cannot be isolated” [67].

The searches agree. The PDG quark table states: “All searches since 1977 have had negative results” [59]. A bound on fractional charge comes from the sum of the proton and electron charges: $|q_p + q_e|/e < 1 \times 10^{-21}$ [69].

The strength of the strong force is the coupling α_s. It is quoted at one scale by convention: “it has become standard practice to quote the value of αs at a given scale (typically the mass of the Z boson, mZ)” [66]. There the PDG gives $\alpha_s(m_Z) = 0.1180(9)$, a relative uncertainty of $0.0009/0.1180 = 7.6 \times 10^{-3}$ [13][152].

The coupling falls as the energy rises. “For momentum transfers in the 0.1–1 TeV range, αs ~ 0.1” [66]. At low momentum transfer the evidence points to “a moderately large coupling, typically of value 1-3” [67].

From 1–3 at low energy to 0.118 at 91 GeV is a fall by a factor of 8.5 to 25. The electromagnetic coupling moves the other way, from 1/137 to about 1/128, by 7 %.

The confinement scale is defined as “the scale at which the perturbatively defined strong coupling constant diverges” [67]. At low temperature quarks stay bound in hadrons. Above a certain temperature they do not.

Lattice QCD fixes that temperature. With two light flavours and a strange quark at their physical masses, in the continuum limit, the HotQCD collaboration found in 2019: “We obtained a precise result for $T_c(0) = (156.5 \pm 1.5)$ MeV” [70]. In kelvin, $156.5 \text{ MeV} \times 1.16045 \times 10^{10} \text{ K/MeV} = 1.82 \times 10^{12}$ K.

The same work gave the curvature of the transition line in baryon chemical potential, $\kappa_2^B = 0.012(4)$ and $\kappa_4^B = 0.000(4)$ [70]. At chemical freeze-out the phase boundary “coincides with the lines of constant energy density of 0.42(6) GeV/fm³ and constant entropy density of 3.7(5) fm⁻³” [70].

Earlier lattice values were higher. A 2008 statement, quoted by PHENIX in 2010, reads: “Lattice QCD predicts a phase transition to quark gluon plasma at ~ 170 MeV” [167]. Wikipedia gives approximately 175 MeV for older lattice work and about 156 MeV for the 2019 result [68].

The spectra of hadrons show a limiting temperature of their own, the Hagedorn temperature. One Wikipedia article gives “approximately 130–140 MeV per particle”, about 2×10^{12} K [67].

Another gives 150 MeV [68]. Chapter 3 tells how the quark–gluon plasma was made in collisions above this line.

Gluons may bind to each other. A bound state of gluons alone would be a glueball, and three candidates are measured. None is established as a pure glueball.

Two are scalars in the PDG 2024 meson table, which does not call them glueballs [92]. The $f_0(1500)$ has a Breit–Wigner mass of 1522 ± 25 MeV and a T-matrix pole at $\sqrt{s} = (1430–1530) - i(40–90)$ MeV. The $f_0(1710)$ has $1733\ (+8/-7)$ MeV and a pole at $(1680–1820) - i(50–180)$ MeV.

The third came in 2024 from BESIII, in $(10{,}087 \pm 44) \times 10^6$ J/ψ events: the state X(2370), of mass 2395 ± 11 (stat) $(+26/-94)$ (syst) MeV [100]. Its width is $188\ (+18/-17)$ (stat) $(+124/-33)$ (syst) MeV. Its spin and parity were fixed as 0^{-+} “for the first time”, at more than 11.7σ.

The mass and the spin-parity are “consistent with the predictions of the lightest pseudoscalar glueball” [100]. The product branching fraction is $(1.31 \pm 0.22\ (+2.85/-0.84)) \times 10^{-5}$. The mass is 2395/938.272 = 2.55 proton masses, and the width gives $\tau = \hbar/\Gamma = 3.5 \times 10^{-24}$ s, position −16.01.

The strong force sets the shortest lifetimes among the hadrons. The ρ(770) has a width

of 147.4 ± 0.8 MeV, which gives 4.47 × 10^{-24} s, position −15.79 [92].

The Δ(1232) has a width of about 117 MeV, which gives 5.63 × 10^{-24} s, position −15.58 [69]. The ω(782), with 8.68 ± 0.13 MeV, lives 7.58 × 10^{-23} s, position −13.21 [92].

The three forces on the ladder

Each force leaves its mark in time as the lifetime of the particles that decay through it. The table sets the measured cases side by side, ordered by position.

Decay through	Particle	Mean life	Position	Source
weak (carrier)	Z	2.64 × 10^{-25} s	−18.36	[113]
weak (carrier)	W	3.08 × 10^{-25} s	−18.22	[113]
weak	top quark	4.6 × 10^{-25} s	−17.85	[59]
strong	X(2370)	3.5 × 10^{-24} s	−16.01	[100]
strong	ρ(770)	4.47 × 10^{-24} s	−15.79	[92]
strong	Δ(1232)	5.63 × 10^{-24} s	−15.58	[69]
strong	ω(782)	7.58 × 10^{-23} s	−13.21	[92]
electromagnetic	η	5.02 × 10^{-19} s	−5.20	[92]
electromagnetic	π^0	8.43 × 10^{-17} s	−0.54	[113]
weak	τ lepton	2.903 × 10^{-13} s	6.88	[113]
weak	K^0_S	8.954 × 10^{-11} s	12.09	[113]
weak	π±	2.6033 × 10^{-8} s	17.26	[113]
weak	K^0_L	5.116 × 10^{-8} s	17.87	[113]
weak	muon	2.1969811 × 10^{-6} s	21.29	[113]
weak	neutron	878.4 s	39.32	[69]
none seen	photon	stable; > 10^{18} yr if massive	> 86.60	[7][151]

The η width of 1.31 ± 0.05 keV gives its lifetime of 5.02 × 10^{-19} s [92]. The strong decays sit between −16.0 and −13.2, the electromagnetic ones between −5.2 and −0.5. The weak decays of the light particles run from 6.88 to 39.32.

The carriers of the weak force themselves sit lowest of all, at −18.4 to −18.2. They decay through the force they carry.

In size the carriers stand at the two ends of the ladder. The W and the Z have reduced Compton wavelengths of 2.455 and 2.164 × 10^{-18} m, at −21.52 and −21.64. The photon’s, by the PDG mass bound, is longer than 1.97 × 10^{11} m, above 39.06.

Between these two lie 39.06 − (−21.64) = 60.70 positions. The proton, at −16.21, lies 5.43 positions above the Z length.

What this part of the history shows

Read in the forms of the net, confinement has the form of what closes, stays. No free quark has been found in any search since 1977, and colour-charged particles cannot be isolated [59][67]. What is found free is a closed combination of colours: a proton, a pion, at most a glueball candidate.

The net’s second axiom has this form: “A configuration persists only if it closes on itself. What does not close does not persist as a configuration; its tension moves to the neighbouring meshes.” [26]

Read as form and carrier (form 3), the W and Z are the open carriers. They live 2.6 to 3.2 × 10^{-25} s, at −18.4 to −18.2, and in that time a W turns one kind of quark or lepton into another. The closed forms it joins last; the open carrier between them decays.

The photon reads in the net texts as the strand itself: a free photon is one directed stretch, a photon on an open path [26]. It is listed as stable, with its mass below 1 ×

10^{-18} eV and its charge below 1×10^{-35} e [7].

Read in the forms of the net, parity shows the form of one direction (form 2). The beta asymmetry of cobalt-60 is -1.01 ± 0.02, the largest possible, and in top decays the right-handed W fraction is -0.005 ± 0.007 [155][59]. In the net texts the net keeps the orientation of what was first laid down, and on the cube of three the pseudoscalar is handedness [26][32].

The CP asymmetry is small beside it. In kaons $|\varepsilon| = 2.228 \times 10^{-3}$; in B mesons $\sin 2\beta = 0.709$; the Jarlskog measure is 3.12×10^{-5} [113][160].

Read as context (form 14), the electromagnetic coupling is 1/137.036 at zero momentum and about 1/128 near the W mass [152]. The strong coupling is 1 to 3 at low momentum, 0.118 at 91 GeV and about 0.1 at 0.1–1 TeV [66][67]. The net texts call this change measured, not supposed: 1/137 at low energy and about 1/127 at high [168].

The crossover reads as the same form at a larger scale. Below 156.5 MeV quarks stay in hadrons; above it they flow as a plasma [70].

The net texts read short range as the net remembering two steps back and no more, the form of reach two [31]. Set beside it are the measured lengths: the reduced Compton wavelengths of the weak carriers, 2.2 and 2.5×10^{-18} m, and the proton's 0.84 fm, within which the strong force binds.

Read as rest and discharge (form 16), the lifetimes fall into bands: a carrier 10^{-25} s, a strong resonance 10^{-24} s, an electromagnetic decay 10^{-19} to 10^{-17} s, a weak decay 10^{-13} to 10^{3} s. The net texts read decay as tension leaving the rest zone, and its apparent chance as dependence on the surroundings [31].

6. The Higgs

The weak force has a scale of energy. It follows from the Fermi constant of chapter 5, $G_F/(\hbar c)^3 = 1.1663785(6) \times 10^{-5}$ GeV^{-2} [152]. At tree level the vacuum value of the Higgs field is $v = (\sqrt{2}\, G_F)^{(-1/2)} = 246.22$ GeV.

The Higgs boson is the particle of that field. It was found in 2012 at the Large Hadron Collider at CERN, by two experiments at once. Its mass is now known to better than one part in a thousand: 125.20 ± 0.11 GeV [113].

This chapter tells the discovery, the measurements of the mass, the width, the couplings and the self-coupling, and the count of Higgs bosons made so far. It ends with the calculation that takes the measured masses of the Higgs and the top quark and asks how stable the vacuum is. The answer is a lifetime of 10^{139} years [180].

The scale before the particle

The Higgs field has a measured value before the Higgs boson has a measured mass. From $G_F = 1.1663785 \times 10^{-5}$ GeV^{-2}, $v = 1/\sqrt{(\sqrt{2} \times 1.1663785 \times 10^{-5})}$ GeV = 246.22 GeV [152]. Its reduced Compton length, $\hbar c/v = 0.1973269804$ GeV fm / 246.22 GeV, is 8.01×10^{-19} m, position −22.54.

The early universe passed through the electroweak scale. Lattice calculation places the electroweak crossover at $T_c = 159.5 \pm 1.5$ GeV [181]. With 1.16045×10^{13} K per GeV, that is 1.85×10^{15} K.

A review of 2012 on matter and antimatter in the universe (chapter 7) states: “A first order phase transition could only occur if the Higgs mass were below 72 GeV” [182]. The measured mass, 125.20 GeV, lies 53 GeV above that bound.

The discovery, 2012

The ATLAS discovery paper was submitted to arXiv on 31 July 2012 [169]. ATLAS and CMS each used about 10 fb^{-1} of proton collisions at 7 and 8 TeV [169][170].

ATLAS used about 4.8 fb^{-1} at 7 TeV, recorded in 2011, and 5.8 fb^{-1} at 8 TeV, recorded in 2012 [169]. It found a new particle at 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV. The excess had a significance of 5.9 standard deviations; the probability that the background alone fluctuated so far was 1.7×10^{-9} [169].

CMS used up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV [170]. It found a new boson at 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV. The local significance was 5.0 standard deviations, against 5.8 expected [170].

The combined errors were $\sqrt{(0.4^2 + 0.4^2)} = 0.57$ GeV for ATLAS and $\sqrt{(0.4^2 + 0.5^2)} = 0.64$ GeV for CMS. The two masses differed by 0.7 GeV, inside those errors. The CMS title named the mass: “Observation of a new boson at a mass of 125 GeV” [170].

The mass

The mass sharpened year by year. The PDG 2025 listing holds the results below, each in GeV [171].

Year	Experiment	Channel or data	Mass (GeV)	Source
2012	ATLAS	discovery	126.0 ± 0.4 ± 0.4	[171][169]
2012	CMS	discovery	125.3 ± 0.4 ± 0.5	[171][170]
2014	CMS	ττ	122 ± 7	[171]
2015	CMS	combination	125.02 (+0.26/−0.27) (+0.14/−0.15)	[171]

2017	CMS	four leptons	125.26 ± 0.20 ± 0.08	[171]
2018	ATLAS	combination	124.97 ± 0.24	[171]
2020	CMS	diphoton, 2016 data	125.78 ± 0.26	[173]
2020	CMS	with four leptons	125.46 ± 0.16	[173]
2020	CMS	with Run 1	125.38 ± 0.14	[173]
2023	ATLAS	four leptons	124.94 ± 0.17 ± 0.03	[171]
2023	ATLAS	diphoton	125.22 ± 0.11 ± 0.09	[171]
2023	ATLAS	γγ + 4ℓ, Run 1 + Run 2	125.11 ± 0.11	[172]
2025	PDG average (S = 1.4)	all	125.20 ± 0.11	[113][171]

The ATLAS result of 2023 is 125.11 ± 0.09 (stat) ± 0.06 (syst) GeV, a precision of 0.09 % [172]. The PDG listing also has an ATLAS value of 125.10 ± 0.11 GeV from 13 TeV data, used in the average [171].

The CMS combination of 125.38 ± 0.14 GeV and the ATLAS one of 125.11 ± 0.11 GeV differ by 0.27 GeV. With $\sqrt{(0.14^2 + 0.11^2)} = 0.18$ GeV, that is 1.5σ.

Since 2012 the individual results have ranged from 124.94 to 126.0 GeV, apart from the coarse ττ value. In eleven years the error of each experiment fell from about 0.6 GeV to 0.11–0.14 GeV, by a factor of about five.

The Higgs mass sits between the weak bosons and the top quark. It is 125.20/80.3692 = 1.558 times the W mass and 125.20/91.1880 = 1.373 times the Z mass. The top quark, at 172.56 ± 0.31 GeV from direct measurements, is 172.56/125.20 = 1.378 times the Higgs mass [113].

The Higgs mass also gives a length. Its reduced Compton wavelength is 0.1973269804 GeV fm / 125.20 GeV = 1.576×10^{-18} m, position −21.93. The Z stands at −21.64, the W at −21.52, the top at −22.22 and the vacuum value v at −22.54.

The width and the lifetime

The Higgs is narrow, too narrow to be measured from the shape of its peak. The direct line-shape bound is only about 50 MeV at 68 % CL and 330 MeV at 95 % CL [174]. The Standard Model expects $\Gamma_H = 4.1$ MeV, with an uncertainty of 1.37 % [174].

The width was reached another way. A Higgs boson can also contribute to the production of two Z bosons far from its own mass, off its shell. In 2022 CMS reported evidence for these off-shell contributions [177].

“The scenario with no off-shell contribution is excluded at a p-value of 0.0003 (3.6 standard deviations)” [177]. From these data CMS gave $\Gamma_H = 3.2$ (+2.4/−1.7) MeV [177][175]. The PDG 2025 gives 3.7 (+1.9/−1.4) MeV, assuming equal on-shell and off-shell effective couplings [113].

The lifetime is $\tau = \hbar/\Gamma$, with $\hbar = 6.582119569 \times 10^{-25}$ GeV s. The PDG width gives $6.582119569 \times 10^{-25} / 3.7 \times 10^{-3} = 1.78 \times 10^{-22}$ s, position −12.43. The CMS width gives 2.06×10^{-22} s, position −12.30; the expected 4.1 MeV gives 1.61×10^{-22} s, position −12.53.

Width	Value	Lifetime	Position	Source
PDG 2025	3.7 (+1.9/−1.4) MeV	1.78×10^{-22} s	−12.43	[113]
CMS 2022	3.2 (+2.4/−1.7) MeV	2.06×10^{-22} s	−12.30	[177]
Standard Model	4.1 MeV ± 1.37 %	1.61×10^{-22} s	−12.53	[174]
line shape, 68 % CL	< about 50 MeV	$> 1.3 \times 10^{-23}$ s	> −14.80	[174]

line shape, 95 % CL	< about 330 MeV	> 2.0 × 10⁻²⁴ s	> −16.52	[174]

The Higgs lives much longer than the particles around it in mass. The Z, at 91.19 GeV, lives 2.64 × 10⁻²⁵ s; the Higgs lives 1.78 × 10⁻²² / 2.64 × 10⁻²⁵ = 674 times longer, 5.93 positions higher. The W and the top quark live 3.1 and 4.6 × 10⁻²⁵ s.

The ratio Γ/m shows the same. For the Higgs it is 3.7 × 10⁻³ / 125.20 = 3.0 × 10⁻⁵. For the Z it is 2.7 × 10⁻², for the W 2.6 × 10⁻², for the top 8.2 × 10⁻³.

The couplings

The Higgs is measured through what it decays into and how it is made. Each rate is compared with the Standard Model value; the ratio is the signal strength μ. The PDG 2025 values are these [113].

Channel	Signal strength μ	Source
combined	1.03 ± 0.04	[113]
WW*	1.00 ± 0.08	[113]
ZZ*	1.02 ± 0.08	[113]
γγ	1.10 ± 0.06	[113]
$b\bar{b}$	0.99 ± 0.12	[113]
$\tau^+\tau^-$	0.91 ± 0.09	[113]
$\mu^+\mu^-$	1.21 ± 0.35	[113]
Zγ	2.2 ± 0.7	[113]
γ*γ	1.5 ± 0.5	[113]
$c\bar{c}$	< 14 (95 % CL)	[113]

The couplings themselves are written as modifiers κ, equal to 1 in the Standard Model. The PDG 2025 gives κ_F = 0.94 ± 0.05 for fermions and κ_V = 1.023 ± 0.026 for the weak bosons [113]. For two weak bosons at once, κ_2V = 1.02 ± 0.23.

Production with top quarks measures the top coupling directly. The PDG gives $t\bar{t}H$ production at 1.10 ± 0.18 of the Standard Model rate and single tH at 6 ± 4 [113]. Production with bottom quarks, $b\bar{b}H$, is below 3.7 times the expected rate (95 %) [113].

Ten years after the discovery, in 2022, both experiments published their maps in *Nature*. ATLAS, with 139 fb⁻¹, gave μ = 1.05 ± 0.06, κ_V = 1.035 ± 0.031 and κ_F = 0.95 ± 0.05 [176]. Its top, bottom and tau couplings were known to about 7–12 %, its weak-boson couplings to about 5 % [176].

ATLAS also set κ_c below 5.7 times the Standard Model value (expected 7.6), at 95 % CL [176]. It bounded the invisible branching fraction below 0.13 (expected 0.08) [176].

CMS, with up to 138 fb⁻¹, gave “μ = 1.002 ± 0.057” [175]. It probed the coupling modifiers to about 10 %, κ_b and κ_μ to about 20 %, and κ_Zγ to about 40 % [175].

Decays into nothing visible are limited further. The ATLAS combination of 7, 8 and 13 TeV gives B(H → invisible) < 0.107 at 95 % CL [171]. In the PDG figure of signal strengths, the compatibility with the Standard Model is p = 3 % for CMS and 84 % for ATLAS [174].

The self-coupling

The Higgs field also couples to itself. At tree level the quartic coupling is λ = m_H²/(2v²) = 125.20²/(2 × 246.22²) = 0.129. Its measured trace is the production of Higgs pairs.

Pairs are rare. The Standard Model cross section for gg → HH at 13 TeV is 33.47 (+0.88 %/−0.85 %) fb, and vector-boson fusion adds about 1.7 fb [174]. Against the total single-Higgs cross section of 55.6 pb, that is 33.47 × 10⁻³ / 55.6 = 6.0 × 10⁻⁴: one pair for every 1,660 single bosons.

The self-coupling is written as κ_λ, equal to 1 in the Standard Model. The searches for

pairs bound it.

Result	HH rate (95 % CL)	κ_λ range (95 % CL)	Source
CMS 2022	< 3.4 × SM	−1.24 to 6.49	[175]
ATLAS 2024 (126–140 fb⁻¹)	< 2.9 × SM (expected 2.4)	−1.2 to 7.2	[178]
PDG 2025	< 2.4 × SM	κ_λ = 3.8 (+2.1/−4.0)	[113]

ATLAS also bounded the coupling of two Higgs bosons to two weak bosons: 0.6 < κ_2V < 1.5 at 95 % CL [178]. The self-coupling range is still eight units wide.

How many Higgs bosons have been made

At 13 TeV, with m_H = 125 GeV, the Standard Model cross section for making a Higgs boson is 55.6 pb (+6.0 %/−8.3 %) [174]. It divides among the production modes as follows [174].

Mode	Cross section (pb)	Share
gluon fusion (ggF)	48.4	87 %
vector-boson fusion (VBF)	3.81	6.9 %
WH	1.38	2.5 %
ZH	0.893	1.6 %
$t\bar{t}H$	0.531	1.0 %
$b\bar{b}H$	0.528	0.9 %
tH	0.076	0.1 %
total	55.6	100 %

One Higgs boson is made for each 1/55.6 pb⁻¹ = 18 nb⁻¹ of integrated luminosity. In 139 fb⁻¹ = 139,000 pb⁻¹ that gives 55.6 × 139,000 = 7.7 million.

The experiments state their own numbers. For Run 2 of 2015–2018, ATLAS writes: “About 9 million Higgs bosons are predicted to have been produced in the ATLAS detector during this period” [176]. CMS writes that “approximately 8 million Higgs bosons have been produced” in its 138 fb⁻¹ [175].

That is about 30 times the number at the discovery [175][176]. About 0.3 % of them are experimentally accessible, which is 0.003 × 9 million = 27,000 per experiment [176]. CMS expects an order of magnitude more over the next fifteen years [175].

The stability of the vacuum

The measured masses of the Higgs and the top quark enter a calculation of the vacuum itself. In 2013 Buttazzo and colleagues ran the Higgs quartic coupling up to the Planck scale with three-loop equations [179]. Their inputs were M_t = 173.34 GeV, M_h = 125.15 ± 0.24 GeV and $\alpha_3(M_Z) = 0.1184 \pm 0.0007$ [179].

With these inputs λ crosses zero at about 10^{10} GeV [179]. The gauge-independent instability scale is $\log_{10}(\Lambda_V/\mathrm{GeV}) = 9.5 + 0.7\,(M_h - 125.15) - 1.0\,(M_t - 173.34) + 0.3\,(\alpha_3 - 0.1184)/0.0007$, about 3×10^9 GeV at the central inputs [179].

At the Planck scale the coupling is $\lambda(M_{Pl}) = -0.0143 - 0.0066\,(M_t - 173.34) + 0.0029\,(M_h - 125.15)$, plus a term in α_3 [179]. The energies have lengths: $\hbar c/(10^{10}\ \mathrm{GeV}) = 1.97 \times 10^{-26}$ m, position −38.49; $\hbar c/(3 \times 10^9\ \mathrm{GeV}) = 6.58 \times 10^{-26}$ m, position −37.39. The Planck length, 1.616255×10^{-35} m, stands at −57.53 [1].

A vacuum stable up to the Planck scale needs $M_h > 129.6\ \mathrm{GeV} + 2.0\,(M_t - 173.34\ \mathrm{GeV}) - 0.5\ \mathrm{GeV} \times (\alpha_3(M_Z) - 0.1184)/0.0007 \pm 0.3\ \mathrm{GeV}$ [179]. In short, $M_h > (129.6 \pm 1.5)$ GeV, or equivalently $M_t < (171.53 \pm 0.42)$ GeV [179]. With the 2013 inputs, stability up to the Planck scale is excluded at 2.8σ, 99.8 % one-sided [179].

The present inputs are M_t = 172.56 GeV, M_h = 125.20 GeV and α_s = 0.1180 [113] [152]. Put into the same linear formula, the threshold becomes 129.6 + 2.0 × (−0.78) −

0.5 × (−0.571) = 128.33 GeV. The measured Higgs mass lies 3.13 GeV below it.

The same inputs give λ(M_Pl) ≈ −0.0143 + 0.0051 + 0.0001 = −0.009, leaving out the α_3 term. The measured top mass, 172.56 ± 0.31 GeV, lies 1.03 GeV above the stability line of 171.53 GeV. These two numbers apply the paper's fitted formulas to new inputs; they are not results printed in the paper.

The vacuum so described is metastable. In 2018 Andreassen, Frost and Schwartz gave "the first complete calculation of the lifetime of our universe: 10^139 years" [180]. At 95 % confidence the lifetime is "more than 10^58 years" [180].

To exclude absolute stability at 3σ, the error on the top pole mass must fall below 250 MeV, or the error on α_s(m_Z) below 0.00025 [180]. The present direct top-mass error is 310 MeV [113].

The ladder places these times. With one year = 3.15576×10^7 s, 10^{139} years is position 340.20 and 10^{58} years is position 170.43. The present age of the universe, 13.797 ± 0.023 Gyr, is at 70.12 [25].

The central lifetime is $10^{139} / 13.797 \times 10^9 = 7 \times 10^{128}$ times the present age. The lower bound is 7×10^{47} times that age.

The Higgs on the ladder

The measured and computed scales of this chapter, ordered by position, are these.

Quantity	Value	Position	Source
Planck length (reference)	1.616255×10^{-35} m	size −57.53	[1]
instability scale ħc/(10^{10} GeV)	1.97×10^{-26} m	size −38.49	[179]
instability scale ħc/(3×10^9 GeV)	6.58×10^{-26} m	size −37.39	[179]
vacuum value ħc/v	8.01×10^{-19} m	size −22.54	[152]
top quark ħc/(m_t c^2)	1.144×10^{-18} m	size −22.22	[113]
Higgs ħc/(m_H c^2)	1.576×10^{-18} m	size −21.93	[113]
Z ħc/(m_Z c^2)	2.164×10^{-18} m	size −21.64	[113]
W ħc/(m_W c^2)	2.455×10^{-18} m	size −21.52	[113]
Z lifetime	2.64×10^{-25} s	time −18.36	[113]
Higgs lifetime, expected (4.1 MeV)	1.61×10^{-22} s	time −12.53	[174]
Higgs lifetime, PDG (3.7 MeV)	1.78×10^{-22} s	time −12.43	[113]
Higgs lifetime, CMS (3.2 MeV)	2.06×10^{-22} s	time −12.30	[177]
age of the universe	13.797 Gyr	time 70.12	[25]
vacuum lifetime, 95 % lower bound	10^{58} yr	time 170.43	[180]
vacuum lifetime, central	10^{139} yr	time 340.20	[180]

The four heavy particles stand within 0.70 positions of each other in size, from −22.22 to −21.52. The vacuum value lies 0.32 positions below the top. In time the Higgs stands six positions above the weak bosons.

What this part of the history shows

The Higgs measurements bear on mass. In the texts' words, "A knot is what current physics calls mass" [26]. The measured couplings of the Higgs to the massive weak bosons and fermions stand at κ_V = 1.023 ± 0.026 and κ_F = 0.94 ± 0.05 of the Standard Model values [113].

The vacuum value has the form of context. The scale v = 246.22 GeV is a value of the

vacuum, read from the measured Fermi constant [152].

The texts name constants state functions of the local vacuum [26]. The lattice places the electroweak crossover, a change in the state of the vacuum, at 159.5 GeV or 1.85×10^{15} K [181].

The Higgs boson shows the form of form and carrier. It does not persist: it decays in 1.78×10^{-22} s, position −12.43 [113]. It is the narrowest of the heavy particles, $\Gamma/m = 3.0 \times 10^{-5}$, and lives 674 times longer than the Z.

The texts read decay as tension leaving the rest zone [31]. Read in that form, the Higgs leaves the rest zone later than the W, the Z and the top: 1.78×10^{-22} s against 2.6 to 4.6 $\times 10^{-25}$ s.

The vacuum sits close to a line and not on it. The present inputs put the stability threshold at 128.33 GeV and the measured mass 3.13 GeV below it. At the Planck scale the quartic coupling is −0.0143 with the 2013 inputs and about −0.009 with the present ones [179].

The texts state that the tuning of α is exact only at the renormalization fixed point and leaves a residue [58]. Read in the same form, the remainder of the Higgs vacuum is small, and it is computed from measured masses.

The vacuum shows the form of holding. Its computed lifetime is 10^{139} years, position 340.20; at 95 % confidence more than 10^{58} years, position 170.43 [180].

The present age stands at 70.12. Read as rest and discharge, the state holds, and its discharge lies 100 to 270 positions ahead.

The count of Higgs bosons reads as a kind opened once and then filled many times. The kind was opened in 2012 with about 10 fb^{-1} per experiment [169][170]. By 2018 each experiment had received 8 to 9 million, 30 times the discovery sample [175][176].

7. Antimatter

Matter has a mirror. Each antiparticle carries the opposite charge of its partner, and every property measured on both agrees within its error. The positron mirrors the electron, the antiproton the proton, and antihydrogen the hydrogen atom.

The history runs from an equation in 1928 to an antiatom falling in the Earth's field in 2023. The positron was found in 1932, the antiproton in 1955, the first antiatoms in 1995. Antihydrogen has been held for 1,000 s, and its spectrum matches that of hydrogen to 2 parts in 10^{12}.

The universe itself holds almost none of it. For every ten billion photons there are about six baryons, and any domain of antimatter must be as large as the observable universe. This chapter tells the finds in order, the precision of the mirror, and the measured shortage.

The prediction and the positron

P. A. M. Dirac published "The quantum theory of the electron" in the *Proceedings of the Royal Society* on 1 February 1928 [183]. The equation allowed states of both signs of charge [184]. In 1931 Dirac predicted a particle he called an "anti-electron" [184].

Tracks of the opposite curvature had been seen before. From 1923 Skobeltsyn photographed tracks that "curved in the opposite direction in an applied magnetic field", with photographs dated July 1928 [184]. In 1929 Chung-Yao Chao at Caltech "noticed some anomalous results" [184].

On 2 August 1932 Carl Anderson found the positron in a cloud chamber in a magnetic field [184]. "A 6 mm lead plate separates the chamber" [184].

Anderson published "The Positive Electron" in *Physical Review* on 15 March 1933 [185]. He received the Nobel Prize in 1936 [184]. From 1932 to 2026 is 94 years, position 53.01.

Light into matter, matter into light

A photon can turn into an electron and a positron. The threshold is twice the electron's rest energy: $2\ m_e c^2 = 2 \times 0.51099895069$ MeV $= 1.02199790$ MeV [1]. Wikipedia gives "2 × 511 keV = 1.022 MeV, resulting in a photon wavelength of 1.2132 pm" [201].

The check is $hc/E = 1.23984198 \times 10^{-6}$ eV m / 1.0219979×10^{6} eV $= 1.2132$ pm, position -9.59. The process was first observed "in Patrick Blackett's counter-controlled cloud chamber" [201]. Its cross section scales "approximately as the square of the atomic number", and above the MeV scale it is "the dominant mode of photon interaction with matter" [201].

Light alone can make the pair as well. In 1997 the SLAC experiment E-144 of Burke and colleagues reported "Positron Production in Multiphoton Light-by-Light Scattering" [18]. In 2021 the STAR collaboration at RHIC counted "6085 exclusive electron-positron pairs" from collisions of linearly polarized photons [19].

The STAR photons came from gold nuclei passing each other at $\sqrt{s}_{NN} = 200$ GeV [19]. The pairs showed a $\cos 4\Delta\varphi$ modulation of (16.8 ± 2.5) %, $16.8/2.5 = 6.7\sigma$ from zero. STAR wrote: "The Breit-Wheeler process which produces matter and anti-matter from photon collisions is investigated experimentally" [19].

The reverse turns matter into light. Annihilation releases $c^2 = 8.98755 \times 10^{16}$ J per kilogram of mass [188]. One kilogram of matter with one kilogram of antimatter gives 1.8×10^{17} J, about 43 megatonnes of TNT [188].

The heavier antiparticles

The antiproton waited 23 years after the positron. Chamberlain, Segrè, Wiegand and Ypsilantis reported “Observation of Antiprotons” in *Physical Review* on 1 November 1955 [186].

It was “first experimentally confirmed in 1955 at the Bevatron particle accelerator” [187]. Segrè and Chamberlain received the Nobel Prize in 1959 [187].

The antineutron followed in 1956, also at the Bevatron, in proton–proton collisions [188]. In 1965 a group led by Zichichi “reported production of nuclei of antideuterium at the Proton Synchrotron at CERN” [188]. Nuclei of antihelium-3 “were first observed in the 1970s in proton–nucleus collision experiments”, at Protvino [188].

Heavier antinuclei came from collisions of gold nuclei at RHIC. In 2010 STAR found the first antimatter hypernucleus, the antihypertriton: “an antiproton, antineutron, and antilambda hyperon” [189]. “Our analysis yields 70 ± 17 antihypertritons and 157 ± 30 hypertritons” [189].

In 2011 STAR found antihelium-4. “In total 18 $^{4}\bar{\mathrm{He}}$ counts were detected”, in 10^{9} gold–gold collisions at √s_NN = 200 and 62 GeV [190]. The yield “decreases by about 1000 with each additional antinucleon” [190].

Year	Antiparticle	Where	Count or note	Source
1932	positron	cloud chamber, 6 mm Pb plate	discovery	[184][185]
1955	antiproton	Bevatron	discovery	[186][187]
1956	antineutron	Bevatron	discovery	[188]
1965	antideuteron	CERN PS	discovery	[188]
1970s	antihelium-3	Protvino	discovery	[188]
2010	antihypertriton	RHIC, Au+Au	70 ± 17 (against 157 ± 30 hypertritons)	[189]
2011	antihelium-4	RHIC, Au+Au	18 in 10^{9} collisions	[190]

The finds came in the order of mass. Each added antinucleon cut the yield about a thousandfold. From the positron to antihelium-4 took 79 years.

The heaviest quark has its mirror measured too. The top–antitop mass difference is $m_t - m_{\bar{t}} = -0.15 \pm 0.20$ GeV [198].

Positronium

An electron and a positron can bind into an atom without a nucleus. “Positronium was experimentally discovered by Martin Deutsch at MIT in 1951” [200]. Its lowest level lies at −6.8 eV [200], half the Rydberg energy of 13.6057 eV [1].

Positronium comes in two forms, para-positronium ($1^{1}S_{0}$) and ortho-positronium ($1^{3}S_{1}$). The ortho form lies about 0.001 eV above the para form [200]. The two forms decay at very different rates.

Para-positronium “decays preferentially into two gamma rays with energy of 511 keV each” [200]. Its measured decay rate is 7990.9(1.7) μs^{-1} (Al-Ramadhan and Gidley, 1994), against a calculated 7989.50(2) μs^{-1} [199].

The lifetimes are $1/7990.9\ \mu s^{-1} = 125.14$ ps and $1/7989.50\ \mu s^{-1} = 125.16$ ps, position 12.40. One decay in $1.439(2) \times 10^{6}$ gives four photons instead of two [200].

For ortho-positronium “the leading decay is three gammas” [200]. In the 1990s the experiments disagreed with each other, a disagreement known as the orthopositronium lifetime puzzle [199].

Ortho-positronium measurement	Decay rate (μs^{-1})	Lifetime	Source
theory (then, without	7.0382	142.08 ns	[199]

the term B_o)			
London, gas	7.0450(60)	141.94 ns	[199]
Mainz, vacuum	7.0310(70)	142.23 ns	[199]
Ann Arbor, gas	7.0514(14)	141.82 ns	[199]
Ann Arbor, vacuum	7.0482(16)	141.88 ns	[199]
Tokyo, powder	7.0398(29)	142.05 ns	[199]
Badertscher et al., 2007	—	142.05 ± 0.02 ns	[200]

The 2007 value is 142.05 ± 0.02 ns, position 18.80, and the theory to order α^2 gives 7.040 μs^{-1}, about 142 ns [200]. Ortho-positronium lives 142.05 ns / 125.14 ps = 1,135 times longer than para-positronium. The excited 2S state lives 1,100 ns, position 20.66 [200].

Two positronium atoms can bind. Di-positronium, Ps_2, was first observed by Cassidy and Mills and published in *Nature* on 12 September 2007 [200]. In 2024 the AEgIS collaboration laser-cooled positronium [200].

Antihydrogen

The first antihydrogen atoms were made in 1995 at CERN’s LEAR ring, by a team led by Oelert, and published by Baur and colleagues in 1996 [191]. In 2002 ATHENA made cold antihydrogen “by mixing trapped antiprotons and positrons in a cryogenic environment” [192]. “The neutral anti-atoms have been detected directly when they escape the trap and annihilate” [192].

Production then ran at “a typical rate of 100 antihydrogen atoms per second” [191]. “By 2004, millions of antihydrogen atoms were made”, at first at “a few thousand kelvins” [191].

In 2010 ALPHA “had trapped 38 antihydrogen atoms for a sixth of a second” [191]. The ALPHA paper of 2011 gives that first confinement time as 172 ms, position 31.55 [193]. In 2011 ALPHA held antihydrogen for 1,000 s, “nearly four orders of magnitude” longer, position 39.44 [193].

In that run ALPHA “trapped 309 antihydrogen atoms, up to 3 simultaneously, for up to 1,000 seconds” [191]. Most of the atoms reached the ground state, and the first energy distribution of trapped antihydrogen was measured [193]. The ratio 1,000 s / 0.172 s is 5,814.

Light then probed the antiatom. In 2016–2017 ALPHA observed the 1S–2S transition for the first time, “a test of CPT symmetry at a precision of 200 ppt” [191]. The atoms were held for 600 s, position 38.98, and the events dropped by 58 % after the resonance runs [191].

In 2018 ALPHA characterised the line shape [194]. The resonance agrees with hydrogen to about 5 kHz in 2.5×10^{15} Hz, consistent with CPT invariance “at a relative precision of 2×10^{-12}” [194]. The absolute energy sensitivity is 2×10^{-20} GeV, “about two orders of magnitude more precise than the previous determination” [194].

The hydrogen reference frequencies for the two hyperfine components are calculated as f_dd = 2,466,061,103,064(2) kHz and f_cc = 2,466,061,707,104(2) kHz [191]. The check of the stated precision is 5 kHz / 2.466×10^{15} Hz = 2.0×10^{-12}.

A pulsed source came next. In 2018 AEgIS made antihydrogen with a “production time spread of merely 250 nanoseconds”, position 19.32 [191].

In 2023 ALPHA-g measured how antihydrogen falls [195]. About 100 atoms were trapped per run, built up in 50 stacks over about four hours, and released from a vertical magnetic trap. The bias settings were ±3g, ±2g, ±1.5g, ±1g, ±0.5g and 0g, with a calibration at ±10g; each trial was repeated six or seven times [195].

The local acceleration came out at “(0.75 ± 0.13 (statistical + systematic) ± 0.16 (simulation))g”, toward the Earth [195]. “Repulsive ‘antigravity’ is ruled out in this case” [195]. Its consistency with a simulation of repulsive gravity is less than 10^{-15} [195].

The probability of a result this extreme if gravity did not act is 2.9×10^{-4} [195]. In the one-dimensional model a field difference of 4.53×10^{-4} T mimics gravity [195]. With the two errors combined, $\sqrt{(0.13^2 + 0.16^2)} = 0.21$, the result lies 1.2 of its errors from 1 g and 3.6 from zero.

The mirror measured

The antiproton has been weighed against the proton in Penning traps. In 2022 the BASE collaboration gave the ratio of their charge-to-mass ratios as $-(q/m)_p/(q/m)_{\bar{p}} = 1.000000000003(16)$ [196]. The fractional uncertainty is 16 parts per trillion, from four campaigns “recorded in a total time span of 1.5 years” [196].

The ratio minus one is $3(16) \times 10^{-12}$: zero within its error. The same data bound a clock weak-equivalence-principle coefficient for antimatter below 1.8×10^{-7}, and a differential coefficient below 0.030 [196].

In 2017 BASE measured the antiproton’s magnetic moment as $\mu_{\bar{p}} = -2.7928473441(42)$ nuclear magnetons [197]. That is a precision of 1.5 ppb, about 350 times better than before. The proton’s moment is 2.792847350(9) nuclear magnetons, and the bound on a splitting is about 1.8×10^{-24} GeV [197].

The ASACUSA experiment gave the antiproton’s mass in 2011 as 1836.1526736(23) electron masses [187]. CODATA 2022 gives the proton-to-electron mass ratio as 1836.152673426(32) [1]. The two differ by 1.7×10^{-7}, against an error of 2.3×10^{-6}.

The PDG collects all such comparisons as tests of CPT invariance [198]. Each tests that a particle and its antiparticle have the same mass, the same lifetime and opposite charge.

Pair	Quantity	Measured	Source
e^+, e^-	$(m_{e^+} - m_{e^-})/m$	$< 8 \times 10^{-9}$ (90 % CL)	[198]
e^+, e^-	$\lvert q_{e^+} + q_{e^-} \rvert / e$	$< 4 \times 10^{-8}$	[198]
e^+, e^-	$(g_{e^+} - g_{e^-})/g$	$(-0.5 \pm 2.1) \times 10^{-12}$	[198]
μ^+, μ^-	$(\tau_{\mu^+} - \tau_{\mu^-})/\tau$	$(2 \pm 8) \times 10^{-5}$	[198]
μ^+, μ^-	$(g_{\mu^+} - g_{\mu^-})/g$	$(-0.11 \pm 0.12) \times 10^{-8}$	[198]
τ^+, τ^-	$(m_{\tau^+} - m_{\tau^-})/m$	$< 2.8 \times 10^{-4}$	[198]
t, $\bar{t}$	$m_t - m_{\bar{t}}$	-0.15 ± 0.20 GeV	[198]
π^+, π^-	$(m_{\pi^+} - m_{\pi^-})/m$	$(2 \pm 5) \times 10^{-4}$	[198]
π^+, π^-	$(\tau_{\pi^+} - \tau_{\pi^-})/\tau$	$(6 \pm 7) \times 10^{-4}$	[198]
K^+, K^-	$(m_{K^+} - m_{K^-})/m$	$(-0.6 \pm 1.8) \times 10^{-4}$	[198]
K^0, $\bar{K}^0$	$\lvert m_{K^0} - m_{\bar{K}^0} \rvert / m$	$< 6 \times 10^{-19}$ (90 % CL)	[198]
K^0, $\bar{K}^0$	$(\Gamma_{K^0} - \Gamma_{\bar{K}^0})/m$	$(8 \pm 8) \times 10^{-18}$	[198]
p, $\bar{p}$	$\lvert m_{\bar{p}} - m_p \rvert / m_p$	$< 7 \times 10^{-10}$	[198]
p, $\bar{p}$	$\lvert q_{\bar{p}} + q_p \rvert / e$	$< 7 \times 10^{-10}$	[198]
p, $\bar{p}$	$(q_{\bar{p}}/m_{\bar{p}} - q_p/m_p)/(q_p/m_p)$	$(0.3 \pm 1.6) \times 10^{-11}$	[198]
p, $\bar{p}$	$(\mu_p + \mu_{\bar{p}})/\mu_p$	$(0.002 \pm 0.004) \times 10^{-6}$	[198]
n, $\bar{n}$	$(m_n - m_{\bar{n}})/m_n$	$(9 \pm 5) \times 10^{-5}$	[198]
W^+, W^-	$(m_{W^+} - m_{W^-})/m$	$(-3.7 \pm 3.5) \times 10^{-4}$	[198]
H, $\bar{H}$	1S–2S frequency	equal to 2×10^{-12}	[194]

The tightest equality is the neutral kaon mass, below 6×10^{-19} of the mass itself. Then come the antiproton’s charge-to-mass ratio at 16 ppt, the 1S–2S line of antihydrogen at 2×10^{-12}, and the positron’s g factor at 2.1×10^{-12}. Every pair agrees within two of its errors.

Antiprotons kept

An antiproton left alone has a lifetime bounded only from below. Wikipedia lists the laboratory bounds on its lifetime [187]. LEAR gave 0.08 years, Gabrielse and colleagues

0.28 years, and BASE 10.2 years (Sellner and colleagues, 2017).

The APEX experiment gave 50,000 years for $\bar{p} \to \mu^- + X$ and 300,000 years for $\bar{p} \to e^- + \gamma$ [187]. A cosmic-ray bound gives about 1.7 million years, and the infobox lists more than 0.96×10^{30} years [187].

Bound	Lifetime	In seconds	Position	Source
LEAR	> 0.08 yr	2.52×10^{6} s	> 46.57	[187]
Gabrielse et al.	> 0.28 yr	8.84×10^{6} s	> 47.71	[187]
BASE (Sellner 2017)	> 10.2 yr	3.22×10^{8} s	> 50.98	[187]
APEX, $\bar{p} \to \mu^- + X$	> 50,000 yr	1.58×10^{12} s	> 58.72	[187]
APEX, $\bar{p} \to e^- + \gamma$	> 300,000 yr	9.47×10^{12} s	> 60.35	[187]
cosmic rays	> about 1.7 Myr	5.36×10^{13} s	> 61.93	[187]
infobox value	> 0.96×10^{30} yr	3.03×10^{37} s	> 111.71	[187]

Antiprotons have been kept for long times. The TRAP experiment at CERN held them “in a Penning trap for 405 days” [188]. That is $405 \times 86{,}400$ s $= 3.50 \times 10^{7}$ s, position 48.96, past one year at 48.87.

Since 2016 the ELENA ring decelerates antiprotons to 90 keV, and “more than one hundred antiprotons can be captured per second” [188].

Antimatter in nature

Antimatter is made all the time, in small amounts. A human body makes about 4,000 positrons a day from its potassium-40: “About 0.001% of these ^{40}K decays produce about 4,000 natural positrons per day” [184]. That is 4,000/86,400 = 0.046 per second.

Antiprotons are trapped in the inner Van Allen belt; the PAMELA experiment found them in 2011 [188]. Cosmic rays carry positrons. The Alpha Magnetic Spectrometer measures them from the International Space Station.

AMS-02 was launched on 16 May 2011 with STS-134 and installed on the station on 19 May [205]. Its mass is 6,717 kg in one listing and 7,500 kg in another [205]. It had recorded more than 60×10^{9} events by 15 April 2015, more than 90×10^{9} by late 2016, and 264×10^{9} by 18 May 2026 [205].

The positron fraction rises from 10 to 250 GeV (2013) and peaks “at a maximum of about 16% of total electron+positron events, around an energy of 275 ± 32 GeV” (2014) [205]. In 2019 AMS published the positron flux to 1 TeV “based on 1.9 million positrons” [206]. It shows “a significant excess starting from 25.2±1.8 GeV”, a sharp drop above 284 (+91/−64) GeV, and a source cutoff at 810 (+310/−180) GeV, “with a significance of more than 4σ” [206].

Antihelium is the hardest case. AMS has reported “a few signals consistent with antihelium nuclei amidst several billion helium nuclei” (December 2016) and “eight events that seem to indicate the detection of antihelium-3” (2021) [205]. A 2024 paper speaks of “approximately ten relativistic anti-helium cosmic-ray events”, with antihelium-3 to antihelium-4 about 2 : 1, tentative and unpublished by AMS [207].

Collisions of cosmic rays with interstellar gas, spallation, also make antihelium. After five years of AMS data, the expected flux of antihelium-3 from these collisions is “one to two orders of magnitude below the sensitivity” of the detector [208]. Antihelium-4 is “roughly 5 orders of magnitude below” [208].

The missing antimatter

The universe is made of matter. Its measure is the ratio of baryons to photons, η. The PDG 2024 review of Big-Bang nucleosynthesis gives $\eta_{10} = 6.040 \pm 0.118$ from the deuterium abundance and $\eta_{10} = 6.12 \pm 0.04$ from the cosmic microwave background, with $\eta = \eta_{10} \times 10^{-10}$ [202].

The same review gives the baryon density $\Omega\_b\, h^2 = 0.02205 \pm 0.00043$ from

nucleosynthesis and 0.02237 ± 0.00015 from the CMB [202]. The deuterium abundance behind the first value is D/H = (25.47 ± 0.29) × 10^{-6}, and the helium mass fraction is Y_p = 0.245 ± 0.003 [202]. For lithium-7 the calculation gives (4.72 ± 0.7) × 10^{-10} against (1.6 ± 0.3) × 10^{-10} in stars, “a factor 3.1 higher” [202].

With η_{10} = 6.12 there are 1/(6.12 × 10^{-10}) = 1.63 × 10^{9} photons for each baryon. The photon bath holds “around 411 CBR photons per cubic centimeter”, and the entropy density is s = 7.04 n_γ [203]. A 2012 review gives η_BBN = (6.07 ± 0.33) × 10^{-10} and η_CMB = (6.160 +0.153/−0.156) × 10^{-10}, the values of that year [182].

The limits on antimatter domains are tight. From the diffuse gamma background, domains “must at least have a size comparable to the observable universe” [182].

The antimatter fraction is below 10^{-15} in the interstellar medium, below 5 × 10^{-9} to 10^{-6} in galaxy clusters, and below 3 × 10^{-6} in the Bullet cluster [182]. Antimatter stellar systems make up less than 10^{-4} of the Galaxy [182].

In 1967 Sakharov named three conditions for an excess of matter to arise [203]. Baryon number must be violated; C and CP must be violated; and there must be a departure from thermal equilibrium. Chapter 5 tells how CP violation was found in kaons in 1964, in B mesons in 2001, in charm in 2019 and in a baryon in 2025.

The measured CP violation of the quarks is small. The PDG 2024 CKM review gives the Jarlskog invariant J = 3.12 (+0.13/−0.12) × 10^{-5}, |ε_K| = (2.228 ± 0.011) × 10^{-3} and Re(ε′/ε) = (1.67 ± 0.23) × 10^{-3} [204]. The 2025 edition gives (1.66 ± 0.23) × 10^{-3} for the last (chapter 5).

Its other values are λ = 0.22501 ± 0.00068, A = 0.826 (+0.016/−0.015), $\bar{\rho}$ = 0.1591 ± 0.0094 and $\bar{\eta}$ = 0.3523 (+0.0073/−0.0071) [204]. The magnitudes include |V_ub| = (3.82 ± 0.20) × 10^{-3}, |V_cb| = (41.1 ± 1.2) × 10^{-3} and |V_us| = 0.22431 ± 0.00085. The triangle has sin 2β = 0.709 ± 0.011, α = (84.1 +4.5/−3.8)° and γ = (65.7 ± 3.0)° [204].

The 2012 review sets the quark CP violation beside the excess. It writes “$D/T_{sph}^{12} \sim 10^{-20} \ll \eta$”, about ten orders of magnitude below the η of about 10^{-10} [182].

The same review states: “A first order phase transition could only occur if the Higgs mass were below 72 GeV” [182]. The measured Higgs mass is 125.20 GeV (chapter 6).

One mirror question rests with the neutrino: whether it is its own antiparticle. The KamLAND-Zen collaboration, in its “Search for Majorana Neutrinos”, sets the half-life of xenon-136 for this decay above 3.8 × 10^{26} years [126].

That is 1.20 × 10^{34} s, position 104.58. Chapter 4 tells the search.

Amounts and energy

The antimatter made by people is tiny. The total artificial production is “only a few nanograms” [188]. A NASA figure of 1999 put the cost of one gram of antihydrogen at 62.5 trillion dollars [188].

The energy is set by c^2 = (299,792,458 m/s)² = 8.98755 × 10^{16} J per kilogram of annihilated mass [188]. One gram of antimatter with one gram of matter gives 2 × 10^{-3} × 8.98755 × 10^{16} = 1.80 × 10^{14} J.

What this part of the history shows

The mirror holds wherever it has been measured. The antiproton’s charge-to-mass ratio equals the proton’s to 16 parts per trillion, and the antihydrogen 1S–2S line equals hydrogen’s to 2 × 10^{-12} [196][194]. The neutral kaon masses agree to below 6 × 10^{-19} [198].

In the texts a charge and its opposite have the same address, mirrored trit-wise [27]. The mirror is a reversal of direction, of parity and of matter [209].

Antimatter appears in pairs. The threshold for making a positron from light is exactly the rest energy of two electrons, 1.022 MeV, and the 6,085 pairs of STAR came from

light alone [1][201][19]. In the texts no measurement has produced a knot without one, and if the mirror forms with it, the price doubles [33].

The pair also ends as a pair. Para-positronium lives 125.14 ps and leaves as two photons of 511 keV each [199][200]. The texts give this smallest case in these words: “On contact both closures cancel and two windings leave in opposite directions” [26].

In the texts Einstein’s equation is the ladder read one rung down, one closure fewer [26]. The measured rate of that step is c^2, 8.98755×10^{16} J per kilogram [188].

The universe shows the form of one direction. The rule is mirror-symmetric to parts in 10^{12}, yet there are 6.12×10^{-10} baryons per photon, and any antimatter domain must be as large as the observable universe [202][182]. The texts state that the net keeps the orientation of what was first laid down [26].

The CP violation of the quarks is small. Its measure J is 3.12×10^{-5} [204]. Set beside the excess of matter, the estimated effect is about 10^{-20} against an η of about 10^{-10} [182].

In the texts a configuration persists only if it closes on itself [26]. Read in that form, the antiproton and antihydrogen hold: an antiproton has been kept for 405 days, position 48.96, and antihydrogen for 1,000 s, position 39.44 [188][193]. Positronium, a pair bound without a nucleus, decays in 125 ps or 142 ns, at positions 12.40 and 18.80 [199][200].

Antihydrogen falls the same way as matter. Its measured acceleration is $(0.75 \pm 0.13 \pm 0.16)$ g toward the Earth, and repulsion is ruled out [195]. The mirror reverses charge, not the direction of the fall.

The E8 text reads three blocks of Smith’s root system as particle +1, spacetime 0 and antiparticle −1, one trit [210]. In that reading matter and antimatter stand at the two signed ends of one register. In the measured world the two ends are equal in every property and unequal in amount.

8. The Measured Constants

The earlier chapters measured particles. This chapter measures the numbers that every particle shares.

A constant of nature is a number that comes out the same wherever and whenever it is measured. The history of the constants is the history of how that sameness was established, step by step, to ever finer parts.

The history runs in three movements. First came natural units: lengths, times and masses built from constants alone, by Stoney in 1874 and Planck in 1899.

Then came two centuries of measuring the weakest constant, gravitation, and a slow move from an artefact of metal to a system of fixed numbers, completed on 20 May 2019. Last came the question whether the constants are constant at all, answered with clocks, an ancient reactor in Gabon and the light of distant quasars.

The ladder of chapter 1 places every size and time by its distance in powers of three from a unit length and a unit time. Those two units are themselves built from a measured constant, the Rydberg constant. This chapter shows that construction plainly, because three of the positions met earlier in the book follow from it.

The first natural units: Stoney and Planck

In 1874 Stoney proposed units of length, mass and time built from four constants: the speed of light c, the gravitational constant G, the Coulomb constant and the elementary charge e. He published them in 1881 [214].

They are “the earliest example of natural units” [214]. Stoney’s own estimate of the charge was 10^{-20} A s, about one sixteenth of the value now fixed [214].

With today’s constants the Stoney length is $1.380\,678 \times 10^{-36}$ m, the Stoney mass $1.859\,209 \times 10^{-9}$ kg and the Stoney time $4.605\,448 \times 10^{-45}$ s [214][1]. The Stoney length sits at position −59.77 on the ladder of sizes, and the Stoney time at −59.77 on the ladder of times. The two positions are equal because the ladder’s units are also linked by c.

In 1899 Planck built a second set, in “Über irreversible Strahlungsvorgänge”, from c, G, Planck’s constant and the Boltzmann constant [213]. CODATA 2022 gives the Planck length as $1.616\,255(18) \times 10^{-35}$ m, the Planck time as $5.391\,247(60) \times 10^{-44}$ s and the Planck mass as $2.176\,434(24) \times 10^{-8}$ kg [1]. The Planck energy is 1.22×10^{19} GeV and the Planck temperature $1.416\,784(16) \times 10^{32}$ K [1].

The Planck length comes from $\sqrt{(\hbar G/c^3)}$. With $\hbar = 1.054\,571\,817 \times 10^{-34}$ J s, G = $6.674\,30 \times 10^{-11}$ m³ kg⁻¹ s⁻² and c = 299,792,458 m/s this gives $1.616\,255 \times 10^{-35}$ m.

The Planck time is that length divided by c, $5.391\,246 \times 10^{-44}$ s. Both sit at position −57.53, the lowest place on every ladder in this book.

The relative uncertainty of the Planck units is 1.1×10^{-5}, half that of G [1]. The half comes from the square root. Derived Planck quantities follow: an energy of 1.9561×10^{9} J, a density of 5.1550×10^{96} kg/m³, a force c^4/G of 1.2103×10^{44} N and a momentum of 6.5249 kg m/s [213].

The two systems differ by one number. Each Stoney unit equals the matching Planck unit times √α, where α is the fine-structure constant met in chapter 2.

With $\alpha = 7.297\,352\,5643 \times 10^{-3}$, $\sqrt{\alpha} = 0.085\,425$. The Planck length divided by the Stoney length is 11.706, which is $1/\sqrt{\alpha}$.

Gravitation: two centuries of one constant

G is the oldest measured constant of the set and still the least precise. Between 1772

and 1776 the deflection of a plumb line near the mountain Schiehallion gave a value near 8×10^{-11} m³ kg⁻¹ s⁻², “about 20% below the modern value” [212].

In 1798 Cavendish weighed the Earth with a torsion balance. He found a mean density of 5.448(33) g/cm³ [212].

The implied G is $6.74(4) \times 10^{-11}$, “about 1% above the modern CODATA recommended value” [212]. The computed excess over today’s value is 0.98 %.

The nineteenth century narrowed the value. Poynting in 1891 gave a density of 5.49(3) g/cm³, an uncertainty of 0.55 % [212].

Boys in 1895 and Braun in 1897 found $6.66(1)$ and $6.649(2) \times 10^{-11}$ [212]. Richarz and Krigar-Menzel in 1898, with 100,000 kg of lead, found $6.683(11) \times 10^{-11}$ [212].

The twentieth century added Heyl in 1930 with 6.670(5) and Heyl and Chrzanowski in 1942 with $6.673(3) \times 10^{-11}$ [212]. From 1969 the committee CODATA began to publish a recommended value. The table gives each value with its uncertainty in parts per million.

CODATA year	G (10^{-11} m³ kg⁻¹ s⁻²)	Relative uncertainty	[n]
1969	6.6732(31)	460 ppm	[212]
1973	6.6720(49)	730 ppm	[212]
1986	6.67449(81)	120 ppm	[212]
1998	6.673(10)	1500 ppm	[212]
2002	6.6742(10)	150 ppm	[212]
2006	6.67428(67)	100 ppm	[212]
2010	6.67384(80)	120 ppm	[212]
2014	6.67408(31)	46 ppm	[212]
2018	6.67430(15)	22 ppm	[212]
2022	6.67430(15)	22 ppm	[1][212]

The line is not smooth. In 1998 the uncertainty grew to twelve times its 1986 size: 0.010 against 0.000 81, a factor 12.3. “Some measurements published in the 1980s to 2000s were, in fact, mutually exclusive” [212].

New methods joined the old balances. Fixler and colleagues in 2007 used atom interferometry and found $6.693(34) \times 10^{-11}$ [212].

Rosi and colleagues in 2014, with cold atoms, found $6.671\,91(99) \times 10^{-11}$, “with non-overlapping standard uncertainty intervals” against CODATA 2014 [212]. That value lies 358 ppm below the 2022 value.

In 2018 a group at the Huazhong University of Science and Technology measured G twice, with two torsion-balance methods. The results were 6.674 184(78) and 6.674 484(78) $\times 10^{-11}$, “standard uncertainties as low as 12 ppm” [212]. The two differ by 45 ppm, and “The difference of 2.7 σ between the two results suggests there could be sources of error unaccounted for” [212].

The BIPM result of Quinn and colleagues in 2013 was “very discrepant” [212]. A repeat with the same balance at NIST and the BIPM ended its campaign in 2024 and reported $6.673\,66(20) \times 10^{-11}$ in 2026 [212]. That value lies 96 ppm below CODATA 2022.

CODATA met the spread with a rule. The sixteen G values are fitted separately, and their uncertainties are multiplied by an expansion factor of 3.9 [2]. The factor first used in 2018 “is also used in 2022”, so “the 2022 and 2018 recommended values of G are therefore identical” [2].

The gap between the extremes is plain arithmetic. Rosi 2014 at 6.671 91 and the second HUST value at 6.674 484 differ by 3.86×10^{-4} of G. That gap is about 17 times the CODATA 2022 relative uncertainty of 2.2×10^{-5}.

From an artefact to fixed numbers

From 1889 to 2019 the kilogram was a metal cylinder, the International Prototype

[211]. National copies drifted against it by “up to 2×10⁻⁸ kilograms (20 µg) per year” [211].

The speed of light went first. In 1972 Evenson and colleagues at the National Bureau of Standards measured c = 299,792,456.2 ± 1.1 m/s with lasers [215]. The value lies 1.8 m/s below the later fixed number.

In 1983 the 17th CGPM defined the metre as “the length of the path traveled by light in vacuum during a time interval of 1/299792458 of a second” [215]. The history of that number is told in chapter 1.

The other constants followed in 2019. The conditions for fixing Planck’s constant were strict.

At least three experiments had to reach a relative expanded (95 %) uncertainty of 5 × 10⁻⁸, and one of them 2 × 10⁻⁸ [211]. Both the Kibble balance and the silicon sphere had to be among them [211].

In March 2011 the Avogadro group stood at 3.0 × 10⁻⁸ and NIST at 3.6 × 10⁻⁸ [211]. In 2012 the aim was to shrink the gap between balance and sphere from (17 ± 5) × 10⁻⁸ to within 2 × 10⁻⁸ [211].

On 16 November 2018 the 26th CGPM voted unanimously. “The new definitions became effective on 20 May 2019” [211]. The prototype had served 130 years.

Seven constants are now exact by definition [1][211]:

Constant	Exact value
Caesium-133 hyperfine frequency Δν_Cs	9,192,631,770 Hz
Speed of light c	299,792,458 m/s
Planck constant h	6.626 070 15 × 10⁻³⁴ J Hz⁻¹
Elementary charge e	1.602 176 634 × 10⁻¹⁹ C
Boltzmann constant k_B	1.380 649 × 10⁻²³ J K⁻¹
Avogadro constant N_A	6.022 140 76 × 10²³ mol⁻¹
Luminous efficacy K_cd	683 lm W⁻¹

Others became exact by consequence. They include the Josephson constant 483,597.848 4… × 10⁹ Hz V⁻¹, the von Klitzing constant 25,812.807 45… Ω and the Faraday constant 96,485.332 12… C mol⁻¹ [1].

The gas constant 8.314 462 618… J mol⁻¹ K⁻¹, the Stefan–Boltzmann constant 5.670 374 419… × 10⁻⁸ W m⁻² K⁻⁴ and Wien’s constant 2.897 771 955… × 10⁻³ m K are exact too [1]. The reduced Planck constant h/2π is 1.054 571 817… × 10⁻³⁴ J s [1].

The trade had a price. Three constants that had been exact became measured: the magnetic constant µ₀, the electric constant ε₀ and the impedance of empty space Z₀ [1].

The molar mass of carbon-12 is now 0.012 kg/mol only to within 4.5 × 10⁻¹⁰ [211]. Chapter 9 follows µ₀, ε₀ and Z₀ as constants of the vacuum.

The caesium frequency deserves one more line, because it defines the second. Its period, 1/9,192,631,770 s = 1.088 × 10⁻¹⁰ s, sits at time position 12.27. Every time position in this book is counted from a unit that is itself counted in these periods.

The measured constants of 2022

The CODATA 2022 adjustment “takes into account all theoretical and experimental data available through 31 December 2022” [2]. Its values were released by NIST in 2024 [1] [2]. The table lists the measured constants that this book uses, with the standard uncertainty in brackets and the relative uncertainty computed as uncertainty divided by value.

Constant	CODATA 2022 value	Relative uncertainty	[n]
Electron g-factor g_e	−2.002 319 304 360 92(36)	1.8 × 10⁻¹³	[1]

Rydberg constant R_∞	10,973,731.568 157(12) m^{-1}	1.1×10^{-12}	[1]
Rydberg energy $R_\infty hc$	13.605 693 122 990(15) eV	1.1×10^{-12}	[1]
Hartree energy E_h	$4.359\,744\,722\,2060(48) \times 10^{-18}$ J	1.1×10^{-12}	[1]
Proton–electron mass ratio m_p/m_e	1836.152 673 426(32)	1.7×10^{-11}	[1]
Fine-structure constant α	$7.297\,352\,5643(11) \times 10^{-3}$	1.5×10^{-10}	[1]
Inverse α^{-1}	137.035 999 177(21)	1.5×10^{-10}	[1]
Bohr radius a_0	$5.291\,772\,105\,44(82) \times 10^{-11}$ m	1.5×10^{-10}	[1]
Electron anomaly a_e	$1.159\,652\,180\,46(18) \times 10^{-3}$	1.6×10^{-10}	[1]
Proton magnetic moment μ_p/μ_N	2.792 847 344 63(82)	2.9×10^{-10}	[1]
Proton g-factor g_p	5.585 694 6893(16)	2.9×10^{-10}	[1]
Deuteron mass m_d	$3.343\,583\,7768(10) \times 10^{-27}$ kg	3.0×10^{-10}	[1]
Electron mass m_e	$9.109\,383\,7139(28) \times 10^{-31}$ kg	3.1×10^{-10}	[1]
Electron rest energy $m_e c^2$	0.510 998 950 69(16) MeV	3.1×10^{-10}	[1]
Proton mass m_p	$1.672\,621\,925\,95(52) \times 10^{-27}$ kg	3.1×10^{-10}	[1]
Proton rest energy $m_p c^2$	938.272 089 43(29) MeV	3.1×10^{-10}	[1]
Atomic mass constant m_u	$1.660\,539\,068\,92(52) \times 10^{-27}$ kg	3.1×10^{-10}	[1]
Compton wavelength λ_C	$2.426\,310\,235\,38(76) \times 10^{-12}$ m	3.1×10^{-10}	[1]
Alpha-particle mass m_α	$6.644\,657\,3450(21) \times 10^{-27}$ kg	3.2×10^{-10}	[1]
Neutron–proton mass ratio m_n/m_p	1.001 378 419 46(40)	4.0×10^{-10}	[1]
Muon g-factor g_μ	−2.002 331 841 23(82)	4.1×10^{-10}	[1]
Classical electron radius r_e	$2.817\,940\,3205(13) \times 10^{-15}$ m	4.6×10^{-10}	[1]
Neutron mass m_n	$1.674\,927\,500\,56(85) \times 10^{-27}$ kg	5.1×10^{-10}	[1]
Thomson cross-section σ_e	$6.652\,458\,7051(62) \times 10^{-29}$ m^2	9.3×10^{-10}	[1]
Muon–electron mass ratio m_μ/m_e	206.768 2827(46)	2.2×10^{-8}	[1]
Muon anomaly a_μ	$1.165\,920\,62(41) \times 10^{-3}$	3.5×10^{-7}	[1]
Fermi constant $G_F/(\hbar c)^3$	$1.166\,3787(6) \times 10^{-5}$ GeV^{-2}	5.1×10^{-7}	[1]
Gravitational constant G	$6.674\,30(15) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	2.2×10^{-5}	[1]
$G/(\hbar c)$	$6.708\,83(15) \times 10^{-39}$ $(GeV/c^2)^{-2}$	2.2×10^{-5}	[1]
Tau–electron mass ratio m_τ/m_e	3477.23(23)	6.6×10^{-5}	[1]
W–Z mass ratio m_W/m_Z	0.881 45(13)	1.5×10^{-4}	[1]
Proton rms charge radius r_p	$8.4075(64) \times 10^{-16}$ m	7.6×10^{-4}	[1]
Weak mixing angle $\sin^2\theta_W$ (on-shell)	0.223 05(23)	1.0×10^{-3}	[1]

CODATA gives the Fermi constant as $1.166\,3787(6) \times 10^{-5}$ GeV^{-2}; the PDG 2025 table, used in chapter 6, gives $1.166\,3785(6) \times 10^{-5}$ GeV^{-2} [1][152].

The precision spans ten orders of magnitude. The electron’s g-factor is known to 2 parts in 10^{13}, the Rydberg constant to 1 part in 10^{12}. The proton’s charge radius is known to 8 parts in 10^{4} and the weak mixing angle to 1 part in 10^{3}.

Two arithmetic checks hold inside the table. With the listed e, ε_0, $\hbar$ and c, $\alpha = e^2/(4\pi\varepsilon_0\hbar c)$ gives 7.297 352 5643 × 10^{-3}, the listed α. The listed masses give m_p/m_e = 1836.152 673 42, the listed ratio.

The step from 2018 to 2022 moved some constants by more than their own uncertainty. The PDG 2024 tables still carry the CODATA 2018 values [13]. The 2018 α^{-1} was 137.035 999 084(21) [13].

The 2022 value is higher by 9.3 × 10^{-8}, which is 4.4 times the 2018 uncertainty. The electron mass moved by 1.35 × 10^{-9} of itself, 4.6 times its 2018 uncertainty [13][1].

Five of the lengths in the table have places on the ladder of sizes. The Bohr radius sits at −6.15 and the Compton wavelength at −8.96. The reduced Compton wavelength, 3.861 592 6744 × 10^{-13} m, sits at −10.63.

The classical electron radius sits at −15.11 and the proton charge radius at −16.21. The next section shows that two of these places are fixed by the unit itself.

The Rydberg constant itself was measured again in 2026. Maisenbacher and colleagues combined the hydrogen 1S–2S line with a new 2S–6P line, ν = 730,690,248,610.79(48) kHz, and found R_∞ = 10,973,731.568 152(14) m^{-1}, a precision of 1.3 parts in 10^{12} [50].

The difference from CODATA 2022 is −5 × 10^{-6} m^{-1}, 0.27 times the combined uncertainty. The same work gives a proton radius of 0.8406(15) fm [50].

The unit of the ladder is the Rydberg length

The ladder of this book counts in units built from one measured constant. The texts of the net take the unit of time T_0 as half the period of the Rydberg frequency, and the unit of space S_0 as c times T_0, about 45.6 nm [26]. The values used throughout this book are T_0 = 1.520 655 × 10^{-16} s and S_0 = 4.558 816 × 10^{-8} m.

The arithmetic shows which Rydberg constant is meant. With R_∞, $1/(2R_\infty c)$ = 1.519 830 × 10^{-16} s and $1/(2R_\infty)$ = 45.5634 nm.

With the hydrogen Rydberg constant $R_H = R_\infty/(1 + m_e/m_p)$, $1/(2R_H c)$ = 1.520 658 × 10^{-16} s and $1/(2R_H)$ = 45.5882 nm. The book’s units match R_H to 2 parts in 10^{6}.

So $S_0 = 1/(2R_H)$. It is half the Lyman limit of hydrogen, the shortest wavelength of its spectrum, 91.18 nm.

The Lyman limit itself sits at position $\log_3 2$ = 0.63. The two possible units differ by m_e/m_p, 0.054 %, which is 0.0005 of a position and invisible at two decimals.

Because the unit is a Rydberg length, two places on the ladder are identities. The Rydberg constant obeys $R_\infty = \alpha^2 m_e c/(2h)$.

It follows that the Compton wavelength $h/(m_e c)$ equals $\alpha^2 \cdot S_0$ and the Bohr radius equals $(\alpha/2\pi)\cdot S_0$, with $S_0 = 1/(2R_\infty)$. The computed ratios are λ_C/S_0 = 5.3251 × 10^{-5} = α^2 and a_0/S_0 = 0.001 161 41 = $\alpha/2\pi$.

The positions follow from α alone. The Compton wavelength sits at $2\cdot\log_3\alpha$ = −8.96, and the Bohr radius at $\log_3(\alpha/2\pi)$ = −6.15.

The texts of the net list these two places with the hydrogen atom and the electron wavelength [30]. They are the arithmetic of the unit, not separate findings.

A third identity sits in time. The classical period of the electron on the first Bohr orbit, $2\pi a_0/(\alpha c)$, computes to 1.519 830 × 10^{-16} s. That is $1/(2R_\infty c)$, the unit of time itself, to nine digits.

The net’s climate text places the orbit of the electron in hydrogen, 0.152 fs, on layer 0 of time [29]. The place is the definition restated.

A fourth sits in the Balmer series of hydrogen. The Hδ line, from level 6 to level 2, has $1/\lambda = R_H(1/4 - 1/36) = (2/9)R_H$.

So $\lambda = 9/(2R_H) = 9 \cdot S_0$. Computed, $9/(2R_H) = 410.2935$ nm and $9 \times 45.588\ 16$ nm = 410.2934 nm; the line sits at position 2.00 exactly.

The proton is different. Its charge radius, 0.840 75 fm, sits at −16.21, a free placement on the ladder. The ladder carries it as a coordinate.

The fine-structure constant: one number, three routes

α sets the strength of the coupling between light and charge.

Eddington first set $\alpha^{-1} = 136$ and then 137 [153]. The measured value is 137.035 999 177(21) [1].

Two kinds of experiment measure it. One weighs the recoil of an atom that absorbs a photon, which gives h/m for the atom and, through the Rydberg constant, α. The other measures the electron's magnetic anomaly and reads α from the theory of quantum electrodynamics.

The electron route came first in precision. In 2008 Hanneke, Fogwell and Gabrielse found $\alpha^{-1} = 137.035\ 999\ 084(51)$, 0.37 parts per billion [39].

In 2018 Parker and colleagues at Berkeley measured caesium recoil, with an interferometer phase of 12 million radians, and found $\alpha = 1/137.035\ 999\ 046(27)$ "at 2.0 x 10^-10 accuracy" [41]. They reported "a 2.5 sigma tension" with the electron value [41].

In 2020 Morel, Yao, Cladé and Guellati-Khélifa in Paris measured rubidium recoil. They found $\alpha^{-1} = 137.035\ 999\ 206(11)$, a "relative accuracy of 81 parts per trillion" [42]. It "differs by more than 5 standard deviations from the best available result from caesium recoil measurements" [42].

The gap computes as follows. Rb minus Cs is 1.60×10^{-7} in α^{-1}, or 1.17 parts per billion. The combined uncertainty is $\sqrt{(0.011^2 + 0.027^2)} \times 10^{-6} = 2.9 \times 10^{-8}$, so the gap is 5.5 standard deviations.

In 2023 Fan, Myers, Sukra and Gabrielse measured the electron's moment again: g/2 = 1.001 159 652 180 59(13), 0.13 parts per trillion [38]. It "is determined 2.2 times more accurately than the value that stood for 14 years" [38]. With the Standard Model it gives $\alpha^{-1} = 137.035\ 999\ 166(15)$, "with an uncertainty ten times smaller than the current disagreement between measured α values" [38].

Year	Method	α^{-1}	Relative uncertainty	[n]
2008	electron g − 2 with QED	137.035 999 084(51)	3.7×10^{-10}	[39]
2018	caesium recoil	137.035 999 046(27)	2.0×10^{-10}	[41]
2018	CODATA adjustment	137.035 999 084(21)	1.5×10^{-10}	[13]
2020	rubidium recoil	137.035 999 206(11)	8.1×10^{-11}	[42]
2023	electron g − 2 with QED	137.035 999 166(15)	1.1×10^{-10}	[38]
2022	CODATA adjustment	137.035 999 177(21)	1.5×10^{-10}	[1][2]

The 2023 value lies 2.1 standard deviations from rubidium and 3.9 from caesium. CODATA 2022 lies 1.1×10^{-8} above it, between the two recoil values [2]. CODATA calls the electron moment "one of the three most accurate determinations of the fine-structure constant α", with caesium and rubidium recoil providing "the two other accurate values" [2].

α changes with the energy of the probe. At low energy it is 1/137.

At the mass of the W and Z it is “about 1/128” in the PDG tables [13]. Another secondary source gives $\alpha \approx 1/127$ at about 90 GeV [153]; the two differ by 0.8 %.

The muon’s anomaly is the sister measurement. CODATA 2022 gives $a_\mu = 1.165\,920\,62(41) \times 10^{-3}$ [1]. The 2025 theory update finds $a_\mu(\text{experiment}) - a_\mu(\text{Standard Model}) = 38(63) \times 10^{-11}$ and “no tension between the SM and experiment at the current level of precision” [44].

The proton radius

The proton’s size is the least precise of the listed constants. CODATA 2022 gives $r_p = 0.840\,75(64)$ fm [2]. Electronic hydrogen and deuterium alone give 0.8529(13) fm; muonic Lamb shifts give 0.840 60(66) fm [2].

The two values differ by 2.8 standard deviations [2]. The 2026 hydrogen value, 0.8406(15) fm, lies with the muonic one [50]. Chapter 3 tells the history of the puzzle.

The numbers without units

A dimensionless constant has the same value in every system of units. The Standard Model “requires 25 fundamental dimensionless constants” [153]. They are α, the strong coupling, six quark masses, three charged-lepton masses, three neutrino masses, the masses of the W, the Z and the Higgs, four quark-mixing parameters and four neutrino-mixing parameters [153].

The masses enter as ratios to the Planck mass. The electron’s ratio is $4.185\,46 \times 10^{-23}$, the muon’s $8.654\,18 \times 10^{-21}$, the tau’s $1.455\,35 \times 10^{-19}$ and the top quark’s 1.415×10^{-17} [153].

The W stands at 6.5841×10^{-18}, the Z at $7.468\,88 \times 10^{-18}$ and the Higgs near 1.02×10^{-17} [153]. From CODATA, $m_e/m_P = 9.109\,383\,7139 \times 10^{-31} / 2.176\,434 \times 10^{-8} = 4.185\,46 \times 10^{-23}$, the same.

The quark-mixing angles are $\theta_{12} = 0.227\,59$, $\theta_{23} = 0.041\,54$ and $\theta_{13} = 0.003\,508$ rad, with a phase $\delta = 1.201$ rad [153]. The neutrino-mixing angles are $\theta_{12} = 0.583\,64$, $\theta_{23} = 0.8587$ and $\theta_{13} = 0.1496$ rad, with a phase between 2.95 and 4.294 rad [153]. The vacuum angle of the strong force is “indistinguishable from zero” [153].

The cosmological constant, about 10^{-122} in Planck units, is counted apart [153]. Chapter 9 returns to it.

Rees in 1999 named six numbers [153]. $N \approx 10^{36}$ is the ratio of the electric to the gravitational force between two protons. $\varepsilon \approx 0.007$ is the fraction of mass released when four protons fuse to helium; $\Omega \approx 0.3$, $\lambda \approx 0.7$, $Q \approx 10^{-5}$ and $D = 3$ complete the set.

N computes from CODATA as $e^2/(4\pi\varepsilon_0 G m_p^2) = 1.2356 \times 10^{36}$. The gravitational coupling of two protons, $Gm_p^2/(\hbar c)$, is 5.906×10^{-39}, and of two electrons 1.752×10^{-45}. N times the proton coupling returns α, 0.007 297 5, because the two products share every factor but the charge.

Are the constants constant?

The constants are measured as fixed. The question is how fixed. Three kinds of record answer it: present-day clocks, an ancient reactor and distant gas clouds.

The Oklo reactors, about two billion years ago

In Gabon, at Oklo, natural fission reactors “operated about two billion years ago” [217]. The rare-earth isotopes they left behind record the energies of neutron-capture resonances at that time. Damour and Dyson in 1996 converted them into a bound on α, with the reactor temperature included [217].

They found $-0.9 \times 10^{-7} < (\alpha_{\text{Oklo}} - \alpha_{\text{now}})/\alpha < 1.2 \times 10^{-7}$ at 95 % confidence [217]. Averaged over the time, $-6.7 \times 10^{-17} < \dot{\alpha}/\alpha < 5.0 \times 10^{-17}$ per year [217]. Two billion years, 6.31×10^{16} s, sit at time position 68.36.

The quasars

In 2012 King, Webb, Murphy, Flambaum and colleagues analysed 154 absorbers seen with the VLT and 141 earlier absorbers seen with Keck [218]. They reported a dipole in α across the sky, of amplitude $(0.97 \pm 0.22/-0.20) \times 10^{-5}$, toward right ascension 17.3 ± 1.0 h and declination −61 ± 10° [218]. The dipole is preferred over a uniform shift at 4.1σ; a model scaled with distance, $(1.1 \pm 0.2) \times 10^{-6}$ per billion light-years, at 4.2σ [218].

In the VLT sample alone α appears larger at large distance; the Keck sample had shown a smaller α in distant clouds [218]. The authors “found no single systematic effect that reproduces it” [218]. The claim is spatial, at the level of 10^{-5}, and stands beside the null results of the clocks and of Oklo.

The clocks

In 2021 Lange and colleagues compared two optical clocks built on the E2 and E3 transitions of one ytterbium ion, $^{171}\text{Yb}^{+}$, over several years, together with two caesium fountains [216]. The frequency ratio ν_{E3}/ν_{E2} is 0.932 829 404 530 965 376(32), known to 3.4×10^{-17} [216]. The E3 frequency is 642,121,496,772,645.10(8) Hz against caesium, known to 1.2×10^{-16} [216].

From the drift of these ratios they found $\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}$ per year [216]. For $\mu = m_p/m_e$ they found $-8(36) \times 10^{-18}$ per year [216]. The α limit is about 20 times tighter, and the μ limit about 2 times tighter, than before [216].

The same clocks ride the Earth’s orbit through the Sun’s gravitational potential. The coupling to that potential is $(c^2/\alpha)(d\alpha/d\Phi) = 14(11) \times 10^{-9}$ and $(c^2/\mu)(d\mu/d\Phi) = 7(45) \times 10^{-8}$ [216]. Both are consistent with zero.

Record	Span	Bound or claim	[n]
Yb^{+} clocks, 2021	several years, now	$\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}$ yr^{-1}	[216]
Yb^{+} against Cs, 2021	several years, now	$\dot{\mu}/\mu = -8(36) \times 10^{-18}$ yr^{-1}	[216]
Oklo, 1996 analysis	2×10^{9} yr (time 68.36)	$\Delta\alpha/\alpha$ from −0.9 to +1.2 $\times 10^{-7}$	[217]
Oklo, time average	2×10^{9} yr	$\dot{\alpha}/\alpha$ from −6.7 to +5.0 $\times 10^{-17}$ yr^{-1}	[217]
Quasars, 2012	295 absorbers	dipole $(0.97 +0.22/-0.20) \times 10^{-5}$, 4.1σ	[218]

The finest clocks and the first nuclear clock

The bounds on drift are only as good as the clocks. In 2019 Brewer and colleagues at NIST built a clock on the $^{1}S_0 \leftrightarrow {}^{3}P_0$ transition of one aluminium ion, $^{27}\text{Al}^{+}$, read out through a co-trapped magnesium ion, $^{25}\text{Mg}^{+}$ [219]. Its systematic uncertainty is 9.4×10^{-19}, and its stability $1.2 \times 10^{-15}/\sqrt{\tau}$ [219].

At that level one second of error builds up in $1/(9.4 \times 10^{-19})$ s $= 1.06 \times 10^{18}$ s. That is 3.4×10^{10} years, more than twice the age of the universe. The span sits at time position 70.93.

The ytterbium clock of 2021 shows the other limit. Its frequency, 642,121,496,772,645.10 Hz, is known only to 1.2×10^{-16} because it is measured against caesium, and the caesium fountains carry that uncertainty [216].

The SI second is now the coarser partner. One period of the E3 light, 1.557×10^{-15} s, sits at time position 2.12.

In 2024 a nucleus joined the clocks. The isomer of thorium-229, ^{229m}Th, has the lowest known nuclear excitation.

Zhang and colleagues used a vacuum-ultraviolet frequency comb, the seventh harmonic of an infrared comb, stabilised to the JILA ^{87}Sr clock, and excited the nuclear transition in thorium doped into CaF_2 [220]. They called it “the first comparison, to our knowledge, of nuclear and atomic clocks for fundamental physics studies” [220].

The photon frequency is 2,020,407,384,335 ± 2 kHz [221]. With the exact h, c and e this gives an energy of 8.355 733 554 eV and a wavelength of 148.382 182 883 nm, as the source states [221]. The relative uncertainty is 2 kHz in 2.02×10^{15} Hz, 1.0×10^{-12}.

The wavelength sits at size position 1.07, and one period of the nuclear light, 4.95×10^{-16} s, at time position 1.07. The two coincide because the ladder’s units are linked by c.

Earlier in 2024 two groups had excited Th^{4+} in ionic crystals by laser at about one part per million [221]. Tiedau and colleagues found 2020.409(7) THz [221].

That lies 1.6 GHz above the comb value, within a quarter of its own 7 GHz uncertainty. Elwell and colleagues, in $LiSrAlF_6$, found 8.355733(2)(10) eV [221].

The isomer’s lifetime was measured in the same work. In the crystal its fluorescence lifetime is 630(15) s, at time position 39.02 [221].

For an isolated nucleus in vacuum the extrapolated half-life is 1740(50) s, at 39.94 [221]. The ground state of thorium-229 decays by alpha emission with a half-life of 7916 years [221].

Clock	Year	Figure	Value	[n]
$^{27}Al^+$	2019	systematic uncertainty	9.4×10^{-19}	[219]
$^{171}Yb^+$ E3/E2	2021	ratio uncertainty	3.4×10^{-17}	[216]
$^{171}Yb^+$ E3 against Cs	2021	frequency uncertainty	1.2×10^{-16}	[216]
^{229m}Th against ^{87}Sr	2024	frequency uncertainty	1.0×10^{-12}	[220][221]

What this part of the history shows

The constants were fixed in a definite order. The speed of light became a definition in 1983, and Planck’s constant, the elementary charge, the Boltzmann constant and the Avogadro constant followed on 20 May 2019. Every later measurement is read against those seven numbers.

The precisions form a long ladder of their own. The electron g-factor is known to 1.8×10^{-13} and the Rydberg constant to 1.1×10^{-12}. α is known to 1.5×10^{-10}, the muon–electron mass ratio to 2.2×10^{-8}, G to 2.2×10^{-5} and the proton radius to 7.6×10^{-4}.

The finest measurements still part. The rubidium and caesium values of α differ by 5.5 standard deviations. Two G values from one laboratory differ by 2.7, and the CODATA values of G carry an expansion factor of 3.9.

The ladder’s unit is a Rydberg length. $S_0 = 1/(2R_H)$ is half the Lyman limit. From that one choice the Bohr radius sits at $\log_3(\alpha/2\pi) = -6.15$, the Compton wavelength at $2\cdot\log_3\alpha = -8.96$, the first Bohr orbit at time 0.00 and the Hδ line at size 2.00.

These are identities of the unit. The proton at −16.21 is a coordinate.

The constants show the form of context in its stiffest case. The texts of the net hold that constants are state functions of the local vacuum: nothing is universal; everything is local and read [26]. For α they add a plain sentence: “The fine-structure constant α is stiff and cannot be moved by any reachable state change” [56].

The measured record has that form. The clocks bound the present drift of α at $1.0(1.1) \times 10^{-18}$ per year and of μ at $-8(36) \times 10^{-18}$ [216]. The Oklo reactors bound the change over two billion years at about 10^{-7}, and the coupling of α to the Sun’s potential, 14(11)

× 10^{-9} in units of c^2, is consistent with zero [217][216].

α does change where the surroundings change most. Probed at the mass of the W and Z it is about 1/128 rather than 1/137 [13]. The texts of the net give the same pair, 1/137 at low energy and about 1/127 at high energy, as measured and not supposed [168].

The only claim of a change in space, the quasar dipole at 10^{-5}, stands as a claim beside the null results [218].

The Maxwell text reads K, C and μ as properties of the local vacuum, on the same footing as the elasticity of steel [28]. The texts of the net read the constants as elastic moduli of the vacuum [222]. The modern record shows a modulus measured to ten digits and unmoved over two billion years.

9. The Vacuum Measured

Empty space was once the stage on which physics happened. In the twentieth century it became a thing that could be measured. It moves an atomic level, pulls two plates together, turns a moving mirror into a source of light and bends polarisation near a neutron star.

This chapter tells that history in order. It begins with the constants of empty space, which became measured numbers in 2019. It then follows the measured effects of the vacuum: the Lamb shift of 1947 and the Casimir force from 1958 to 2002.

Then come the vacuum in strong fields, the dynamical Casimir effect of 2011 and the horizons built in water and in atom clouds. It ends with the one number cosmology gives for the energy of empty space.

The basics of the net were set out in chapter 1. In the texts of the net the vacuum is not a background but the net itself. This chapter sets the measured vacuum and that form side by side.

The constants of empty space

Three numbers describe empty space as a medium for light. The electric constant ε_0 fixes how a field spreads from a charge. The magnetic constant μ_0 fixes how a field circles a current, and their ratio gives the impedance of empty space.

Until 2019 μ_0 was a defined number, $4\pi \times 10^{-7}$ N A^{-2}, and ε_0 followed from it and from c. Since 20 May 2019 the elementary charge and Planck's constant are fixed instead (chapter 8). μ_0 and ε_0 are now measured [1].

Constant	CODATA 2022 value	Relative uncertainty	[n]
Electric constant ε_0	8.854 187 8188(14) × 10^{-12} F/m	1.6×10^{-10}	[1]
Magnetic constant μ_0	1.256 637 061 27(20) × 10^{-6} N/A^2	1.6×10^{-10}	[1]
Impedance of empty space Z_0	376.730 313 412(59) Ω	1.6×10^{-10}	[1]
Speed of light c	299,792,458 m/s	exact	[1]

The three agree with one another to the last digit. $Z_0 = \sqrt{(\mu_0/\varepsilon_0)}$ and $Z_0 = \mu_0 c$ both give 376.730 313 412 Ω. And $1/\sqrt{(\varepsilon_0\mu_0)}$ gives 299,792,458.0 m/s, to the rounding of the inputs.

The new μ_0 lies just below the old one. $\mu_0/(4\pi \times 10^{-7}\ \text{N A}^{-2}) = 0.999\ 999\ 999\ 87$, a difference of -1.3×10^{-10}. Empty space was measured as a medium and found to differ from its former definition by about one part in 10^{10}.

The uncertainty of ε_0 and μ_0 is the uncertainty of α. With e, h and c exact, $\varepsilon_0 = e^2/(2\alpha hc)$, and computed with the CODATA α this gives 8.854 187 8188 × 10^{-12} F/m. The relative uncertainties, 1.6×10^{-10} for ε_0 and 1.5×10^{-10} for α, match.

The free field of empty space has its own quantum, the photon. The PDG gives its mean life as "Stable" [7]. Its mass is below 1×10^{-18} eV, which is 1.8×10^{-54} kg [7].

A photon of that mass would have a Compton wavelength of 1.24×10^{12} m, at size position 40.73. Its charge is below 1×10^{-46} e for mixed charge and below 1×10^{-35} e for a single charge [7]. A laboratory search by laser deflection gives below 8.5×10^{-17} e [8].

An older measurement of empty space came first. In 1887 Michelson and Morley looked for motion of the Earth through an aether and found "a null result" [223].

The Lamb shift, 1947

In 1947 W. E. Lamb and R. C. Retherford measured hydrogen with microwaves. They found “a rise of about 1000 MHz (0.03 cm−1) of the 2S1/2 level above the 2P1/2 level” [224]. The same source gives “the observed shift of 1057 MHz” [224].

The energy of the gap is E = hf. With h = 6.626 070 15 × 10^{-34} J s and f = 1057 MHz it is 7.00 × 10^{-25} J, or 4.37 × 10^{-6} eV.

The period of the shift, 1/f = 9.46 × 10^{-10} s, sits at time position 14.24. In the same year Hans Bethe was “the first to explain the Lamb shift in the hydrogen spectrum” [224]. The shift is attributed to “interactions between the virtual photons created through vacuum energy fluctuations” [224].

The modern measurement resolves the shift to kilohertz. In 2019 Bezginov and colleagues measured the $2S_{1/2}(f = 0)$ to $2P_{1/2}(f = 1)$ interval as 909.8717(32) MHz, a relative uncertainty of 3.5 × 10^{-6} [48]. From it they found a proton radius of 0.833(10) fm [48]; the period of that interval sits at 14.38.

The Casimir force, 1948 to 2002

In 1948 H. B. G. Casimir computed the force between two perfectly conducting plates with vacuum between them [225]. “The force is negative, indicating that the force is attractive” [225]. In the same year Casimir and Polder computed the force between an atom and a wall [225].

For ideal plates the pressure is $P = \pi^2\hbar c/(240d^4)$, where d is the gap. The fourth power makes the force steep: a factor 10 in distance is a factor 10^4 in pressure. The table gives the computed pressure at the separations where it was later measured.

Gap d	Pressure (Pa)	Pressure (atm)	Size position
10 nm	1.30 × 10^{5}	1.28	−1.38
100 nm	13.0	1.28 × 10^{-4}	0.72
500 nm	2.08 × 10^{-2}	2.05 × 10^{-7}	2.18
600 nm	1.00 × 10^{-2}	9.9 × 10^{-8}	2.35
1 µm	1.30 × 10^{-3}	1.28 × 10^{-8}	2.81
3 µm	1.61 × 10^{-5}	1.58 × 10^{-10}	3.81
6 µm	1.00 × 10^{-6}	9.9 × 10^{-12}	4.44

At 10 nm “the Casimir effect produces the equivalent of about 1 atmosphere of pressure” [225]. The computed value is 1.28 atm. At 6 µm the pressure has fallen to 10^{-11} atm.

The first attempt came from M. J. Sparnaay in 1957 and 1958, with parallel plates [225].

His results were “not in contradiction with the Casimir theory”, but “with large experimental errors” [225].

In 1993 Sukenik, Boshier, Cho, Sandoghdar and Hinds sent ground-state sodium atoms through a parallel-plate cavity a few microns wide [226]. The transmitted beam depended on the plate gap. “This experiment provides clear evidence for the existence of the Casimir-Polder force” [226].

“Our results confirm the magnitude of the force and the distance dependence predicted by quantum electrodynamics” [226]. The abstract ties the force to a change of the ground-state Lamb shift inside the cavity [226]. The atom–wall force thus appears as a change of the kind of level shift measured in 1947.

In 1997 S. K. Lamoreaux measured the force between closely spaced conducting surfaces with a torsion pendulum [227].

His range was 0.6 to 6 µm, size positions 2.35 to 4.44. He found the force “to within 5% of the value predicted by the theory” [225].

In 1998 Mohideen and Roy used an atomic force microscope, with a metallised sphere

of diameter 196 µm above a flat plate [228]. They measured “for plate-sphere separations from 0.1 to 0.9 microns”, size positions 0.72 to 2.72 [228]. “The root mean square average deviation of 1.6 pN between theory and experiment” corresponds “to a 1% deviation at the smallest separation” [228].

The size of that force can be computed. For an ideal sphere of radius R above a plate, $F = \pi^3 \hbar c R/(360 d^3)$. With R = 98 µm this gives 2.67×10^{-10} N at 100 nm and 3.66×10^{-13} N at 900 nm; 1.6 pN is 0.6 % of the first.

In 2002 Bressi, Carugno, Onofrio and Ruoso measured the force in Casimir’s own geometry, two parallel surfaces [229]. They used a silicon cantilever coated with chromium and a similar rigid surface, and read the force from shifts of the cantilever frequency [229]. “The scaling of the force with the distance between the surfaces was tested in the 0.5 - 3.0 µm range”, and “the related force coefficient was determined at the 15% precision level” [229].

Year	Experiment	Geometry	Range	Result	[n]
1957–58	Sparnaay	parallel plates	—	not in contradiction, large errors	[225]
1993	Sukenik et al.	sodium atoms in a plate cavity	micron gap	magnitude and distance law confirmed	[226]
1997	Lamoreaux	torsion pendulum	0.6–6 µm (2.35 to 4.44)	within 5 %	[227][225]
1998	Mohideen and Roy	AFM, 196 µm sphere and plate	0.1–0.9 µm (0.72 to 2.72)	1.6 pN rms; 1 % at closest	[228]
2002	Bressi et al.	parallel plates	0.5–3.0 µm (2.18 to 3.81)	coefficient to 15 %	[229]

All measured separations lie between size positions 0.72 and 4.44. They lie 0.7 to 4.4 steps of three above the unit of space, 45.6 nm at position 0. The precision rose from “not in contradiction” in 1958 to 5 % in 1997 and 1 % at 100 nm in 1998.

The vacuum in strong fields

The scale of the vacuum in strong fields is the Schwinger field, $E_S = m_e^2 c^3/(e\hbar)$. With the CODATA electron mass and the exact e, ħ and c it computes to 1.323×10^{18} V/m.

The same number is the electron’s rest energy divided by e and by its reduced Compton wavelength: $m_e c^2/(e \cdot \lambda\!\!\!^{-}_C) = 1.323 \times 10^{18}$ V/m. The matching magnetic field is $E_S/c = 4.414 \times 10^9$ T. A plane wave at that field carries $\tfrac{1}{2}\varepsilon_0 c E_S^2 = 2.32 \times 10^{33}$ W/m², or 2.3×10^{29} W/cm².

Below that scale a magnetic field is predicted to give empty space two refractive indices, one for each polarisation. At 2.5 T the predicted difference is $\Delta n = 2.5 \times 10^{-23}$ [230]. That field is 5.7×10^{-10} of the critical field.

The PVLAS experiment spent 25 years on that number. Its first phase used a rotating superconducting magnet, its second two rotating permanent magnets [230]. The final result, published in 2020, is $\Delta n = (12 \pm 17) \times 10^{-23}$ and a dichroism $|\Delta\kappa| = (10 \pm 28) \times 10^{-23}$ [230].

“The experiment was not able to reach the predicted value from QED” [230]. The uncertainty is “about a factor 7 above the predicted value” [230]. Computed, 17/2.5 = 6.8.

Nature supplies stronger fields. The isolated neutron star RX J1856.5−3754 belongs to a class whose surface fields are inferred near 10^{13} G, or 10^9 T [231]. That is 0.23 of the critical field.

In 2017 Mignani and colleagues measured the star’s optical polarisation with the Very Large Telescope. They found a linear polarisation of 16.43 % ± 5.26 % at a position angle of 145.39° ± 9.44° [231]. “The P.D. that we derive is large enough to support the presence of vacuum birefringence, as predicted by QED” [231]; the ratio 16.43/5.26 is

3.1.

The strongest fields on Earth come from heavy ions passing close without touching. In 2017 ATLAS at the LHC studied lead–lead collisions at 5.02 TeV per nucleon pair, with 480 μb⁻¹ of data [20]. “A total of 13 candidate events are observed with an expected background of 2.6±0.7 events” [20].

The cross-section “is measured to be 70 ± 24 (stat.) ± 17 (syst.) nb, which is in agreement with Standard Model predictions” [20]. Two photons had scattered off each other in empty space. In 2019 ATLAS observed the same process with 59 events against a background of 12 ± 3, at 8.2 standard deviations, and a cross-section of 78 ± 13 ± 7 ± 3 nb [21].

The fields there reach “as large as 10^{25} V/m”, “well in excess of the Schwinger limit” [232]. Laser facilities stay below it. The ELI Ultra High Field Facility “is likely to remain well below the Schwinger limit”, while the Station of Extreme Light “should be powerful enough to observe the effect” [232].

Nonlinear quantum electrodynamics “has already been observed through inelastic channels in SLAC Experiment 144” [232]. The measured record thus runs across eighteen orders of field. At 2.5 T the measured error is 6.8 times the predicted effect; near 10^{9} T the effect shows as polarisation; far above 10^{18} V/m light scatters on light.

Case	Field	Measured	Expected	[n]
PVLAS, 2020	2.5 T	$\Delta n = (12 \pm 17) \times 10^{-23}$	2.5×10^{-23}	[230]
PVLAS dichroism	2.5 T	$\Delta\kappa = (10 \pm 28) \times 10^{-23}$	—	[230]
RX J1856.5−3754, 2017	about 10^{9} T (class value)	16.43 % ± 5.26 %	supports QED	[231]
ATLAS, 2017	heavy-ion fields	13 events, background 2.6 ± 0.7; 70 ± 24 ± 17 nb	Standard Model	[20]
ATLAS, 2019	up to 10^{25} V/m	59 events, background 12 ± 3; 8.2σ; 78 ± 13 ± 7 ± 3 nb	Standard Model	[21][232]
Schwinger field	—	$E_S = 1.323 \times 10^{18}$ V/m; $B_S = 4.414 \times 10^{9}$ T	—	computed

Light from moving boundaries and from nothing

In May 2011 a group at Chalmers reported light made by a moving boundary [233] [225]. Wilson, Johansson, Pourkabirian, Johansson, Duty, Nori and Delsing changed the effective length of a superconducting transmission line with a SQUID at about 11 GHz [233]. “Using a superconducting circuit, we have observed the DCE for the first time” [233].

Photons were emitted, and the emitted radiation showed two-mode squeezing [233]. “Microwave photons were generated out of the vacuum in a superconducting microwave resonator” [225]. The period of an 11 GHz drive is 9.1×10^{-11} s, at time position 12.11.

The paper opens with a sentence of its own: “One of the most surprising predictions of modern quantum theory is that the vacuum of space is not empty” [233]. Later cases followed in a Josephson metamaterial in 2013 and in an optical analogue in 2019 [225].

Year	Experiment	What was measured	Number	[n]
2011	Wilson et al.	photons from a modulated boundary	drive about 11 GHz (time 12.11); two-mode squeezing	[233]

Horizons in water and in atom clouds

A black hole should glow at a temperature set by the surface gravity of its horizon. A uniformly accelerated observer should see a warm vacuum. Both have been built as analogues, in water and in atom clouds.

In 2011 Weinfurtner, Tedford, Penrice, Unruh and Lawrence placed an obstacle in a water channel [234]. The fast flow above it acted as a horizon for surface waves, an analogue of a white hole. Long waves were converted into short ones, and “our measurements of the amplitudes of the converted waves demonstrate the thermal nature of the conversion process” [234].

In 2016 J. Steinhauer built an analogue black hole in a Bose–Einstein condensate [235].

“We observe spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations”, “emanating from an analogue black hole in an atomic Bose-Einstein condensate” [235]. “The entanglement verifies the quantum nature of the Hawking radiation” [235].

The high-energy pairs are entangled; the low-energy pairs are not [235].

In 2019 Muñoz de Nova, Golubkov, Kolobov and Steinhauer measured the full spectrum [236]. The condensate held 8000 atoms, and “The experiment is repeated 7400 times” [236]. They found the spectrum “to be thermal at the Hawking temperature implied by the analogue surface gravity” [236].

That predicted temperature is 0.35 nK, or 0.12 mc^2_out in the units of the condensate [236]. “Very good agreement with the measured spectrum of Hawking radiation is seen, with no free parameters” [236]. Inside the analogue black hole “the radiation … is seen to be composed of negative-energy partners only” [236].

In the same year Hu, Feng, Zhang and Chin drove a condensate of about 10^5 atoms parametrically [237]. “We observe a matterwave field which follows a Boltzmann distribution for a local observer” [237]. “The extracted temperature and entropy from the atomic distribution are in agreement with Unruh’s predictions” [237].

Year	System	Observation	Number	[n]
2011	water channel	stimulated conversion, thermal amplitudes	—	[234]
2016	condensate	spontaneous Hawking pairs, entangled at high energy	—	[235]
2019	condensate of 8000 atoms, 7400 runs	thermal spectrum at the predicted temperature	0.35 nK, no free parameters	[236]
2019	driven condensate of about 10^5 atoms	Boltzmann matter-wave field	agrees with Unruh	[237]

The order of the record is plain. Stimulated emission came in 2011, spontaneous and entangled emission in 2016, and a thermal spectrum at the predicted temperature in 2019.

The energy of empty space

Cosmology measures one number for the vacuum: its energy density, read from the expansion of the universe. The Planck satellite measured the temperature and polarisation of the cosmic microwave background and fitted a flat model with six parameters [238]. “We find no compelling evidence for extensions to the base-ΛCDM model” [238].

The 2018 results give a Hubble constant $H_0 = 67.4 \pm 0.5$ km/s/Mpc and a matter density parameter $\Omega_m = 0.315 \pm 0.007$ [238]. The dark-energy density parameter is $\Omega_\Lambda = 0.6847 \pm 0.0073$, and the age of the universe $(13.787 \pm 0.020) \times 10^9$ years [239].

Another page gives Ω_Λ = 0.714 for the same release [241].

The Planck age, 4.35 × 10^{17} s, sits at time position 70.12; the PDG 2024 table gives 13.797 ± 0.023 Gyr [25]. The Planck 2015 release gave the vacuum density directly as “ρvac = 5.96×10−27 kg/m3 ≙ 5.3566×10−10 J/m3 = 3.35 GeV/m3” [240]. In natural units that is about 2.5 × 10^{-47} GeV^4 [240].

The 2018 value follows in three steps. First, H_0 = 67.4 km/s/Mpc is 2.1843 × 10^{-18} s^{-1}, with 1 Mpc = 3.085 677 58 × 10^{22} m. Second, the critical density $3H_0^2/(8\pi G)$ is 8.53 × 10^{-27} kg/m^3, with the CODATA G.

Third, ρ_Λ = Ω_Λ × ρ_crit = 0.6847 × 8.53 × 10^{-27} = 5.84 × 10^{-27} kg/m^3, with an uncertainty of about 0.1 × 10^{-27} from H_0 and Ω_Λ. Times c^2 this is 5.25 × 10^{-10} J/m^3, or 3.28 GeV per cubic metre. The 2015 and 2018 figures differ by 2 %.

The density can be written as one energy to the fourth power. With u = ρ_Λc^2, the energy (u(ħc)³)^(1/4) is 2.24 × 10^{-3} eV. A photon of 2.24 meV has a wavelength of 0.55 mm, at size position 8.56.

The cosmological constant itself is “measured to be on the order of 10−52 m−2” [241]. It “may be expressed as 10−35 s−2” or “as 10−122 ℓP−2” [241]. Computed from ρ_Λ, Λ = $8\pi G\rho_\Lambda/c^2$ = 1.09 × 10^{-52} m^{-2}, and in Planck units Λℓ_P^2 = 2.85 × 10^{-122}.

The length Λ^(−1/2) is 9.58 × 10^{25} m, at size position 69.84. The Hubble length c/H_0 is 1.37 × 10^{26} m, at 70.17. The energy of empty space and the size of the observed universe sit at the same depth of the ladder, because $\Lambda = 3\Omega_\Lambda H_0^2/c^2$.

Field theory estimates the same density from the zero-point energy of every mode. The estimates have a history of their own [240][241]:

Estimate	Excess over the measured density	[n]
Zel’dovich, 1960s	“forty orders of magnitude bigger”	[240]
Weinberg, 1989	“120 to 122 orders of magnitude”	[240]
Adler, Casey and Jacob 1995; Bengochea et al. 2020	“between 50 and as many as 122 orders of magnitude”	[240]
Calcagni, Di Luca and Fodran 2022, Planck-mass cutoff	“a difference of 120 orders of magnitude”	[240]
Same, dimensional regularisation	“about 56 orders of magnitude”	[240]
Martin 2012 and Straumann 2002, with Lorentz invariance	“closer to 60 orders of magnitude”; Martin about 10^8 GeV^4, “about 55 orders”	[240]

Adler and colleagues called it “the largest discrepancy between theory and experiment in all of science” [240]. The 120-order figure is the Planck density over the measured one. Computed, $c^7/(\hbar G^2)$ = 4.63 × 10^{113} J/m^3, and divided by 5.25 × 10^{-10} J/m^3 this is 8.8 × 10^{122}, a logarithm of 122.9.

Martin’s own review of 2012 treats “the properly renormalized value of the zero-point energy density today (for a free theory)” [242]. That value “is in fact far from being 122 orders of magnitude larger than the critical energy density” [242].

The 122-order figure is the one cited “as often quoted in the literature” [242]. The published estimates thus run from 40 to 122 orders, set by the cutoff and by whether Lorentz invariance is kept.

The present state of the vacuum is also computed from particle masses. With the 2013 inputs, Buttazzo and colleagues found that the Higgs coupling turns negative near 10^{10} GeV, and that full stability would need a Higgs mass above 129.6 ± 1.5 GeV [179]. The measured mass is 125.20 GeV (chapter 6).

Andreassen, Frost and Schwartz in 2018 called their result “the first complete calculation of the lifetime of our universe: 10^139 years” [180]. At 95 % confidence the lifetime is “more than 10^58 years” [180]. These are calculations from measured masses; chapter 10 places them on the time axis.

Quantity	Value	[n]

H_0 (Planck 2018)	67.4 ± 0.5 km/s/Mpc	[238]
Ω_m	0.315 ± 0.007	[238]
Ω_Λ	0.6847 ± 0.0073 (another page: 0.714)	[239][241]
ρ_vac (Planck 2015)	5.96×10^{-27} kg/m³ = 5.3566×10^{-10} J/m³	[240]
ρ_Λ (Planck 2018, computed)	5.84×10^{-27} kg/m³ = 5.25×10^{-10} J/m³	[238][239]
Energy scale	$(2.24\ \text{meV})^4$; wavelength 0.55 mm at size 8.56	computed
Λ	about 10^{-52} m^{-2}; computed 1.09×10^{-52} m^{-2}	[241]
Λ in Planck units	about 10^{-122}; computed 2.85×10^{-122}	[241]
Planck density / measured density	8.8×10^{122}	computed
Age of the universe	13.787 ± 0.020 Gyr = 4.35×10^{17} s, time 70.12	[239]

What this part of the history shows

The vacuum entered physics as an absence and left the twentieth century as a measured medium. Its electric and magnetic constants are known to 1.6 parts in 10^{10}. Its effects have been measured on a level of hydrogen, between plates, at a moving boundary, near a neutron star, in collisions of lead ions and in the expansion of the universe.

The texts of the net state this form in one sentence: “The vacuum is a net of closed meshes” [28]. In that reading empty space is not a stage but the net itself.

The form of context shows in the constants of empty space: the Maxwell text reads K, C and μ as properties of the local vacuum, on the same footing as the elasticity of steel [28]. The texts of the net read the constants as state functions of the local vacuum [222]. The modern record has fixed ε_0 and μ_0 to ten digits, and since 2019 they are measured, no longer defined.

In the texts the same winding appears at every depth [26]. Read in that form, one vacuum effect moves the 2S level of hydrogen by 1057 MHz [224], and changed by nearby walls it gives the Casimir–Polder force on a sodium atom [226]. Between two surfaces it gives the Casimir pressure, measured from size 0.72 to 4.44.

The ladder places the measured vacuum on both sides of its unit. The finest Casimir gap, 100 nm, sits at 0.72, less than one step above S_0, and the ideal-plate pressure reaches one atmosphere at 10 nm, at −1.38.

The texts of the net take Casimir’s count of 1948 one step back, to a single mesh at the unit of space [26]. With $S_0 = 4.559 \times 10^{-8}$ m they give $\pi^2\hbar c/(720 \cdot S_0) = 9.5 \times 10^{-21}$ J per mesh, which computes to 9.506×10^{-21} J, or 0.0593 eV. This is a number of the net’s own texts, set beside the measured Casimir force as its reverse step.

Empty space carries energy without matter. The measured vacuum density, 5.84×10^{-27} kg/m³, enters cosmology as $\Omega_\Lambda = 0.6847$, apart from the matter fraction $\Omega_m = 0.315$. The texts of the net read empty space in the same way: the strand runs there, but it does not become round, so there is energy and no mass [31].

The moving boundary of 2011 shows the vacuum giving up real light. A boundary changed at 11 GHz, at time position 12.11, released microwave photons in squeezed pairs [233].

The analogue horizons show pairs that belong together. The Hawking phonons of 2016 are entangled at high energy, and inside the horizon only negative-energy partners are found [235][236]. The texts of the net read entanglement as shared prefix: two partners share one slot higher in the tree, and that slot is one thing [31].

The vacuum’s single cosmological number and the size of the visible universe sit together at the top of the ladder. Λ^(−1/2) lies at size 69.84 and the Hubble length at

70.17, while the age of the universe lies at time 70.12.

10. The Lifetimes of the Unstable

Most particles do not last. Of the particles measured in the earlier chapters, three have lifetimes known only as lower bounds: the photon, the electron and the proton. Most of the others live for a measured time and then become something else.

This chapter sets every measured lifetime in one place. It runs from the Z boson, which lives 2.6×10^{-25} s, to the free neutron, which lives 878 s. It adds the bound systems and nuclei that extend the axis, from hydrogen-5 at 8.6×10^{-23} s to tellurium-128 at more than 10^{24} years, and the limits on the stable three.

Lifetimes are measured in two ways. A long-lived particle is timed directly: its decay length or its decay clock gives the mean life τ. A short-lived particle is measured by its width Γ, the spread of its mass, and the mean life follows as $\tau = \hbar/\Gamma$, with $\hbar = 6.582\,119\,569 \times 10^{-22}$ MeV s [35].

An example shows the step. The $\rho(770)$ meson has a width of 147.4 MeV [92]. Its mean life is $6.582\,119\,569 \times 10^{-22}$ MeV s / 147.4 MeV = 4.47×10^{-24} s, at time position −15.79.

The ladder of time from chapter 1 places each lifetime as a coordinate. For orientation, one minute sits at 36.88, one hour at 40.61, one day at 43.50 and one year at 48.87. The full table at the end of the chapter lists every case.

The stable and their bounds

The electron’s lifetime is bounded from below. In 2015 the Borexino neutrino detector searched for an electron turning into a neutrino and “a single mono-energetic photon” [36]. “This new bound, tau > 6.6 10**28 yr at 90 % C.L., is two orders of magnitude better than the previous limit” [36].

That bound is 2.08×10^{36} s, at time position 109.27. It is 4.8×10^{18} times the age of the universe.

The photon’s mean life is listed as “Stable” [7]. If the photon had a small mass, its lifetime would be “more than 10^{18} years” [151]. That bound sits at time position 86.60.

The proton’s limits come from large water detectors. The PDG gives a mean life above 9×10^{29} years for any decay into invisible products [69]. That is 2.84×10^{37} s, at time position 111.65.

For particular decays the limits are higher. Super-Kamiokande ran from April 1996 to May 2018 with an exposure of 450 kiloton-years, enlarging its fiducial volume from 22.5 to 27.2 kilotons [73]. It counted zero candidates for $p \to e^+\pi^0$ and one for $p \to \mu^+\pi^0$, “consistent with the atmospheric neutrino background” [73].

The result is “$\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ years” and $\tau/B(p \to \mu^+\pi^0) > 1.6 \times 10^{34}$ years [73]. The first is 7.6×10^{41} s, at time position 120.93. The PDG lists further partial limits, in years [69]:

Decay of the proton	τ/B lower limit (yr)	Time position	[n]
$e^+e^+e^-$	3.4×10^{34}	> 121.24	[69]
$e^+\pi^0$	2.4×10^{34}	> 120.93	[69][73]
$\mu^+\pi^0$	1.6×10^{34}	> 120.56	[69][73]
$e^+\eta$	1.0×10^{34}	> 120.13	[69]
$\bar{\nu}K^+$	5.9×10^{33}	> 119.65	[69]
$\mu^+\eta$	4.7×10^{33}	> 119.44	[69]
e^+K^0	1.0×10^{33}	> 118.04	[69]
$e^+\gamma$	6.7×10^{32}	> 117.67	[69]
$\bar{\nu}\pi^+$	3.9×10^{32}	> 117.18	[69]
invisible	9×10^{29}	> 111.65	[69]

The antiproton has been held and watched. Antiprotons “were kept in a Penning trap for 405 days” [243]. The laboratory bounds on its lifetime grew from 0.08 years at LEAR to 0.28 years from Gabrielse and colleagues and 10.2 years from BASE in 2017 [243].

A cosmic-ray bound gives about 1.7 million years [243]. The APEX search gives 50,000 years for $\bar{p} \to \mu^- + X$ and 300,000 years for $\bar{p} \to e^- + \gamma$ [243]. The highest of these, 9.5×10^{12} s, sits at time position 60.35.

The muon and the tau

The muon is the longest-lived unstable particle after the neutron. The PDG gives “Mean life τ = (2.1969811 ± 0.0000022) × 10−6s”, with cτ = 658.6384 m [35]. Its time position is 21.29.

The MuLan experiment of 2013 timed positive muons to 2,196,980.3(2.2) ps, a precision of one part per million [45]. It was “thirty times more precise than previous generations of lifetime experiments” [45]. From it came the Fermi constant, G_F = 1.166 3787(6) × 10^{-5} GeV^{-2}, to 0.5 parts per million [45].

The net’s climate text places the muon’s lifetime, 2.2 µs, on layer 21 of its ladder [29]. Computed from the PDG value the position is 21.29.

The muon and its antiparticle live equally long. The PDG gives $(\tau_{\mu^+} - \tau_{\mu^-})/\tau = (2 \pm 8) \times 10^{-5}$ [198]. The difference is zero within its error.

The tau lepton lives “(290.3 ± 0.5) × 10−15 s”, with cτ = 87.03 µm [35]. Its time position is 6.88. The muon outlives it by a factor 7.57×10^6, while it is 16.82 times heavier.

The light mesons

The pions and kaons are timed directly. The charged pion lives “(2.6033 ± 0.0005) × 10−8s”, with cτ = 7.8045 m [92]. The neutral pion lives “(8.43 ± 0.13) × 10−17 s”, with cτ = 25.3 nm [92].

The two pions differ by 4.59 MeV in mass, 3.4 %. Their lifetimes differ by a factor 3.09×10^8. The charged pion sits at time position 17.26, the neutral one at −0.54.

The charged pion and its antiparticle live equally long within $(6 \pm 7) \times 10^{-4}$ [198]. The charged kaon lives “(1.2380 ± 0.0020) × 10−8s”, with cτ = 3.711 m, at 16.58 [92].

The neutral kaons come in two lifetimes. The short-lived K^0_S lives (0.8954 ± 0.0004) × 10^{-10} s, “Assuming CPT”, with cτ = 2.6844 cm [92]. The long-lived K^0_L lives (5.116 ± 0.021) × 10^{-8} s, with cτ = 15.34 m [92].

The ratio is 571. K^0_S sits at 12.09 and K^0_L at 17.87. For the neutral kaon and its antiparticle the PDG gives $(\Gamma_{K^0} - \Gamma_{\bar{K}^0})/m = (8 \pm 8) \times 10^{-18}$ [198].

The other light mesons are measured by their widths. The η has Γ = 1.31 ± 0.05 keV, so τ = 5.02 × 10^{-19} s, at −5.20 [92]. The η′(958) has Γ = 0.188 ± 0.006 MeV, τ = 3.50 × 10^{-21} s, at −9.72 [92].

The vector mesons are shorter still. The φ(1020) has Γ = 4.249 MeV and τ = 1.55 × 10^{-22} s, at −12.56 [92]. The ω(782) has Γ = 8.68 MeV and τ = 7.58 × 10^{-23} s, at −13.21, and the ρ(770) has τ = 4.47 × 10^{-24} s, at −15.79 [92].

The K*(892) is measured in two ways. Produced in hadron collisions, the charged state has Γ = 51.4 ± 0.8 MeV; in tau decays, 46.2 ± 1.3 MeV [92]. The neutral state has Γ = 47.3 ± 0.5 MeV [92].

The lifetimes are 1.28 × 10^{-23} s, 1.42 × 10^{-23} s and 1.39 × 10^{-23} s, near position −14.8. The widest light states in the tables have widths above 400 MeV. $K^*_0(700)$ has 468 ± 30 MeV, $f_2(1950)$ 464 ± 24 MeV and $f_0(2020)$ 440 ± 50 MeV, all near τ = 1.4 × 10^{-24} s and position −16.8 [92].

The light mesons fall into three groups on the ladder. The pions and kaons that are

timed directly sit at 12.09 to 17.87.

The π^0 and η sit at -5.20 to -0.54. The states measured by width sit at -16.84 to -9.72.

Charm and bottom mesons

The ground-state mesons with a charm or bottom quark are all timed directly. They live between 0.41 and 1.64 picoseconds [108][244][245][246][247][248]:

Meson	Mass (MeV)	τ (s)	cτ	Time position	[n]
D^0	1864.84	4.103×10^{-13}	123.01 µm	7.19	[108]
D_s±	1968.35	5.012×10^{-13}	150.3 µm	7.37	[244]
B_c±	6274.47	5.10×10^{-13}	152.9 µm	7.39	[248]
D±	1869.66	1.033×10^{-12}	309.8 µm	8.03	[108]
B^0	5279.63	1.517×10^{-12}	454.8 µm	8.38	[246]
B^0_s	5366.93	1.520×10^{-12}	455.7 µm	8.38	[247]
B±	5279.41	1.638×10^{-12}	491.1 µm	8.45	[245]

The spread is a factor 4.0 over a mass range from 1.86 to 6.27 GeV. The charged D lives 2.52 times longer than the neutral D. The charged B lives 1.080 times longer than the neutral B.

The B^0_s oscillates into its antiparticle while it lives. Its mass splitting is $\Delta m_s = (17.765 \pm 0.006) \times 10^{12}\ \hbar\ s^{-1}$, and its width splitting $\Delta\Gamma = (0.083 \pm 0.005) \times 10^{12}\ s^{-1}$ [247]. The oscillation period $2\pi/\Delta m_s$ is 3.537×10^{-13} s, so the meson turns over 4.3 times in one mean life.

The excited charm mesons decay much faster. The *D(2010)± has Γ = 83.4 ± 1.8 keV and τ = 7.89 × 10⁻²¹ s, at −8.98 [108]. The widths of the D*(2007)⁰ and the D*_s± are bounded below 2.1 and 1.9 MeV at 90 % CL, so their lifetimes exceed 3.1×10^{-22} and 3.5×10^{-22} s [108][244].

The quarkonia

A quark bound to its own antiquark is a quarkonium. All the quarkonia listed here are measured by their widths [101][249]:

State	Mass (MeV)	Γ	τ (s)	Time position	[n]
Υ(3S)	10355.1	20.32 ± 1.85 keV	3.24×10^{-20}	−7.70	[249]
Υ(2S)	10023.4	31.98 ± 2.63 keV	2.06×10^{-20}	−8.11	[249]
Υ(1S)	9460.40	54.02 ± 1.25 keV	1.22×10^{-20}	−8.59	[249]
J/ψ(1S)	3096.900	92.6 ± 1.7 keV	7.11×10^{-21}	−9.08	[101]
ψ(2S)	3686.097	293 ± 9 keV	2.25×10^{-21}	−10.12	[101]
χ_c1(1P)	3510.67	0.84 ± 0.04 MeV	7.84×10^{-22}	−11.08	[101]
χ_c2(1P)	3556.17	1.98 ± 0.09 MeV	3.32×10^{-22}	−11.86	[101]
η_b(1S)	9398.7	10 +5/−4 MeV	6.6×10^{-23}	−13.34	[249]
χ_c0(1P)	3414.71	10.7 ± 0.6 MeV	6.15×10^{-23}	−13.40	[101]
Υ(4S)	10579.4	20.5 ± 2.5 MeV	3.21×10^{-23}	−13.99	[249]
η_c(1S)	2984.1	30.5 ± 0.5 MeV	2.16×10^{-23}	−14.35	[101]

The narrow states have widths of tens of keV and live 10^{-21} to 10^{-20} s. The broad states have widths of 10 to 30 MeV and live 2 to 7×10^{-23} s. The quarkonia are 10^7 to 10^{11} times shorter-lived than the open charm and bottom mesons.

In the Υ family the lifetime rises from 1S to 3S. At 4S it falls by a factor of 1009: the width grows from 20.32 keV to 20.5 MeV for a mass only 224 MeV higher [249].

The baryons

The strange ground-state baryons, the hyperons, are timed directly [69]. Six of them live between 0.80 and 2.90 × 10⁻¹⁰ s, a spread of a factor 3.6:

Baryon	Mass (MeV)	τ (s)	cτ	Time position	[n]
Σ⁺	1189.37	8.018 × 10⁻¹¹	2.40 cm	11.99	[69]
Ω⁻	1672.45	8.21 × 10⁻¹¹	2.46 cm	12.01	[69]
Σ⁻	1197.449	1.479 × 10⁻¹⁰	4.43 cm	12.55	[69]
Ξ⁻	1321.71	1.639 × 10⁻¹⁰	4.91 cm	12.64	[69]
Λ	1115.683	2.617 × 10⁻¹⁰	7.85 cm	13.07	[69]
Ξ⁰	1314.86	2.90 × 10⁻¹⁰	8.69 cm	13.16	[69]

The seventh, Σ⁰, stands apart. It lives “(7.4 ± 0.7) × 10−20 s”, with cτ = 22 pm, at time position −6.94 [69]. Its charged sibling Σ⁺ lives 1.08 × 10⁹ times longer, for a mass 3.3 MeV lower.

The baryon resonances are measured by width. The Δ(1232) has a “Breit-Wigner full width (mixed charges) = 114 to 120 (≈ 117) MeV” [69]. Its mean life is 5.63 × 10⁻²⁴ s for 117 MeV, between 5.49 and 5.77 × 10⁻²⁴ s across that range, at −15.58.

The Σ(1385) has widths of 36.2 ± 0.7 MeV for the positive state, 36 ± 5 MeV for the neutral and 39.4 ± 2.1 MeV for the negative [69]. Their lifetimes are 1.82, 1.83 and 1.67 × 10⁻²³ s, near −14.5.

The charmed baryons live 0.15 to 0.45 picoseconds [69][250][251]:

Baryon	Mass (MeV)	τ (s)	cτ	Time position	[n]
Ξ_c⁰	2470.44	1.504 × 10⁻¹³	45.1 µm	6.28	[250]
Λ_c⁺	2286.46	2.026 × 10⁻¹³	60.7 µm	6.55	[69][250]
Ξ_cc⁺⁺	3621.6	2.56 × 10⁻¹³	76.7 µm	6.76	[251]
Ω_c⁰	2695.2	2.73 × 10⁻¹³	81.8 µm	6.82	[250]
Ξ_c⁺	2467.71	4.53 × 10⁻¹³	135.8 µm	7.28	[250]

The doubly charmed Ξ_cc⁺⁺ lives within the range of the singly charmed. The excited Σ_c(2455) states have widths of 1.89 +0.09/−0.18 MeV (doubly charged) and 1.83 +0.11/−0.19 MeV (neutral), so lifetimes of 3.48 and 3.60 × 10⁻²² s, near −11.8 [250]. For the Ξ′_c states the table gives masses of 2578.2 and 2578.7 MeV [250].

The bottom baryons live 1.47 to 1.64 picoseconds [252]:

Baryon	Mass (MeV)	τ (s)	Time position	[n]
Λ_b⁰	5619.60	1.471 × 10⁻¹²	8.35	[252]
Ξ_b⁰	5791.9	1.480 × 10⁻¹²	8.36	[252]
Ξ_b⁻	5797.0	1.572 × 10⁻¹²	8.41	[252]
Ω_b⁻	6045.8	1.64 +0.18/−0.17 × 10⁻¹²	8.45	[252]

The spread is 11 %, and the four sit with the B mesons at 8.35 to 8.45. The excited Σ_b states have widths of 5.0 ± 0.5 and 5.3 ± 0.5 MeV, so lifetimes of 1.32 and 1.24 × 10⁻²² s, near −12.7 [252].

The heaviest: W, Z, top and Higgs

The force carriers of the weak interaction and the top quark are the shortest-lived particles with measured widths. The Z has Γ = 2.4955 ± 0.0023 GeV, known to 0.09 % [7]. Its mean life is 2.638 × 10⁻²⁵ s, at time position −18.36.

The W width has three measured values. The PDG 2024 gives 2.085 ± 0.042 GeV [7]; the PDG 2025 gives 2.14 ± 0.05 GeV [113]; ATLAS in 2024 gives 2,202 ± 47 MeV [165]. The lifetimes are 3.16, 3.08 and 2.99 × 10⁻²⁵ s, at −18.20, −18.22 and −18.25.

The top quark has “Full width Γ = 1.42+ 0.19 −0.15 GeV” [59]. Its mean life is 4.64 × 10⁻²⁵ s, between 4.1 and 5.2 × 10⁻²⁵ s across the errors, at −17.85. Its direct mass is 172.57 ± 0.29 GeV in the PDG 2024 table and 172.56 ± 0.31 GeV in the 2025 edition [59][264].

The Higgs boson has the narrowest width of the four. The PDG gives “Full width Γ = 3.7 +1.9 −1.4 MeV”, assuming equal on-shell and off-shell couplings [7]. Its mean life is 1.78×10^{-22} s, at −12.43.

CMS measured the width in 2022 through Higgs bosons produced off their mass shell [177]. “The scenario with no off-shell contribution is excluded at a p-value of 0.0003 (3.6 standard deviations)” [177]. The result is Γ_H = 3.2 +2.4/−1.7 MeV, against a Standard Model value of 4.1 MeV [177].

These give lifetimes of 2.06×10^{-22} s and 1.61×10^{-22} s, at −12.30 and −12.53. The Higgs lives 674 times longer than the Z and 384 times longer than the top quark.

The widths also differ relative to the masses. For the Z, Γ/m = 0.0274; for the W, 0.0259; for the top, 0.0082. For the Higgs it is 3.0×10^{-5}.

Particle	Mass	Γ	τ (s)	Time position	[n]
Z	91.1880 GeV	2.4955 GeV	2.638×10^{-25}	−18.36	[7]
W (ATLAS 2024)	80.3665 GeV	2.202 GeV	2.99×10^{-25}	−18.25	[165]
W (PDG 2025)	—	2.14 GeV	3.08×10^{-25}	−18.22	[113]
W (PDG 2024)	80.3692 GeV	2.085 GeV	3.16×10^{-25}	−18.20	[7]
top quark	172.57 GeV	1.42 GeV	4.64×10^{-25}	−17.85	[59]
Higgs (SM value)	—	4.1 MeV	1.61×10^{-22}	−12.53	[177]
Higgs (PDG 2024)	125.20 GeV	3.7 MeV	1.78×10^{-22}	−12.43	[7]
Higgs (CMS 2022)	—	3.2 MeV	2.06×10^{-22}	−12.30	[177]

The neutron: two methods, two lifetimes

The free neutron lives longest of all unstable particles. The PDG average is “Mean life τ = 878.4 ± 0.5 s (S = 1.8)” [69]. That is 14.6 minutes, at time position 39.32, below the hour at 40.61.

The PDG enlarges its error by the scale factor 1.8. Two methods give two values. In the bottle method, ultracold neutrons are stored and counted after a holding time; in the beam method, the protons from decays in a beam are counted.

The UCNτ experiment at LANSCE stored neutrons in a magneto-gravitational trap and counted about 38 million survivors in 2017 and 2018 [253]. It found “τn=877.75±0.28 stat+0.22/−0.16 syst s” [253]. The NIST beam experiment re-normalised its 2005 result of 886.3 ± 1.2 ± 3.2 s with a neutron-monitor efficiency measured to 0.057 % [254].

“The updated lifetime is τn = (887.7 ± 1.2 [stat] ± 1.9 [syst]) s” [254]. The difference is 887.7 − 877.75 = 9.95 s. The combined uncertainty is $\sqrt{(1.2^2 + 1.9^2 + 0.28^2 + 0.19^2)} = 2.27$ s, so the gap is 4.4 standard deviations.

Method	τ (s)	Uncertainty (s)	Time position	[n]
PDG 2024 average	878.4	0.5 (S = 1.8)	39.32	[69]
UCNτ 2021, stored	877.75	0.28 stat, +0.22/−0.16 syst	39.32	[253]
NIST beam 2013	887.7	1.2 stat, 1.9 syst	39.33	[254]
Beam 2005	886.3	1.2 stat, 3.2 syst	39.33	[254]

The neutron lives 4.0×10^8 times longer than the muon. On the ladder the gap is only 0.01 positions wide between the two methods, but the two numbers stand apart.

Bound pairs and nuclei

Positronium, an electron bound to a positron, decays in two ways. It was found by Martin Deutsch at MIT in 1951 [200]. The para state decays “preferentially into two

gamma rays with energy of 511 keV each” [200].

Its decay rate was measured as 7990.9(1.7) μs⁻¹, against a theory of 7989.50(2) μs⁻¹ [199]. The lifetimes are 125.14 ps and 125.16 ps, at time position 12.40. The four-photon branch is 1.439(2) × 10⁻⁶ [200].

The ortho state decays mainly into three photons and lives about 1135 times longer [200]. In the 1990s the experiments disagreed, as the table shows [199]. A later measurement gave 142.05 ± 0.02 ns in 2007, at 18.80 [200].

Ortho-positronium	Decay rate (μs⁻¹)	Lifetime (ns)	[n]
Theory, 1999	7.0382	142.08	[199]
London, gas	7.0450(60)	141.94	[199]
Mainz, vacuum	7.0310(70)	142.23	[199]
Ann Arbor, gas	7.0514(14)	141.82	[199]
Ann Arbor, vacuum	7.0482(16)	141.88	[199]
Tokyo, powder	7.0398(29)	142.05	[199]
Badertscher et al., 2007	—	142.05 ± 0.02	[200]

The 2S state of positronium lives 1100 ns, at 20.66 [200]. The same bound pair has three lifetimes that span a factor of 8800 between its para ground state and its 2S state.

The shortest-lived nuclei are the heavy hydrogens. NUBASE2020 gives hydrogen-5 a half-life of 86(6) ys, hydrogen-4 139(10) ys and hydrogen-7 652(558) ys [255]. Hydrogen-6 has 294(67) × 10⁻²⁴ s [255].

Nuclide	Half-life	T½ (s)	Time position	[n]
^{5}H	86(6) ys	8.6 × 10⁻²³	−13.09	[255]
^{4}H	139(10) ys	1.39 × 10⁻²²	−12.66	[255]
^{6}H	294(67) ys	2.94 × 10⁻²²	−11.98	[255]
^{7}H	652(558) ys	6.5 × 10⁻²²	−11.25	[255]
^{3}H	12.32(2) yr	3.888 × 10⁸	51.16	[255]

These nuclei sit at −13.09 to −11.25, among the wide hadron resonances and the Higgs. Tritium, at 51.16, lives 12.32 years.

The heaviest element made is oganesson. ^{294}Og was made at Dubna from californium-249 and calcium-48, “a total of three (possibly four) nuclei”, with a half-life of 0.7 ms [90]. That sits at time position 26.54.

The thorium-229 isomer of chapter 8 has two lifetimes. In a crystal its fluorescence lifetime is 630(15) s, at 39.02 [221]. For a nucleus alone in vacuum the extrapolated half-life is 1740(50) s, at 39.94 [221].

The surroundings of a nucleus change its decay. The net’s text on transmutation collects four measured cases [263]. Dysprosium-163 with all 66 electrons removed decays to holmium-163 with a half-life of 47 days (Jung and colleagues, 1992) [263].

Fully ionized rhenium-187 has a half-life of 32.9 years, against 43 × 10⁹ years for the neutral atom (Bosch and colleagues, 1996) [263]. That is a factor 1.3 × 10⁹, from time position 71.16 down to 52.05. Fully ionized thallium-205 decays to lead-205 with a half-life of 291 days (Leckenby and colleagues, 2024) [263].

Beryllium-7 inside a C_{60} cage has a half-life of 52.68 days, against 53.12 days in ordinary surroundings (Ohtsuki and colleagues, 2004) [263]. The shift is 0.83 %.

The long half-lives of the Earth’s own heat sources are listed in the net’s text on geoneutrinos [30]. Potassium-40 has 1.248 × 10⁹ years, at 67.94. Uranium-238 has 4.468 × 10⁹ years, which is 1.410 × 10¹⁷ s, at 69.10; thorium-232 has 14.05 × 10⁹ years, at 70.14.

The longest measured half-lives belong to double beta decay and double electron capture. The 2020 review of Barabash gives the averages and recommended values [256]:

Nuclide	Decay	T½ (yr)	Time position	[n]

^{100}Mo	2νββ	7.06 +0.15/−0.13 × 10^{18}	88.38	[256]
^{150}Nd	2νββ	(9.34 ± 0.65) × 10^{18}	88.63	[256]
^{96}Zr	2νββ	(2.3 ± 0.2) × 10^{19}	89.45	[256]
^{116}Cd	2νββ	(2.69 ± 0.09) × 10^{19}	89.59	[256]
^{48}Ca	2νββ	5.3 +1.2/−0.8 × 10^{19}	90.21	[256]
^{82}Se	2νββ	0.87 +0.02/−0.01 × 10^{20}	90.66	[256]
^{130}Te	2νββ	(7.91 ± 0.21) × 10^{20}	92.67	[256]
^{76}Ge	2νββ	(1.88 ± 0.08) × 10^{21}	93.46	[256]
^{238}U	2νββ, radiochemical	(2.0 ± 0.6) × 10^{21}	93.52	[256]
^{136}Xe	2νββ	(2.18 ± 0.05) × 10^{21}	93.59	[256]
^{130}Ba	2νεε	(2.2 ± 0.5) × 10^{21}	93.60	[256]
^{124}Xe	2νεε	(1.8 ± 0.5) × 10^{22}	95.52	[256][260]
^{78}Kr	2νεε	1.9 +1.3/−0.8 × 10^{22}	95.56	[256]
^{128}Te	2νββ	(2.25 ± 0.09) × 10^{24}	99.91	[256]

For barium-130 geochemical studies give 0.5 to 2.7 × 10^{21} years [261]. For krypton-78 the BAKSAN experiment gives 9.2 +5.5/−2.6 ± 1.3 × 10^{21} years [261].

In 2019 the XENON1T dark-matter detector saw xenon-124 capture two electrons at once [260]. The half-life is (1.8 ± 0.5 stat ± 0.1 sys) × 10^{22} years, at 4.4 standard deviations, “the longest half-life ever measured directly” for this process [260]. A 2022 analysis of the same detector gives (1.1 ± 0.2 ± 0.1) × 10^{22} years [261].

Tellurium-128 has the longest half-life measured, and its values disagree. Barabash recommends (2.25 ± 0.09) × 10^{24} years [256]. The IAEA value is 7.7 × 10^{24} years, “the longest half-life of all nuclides proven to be radioactive” [262]; geochemical studies give (7200 ± 400) × 10^{21} and (1800 ± 700) × 10^{21} years [261].

The highest value is 3.4 times the recommended one. The positions run from 99.71 to 101.03.

Bismuth-209 was long counted as stable. In 2003 de Marcillac and colleagues detected its alpha particles [258]. In 2012 Beeman and colleagues found “τ1/2= (2.01±0.08)·10^19 years” [257].

The alpha particle carries 3.14 MeV, and the daughter is thallium-205 [259]. The half-life is 1.46 × 10^{9} times the age of the universe and sits at 89.33.

The limit on the neutrinoless form of double beta decay extends the axis further. With 745 kg of enriched xenon and an exposure of 2.1 ton-years, KamLAND-Zen found “T1/2 0ν > 3.8 × 10^26 yr at 90% C.L.” [126]. That bound is 1.20 × 10^{34} s, at time position 104.58, and 1.7 × 10^{5} times the two-neutrino half-life of the same nuclide.

Last comes a lifetime that is calculated, not measured. From the measured masses of the top quark and the Higgs, Andreassen, Frost and Schwartz found “the first complete calculation of the lifetime of our universe: 10^139 years” [180]. At 95 % confidence it is “more than 10^58 years” [180]; the two sit at 340.20 and 170.43.

The full table

The table lists every lifetime in this chapter, shortest first. For particles it gives the mean life τ, timed directly or computed from the width as τ = ħ/Γ. For nuclei it gives the half-life T½ as published; the mean life is T½/ln 2.

Lower limits carry the sign >. The two calculated lifetimes of the vacuum state close the table. Positions are coordinates on the ladder of time, $\log_3(t / 1.520\,655 \times 10^{-16}\ \text{s})$.

τ or T½ (s)	Time position	Case	Kind	Measured as	[n]
2.638 × 10^{-25}	−18.36	Z	from width	Γ = 2.4955 GeV	[7]
2.989 × 10^{-25}	−18.25	W (ATLAS 2024)	from width	Γ = 2.202 GeV	[165]
3.076 × 10^{-25}	−18.22	W (PDG 2025)	from width	Γ = 2.14 GeV	[113]
3.157 × 10^{-25}	−18.20	W (PDG 2024)	from width	Γ = 2.085 GeV	[7]

4.635×10^{-25}	−17.85	top quark	from width	Γ = 1.42 GeV	[59]
1.406×10^{-24}	−16.84	$K^*_0(700)$	from width	Γ = 468 MeV	[92]
1.419×10^{-24}	−16.83	$f_2(1950)$	from width	Γ = 464 MeV	[92]
1.496×10^{-24}	−16.78	$f_0(2020)$	from width	Γ = 440 MeV	[92]
4.465×10^{-24}	−15.79	$\rho(770)^0$	from width	Γ = 147.4 MeV	[92]
5.626×10^{-24}	−15.58	Δ(1232)	from width	Γ = 117 MeV	[69]
1.281×10^{-23}	−14.83	K*(892)± (hadroproduced)	from width	Γ = 51.4 MeV	[92]
1.392×10^{-23}	−14.75	$K^*(892)^0$	from width	Γ = 47.3 MeV	[92]
1.425×10^{-23}	−14.73	K*(892)± (τ decays)	from width	Γ = 46.2 MeV	[92]
1.671×10^{-23}	−14.59	$\Sigma(1385)^-$	from width	Γ = 39.4 MeV	[69]
1.818×10^{-23}	−14.51	$\Sigma(1385)^+$	from width	Γ = 36.2 MeV	[69]
1.828×10^{-23}	−14.50	$\Sigma(1385)^0$	from width	Γ = 36 MeV	[69]
2.158×10^{-23}	−14.35	η_c(1S)	from width	Γ = 30.5 MeV	[101]
3.211×10^{-23}	−13.99	Υ(4S)	from width	Γ = 20.5 MeV	[249]
6.152×10^{-23}	−13.40	χ_c0(1P)	from width	Γ = 10.7 MeV	[101]
6.582×10^{-23}	−13.34	η_b(1S)	from width	Γ = 10 MeV	[249]
7.583×10^{-23}	−13.21	ω(782)	from width	Γ = 8.68 MeV	[92]
8.6×10^{-23}	−13.09	hydrogen-5	half-life	86 ys	[255]
1.242×10^{-22}	−12.76	Σ_b^-	from width	Γ = 5.3 MeV	[252]
1.316×10^{-22}	−12.71	Σ_b^+	from width	Γ = 5 MeV	[252]
1.39×10^{-22}	−12.66	hydrogen-4	half-life	139 ys	[255]
1.549×10^{-22}	−12.56	φ(1020)	from width	Γ = 4.249 MeV	[92]
1.605×10^{-22}	−12.53	Higgs (Standard Model value)	from width	Γ = 4.1 MeV	[177]
1.779×10^{-22}	−12.43	Higgs (PDG 2024 average)	from width	Γ = 3.7 MeV	[7]
2.057×10^{-22}	−12.30	Higgs (CMS 2022)	from width	Γ = 3.2 MeV	[177]
2.94×10^{-22}	−11.98	hydrogen-6	half-life	294 ys	[255]
$> 3.134 \times 10^{-22}$	> −11.92	$D^*(2007)^0$ (Γ < 2.1 MeV)	lower limit (from width bound)		[108]
3.324×10^{-22}	−11.86	χ_c2(1P)	from width	Γ = 1.98 MeV	[101]
$> 3.464 \times 10^{-22}$	> −11.83	D*_s± (Γ < 1.9 MeV)	lower limit (from width bound)		[244]
3.483×10^{-22}	−11.82	$\Sigma_c(2455)^{++}$	from width	Γ = 1.89 MeV	[250]
3.597×10^{-22}	−11.79	$\Sigma_c(2455)^0$	from width	Γ = 1.83 MeV	[250]
6.52×10^{-22}	−11.25	hydrogen-7	half-life	652 ys	[255]
7.836×10^{-22}	−11.08	χ_c1(1P)	from width	Γ = 840 keV	[101]
2.246×10^{-21}	−10.12	ψ(2S)	from width	Γ = 293 keV	[101]
3.501×10^{-21}	−9.72	η′(958)	from width	Γ = 188 keV	[92]
7.108×10^{-21}	−9.08	J/ψ(1S)	from width	Γ = 92.6 keV	[101]
7.892×10^{-21}	−8.98	D*(2010)±	from width	Γ = 83.4 keV	[108]
1.218×10^{-20}	−8.59	Υ(1S)	from width	Γ = 54.02 keV	[249]
2.058×10^{-20}	−8.11	Υ(2S)	from width	Γ = 31.98 keV	[249]
3.239×10^{-20}	−7.70	Υ(3S)	from width	Γ = 20.32 keV	[249]
7.4×10^{-20}	−6.94	Σ^0	mean life		[69]
5.025×10^{-19}	−5.20	η	from width	Γ = 1.31 keV	[92]
8.43×10^{-17}	−0.54	π^0	mean life		[92]
1.504×10^{-13}	6.28	Ξ_c^0	mean life		[250]
2.026×10^{-13}	6.55	Λ_c^+	mean life		[69]
2.56×10^{-13}	6.76	Ξ_{cc}^{++}	mean life		[251]
2.73×10^{-13}	6.82	Ω_c^0	mean life		[250]

2.903×10^{-13}	6.88	tau lepton	mean life		[35]
4.103×10^{-13}	7.19	D^0	mean life		[108]
4.53×10^{-13}	7.28	Ξ_c^+	mean life		[250]
5.012×10^{-13}	7.37	$D_s^\pm$	mean life		[244]
5.1×10^{-13}	7.39	$B_c^\pm$	mean life		[248]
1.033×10^{-12}	8.03	$D^\pm$	mean life		[108]
1.471×10^{-12}	8.35	Λ_b^0	mean life		[252]
1.48×10^{-12}	8.36	Ξ_b^0	mean life		[252]
1.517×10^{-12}	8.38	B^0	mean life		[246]
1.52×10^{-12}	8.38	B^0_s	mean life		[247]
1.572×10^{-12}	8.41	Ξ_b^-	mean life		[252]
1.638×10^{-12}	8.45	$B^\pm$	mean life		[245]
1.64×10^{-12}	8.45	Ω_b^-	mean life		[252]
8.018×10^{-11}	11.99	Σ^+	mean life		[69]
8.21×10^{-11}	12.01	Ω^-	mean life		[69]
8.954×10^{-11}	12.09	K^0_S	mean life		[92]
1.25142×10^{-10}	12.40	para-positronium (exp., 7990.9 μs^{-1})	mean life		[199]
1.25164×10^{-10}	12.40	para-positronium (theory, 7989.50 μs^{-1})	mean life		[199]
1.479×10^{-10}	12.55	Σ^-	mean life		[69]
1.639×10^{-10}	12.64	Ξ^-	mean life		[69]
2.617×10^{-10}	13.07	Λ	mean life		[69]
2.9×10^{-10}	13.16	Ξ^0	mean life		[69]
1.238×10^{-8}	16.58	$K^\pm$	mean life		[92]
2.6033×10^{-8}	17.26	$\pi^\pm$	mean life		[92]
5.116×10^{-8}	17.87	K^0_L	mean life		[92]
1.41816×10^{-7}	18.80	ortho-positronium (Ann Arbor, gas, 7.0514 μs^{-1})	mean life		[199]
1.4188×10^{-7}	18.80	ortho-positronium (Ann Arbor, vacuum, 7.0482 μs^{-1})	mean life		[199]
1.41945×10^{-7}	18.80	ortho-positronium (London, gas, 7.0450 μs^{-1})	mean life		[199]
1.42049×10^{-7}	18.80	ortho-positronium (Tokyo, powder, 7.0398 μs^{-1})	mean life		[199]
1.4205×10^{-7}	18.80	ortho-positronium (2007)	mean life		[200]
1.42082×10^{-7}	18.80	ortho-positronium (theory, 7.0382 μs^{-1})	mean life		[199]
1.42227×10^{-7}	18.80	ortho-positronium (Mainz, vacuum, 7.0310 μs^{-1})	mean life		[199]
1.1×10^{-6}	20.66	positronium 2S	mean life		[200]
2.19698×10^{-6}	21.29	muon, MuLan 2013	mean life		[45]
2.19698×10^{-6}	21.29	muon	mean life		[35]

0.0007	26.54	oganesson-294	half-life		[90]
630	39.02	thorium-229m, in crystal (fluorescence lifetime)	mean life		[221]
877.75	39.32	neutron, UCNτ 2021 (stored)	mean life		[253]
878.4	39.32	neutron (PDG 2024)	mean life		[69]
886.3	39.33	neutron, beam 2005	mean life		[254]
887.7	39.33	neutron, NIST beam 2013	mean life		[254]
1740	39.94	thorium-229m, isolated nucleus (extrapolated half-life)	half-life		[221]
$> 2.525 \times 10^{6}$	> 46.57	antiproton, LEAR bound	lower limit	29.22 days	[243]
4.0608×10^{6}	47.00	dysprosium-163, all 66 electrons removed	half-life	47 days	[263]
4.55155×10^{6}	47.11	beryllium-7 inside C_{60}	half-life	52.68 days	[263]
4.58957×10^{6}	47.12	beryllium-7, ordinary	half-life	53.12 days	[263]
$> 8.836 \times 10^{6}$	> 47.71	antiproton, Gabrielse et al. bound	lower limit	102.27 days	[243]
2.514×10^{7}	48.66	thallium-205, fully ionized	half-life	0.7967 yr	[263]
$> 3.499 \times 10^{7}$	> 48.96	antiproton, stored in a Penning trap	lower limit	> 405 days	[243]
$> 3.219 \times 10^{8}$	> 50.98	antiproton, BASE trap bound	lower limit	> 10.2 yr	[243]
3.888×10^{8}	51.16	tritium	half-life	12.32 yr	[255]
1.038×10^{9}	52.05	rhenium-187, fully ionized	half-life	32.9 yr	[263]
2.498×10^{11}	57.04	thorium-229 ground state	half-life	7916 yr	[221]
$> 1.578 \times 10^{12}$	> 58.72	antiproton, APEX bound ($\bar{p} \to \mu^{-}X$)	lower limit	$> 5 \times 10^{4}$ yr	[243]
$> 9.467 \times 10^{12}$	> 60.35	antiproton, APEX bound ($\bar{p} \to e^{-}\gamma$)	lower limit	$> 3 \times 10^{5}$ yr	[243]
$> 5.365 \times 10^{13}$	> 61.93	antiproton, cosmic-ray bound	lower limit	$> 1.7 \times 10^{6}$ yr	[243]
3.938×10^{16}	67.94	potassium-40	half-life	1.248×10^{9} yr	[30]
1.410×10^{17}	69.10	uranium-238 (α)	half-life	4.468×10^{9} yr	[30]
4.434×10^{17}	70.14	thorium-232	half-life	1.405×10^{10} yr	[30]
1.357×10^{18}	71.16	rhenium-187, neutral atom	half-life	4.3×10^{10} yr	[263]
$> 3.156 \times 10^{25}$	> 86.60	photon (massive-photon bound)	lower limit	$> 1 \times 10^{18}$ yr	[151]
2.228×10^{26}	88.38	molybdenum-100 ($2\nu\beta\beta$)	half-life	7.06×10^{18} yr	[256]
2.947×10^{26}	88.63	neodymium-150 ($2\nu\beta\beta$)	half-life	9.34×10^{18} yr	[256]
6.343×10^{26}	89.33	bismuth-209 (α)	half-life	2.01×10^{19} yr	[257]

7.258×10^{26}	89.45	zirconium-96 ($2\nu\beta\beta$)	half-life	2.3×10^{19} yr	[256]
8.489×10^{26}	89.59	cadmium-116 ($2\nu\beta\beta$)	half-life	2.69×10^{19} yr	[256]
1.673×10^{27}	90.21	calcium-48 ($2\nu\beta\beta$)	half-life	5.3×10^{19} yr	[256]
2.746×10^{27}	90.66	selenium-82 ($2\nu\beta\beta$)	half-life	8.7×10^{19} yr	[256]
2.496×10^{28}	92.67	tellurium-130 ($2\nu\beta\beta$)	half-life	7.91×10^{20} yr	[256]
5.933×10^{28}	93.46	germanium-76 ($2\nu\beta\beta$)	half-life	1.88×10^{21} yr	[256]
6.312×10^{28}	93.52	uranium-238 ($2\nu\beta\beta$, radiochemical)	half-life	2×10^{21} yr	[256]
6.880×10^{28}	93.59	xenon-136 ($2\nu\beta\beta$)	half-life	2.18×10^{21} yr	[256]
6.943×10^{28}	93.60	barium-130 ($2\nu\varepsilon\varepsilon$)	half-life	2.2×10^{21} yr	[256]
2.903×10^{29}	94.90	krypton-78 ($2\nu\varepsilon\varepsilon$, BAKSAN)	half-life	9.2×10^{21} yr	[261]
3.471×10^{29}	95.07	xenon-124 ($2\nu\varepsilon\varepsilon$, XENON1T 2022)	half-life	1.1×10^{22} yr	[261]
5.680×10^{29}	95.52	xenon-124 ($2\nu\varepsilon\varepsilon$, XENON1T 2019)	half-life	1.8×10^{22} yr	[260]
5.996×10^{29}	95.56	krypton-78 ($2\nu\varepsilon\varepsilon$, recommended)	half-life	1.9×10^{22} yr	[256]
5.680×10^{31}	99.71	tellurium-128 (geochemical, 1.8×10^{24})	half-life	1.8×10^{24} yr	[261]
7.100×10^{31}	99.91	tellurium-128 ($2\nu\beta\beta$, recommended)	half-life	2.25×10^{24} yr	[256]
2.272×10^{32}	100.97	tellurium-128 (geochemical, 7.2×10^{24})	half-life	7.2×10^{24} yr	[261]
2.430×10^{32}	101.03	tellurium-128 (IAEA)	half-life	7.7×10^{24} yr	[262]
$> 1.199 \times 10^{34}$	> 104.58	xenon-136 ($0\nu\beta\beta$, limit)	lower limit	$> 3.8 \times 10^{26}$ yr	[126]
$> 2.083 \times 10^{36}$	> 109.27	electron	lower limit	$> 6.6 \times 10^{28}$ yr	[36]
$> 2.840 \times 10^{37}$	> 111.65	proton, invisible mode	lower limit	$> 9 \times 10^{29}$ yr	[69]
$> 1.231 \times 10^{40}$	> 117.18	proton, $p \to \bar{\nu}\pi^+$ (τ/B)	lower limit	$> 3.9 \times 10^{32}$ yr	[69]
$> 2.114 \times 10^{40}$	> 117.67	proton, $p \to e^+\gamma$ (τ/B)	lower limit	$> 6.7 \times 10^{32}$ yr	[69]
$> 3.156 \times 10^{40}$	> 118.04	proton, $p \to e^+K^0$ (τ/B)	lower limit	$> 1 \times 10^{33}$ yr	[69]
$> 1.483 \times 10^{41}$	> 119.44	proton, $p \to \mu^+\eta$ (τ/B)	lower limit	$> 4.7 \times 10^{33}$ yr	[69]
$> 1.862 \times 10^{41}$	> 119.65	proton, $p \to \bar{\nu}K^+$ (τ/B)	lower limit	$> 5.9 \times 10^{33}$ yr	[69]
$> 3.156 \times 10^{41}$	> 120.13	proton, $p \to e^+\eta$ (τ/B)	lower limit	$> 1 \times 10^{34}$ yr	[69]
$> 5.049 \times 10^{41}$	> 120.56	proton, $p \to \mu^+\pi^0$ (τ/B)	lower limit	$> 1.6 \times 10^{34}$ yr	[73]
$> 7.574 \times 10^{41}$	> 120.93	proton, $p \to e^+\pi^0$ (τ/B)	lower limit	$> 2.4 \times 10^{34}$ yr	[73]
$> 1.073 \times 10^{42}$	> 121.24	proton, $p \to e^+e^+e^-$ (τ/B)	lower limit	$> 3.4 \times 10^{34}$ yr	[69]
$> 3.156 \times 10^{65}$	> 170.43	vacuum state, calculated (95 %	calculated, lower limit	$> 1 \times 10^{58}$ yr	[180]

		lower bound)			
3.156×10^{146}	340.20	vacuum state, calculated (central)	calculated	1×10^{139} yr	[180]

What this part of the history shows

The measured lifetimes of unstable particles run from 2.638×10^{-25} s for the Z to 878.4 s for the neutron. That is 27.5 orders of magnitude, or 57.68 positions on the ladder, from −18.36 to 39.32. Nuclei extend the axis to tellurium-128 near 101, and the limits on the electron and the proton reach 109.27 and 121.24.

The first form of the net is the plainest one here. The texts state it as an axiom: “A configuration persists only if it closes on itself” [26]. Three members of the record have lower bounds only, the photon, the electron and the proton; every other case has a measured end.

The lifetimes gather in groups: −18.4 to −17.9 (W, Z, top), −16.8 to −11 (wide resonances, the Higgs, the heavy hydrogens) and −10.1 to −6.9 (η′, narrow quarkonia, Σ^0). Further groups sit at −5.2 to −0.5 (η, π^0), 6.3 to 8.5 (charm and bottom, the tau) and 12 to 13.2 (hyperons, K^0_S, para-positronium). The last are 16.6 to 21.3 (K±, π±, K^0_L, positronium in its ortho and 2S states, the muon) and 39.3 (the neutron).

Wide stretches separate the groups of particles: −0.5 to 6.3, 8.5 to 12, 13.2 to 16.6 and 21.3 to 39.3. Within a group the spread is small: the bottom hadrons differ by 11 %, the six hyperons by a factor 3.6.

The carriers of the weak force are the shortest-lived of all. W and Z last 3.0 to 3.2 and 2.6×10^{-25} s, with widths of 2.6 to 2.7 % of their masses. Here the form is that of form and carrier: in the texts what does not close does not persist as a configuration, and its tension moves to the neighbouring meshes [26].

The mirror keeps the same time: the muon and the antimuon live equally long within $(2 \pm 8) \times 10^{-5}$, the two charged pions within $(6 \pm 7) \times 10^{-4}$ [198]. The neutral kaon widths agree to $(8 \pm 8) \times 10^{-18}$ of the mass [198]. In the texts of the net Q and −Q have the same address, mirrored trit-wise [27].

The texts of the net read decay as a matter of tension and surroundings. A particle decays when its tension leaves the rest zone, and the decay looks random because tension depends on the surroundings, not because the particle is undecided [31]. That is a reading, and the measured record shows its form in the nuclei whose surroundings were changed.

The same nucleus has other lifetimes in other surroundings: the thorium-229 isomer lives 630 s in a crystal and has a half-life of 1740 s alone [221]. Rhenium-187 falls from 4.3×10^{10} years as a neutral atom to 32.9 years when fully ionized, 19.11 positions [263]. In the texts this is the form of context: which elements exist in a place is a function of the state of that place [263].

The neutron shows one particle with two measured lives. Stored neutrons give 877.75 s, a beam gives 887.7 s, and the gap of 9.95 s stands at 4.4 standard deviations [253] [254].

The ladder also places the extremes of method. Mean lives are quoted down to the Σ^0 at −6.94; below that, every particle lifetime is read from a width. Above the neutron the axis is carried by nuclei and by limits.

Part II — The Earth

11. The Making of the Earth

The Earth was assembled from dust and stone in a few tens of millions of years. Its oldest solids are 4,567 million years old. Within about 30 million years of them, the Earth had its metal core.

This chapter follows that making in order. It dates the first solids, the growth of the bodies that became planets, and the parting of metal from rock. It then describes the body that resulted: its mass, its shells, its solid inner core, and the heat it still loses.

The book begins here, and so does the net. Its basics are named once in this chapter, where the history first shows them. Later chapters refer back to them.

The first solids

The oldest solids of the solar system are small inclusions rich in calcium and aluminium, the CAIs. They are found in primitive meteorites. Dated by uranium-corrected lead–lead ages, they formed 4,567.30 ± 0.16 million years ago (Ma) [265].

A single CAI from the meteorite Northwest Africa 2364 gives 4,568.2 Ma [266]. On that grain its authors placed the solar system 0.34 to 1.91 million years older than previously thought. The two determinations differ by 4,568.2 − 4,567.30 = 0.9 million years.

The process that formed the CAIs lasted about 3 million years [265]. The round melt droplets called chondrules formed between 4,567.32 ± 0.42 and 4,564.71 ± 0.30 Ma. Their formation began with the CAIs, and the dated set spans 4,567.30 − 4,564.71 = 2.59 million years [265].

Every size and every time in this book has a position on one ladder. The position is the logarithm, base 3, of a size over 4.558816×10^{-8} m, or of a time over 1.520655×10^{-16} s. One step up the ladder is a factor of three, and the positions are coordinates, given to two decimals.

On this ladder the day sits at 43.50 and the year at 48.87. An age of A years is placed as a duration of $A \times 3.15576 \times 10^{7}$ s. The first solids, $4{,}567.30 \times 10^{6} \times 3.15576 \times 10^{7}$ s = 1.4413×10^{17} s ago, stand at 69.12.

The second CAI age, 4,568.2 Ma, also stands at 69.12. The 3 million years of CAI formation stand at 62.45, the 2.59 million years of the chondrules at 62.31. The whole history of the Earth lies below 69.12.

The clocks of the early solar system count from this start. A review of the hafnium–tungsten clock fixes it at 4,567 million years [268]. A report on the Moon’s age gives the same 4,567 million years, from the decay of uranium in primitive meteorites [269].

Some grains in meteorites are older than the solar system. Presolar grains of silicon carbide, dated by neon made by cosmic rays, spent time in interstellar space before the Sun formed [267]. About 60 % have interstellar lifetimes under 3×10^{8} years, position 66.64, and at least 8 % over 10^{9} years, position 67.73.

The first solids were minerals. A count of 2008 lists about a dozen refractory minerals in the molecular clouds before the Sun [270]. It lists about 60 primary phases in chondrites, formed in the solar nebula, and about 250 minerals in unweathered meteorites, formed by alteration and differentiation on their parent bodies [270][271].

A recount of 2022 assigns each species to the stage in which its mode of origin first appears [272]. It gives 23 pre-terrestrial species before 4.57 Ga in its table, and 296 approved pre-terrestrial species in its text. It gives 86 species for the primary nebular phases of 4.567 to 4.561 Ga, and 261 for planetesimal differentiation and alteration, 4.566 to 4.550 Ga [272].

The nebular stage lasted 4.567 − 4.561 = 6 million years, position 63.08. The planetesimal stage lasted 4.566 − 4.550 = 16 million years, position 63.97. Read in the

net, each new kind of process has the form of a depth opened once and then filled with many species.

A mineral is a crystal: one arrangement of atoms, repeated through the grain. With the crystal the net appears in the history.

The net is a strand, and every crossing of the strand holds one of three values: +1, 0 or −1. Such a value is a trit.

Three trits in a row form a window. A window is closed when its three values add to zero, counted in threes. Of the 3 × 3 × 3 = 27 possible windows, 9 are closed.

Three of the nine hold one value three times: +1 +1 +1, 0 0 0 and −1 −1 −1. That is the form of a crystal. The other six hold all three values once; their content changes while the window stays closed, and that is the form of metabolism.

An open window carries tension. Only what closes, stays. The CAIs show the first kind of closure: their minerals closed 4,567 million years ago and have kept that order, and with it their lead clock, ever since.

Growth by accretion: the clock of hafnium and tungsten

The bodies that became planets grew by collision. The clock that dates their growth is ^{182}Hf, which decays to ^{182}W with a half-life of 9 million years, position 63.45 [268]. Hafnium stays in silicate rock; tungsten follows metal.

The tungsten isotopes of a mantle therefore record when metal left it. The solar system began with $^{182}Hf/^{180}Hf = (1.0 \pm 0.1) \times 10^{-4}$; the chondrite isochron gives $(1.00 \pm 0.08) \times 10^{-4}$ [268]. After 60 million years, 60 / 9 = 6.7 half-lives, the fraction left is 0.5^6.7 = 0.0098: the clock reads the first 60 million years, position 65.17.

The Earth’s silicate shell carries more ^{182}W than the chondrites. Its ε^{182}W is +1.9 ± 0.2 relative to them; the solar initial value, relative to the Earth, is −3.45 ± 0.25 [268]. In the words of the review, “The Earth has a radiogenic W-isotopic composition compared to chondrites” [268].

The clock orders the bodies by size. For the asteroid Vesta the mean time of accretion is 0.8 ± 0.8 million years, position 61.24, and the two-stage time of its core 2.6 million years, position 62.32 [268].

For Mars two meteorite sources give two values. The source of the shergottites gives a mean time of 2 (+3/−2) million years, position 62.08, and a two-stage time of 3.3 million years, position 62.53 [268]. The source of the nakhlites and chassignites gives 4 ± 1 million years, position 62.71, and 9.7 million years, position 63.51 [268].

A study of hafnium, tungsten and thorium found that Mars grew to about half its present size in two million years or less [273]. Its mantle has Hf/W = 3.51 ± 0.45, where earlier estimates ran from 2.6 to 5.0. Earlier estimates of the time of Mars’s accretion ranged from 0 to 15 million years, position 63.91 [273].

The same study names Mars a planetary embryo. Such embryos had diameters of about 1,000 to 5,000 km, positions 27.96 to 29.43 [273]. Planetesimals of about 100 km, position 25.87, were still forming among them.

For the Earth the mean time of accretion is 11 ± 1 million years, position 63.63 [268]. Most of the accumulation occurred in about 10 million years, position 63.54. Accretion ended about 30 million years after the origin of the solar system, position 64.54 [268].

The two-stage model age of the Earth’s core is 29.5 million years, position 64.53 [268]. Models that end the growth with a giant impact give two values [268]. A 9:1 mass ratio of proto-Earth and impactor gives 11.5 million years, position 63.67; a 7:3 ratio gives 13.5 million years, position 63.81.

The planetesimals of 100 km were closed bodies in their own right. They became the parts of embryos of 1,000 to 5,000 km, and embryos became the parts of the Earth; Mars stayed an embryo. That has the form of the residue becoming the alphabet: the closed form of one depth is a letter of the next closure.

The core separates

Until 2002 the hafnium–tungsten clock gave the Earth's core an age of 60 million years or more after the start of the solar system [274]. Two studies in the same issue of *Nature* revised it. Both found the core formed within the first 30 million years, position 64.54 [274][275].

The first study found core formation in Vesta, Mars and the Earth "during the first ~30 million years" [274]. The second found basaltic lava on Vesta within 3 million years, position 62.45, where Vesta's formation had earlier been placed at about 16 million years, position 63.97 [275].

The second study put the main growth of the terrestrial planets at about 10 million years [275]. It found "the bulk of metal–silicate separation in the Solar System was completed within <30 Myr" [275]. An older estimate of the terrestrial-planet timescale had been 62 million years, position 65.20 [275].

A report on the three groups at work put the Earth's core formation at roughly 10 to 30 million years after the birth of the solar system [269]. It gives the Earth's later evolution as perhaps 10 to 100 million years, after a 2004 model [269].

With the start at 4,567.3 Ma, an end of core formation 30 million years later falls at 4,567.3 − 30 = 4,537 Ma, position 69.11. By then less than a tenth of the ^{182}Hf was left: 0.5^(30/9) = 0.099.

The same parting of metal from rock appears in three bodies: Vesta, Mars and the Earth. It completed within 30 million years in all three [274]. Here the form is the same winding at every depth: one separation at the size of an asteroid, of an embryo and of a planet.

Less than 1 % of the Earth's material accreted after the Moon-forming impact [276]. The Moon formed in the same interval or soon after. The tungsten record of its birth follows in chapter 12.

The body that resulted

The Earth now has a mass of 5.9722 × 10^{24} kg [277]. A second NASA sheet gives 5.9724 × 10^{24} kg and a mean density of 5,514 kg m^{-3} [278]. Its mean radius is 6,371.000 km, position 29.65; its diameter of 12,742 km stands at 30.28.

The equatorial radius is 6,378.137 km and the polar radius 6,356.752 km [277]. The difference, 21.385 km at position 24.46, gives a flattening of 21.385 / 6,378.137 = 0.003353. The volume is 108.321 × 10^{10} km^3.

The mean density is 5,513 kg m^{-3} [277]. The check: 5.9722 × 10^{24} kg / (4/3 π (6.371 × 10^6 m)³) = 5.9722 × 10^{24} / 1.0832 × 10^{21} m^3 = 5,513 kg m^{-3}. The surface is 4π R^2 = 5.101 × 10^{14} m^2.

The mass is concentrated toward the centre. The moment of inertia factor I/MR^2 is 0.3308, where a sphere of uniform density gives 0.4 [277]. The gravity term J_2 is 1082.63 × 10^{-6}.

Mean surface gravity is 9.820 m s^{-2} and escape velocity 11.186 km s^{-1} [277]. GM is 0.39860 × 10^6 km^3 s^{-2}. The sidereal rotation takes 23.9345 h, position 43.50.

The Bond albedo is 0.294 and the mean surface temperature 288 K [277]. The atmosphere has a mass of 5.1 × 10^{18} kg.

The shells

Seismic waves fix the shells. The Preliminary Reference Earth Model (PREM) was fitted to the Earth's radius, mass and moment of inertia [279][280]. Its boundaries are these.

Depth	Boundary	Density above → below (g	Vp (km s^{-1})	Vs (km s^{-1})	Pressure (GPa)	Position of depth	Source

		cm⁻³)					
0 km	ocean surface	1.02	1.45	0	0	–	[279]
3 km	ocean floor	1.02 → 2.60	1.45 → 5.80	0 → 3.20	0	22.67	[279]
15 km	upper/lower crust	2.60 → 2.90	5.80 → 6.80	3.20 → 3.90	0.3	24.14	[279]
24.4 km	Moho	2.90 → 3.38	6.80 → 8.11	3.90 → 4.49	0.6	24.58	[279]
220 km	220 km discontinuity	3.36 → 3.44	7.99 → 8.56	4.42 → 4.64	7.1	26.58	[279]
400 km	top of transition zone	3.54 → 3.72	8.91 → 9.13	4.77 → 4.93	13.4	27.13	[279]
670 km	top of lower mantle	3.99 → 4.38	10.27 → 10.75	5.57 → 5.95	23.8	27.60	[279]
2,891 km	core–mantle boundary	5.57 → 9.90	13.72 → 8.06	7.26 → 0	135.8	28.93	[279]
5,149.5 km	inner-core boundary	12.17 → 12.76	10.36 → 11.03	0 → 3.50	329.0	29.45	[279]
6,371 km	centre	13.09	11.26	3.67	364.0	29.65	[279]

In PREM the inner core reaches 1,221.5 km from the centre, position 28.14, and the outer core 3,480.0 km, position 29.10 [280]. The central density is 13.0885 g cm⁻³ [280]. The NASA sheet gives a core radius of 3,485 km, also at 29.10 [277].

Between 2,891 and 5,149.5 km shear waves do not pass: Vs is 0, and the outer core is liquid [279]. Below 5,149.5 km they pass again, in the solid inner core.

The core reaches 3,480 / 6,371 = 54.6 % of the radius. With the NASA radius it holds (3,485 / 6,371)³ = 16.4 % of the volume. The inner core holds (1,221.5 / 6,371)³ = 0.70 %.

Crust, mantle and outer core

The crust is 5 to 70 km thick, positions 23.14 to 25.54 [281]. Oceanic crust is 5 to 10 km, continental crust 25 to 70 km and locally 50 to 80 km. The average is about 15 to 20 km, and the crust is less than one percent of the radius and of the volume [281].

The oldest ocean floor is about 200 million years old, position 66.27 [281]. Continental crust has a mean density of 2.835 g cm⁻³, from 2.66 at the top to 3.1 at the base [281].

The mantle is about 2,900 km thick, position 28.93 [282]. Its upper part runs from the Moho to 410 km, the transition zone from 410 to 660 km, and the lower mantle from 660 to 2,891 km. Its mass is 4.01 × 10²⁴ kg, which is 4.01 / 5.9722 = 67 % of the Earth’s mass [282].

The mantle fills 84 % of the volume [282]; another page gives 83.7 % [283]. Its temperature is about 500 K at the top and about 4,200 K at the core–mantle boundary [282]. The pressure there is 139 GPa in one estimate and about 136 GPa in another [282]; a third page gives about 140 GPa [283], and PREM 135.8 GPa [279].

The viscosity of the upper mantle is 10^{19} to 10^{24} Pa s [282]. Depleted mid-ocean-ridge basalt (MORB) mantle holds, by mass, 44.71 % SiO_2, 38.73 % MgO, 8.18 % FeO, 3.98 % Al_2O_3 and 3.17 % CaO [282].

The outer core is about 2,260 km thick, position 28.70 [284]. One determination puts its radius at 3,483 ± 5 km and that of the inner core at 1,220 ± 10 km. It fills 15.6 % of the Earth’s volume [283].

Its temperature at the core–mantle boundary is 4,137 to 4,300 K, and at the inner-core boundary 5,400 to 6,300 K, in a study of 2021 [284]. A study of 1998 gives 3,000 to 4,500 K for its outer region and 4,000 to 8,000 K near the inner core [284].

The liquid is 5 to 10 % less dense than pure iron would be at core conditions [284]. Besides iron it holds, by mass, about 5 % nickel and 1.7 % sulfur [284].

The other light elements are 0 to 0.26 % hydrogen, 0.2 % carbon, 0.8 to 5.3 % oxygen and 0 to 4.0 % silicon. Its mean magnetic field is about 2.5 mT.

Ring, depth and edge

The net has a second basic form, the ring. A ring of trits can close with all three values only at lengths 3, 6, 9 and so on. At depth 3 the first ring appears that stays closed while all its values change: the first living form.

At depth 6 that ring can divide into two closed rings of three, and both halves keep the parent's direction. That is the form of a single cell. These are the forms of life, and they return when the Earth and life meet, in chapter 22.

Where a living ring touches uniform surroundings, its windows stand open: tension at the edge, rest inside. That is the edge. It is the cell membrane, where the largest step of potential in the cell is found.

The Earth is not a ring of this kind. Its largest step of density stands at a boundary, not inside a shell. At the core–mantle boundary the density rises from 5.57 to 9.90 g cm^{-3}, by 4.33 g cm^{-3} and a factor 9.90 / 5.57 = 1.78 [279].

At the inner-core boundary the step is 12.76 − 12.17 = 0.59 g cm^{-3}, 4.8 % [279]. As a reading, this has the form of the edge: the steps sit where one shell meets the next, and the shells between them are graded.

The solid inner core

The inner core was found in 1936 by Inge Lehmann, who estimated its radius at 1,400 km, position 28.27 [285]. Its radius is now about 1,221 km, position 28.14 [285]. That is 1,221 / 6,371 = 19 % of the Earth's radius, and a volume of 4/3 π (1,221 km)^3 = 7.6 × 10^9 km^3.

Its mass is about 10^{23} kg, given as 1/60 or 1.7 % of the Earth [285]. The division 10^{23} / 5.9722 × 10^{24} gives 1.67 %. Its density is about 12.8 kg L^{-1} at its surface and 13.0 kg L^{-1} at the centre; the liquid just above holds about 12.1 kg L^{-1} [285].

Its pressure is 330 to 360 GPa [285]; PREM gives 329.0 GPa at its surface and 364.0 GPa at the centre [279]. The temperature at its surface is about 5,700 K. Iron at that pressure melts at 6,230 ± 500 K, 530 K above it [285].

The same iron is liquid above the boundary and solid below it. At the boundary its temperature lies below its melting point at that pressure. That is the form of context: the same rule takes other values in other surroundings.

The inner core grows by about 1 mm per year, position 9.10 [284]. That is about 80,000 t of iron per second, or 80,000 × 10^3 kg × 3.15576 × 10^7 s = 2.5 × 10^{15} kg per year [284]. The core cools by about 100 °C per billion years, after a figure of 1953 [285].

The age of the inner core

The age of the solid inner core is read in two ways. The thermal history of the core gives one set of ages; the strength of the ancient magnetic field gives another. The published ages run from about 0.5 to 3.5 billion years [285].

Estimate	Method	Age of inner core	Position	Source
Smirnov et al. 2011	palaeomagnetism	2–3.5 Ga	68.36–68.87	[285]
Labrosse 2003	thermal, with radioactivity in the core	about 2 Ga	68.36	[285]
Biggin et al. 2015	palaeointensity	1–1.5 Ga	67.73–68.10	[286]
Labrosse et al. 2001	thermal, no radioactivity in the core	1 ± 0.5 Ga	67.73	[285]
Ohta et al. 2016	resistivity of iron	less than 0.7 Ga	67.41	[287]

Labrosse 2015	thermal	less than 0.7 Ga	67.41	[285]
Driscoll & Bercovici 2014	thermal	0.65 Ga	67.34	[285]
Bono et al. 2019	palaeointensity	about 0.5 Ga	67.10	[288]
Konôpková et al. 2016	thermal conductivity of iron	less than 4.2 Ga	69.04	[285]

The palaeomagnetic study of 2015 found an increase in both the mean strength and the variability of the field between 1 and 1.5 billion years ago [286]. It read the change as the nucleation of the inner core. Earlier estimates ran “from less than half a billion to nearly two billion years ago” [286].

The experiment of 2016 measured the resistivity of iron at core conditions, at temperatures up to 4,500 K and megabar pressures [287]. The low resistivity means a high thermal conductivity, and a young inner core less than 0.7 billion years old. The same paper notes the rise in palaeointensity around 1.3 billion years ago, position 67.97 [287].

The study of 2019 measured rocks of the Sept-Îles intrusive suite, about 565 million years old, position 67.21 [288]. Their time-averaged dipole moment was about 0.7 × 10^{22} A m², more than ten times smaller than the present field. The angular dispersion was S ≈ 26°.

With 14 other sets of field directions, that study inferred a late onset of inner-core growth [288]. It states that the published onset ages “span 2 billion years”, from about 0.5 to more than 2.5 billion years ago, positions 67.10 to 68.57.

The heat that leaves

The Earth still loses the heat of its making and of its radioactive elements. A compilation of 38,347 heat-flow measurements gives 47 ± 2 TW through the surface [138]. That is 55 % more than earlier estimates, after a correction for water circulating through young ocean crust.

The mean flux is 91.6 mW m⁻²: 70.9 mW m⁻² through the continents and 105.4 mW m⁻² through the ocean floor [150]. The check: 47 × 10^{12} W / 5.101 × 10^{14} m² = 92.1 mW m⁻².

Other totals stand beside it. The geoneutrino study of 2011 uses 44.2 ± 1.0 TW [135]. A review of the core–mantle boundary gives 46 ± 3 TW, and published totals run from 43 to 49 TW [289][150].

Of that flow, 5 to 15 TW crosses the core–mantle boundary [150]. That is 5 / 46 = 11 % to 15 / 46 = 33 % of the surface flow. Estimates of this core heat flow “have generally increased by a factor of 2 to 3” [289].

The rest is shared between decay and stored heat. Published ranges give 15 to 41 TW of radiogenic heat and 12 to 30 TW of primordial heat [150]. The mantle loses 7 to 15 TW of primordial heat, and the crust contributes about 7 TW [150][134].

The four clocks of the heat

Four isotopes supply the radiogenic heat. Per kilogram of mantle they give the following [150].

Isotope	Heat per kg of mantle (W kg⁻¹)	Half-life	Position of half-life	Mean mantle concentration (kg kg⁻¹)	Source
^{232}Th	3.27 × 10^{-12}	14.0 × 10^{9} years	70.14	124 × 10^{-9}	[150]
^{238}U	2.91 × 10^{-12}	4.47 × 10^{9} years	69.10	30.8 × 10^{-9}	[150]
^{40}K	1.08 × 10^{-12}	1.25 × 10^{9} years	67.94	36.9 × 10^{-9}	[150]
^{235}U	0.125 × 10^{-12}	0.704 × 10^{9}	67.41	0.22 × 10^{-9}	[150]

		years			

A text of the net takes the age of the Earth as 4.54 billion years, position 69.11 [30]. Over that age the fraction of each isotope left is 0.5^(age / half-life). For ^{232}Th that is 0.80, for ^{238}U 0.49, for ^{40}K 0.080 and for ^{235}U 0.011.

The three main clocks stand near three neighbouring whole steps of the ladder: ^{40}K at 67.94, ^{238}U at 69.10, ^{232}Th at 70.14. The age of the Earth, 69.11, falls on the step of uranium. A text of the net says: “The clock of uranium is the clock of the planet.” [30]

Geoneutrinos

The decay of uranium and thorium sends out antineutrinos, the geoneutrinos. Large detectors catch a few of them and so weigh the radiogenic heat directly. Detection needs an energy of 1.8 MeV: the geoneutrinos of uranium and thorium reach it, those of potassium stop at 1.3 MeV [30].

KamLAND in Japan reported first in 2005 [134]. It recorded 152 antineutrino events in 749 days of live time, position 49.52, of which 4.5 to 54.2 were geoneutrinos. It set an upper limit of 60 TW on the power of uranium and thorium.

In 2011 KamLAND had 841 candidates and 106 geoneutrinos [134]. Uranium-238 and thorium-232 together gave 20.0 TW. Potassium-40 lies below detection but is known to contribute 4 TW [135].

With the 44.2 ± 1.0 TW of the total, radioactive decay “contributes about half” [135]. The sum 20.0 + 4 = 24 TW is 24 / 44.2 = 54 %. On this measurement the Earth’s primordial heat supply is not exhausted [135].

In 2013 KamLAND reported 116 (+28/−27) electron antineutrino events from ^{238}U and ^{232}Th [136]. The geoneutrino flux at Kamioka was (3.4 ± 0.8) × 10^{6} cm^{-2} s^{-1}, for a chondritic ratio of thorium to uranium. The count had risen from 4.5–54.2 events in 2005 to 116 [134][136].

Borexino in Italy reported in 2010 9.9 geoneutrinos among 15 candidates in 537 days, position 49.22 [134]. It rejected the null hypothesis at 4.2σ and excluded a georeactor above 3 TW at 95 % confidence.

In 2013 Borexino had 14.3 ± 4.4 geoneutrinos in 1,353 days, position 50.06, a mantle signal of 14.1 ± 8.1 TNU and a georeactor limit of 4.5 TW [134]. In 2015 it had 24 geoneutrinos among 77 candidates in 2,056 days, position 50.44, and a radiogenic heat of 23 to 36 TW [134].

One TNU is one event per year per 10^{32} free protons at full efficiency [134]. A flux of 1.0 × 10^{6} cm^{-2} s^{-1} equals 8.9 TNU for a thorium-to-uranium ratio of 4.0.

The full Borexino analysis of 2020 covers 3,262.74 days, position 50.86 [137]. It counts about 52.6 geoneutrinos from ^{238}U and ^{232}Th and a signal of about 47 TNU. The mantle signal is about 21 TNU, or about 24.6 TW of mantle radiogenic heat.

Borexino gives about 38 TW of radiogenic heat in all and a convective Urey ratio of about 0.78 [137]. That is 38 / 47 = 81 % of the surface flow, and the mantle share is 24.6 / 38 = 65 % of the radiogenic heat. The result stands at 2.4σ against the models with the least heat-producing elements, and a central georeactor above 2.4 TW is excluded at 95 % confidence [137].

Models of the Earth’s composition give about 10, about 20 or about 30 TW of radiogenic heat [134].

The lowest follows an enstatite-chondrite Earth (Javoy et al. 2010; O’Neill and Palme 2008). The middle follows Hart and Zindler 1986, McDonough and Sun 1995 and Palme and O’Neill 2003; the highest follows Turcotte and Schubert 2002 [134].

New detectors follow: SNO+ in Canada, 0.8 kt, and JUNO in China, 20 kt [134]. JUNO’s start is given as 2023 and as late 2025 [134].

A text of the net reports JUNO running since August 2025 [30]. It reports SNO+, about 2 km underground near Sudbury, with a first catch of about 50 geoneutrinos in

November 2025.

That text reads the three sites as three values. Japan measured low, Italy high and Canada in between: −1, +1 and 0 [30]. As a reading, −1 + 1 + 0 = 0: the three sites hold all three values and form one closed window.

The heat is carried by nuclei that do not last. Each decaying nucleus carries a share of heat outward and is gone, while the Earth’s shells keep their form. That is the form of form and carrier: the closed form persists, and the unclosed carriers decay and pass tension on.

Read in the net, the flow itself has the form of rest and discharge. Primordial heat was loaded in the making, is held in mantle and core, and is discharged at 44 to 47 TW. About half to four fifths of today’s flow is renewed by decay; the rest is the stored heat of the making.

Tides add a smaller term: the Earth loses 3.78 TW to the Moon’s orbit [290]. That is 3.78 / 47 = 8 % of the surface heat flow. Its history is the subject of chapter 12.

What this part of the history shows

The Earth’s history starts at 69.12 on the ladder, with the first solids of 4,567.30 and 4,568.2 Ma. The making of the planet took place between positions 61 and 65.

Vesta’s core stands at 62.32, half of Mars at 62.08 or less, the Earth’s mean accretion at 63.63 and its core at 64.54. The heat clocks stand at 67.94, 69.10 and 70.14.

The first form is the crystal. The CAIs closed 4,567 million years ago and still hold their order and their lead clock. Their minerals are windows that hold one value three times: what closes, stays.

The mineral counts read as a new kind of process opening once and then filling. The nebula gives 86 species in 6 million years; differentiation on the planetesimals gives 261 in 16 million years.

The bodies were built of bodies. Planetesimals of 100 km made embryos of 1,000 to 5,000 km, and embryos made the Earth. That is the form of the residue becoming the alphabet: each closed body of one depth is a letter of the next.

Metal left rock in the same way at three sizes. Vesta, Mars and the Earth separated their cores within 30 million years, and the Earth’s silicate shell carries the tungsten excess of +1.9 ε that dates it. That is the same winding at every depth.

The finished body is a set of shells, with density rising in steps from 1.02 g cm^{-3} in the ocean to 13.09 at the centre. The largest step, a factor 1.78, sits at the core–mantle boundary at 2,891 km, position 28.93. Read as the edge, the steps stand at the boundaries.

Iron is liquid in the outer core and solid in the inner core, at 329 to 364 GPa and about 5,700 K. The same matter takes another state in other surroundings: the form of context. The age of the solid part is read from 0.5 to 3.5 billion years, positions 67.10 to 68.87.

The heat shows form and carrier. Thorium, uranium and potassium decay and are spent: 80 %, 49 % and 8 % of them remain after 4.54 billion years. The shells keep their form while the carriers pass the heat outward.

The heat flow also has the form of rest and discharge. The Earth discharges 44 to 47 TW, 92 mW m^{-2} on average, and decay renews about half (KamLAND, 24 TW) to four fifths (Borexino, 38 TW) of it. The three measuring sites read low, high and between, which a text of the net reads as one closed window.

12. The Moon

The Earth did not finish its growth alone. A late collision threw out the material of the Moon. Within a few tens to about two hundred million years of the first solids, the Earth had a companion of 1.23 % of its mass.

This chapter follows the Moon from that impact to now. It gives the models of the collision, the dates of the Moon by each method, and the isotopes that tie it to the Earth. It then follows the Moon's own first crust, the rocks brought back, and the slow exchange by which the Moon recedes and the Earth's day grows longer.

The pair carries its history in two records. The rocks keep the dates of the beginning. The tides, written in corals, sediments and laser echoes, keep the length of the day through 2.5 billion years.

The collision

The Moon is thought to have formed from the debris of a giant impact on the young Earth. A model of 2001 placed that impact near the end of the Earth's formation [291]. It used an impactor smaller, and so more likely, than the earlier models, which had needed the impact when the Earth was "only about half formed".

That model conserves the angular momentum of the Earth–Moon system, which has been "nearly conserved over the past 4.5 billion years" [291]. The Moon that results is poor in iron. A model of 2004 gives a velocity at infinity below 4 km s^{-1}, a velocity at impact over 9.3 km s^{-1} and an angle of about 45° [292].

The impactor is named Theia. One estimate puts its mass at about 10 % of the Earth's, a body the size of Mars [292]. The hafnium–tungsten data fit a 9:1 mass ratio of proto-Earth to impactor; a 7:3 merger is "inconsistent with the W isotope data" [268].

Other models change the starting state. In one, the Earth before the collision spun with a day only two to three hours long, positions 41.24 to 41.61 [293]. That is near the limit of stability, about two hours per revolution.

In that model the extra angular momentum was later removed by a resonance [293]. The resonance linked the Earth's orbit around the Sun and the Moon's orbit around the Earth. A second model of the same year let two bodies, each larger than Mars, collide [292][293].

A high-energy, high-angular-momentum impact can make "a new type of planetary structure, named a synestia" [294]. In it the moonlets are "surrounded by tens of bars of bulk silicate Earth (BSE) vapor". They equilibrate with that vapour at the temperature at which silicate vaporises.

A model of 2017 makes the Moon from many impacts [295]. The Moon "could instead be the product of a succession of a variety of smaller collisions". Each collision forms a debris disk and a moonlet.

A hit-and-run or direct impact has been modelled with a Theia of up to 50 % water ice [292]. One study takes about 80 % of the disk material from the proto-Earth; another gives satellites of about 60 % proto-Earth material [292]. A titanium study finds that the models give more than 40 % of the disk from Theia [296].

The impact heated the Earth. Temperatures above 7,000 K reached about 30 % of its mass, by a model cited in a report of 2008 [269]. Mixing between the Earth and the disk followed "between a century and a millennium later", positions 53.06 to 55.16 [269].

The oldest zircon of the Earth, 4.4 billion years old, carries a record of that time [297]. Atom-probe study shows the silicate Earth was mixed before 4.4 billion years ago. That is "consistent with magma ocean formation by an early moon-forming impact" [297].

The date of the Moon

The Moon’s date depends on the clock. Published lunar ages “range from about 30 Myr to 200 Myr after Solar System formation” [298]. In positions that is 64.54 to 66.27.

The hafnium–tungsten clock gives three readings. A review of 2005 gives a two-stage time of 28.1 million years and a mean time of 9.0 ± 0.7 million years, with the Moon formed at about 30 million years [268]. A study of 2019 gives about 50 million years, position 65.01 [298].

The 2019 study notes that ^{182}Hf was “only extant for the first 60 Myr” [298]. It finds the silicate Moon has a higher Hf/W than the Earth’s silicate shell, and reads the Moon’s ^{182}W excess as decay of ^{182}Hf. A study of 2007 gave at least 60 and perhaps up to 100 million years, positions 65.17 to 65.64; earlier Hf–W studies had given about 30 to 50 million years [269].

Zircons give the lunar crust. Hafnium isotopes in Apollo 14 zircons, corrected for cosmic rays, show the crust differentiated by 4.51 Ga, position 69.10 [299]. The Moon then formed within about 60 million years of the solar system’s birth; another page gives 4.51 ± 0.01 Ga [300].

The oldest lunar zircon domains, in the Apollo 17 impact-melt breccia 72255, give a concordant uranium–lead date of 4,460 ± 31 Ma, position 69.09 [301]. Atom-probe tomography shows “the absence of nanoscale clustering of lead”. The date pushes the first preserved lunar crust back by about 40 million years and sets a minimum Moon age within 110 million years of the solar system’s start [301].

The ferroan anorthosite 60025 gives 4,360 ± 3 Ma by three clocks: ^{207}Pb–^{206}Pb, ^{147}Sm–^{143}Nd and ^{146}Sm–^{142}Nd [302]. That age implies the Moon “is either young or did not have a global magma ocean”. The editors put its solidification some 200 million years after the formation of the solar system.

Other methods add more dates. Impact heating in stony meteorites gives 4.47 Ga [292]. Other estimates are about 4.48 Ga and 4.527 ± 0.010 Ga, and simulations matched to the elements of the mantle give about 95 million years after the solar system formed [292].

Samarium–neodymium gives the lunar crust about 120 million years after the start, and lunar anorthosites 4,440 Ma [269]. A study of Mars places the Moon-forming impact 50 to 150 million years after the birth of the solar system [273].

Method	Study	Date	After the first solids (4,567.3 Ma)	Position	Source
Hf–W	review 2005	about 30 Myr after start	30 Myr	64.54	[268]
Hf–W	2019	about 50 Myr after start	50 Myr	65.01	[298]
Hf–W	2007	60–100 Myr after start	60–100 Myr	65.17–65.64	[269]
Hf–W, older studies	before 2007	30–50 Myr after start	30–50 Myr	64.54–65.01	[269]
Zircon Hf	2017	4.51 Ga	57 Myr	69.10	[299]
Simulations and mantle elements	2014	about 95 Myr after start	95 Myr	65.59	[292]
Meteorite impact heating	2015	4.47 Ga	97 Myr	69.10	[292]
Estimate	2008	about 4.48 Ga	87 Myr	69.10	[292]
Estimate	1998	4.527 ± 0.010 Ga	40 Myr	69.11	[292]
Zircon U–Pb, atom probe	2023	4,460 ± 31 Ma	107 Myr	69.09	[301]
Sm–Nd, crust	1988	about 120 Myr after start	120 Myr	65.80	[269]

Sm–Nd, anorthosites	—	4,440 Ma	127 Myr	69.09	[269]
Pb–Pb and Sm–Nd, FAN 60025	2011	4,360 ± 3 Ma	207 Myr	69.07	[302]
Hf–W–Th of Mars	2011	50–150 Myr after start	50–150 Myr	65.01–66.01	[273]

The spread runs from 30 to 207 million years after the first solids, positions 64.54 to 66.30. The Earth's core had closed by 30 million years, so the Earth's body was assembled before the Moon or as it formed.

One signature in two bodies

The Earth and the Moon carry nearly the same isotopes. In oxygen the difference $\Delta'^{17}O$ between them is -1 ± 5 ppm [303]. The material that later rained onto the Earth as a late veneer averages within about 1 ‰ of the terrestrial value.

A study of 2001 (Wiechert and others) found the oxygen ratios of the Moon essentially identical to the Earth's; a study of 2014 (Herwartz and others) found a slightly different signature [292].

In titanium the ratio $^{50}Ti/^{47}Ti$ of the Moon equals the Earth's "within about four parts per million" [296]. That is "only 1/150 of the isotopic range documented in meteorites". The authors take the proto-Earth as a significant source of lunar material.

One difference is measured. The Moon has a ^{182}W excess of 27 ± 4 ppm over the present silicate Earth [304]. Its authors read it as the effect of a late veneer added to the Earth after the giant impact.

Two bodies hold one signature in oxygen and titanium and differ only where the Earth received material afterwards. As a reading, that is the form of the pair: two closures together, made of one stock.

Where Theia went

The Earth's lower mantle holds two continent-sized anomalies, one under Africa and one under the Pacific. They extend about 1,000 km upward from the base of the mantle, position 27.96 [305]. The Pacific one is about 3,000 km across, position 28.96, and together they fill about 8 % of the mantle and 6 % of the Earth [306].

Six percent of the Earth's volume, 1.0832×10^{21} m³ × 0.06, is 6.5×10^{19} m³. The two bodies are named Tuzo and Jason, and may be over a billion years old [306].

A model of 2023 proposes them as remnants of Theia [307]. Theia's mantle material would be "intrinsically 2.0–3.5% denser than proto-Earth's mantle". After the impact it would form "dense TMM blobs with a size of tens of kilometres"; 10 km stands at 23.77.

Tidal tomography measures the density directly. The bottom two-thirds of the two provinces are about 0.5 % denser than the average mantle [305]. The model asks 2.0 to 3.5 %; the tidal measurement gives 0.5 % [305][307].

The magma ocean and the first lunar crust

The young Moon was covered by a magma ocean. Models give it a typical initial depth of 1,000 km, position 27.96, and a basal temperature of 1,900 K [300]. Estimates of the initial depth run from 100 km, position 25.87, to the whole radius of the Moon.

The modelled initial ocean held 47.1 % SiO_2, 33.1 % MgO, 12.0 % FeO, 4.0 % Al_2O_3 and 3.0 % CaO [300].

How long it lasted depends on when it began [300]. If it formed 52 million years after the CAIs, position 65.04, it lasted about 155 million years, position 66.04. If it formed 152 million years after them, position 66.02, it lasted about 55 million years, position 65.09.

The anorthosites give a spread of ages. FAN 67016 gives 4.56 ± 0.07 Ga by Sm–Nd, position 69.11; FAN 62236 gives 4.29 ± 0.06 Ga, position 69.06 [300]. The difference of 270 million years, position 66.54, is tied to large errors and to resetting by impacts.

One precise point anchors the crust: FAN 60025 at 4,360 ± 3 Ma [302]. The oldest lunar zircon, 4,460 ± 31 Ma, is 100 million years older [301]. Zircon hafnium places the crust's differentiation by 4.51 Ga [299].

The last liquid of the magma ocean is called KREEP: potassium (K), rare-earth elements (REE) and phosphorus (P) [308]. It forms after the solidification of the ocean "was about 75% complete". It is concentrated beneath Oceanus Procellarum and Mare Imbrium, as mapped by the gamma-ray spectrometer of Lunar Prospector.

Typical KREEP holds 20 to 25 ppm of rubidium and about 1 % by mass of potassium and phosphorus oxides [308]. Its lanthanum is 300 to 350 times that of carbonaceous chondrites. Its model age, ur-KREEP, is 4.368 ± 0.029 Ga, position 69.08 [300].

The ur-KREEP age and FAN 60025 agree within their errors: 4,368 ± 29 and 4,360 ± 3 Ma. The crust and the last liquid closed together.

KREEP is the last liquid, left after the crystals of the crust had formed. As a reading, it has the form of the residue becoming the alphabet: the remainder of one closure, rich in potassium, rare-earth elements and phosphorus.

What came back

The six Apollo landings of 1969 to 1972 returned 381 kg in 2,200 samples, now catalogued as more than 110,000 pieces [309]. By mission: Apollo 11 21.55 kg, 12 34.30 kg, 14 42.80 kg, 15 76.70 kg, 16 95.20 kg and 17 110.40 kg. The six sum to 380.95 kg.

Three Soviet Luna probes returned 101 g (Luna 16), 30 g (Luna 20) and 170 g (Luna 24), 301 g in all [309]. The Apollo mass is 381 / 0.301 = 1,266 times larger. Chang'e 5 returned about 1,731 g in 2020 and Chang'e 6 1,935.3 g in 2024, together 3.67 kg [309].

More than 370 lunar meteorites are known, with a total of over 1,090 kg [309]. With the returned samples, 381 + 0.301 + 3.67 = 385 kg of lunar rock has been brought back by missions.

The collection spans the Moon's history [309]. Highland rocks reach about 4.44 billion years, position 69.09, and ferroan anorthosites about 4.4 Ga. Mare basalts are given as about 3.16 billion years, position 68.78; the youngest basalts, about 1.2 Ga by crater counts, position 67.90, are unsampled.

The pair now

The Moon has a mass of 0.07346×10^{24} kg and a mean radius of 1,737.4 km, position 28.46 [278]. Its equatorial radius is 1,738.1 km and its polar radius 1,736.0 km. Its mean density is 3,344 kg m^{-3}.

The check: 0.07346×10^{24} kg / (4/3 π $(1.7374 \times 10^{6}$ m$)^3$) = 3,344 kg m^{-3}. The Moon's mass is 0.07346 / 5.9724 = 0.01230 of the Earth's [278]. Its density is 3,344 / 5,513 = 0.61 of the Earth's, and its radius 1,737.4 / 6,371 = 0.273.

Its moment of inertia factor is 0.394, close to a uniform sphere [278]. Surface gravity is 1.62 m s^{-2} and escape velocity 2.38 km s^{-1}. Its atmosphere weighs about 25,000 kg, and the equator ranges from 95 to 390 K between night and day.

The semimajor axis of the orbit is 384,400 km, position 33.38, or 384,400 / 6,371 = 60.3 Earth radii [278]. The perigee is 363,300 km, position 33.33, and the apogee 405,500 km, position 33.43. The eccentricity is 0.0549 and the inclination to the ecliptic 5.145°.

The sidereal month is 27.3217 days, position 46.51; the synodic month 29.53 days, position 46.58 [278]. The two differ by 29.53 − 27.3217 = 2.21 days.

Tides

The Moon raises the main tide of the oceans. Its M2 period is about 12 h 25.2 min, 44,712 s, position 42.90 [310]. The lunar day is about 24 h 50 min, position 43.53.

The solar tidal force is 46 % of the lunar [310]. The two beat: about seven days pass between spring and neap tides, position 45.27. The open-ocean lunar amplitude is about 54 cm, position 14.83, and the open-ocean range is under 1 m [310][311].

On some coasts the range exceeds 10 m, position 17.48 [311]. In the Bay of Fundy and Ungava Bay it reaches up to 16 m; the maximum measured in the Bay of Fundy is 16.3 m, position 17.93 [310].

The tides dissipate about 3.75 TW in all [310]. Altimetry from the Topex/Poseidon satellite mapped about 10^{12} W, 1 TW, of that in the deep ocean, “25–30% of the total dissipation” [312]. The implied total is 1 / 0.30 to 1 / 0.25 = 3.3 to 4.0 TW.

The Moon recedes, the day lengthens

The tides take energy from the Earth’s rotation and give it to the Moon’s orbit. The Earth loses 3.78 TW to the Moon’s orbit [290]. Tidal friction accounts for about 3.64 TW of that, and about 0.121 TW reaches the Moon.

Lasers measure the exchange. The first laser returns from the lunar surface came in 1962 [313]. The first ranging to a retroreflector was reported on 1 August 1969, with the 3.1 m telescope at Lick, position 16.42.

Retroreflectors stand at the Apollo 11, 14 and 15 sites and on Lunokhod 1 and 2 [313]. A sixth was placed by Chandrayaan-3 in August 2023. The APOLLO station ranges with an accuracy of 1.1 mm, position 9.19.

Lunar laser ranging gives a semimajor-axis rate of 38.30 ± 0.08 mm per year, position 12.42 [314]. The mean motion changes by −25.97 ± 0.05″ per century², and the eccentricity by (1.50 ± 0.10) × 10^{-11} per year. The NASA sheet rounds the recession to 3.8 cm per year; another analysis gives about 3.82 cm per year [278][315].

The same ranging gives the tidal deceleration of the Earth’s rotation as −1,316″ per century² [314]. That is 87.5 s per century² in UT1 − AT, and “a 2.395 ms/cent increase in the length of day”, position 27.66 for 2.395 ms. Tidal-dissipation models and the ranging agree to within 1 %.

The ranging also bounds the constant of gravitation [313]. The rate of change Ġ/G is (2 ± 7) × 10^{-13} per year.

At the present rate, 3.8 cm per year over 4.5 billion years would give 0.038 m × 4.5 × 10^{9} = 1.7 × 10^{5} km, position 32.64 [310]. The present distance is 384,400 km.

The record of eclipses

Ancient eclipses give the day’s growth over historical time. Over 2,700 years, position 56.06, the day has lengthened by +1.72 ± 0.03 ms per century, position 27.36 [290]. The tidal change of the Moon’s orbit alone gives +2.4 ms per century.

A study of eclipses from 720 BC to AD 2015 gives +1.8 ms per century, against +2.3 ms per century from tidal friction [316]. The difference, 2.3 − 1.8 = 0.5 ms per century, is non-tidal. With the other pair of numbers it is 2.4 − 1.72 = 0.68 ms per century.

On the same record, fluctuations of 2 to 30 years follow a power law with exponent −1.3, “with evidence of increased power at a period of 6 years” [316]. There is “some indication of an oscillation in lod with a period of roughly 1500 years”, position 55.53.

The day’s shorter rhythms

A study of 2013 found “a 5.9-year period oscillation” in the length of day, position 50.49 [317]. Its jumps are “contemporaneous with geomagnetic jerks”.

A second signal has about 60 years, position 52.60 [318]. The geomagnetic declination at ten observatories shows a period of about 62 ± 3 years, and the inclination at five observatories 58 ± 5 years; the correlation is about 0.6.

The length of day also varies with the seasons [319]. The annual term has an amplitude of 0.34 ms, peaking about 3 February; the semiannual term 0.29 ms, peaking about 8 May. Ten-day fluctuations are of the order of 0.1 ms, and the coupling time of core and mantle is about ten years.

Single events change the day by microseconds [320]. The 2004 Indian Ocean earthquake shortened it by 3 µs; the Three Gorges Dam lengthened it by 0.06 µs. In 2022 one day was completed in 1.59 ms under 24 hours.

About every 25 to 30 years the rotation slows by a few milliseconds per day for a time [320]. The modern day is about 1.7 ms longer than a century ago. The mean solar day is “about 0 to 2 ms longer than 86,400 SI seconds”.

The half step

The day stands at 43.50 on the ladder. A text of the net reads it as lying exactly between two whole steps, and finds two lunar cycles at the same half step [29]. The beat of the two lunar months, 2,190.35 days, stands at 50.50; the Saros eclipse cycle, 6,585.32 days, at 51.50.

Their residues from whole powers of three days are small. The beat is 2,190.35 / 3^{7} = 2,190.35 / 2,187 = 1.0015 of its power; the Saros is 6,585.32 / 3^{8} = 6,585.32 / 6,561 = 1.0037 [29].

The same text derives the beat from two motions of the lunar orbit [29]. The line of apsides turns in 8.85 years, position 50.86; the line of nodes in 18.61 years, position 51.53. Then 1/8.85 + 1/18.61 = 0.1667 per year, a period of 6.00 years, position 50.50.

The length of day carries its oscillation of 5.9 years, position 50.49, with jumps at the geomagnetic jerks of the core [317]. The text sets the two side by side: “Core and Moon share one clock.” [29] As a reading, the core’s rhythm and the Moon’s beat stand 0.01 apart on the ladder.

The beat is 0.15 % from its power of three, the Saros 0.37 %. As a reading, that is the form of the remainder: no closure is ever exact, and each depth leaves a remainder.

The days of the past

Growth bands and tidal layers count the days of past years. With the length of the year held fixed, more days per year mean shorter days. A day length then follows as 365.25 × 24 h divided by the days per year.

Corals lay down daily growth lines within yearly bands. Middle Devonian corals of the Centerfield Limestone, New York (*Heliophyllum*, *Eridophyllum*, *Favosites*), average “~400 lines per annulation” [321]. Living corals give about 360; the Carboniferous coral *Lophophyllidium* gives 390 per year.

A Devonian year of 400 days against 365 now gives a day of 365.25 × 24 / 400 = 21.9 h, position 43.42 [322][321]. The Carboniferous count of 390 gives 22.5 h, position 43.44. The coral study that opened this record dates from 1963 [323].

A rudist shell of the Late Cretaceous, about 70 million years old, position 65.31, records 372 days per year [290]. Its authors give a day of about 23.5 h, position 43.48; the division 365.25 × 24 / 372 gives 23.6 h.

Tidal rhythmites are sediments laid down tide by tide. Rhythmites of South Australia, about 620 million years old, position 67.30, record about 13.1 synodic months and about 400 solar days per year [315]. The day was about 21.9 h, and the Earth–Moon distance about 0.965 of today’s.

The errors are 13.1 ± 0.1 synodic months, 400 ± 7 days and 21.9 ± 0.4 h [290]. The distance is 0.965 × 384,400 = 370,900 km, position 33.35.

A banded iron formation of about 2,450 Ma, position 68.55, records about 14.5 synodic months per year [315]. Its Earth–Moon distance is about 0.906 of today's: 0.906 × 384,400 = 348,300 km, position 33.29.

The mean recession since 620 Ma is about 2.17 cm per year, "a little over half" the present 3.82 cm per year [315]. From 2,450 to 620 Ma it was about 1.24 cm per year. The check: (384,400 − 370,900) km over 620 million years is 2.18 cm per year.

Cycles of the orbit, read in a sequence of rhythmites of about 1.4 Ga, position 68.04, give the Earth–Moon distance directly [324]. The precession constant was 85.79 ± 2.72″ per year, the distance 340,900 ± 2,600 km, position 33.27, and the day 18.68 ± 0.25 h, position 43.27. The method was checked against the Eocene at about 55 Ma, and it shows reduced tidal dissipation in the Proterozoic.

The distance at 1.4 Ga is 340,900 / 384,400 = 0.887 of today's.

Averaged over 620 million years, the day lengthened by (24 − 21.9) h, or 1.22 ms per century. Averaged over 1.4 billion years it lengthened by (24 − 18.68) h, or 1.37 ms per century. Today's rates are 2.395 ms per century by ranging and 1.72 by eclipses.

A compilation of 2023 finds that the day "stalled at about 19 h for about 1 billion years during the mid-Proterozoic", position 43.29 for 19 h and 67.73 for a billion years [325]. It attributes the stall to a tidal resonance.

Epoch	Record	Days per year	Day	Position of day	Earth–Moon distance	Source
Now	—	365.24	24.0000 h	43.50	384,400 km (33.38)	[278]
about 70 Ma	rudist bands	372	about 23.5 h	43.48	—	[290]
Carboniferous	coral bands	390	22.5 h (computed)	43.44	—	[321]
Middle Devonian	coral bands	about 400	21.9 h (computed)	43.42	—	[321]
about 620 Ma	tidal rhythmites	400 ± 7	21.9 ± 0.4 h	43.42	0.965 of now, 370,900 km (33.35)	[315]
about 1.4 Ga	cyclostratigraphy	—	18.68 ± 0.25 h	43.27	340,900 ± 2,600 km (33.27)	[324]
mid-Proterozoic	compilation	—	about 19 h for about 1 Gyr	43.29	—	[325]
about 2,450 Ma	banded iron formation	14.5 synodic months	—	—	0.906 of now, 348,300 km (33.29)	[315]
before the impact	model	—	2–3 h	41.24–41.61	—	[293]

From the model's 2 to 3 hours before the impact to 24 hours now, the day has risen from position 41.24–41.61 to 43.50. The Moon has moved out from 340,900 km at 1.4 Ga to 384,400 km now.

The orbit and the day keep their form while energy passes between them. Spin gives 3.78 TW to the orbit; the day lengthens and the orbit widens. Read in the net, that has the form of form and carrier: the closures hold, and what does not close carries the tension from one to the next.

The angular momentum of the pair laid down at the impact has been nearly conserved for 4.5 billion years [291]. As a reading, that is the form of one direction: the net keeps the direction of what was laid down first.

For about a billion years the day held at 19 h, and by 620 Ma it had reached 21.9 h. As a reading, the form here is holding: the exchange stood still for a billion years, then went on.

What this part of the history shows

The Moon’s birth is dated from 30 to 207 million years after the first solids, positions 64.54 to 66.30. Each clock gives its own date: Hf–W 30, 50 and 60–100 million years; zircon 4.51 and 4.46 Ga; the anorthosite 4.36 Ga. The Earth’s core had closed by 30 million years.

The Earth and the Moon share one signature. Oxygen differs by −1 ± 5 ppm and titanium by less than 4 ppm, 1/150 of the meteorite spread. Only tungsten differs, by 27 ± 4 ppm, where the Earth received a late veneer; read in the net, that is the form of the pair, two closures together of one stock.

The Moon’s first crust shows the crystal and its residue. Anorthosite closed at 4,360 ± 3 Ma; the last liquid, KREEP, closed at 4,368 ± 29 Ma and holds lanthanum at 300 to 350 times the chondrites. As a reading, the form is the residue becoming the alphabet.

The pair’s angular momentum has been nearly conserved for 4.5 billion years. What the impact laid down is kept. That is the form of one direction.

The tides carry energy from spin to orbit: 3.78 TW, of which 0.121 TW reaches the Moon. The orbit widens by 38.30 mm per year and the day grows by 2.395 ms per century. Orbit and day keep their form while the energy passes through them: form and carrier.

The day of the past is written in corals, shells and tidal layers. It grows from 18.68 h at 1.4 Ga to 21.9 h at 620 Ma, 22.5 h in the Carboniferous, 23.5 h at 70 Ma and 24 h now, positions 43.27 to 43.50. A plateau near 19 h for a billion years has the form of holding.

The day stands at the half step 43.50, and the lunar beat and the Saros at 50.50 and 51.50. The length of day oscillates with 5.9 years, the lunar beat with 6.00, positions 50.49 and 50.50. The beat lies 0.15 % and the Saros 0.37 % off its whole power of three: read in the net, no closure is exact.

13. The First Crust

The first 500 million years of the Earth left almost no rock. They left crystals. Single grains of zircon, eroded from vanished crust and caught in later sediments, carry the record of the Hadean Earth.

This chapter follows the first crust from those grains to the continents. It gives the oldest crystal and the first trace of water, the bombardment that struck the Earth and the Moon, and the oldest surviving rocks. It ends with the growth of the continental crust, measured in several ways that do not agree.

The crust is the outer shell of the Earth, the boundary between the solid planet and its water and air. What follows is the history of how that boundary formed and how much of it has lasted.

The oldest crystal

In the Jack Hills of the Yilgarn Craton, Western Australia, one detrital zircon is 4,404 ± 8 million years old, position 69.08 [326]. The Jack Hills lie about 800 km north of Perth, position 27.76 [327]. Earlier Yilgarn zircons reached about 4,276 million years, position 69.06 [326].

The grain is held in a metamorphosed conglomerate of about 3.0 Ga, position 68.73 [327]. The crystal is 1.4 billion years older than the rock that holds it. Elsewhere in the Narryer Gneiss terrane, zircons as old as 4.3 billion years are reported [281].

From the first solids at 4,567.3 Ma to the zircon is 4,567.3 − 4,404 = 163 million years, position 66.08. From the end of core formation, about 4,537 Ma, it is 133 million years, position 65.90. The oldest lunar zircon, 4,460 ± 31 Ma, is 56 million years older than the oldest terrestrial one [301].

A second Hadean zircon was dated at the scale of atoms [297]. In that 4.4-billion-year-old grain, atom-probe tomography found clusters rich in lead, about 10 nm across, position −1.38, spaced 10 to 50 nm apart, positions −1.38 to 0.08. They confirm an age of 4.4 billion years.

That grain carries a high-temperature overgrowth formed about 1 billion years after its core, position 67.73 [297]. Its clusters show the silicate Earth was mixed before 4.4 billion years ago. That is “consistent with magma ocean formation by an early moon-forming impact” [297].

The grains record the temperature of their melts. Titanium in Hadean zircons of the Jack Hills gives crystallisation temperatures clustered near 700 °C, as for zircon growing in modern granites [328]. The authors read wet minimum melting within 200 million years of the solar system’s formation, position 66.27, and crust formation, erosion and sediment recycling by 4.35 Ga, position 69.07.

A study of inclusions in more than 400 Hadean zircons used grains of 4.02 to 4.19 billion years, positions 69.00 to 69.04 [329]. They formed at “about 700 °C and 7 kbar”. The near-surface heat flow they record is about 75 mW m^{-2}, “about three to five times lower than estimates of Hadean global heat flow”.

The magmas formed “largely in an underthrust environment”, “perhaps similar to modern convergent margins” [329]. Today’s mean heat flow is 91.6 mW m^{-2} [150]. The Hadean grains record 75 / 91.6 = 0.82 of it.

A zircon is a crystal: one arrangement repeated through the grain, the window that holds one value three times. The Jack Hills grain has held its order, its lead and its oxygen for 4,404 million years. Only what closes, stays.

The first water

The zircon's oxygen records the water of its time. The ratio of heavy to light oxygen, $\delta^{18}O$, is zoned from 7.4 ‰ to 5.0 ‰ across the 4,404-million-year grain [326]. The melt it grew from carried 8.5 to 9.5 ‰.

On these values the grain is read as "the earliest evidence for continental crust and oceans on the Earth" [326]. The oldest parts of the Acasta Gneiss, at 4,030 million years, position 69.00, are 374 million years younger.

A second study analysed Jack Hills zircons of 3,910 to 4,280 million years, positions 68.97 to 69.06 [330]. Their $\delta^{18}O$ runs from 5.4 ± 0.6 ‰ to 15.0 ± 0.4 ‰. The authors read "a hydrosphere interacting with the crust by 4,300 Myr ago", position 69.06.

From the zircon at 4,404 Ma to the hydrosphere at 4,300 Ma is 104 million years, position 65.67. From the first solids to the first recorded water is 4,567.3 − 4,300 = 267 million years, position 66.53. Liquid water touched the crust within the first 6 % of the Earth's history.

A zircon of 4.10 ± 0.01 Ga, position 69.02, was found among more than 10,000 detrital zircons of the Jack Hills [331]. It holds inclusions of graphite with $\delta^{13}C$ of −24 ± 5 ‰. Its authors describe this carbon as potentially biogenic.

The Hadean zircons also carry magnetic minerals. One reading finds field strengths "between 1.0 and 0.12 times" recent equatorial values in zircons of 3.3 to 4.2 Ga [332]. A second study by the same group finds primary magnetite and "a period of high geomagnetic field strength at 4.1 to 4.0 billion years ago (Ga)" [333].

A third study finds the magnetic carriers in these zircons secondary, formed after the zircons [334]. On that reading "the existence of the geodynamo before 3.5 Ga ago remains unknown". Two readings of the same grains stand; chapter 16 follows the field.

The minerals of the Hadean crust

The first crust added new kinds of minerals. A count of 2008 gives 350 to 420 species for the stage of 4.55 to 4.0 Ga, with "over 100 more that were rare" in the Hadean [271]. Granitoids and pegmatites of 4.0 to 3.5 Ga raised the count to about 1,000.

A recount of 2022 assigns 400 species to the mode of the earliest Hadean crust, before 4.50 Ga, position 69.10 [272]. It assigns 350 to the earliest hydrosphere, before 4.45 Ga, position 69.09. The earliest continental crust, 4.4 to 3.0 Ga, opened modes with 2,385 species.

The same paper finds that "Much of Earth's mineral diversity was established within the first 250 million years" [272]. That is position 66.47. As a reading, a new kind of crust opened once, and its mineral stage then filled with hundreds of species: opened once, filled many times.

The bombardment

While the first crust formed, impacts struck the Earth and the Moon. The Moon keeps the record, because its surface has not been renewed. Three readings of that record stand.

A spike at 3.9 Ga

In 1974 isotopic ages of lunar rocks were read as evidence of a "terminal lunar cataclysm" [335]. A review of 2017 defines that cataclysm as a pulse at 3.9 ± 0.1 Ga, position 68.97 [336]. The ages of impact-melt rocks cluster "between 3.75 and 3.95 Ga", positions 68.94 to 68.98.

A model of 2005 places a cataclysmic spike "~700 million years after the planets formed" [337]. In that model it follows a rapid migration of the giant planets after a quiet period. From the first solids that gives 4,567.3 − 700 = 3,867 Ma, position 68.96.

A model of the Earth's crust under such a bombardment set the window at 4.1 to 3.8

Ga, positions 69.02 to 68.95 [338]. It asked whether the impacts could sterilise the Earth, and found “no plausible situation in which the habitable zone was fully sterilized on Earth”.

In its extreme case the model delivered 100 times the mass, and the crust still stayed habitable to a depth of 4 km, position 22.94 [338].

A wave from 4.2 to 3.5 Ga

The review of 2017 excludes the strong form of the cataclysm [336]. That form had “all of the lunar basins formed within a brief interval (≤200 Ma)”, position 66.27. A cataclysm would need “at least 15 of the major nearside lunar basins (diameter D > 300 km)”, position 26.87, within about 100 to 200 million years.

The review reads an elevated flux “between ~3.5 and ~4.0–4.2 Ga”, positions 68.87 to 69.04 [336]. Before it lay “relative quiescence between ~4.0–4.2 and ~4.4 Ga”. Impact spherules continue to “~2.0–2.5 Ga”, positions 68.36 to 68.57.

Clasts in lunar meteorites give “the oldest apparent ages ~4.2 Ga, a peak at ~3.7 Ga, and a declining number of ages to ~2.5 Ga” [336]. One clast from the Descartes highlands records an event at 4.22 ± 0.01 Ga, position 69.04.

The Moon has “At least 40 and possibly up to 90 lunar basins” [336]. Only a few are dated, and with spread:

Basin	Age	Position	Note	Source
Imbrium	3.91–3.94 Ga	68.97–68.98	627–657 Myr after the first solids	[336]
Orientale	about 3.7 to 3.9 Ga	68.92–68.97	—	[336]
Nectaris	3.92 Ga (1981) or 4.25 ± 0.05 Ga (1974)	68.98 or 69.05	two dates 330 Myr apart	[336]
Serenitatis	20–40 Myr older than Imbrium	—	older work, uncertain	[336]

The two Nectaris dates differ by 4,250 − 3,920 = 330 million years, position 66.72. Of all the basins, only Imbrium has a tight age.

The model of the giant planets offers two timings [336]. The delay of their instability runs from “several tens of millions of years” to “many hundreds of millions”. A sawtooth model has a second wave at 4.1 Ga, and a hybrid late instability falls at about 4.0 Ga to perhaps 4.2 Ga.

The ratio of the impact flux on Mars to that on the Moon is “1, 2.8, or 5.3” by method [336]. The Earth received about 20 times the Moon’s impacts. The review estimates “70–80 craters with D > 150 km”, position 26.23, formed on the Earth between 1.7 and 3.7 Ga, positions 68.22 to 68.92, and “nearly 40 such colossal events”.

A smooth decline

The third reading denies the spike. Argon ages of lunar rocks can be partly reset by later heating, and partial loss of argon biases the dates [339]. Modelled argon loss turns a smoothly declining history of impacts into an apparent peak near 3.9 Ga.

Three readings of one record stand side by side. One has a spike at 3.9 ± 0.1 Ga, one a wave between about 4.2 and 3.5 Ga after a quiet time from 4.4 Ga, one a smooth decline. The oldest zircon (4,404 Ma) and the first recorded water (4,300 Ma) are 400 to 500 million years older than the claimed spike.

In the middle reading a quiet interval from about 4.4 to 4.2–4.0 Ga is followed by an elevated flux to about 3.5 Ga and a tail to 2.0–2.5 Ga. As a reading, that has the form of rest and discharge: the quiet interval is the rest, the elevated flux the discharge.

The oldest rocks

Acasta

The oldest rocks dated by zircon lie in the Acasta Gneiss Complex of the Slave Craton, Northwest Territories, Canada. Its orthogneisses are “Priscoan (4.00–4.03 Ga)”, position 69.00 [340]. The complex lies about 300 km north of Yellowknife, position 26.87 [341].

The Idiwhaa tonalitic gneiss is “exceptionally well-preserved, 4.02-billion-year-old” crust [342]. It formed by a process unlike that of “typical 3.9- to 2.5-billion-year-old Archaean rocks”, in an “Iceland-like setting”. The study’s summary gives 4.03 Ga.

The complex records a long history after its first rocks [341]. Gneisses of 3.96 Ga, position 68.99, were reported in 1989, and polyphase rocks of about 3,920 Ma in 2014. Thermal events followed at 3.85–3.72 Ga and 3.66–3.59 Ga, and intrusions at 3.30, 2.88 and 2.70 Ga, positions 68.82, 68.70 and 68.64.

The complex covers about 13,000 km², of which about 50 km² is mapped in detail [341]. The oldest Acasta rock, 4.03 Ga, is 4,404 − 4,030 = 374 million years younger than the oldest zircon, position 66.84.

Nuvvuagittuq

The Nuvvuagittuq Greenstone Belt lies on the coast of Hudson Bay, Quebec. Its area is approximately 20 km² [343]. Two clocks give it two ages.

The ^{146}Sm–^{142}Nd isochron of a mafic amphibolite unit gives 4,280 (+53/−81) Ma, position 69.06 [344]. Its ε^{142}Nd runs from −0.07 to −0.15 relative to the terrestrial standard. On this clock the belt was proposed as “the oldest preserved crustal section on Earth”.

^{146}Sm is an extinct isotope. Further Sm–Nd work gives 4,321 Ma for intruding gabbros, and the same page prints about 4,388 Ma [343]. An estimated crystallisation age of 4.313 Ga follows from Sm–Nd as well [341].

Zircons give younger ages. Granites that cut the belt give 3,750 Ma by U–Pb zircon, a minimum, position 68.94 [343]. Detrital zircons in a quartz–biotite schist give a maximum of 3,780 Ma; felsic bands are older than 3.768 Ga [343][341].

On the zircon reading the Hadean Sm–Nd age “reflects isotope ratios inherited from Hadean crust” [343]. A gabbroic dike gives 4,157 Ma, position 69.03.

The jaspilite that hosts putative microfossils gives “A Neoarchean (ca. 2500 Ma) age”, position 68.57 [343].

The microfossils themselves were dated “at least 3,770 million and possibly 4,280 million years old” [345]. The two clocks of the belt differ by 4,280 − 3,780 = 500 million years, position 67.10.

Isua and Akilia

In West Greenland the Isua belt holds pillow basalts of about 3.8 Ga that indicate water, position 68.95 [276]. Its banded iron formations are 3,700 to 3,800 Ma [346]. An Isua iron formation of about 3,800 Ma holds isotopically light carbonaceous inclusions, and rocks of Akilia may be older than 3,850 Ma [347].

Isua may also hold the field of its time. A “3.7-billion-year (Ga) old magnetic field may be preserved”, with a strength above 15 μT [348]. The constraint comes from intrusions of 3.26 to 3.5 Ga and folding at 3.6 Ga, positions 68.81 to 68.87 and 68.90.

Body	Region	Age	Method	Position	Source
Jack Hills zircon	Yilgarn, Western Australia	4,404 ± 8 Ma	U–Pb zircon	69.08	[326]
Nuvvuagittuq gabbro	Quebec	about 4,388 Ma	Sm–Nd	69.08	[343]
Nuvvuagittuq gabbro	Quebec	4,321 Ma	Sm–Nd	69.07	[343]
Nuvvuagittuq	Quebec	4.313 Ga	Sm–Nd	69.06	[341]

Narryer zircon	Western Australia	as great as 4.3 Ga	U–Pb	69.06	[281]
Nuvvuagittuq mafic unit	Quebec	4,280 (+53/−81) Ma	^{146}Sm–^{142}Nd	69.06	[344]
Nuvvuagittuq dike	Quebec	4,157 Ma	—	69.03	[343]
Jack Hills zircon with graphite	Western Australia	4.10 ± 0.01 Ga	U–Pb	69.02	[331]
Acasta orthogneiss	Northwest Territories	4.00–4.03 Ga	U–Pb zircon	69.00	[340]
Idiwhaa gneiss	Northwest Territories	4.02 Ga	U–Pb zircon	69.00	[342]
Acasta gneiss	Northwest Territories	3.96 Ga	U–Pb zircon	68.99	[341]
Akilia	West Greenland	possibly older than 3,850 Ma	—	68.96	[347]
Isua pillow basalts	West Greenland	about 3.8 Ga	—	68.95	[276]
Isua iron formation	West Greenland	3,700–3,800 Ma	—	68.92–68.95	[346]
Nuvvuagittuq zircon	Quebec	≤3,780 Ma; 3,750 Ma minimum	U–Pb zircon	68.94	[343]

The oldest rocks are small and few: about 50 km² mapped at Acasta, about 20 km² at Nuvvuagittuq. Their ages run from 4.0 to 4.3 Ga by one clock or another.

How fast the continents grew

The continents of today cover 210.4 × 10⁶ km², about 40 % of the Earth’s surface, and about 33 % of it stands above sea level [349]. Another estimate gives about 41 % of the surface and a volume of about 7 × 10⁹ km³ [350]. The volume over the area, 7 × 10⁹ / 2.104 × 10⁸, gives a mean thickness of 33 km, position 24.86.

The average density of continental crust is about 2.83 g cm⁻³ [350]. Its mean age is about 2.0 billion years, position 68.36 [281]. A measurement on loess gives 1.82 ± 0.07 Ga, position 68.28 [351].

How much of that crust existed early depends on what is counted. Estimates of continental volume at 3 Ga “range from < 10 % to > 120 % of present day volume” [349]. Some curves count rock that survives; others count crust that was made and later destroyed.

Curve	Share of present crust at about 3 Ga	Source
von Huene and Scholl 1991	less than 10 %, before 3.7 Ga	[350]
a summary curve	about 20 % by 3.0 Ga; about 60 % between 3.0 and 2.5 Ga; the last 20 % in 2.5 Gyr	[350]
Taylor and McLennan 1995	about 25 % by 3.0 Ga; about 60 % by 2.6 Ga	[350]
Allègre and Rousseau 1984	25 %, 37 %, 46 % or 65 % for K = 2, 4, 6, 15	[351]
Belousova et al. 2010	about 50 %	[351]
the same databases rerun with one set of equations	about 60 %	[351]
zircon model, Dhuime et al. 2012, 2017	at least 65 %	[351]
Nd model	70–75 %	[351]
Campbell 2003; Dhuime et al.; Pujol et al. 2013	around 70 %	[349]
the highest curves of the	more than 100 %, up to more	[349]

comparison	than 120 %	

The zircon model states that “At least 65% of the present volume of continental crust was established by 3 Ga” [351]. Extreme scenarios at the boundary of the Archaean and Proterozoic give “less than 25%, or more than 100%” [351]. The Archaean crust that survives makes up “less than 15 %” of the present volume, while at least about 75 % of the volume existed by 3 Ga [349].

The rates

The rate of net growth fell near 3 Ga. Before 3 Ga it was 2.9 to 3.4 km³ per year; afterwards 0.6 to 0.9 km³ per year, about 0.8 [351]. The fall is a factor of 2.9 / 0.9 = 3.2 to 3.4 / 0.6 = 5.7.

Generation of new crust stayed high: “~4 to 3 km3yr-1 between the Hadean and the present” [351]. The difference was destruction. “At least 100% of the present volume of the continental crust has been destroyed and recycled” since 3 Ga.

Crustal loss today exceeds addition by “at least 1 km³/a” [349]. The volume may have fallen by “as much as 15 %” since the Neoproterozoic.

Oxygen isotopes and hafnium model ages of dated zircons show “A marked decrease in the rate of crustal growth at ~3 billion years ago” [352]. In the same study, increased rates of crustal destruction “starting around 3 billion years ago” coincide with the onset of plate tectonics driven by subduction [352].

The argon of the old air gives another measure. Hydrothermal quartz of 3.5 Ga, position 68.87, holds atmospheric $^{40}Ar/^{36}Ar$ of 143 ± 24, against 298.6 today [353]. The Archaean ratio is 143 / 298.6 = 0.48 of the present.

Thickness and composition

New crust changed its thickness and its silica [349]. Before 3 Ga it was 20 km thick or less, position 24.40, and mafic, about 48 % SiO_2. From 3 to 1.8 Ga it was about 40 km, position 25.03, and about 57 % SiO_2; today it is 30 to 35 km, positions 24.77 to 24.91, and about 55 % SiO_2.

The continental area was already near 40 % by 3 Ga [349]. The Archaean mantle was 100 to 250 °C warmer than today’s [354]. Estimates of the start of plate motion span “85% of Earth’s history”; subduction may have begun as early as 3.8 Ga, and modern plate tectonics at least by 2.2 Ga [354].

The same making of crust took other values in a hotter Earth. Before 3 Ga the new crust was thin and mafic; after it, thick and rich in silica. As a reading, that is the form of context: one rule, other values in other surroundings.

The continents have kept their area and much of their volume while at least one full volume of crust was recycled since 3 Ga. Read in the net, that is the form of form and carrier. The form lasts; its carriers are replaced.

What this part of the history shows

The record of the first crust is a record of crystals. The oldest terrestrial material is a zircon of 4,404 ± 8 Ma, position 69.08, held in a rock 1.4 billion years younger. A second grain, read atom by atom, keeps its clock of 4.4 billion years: what closes, stays.

The crystals record water and crust within 163 to 267 million years of the first solids. Oxygen up to 15.0 ‰ and melts near 700 °C and 7 kbar place granite-like crust and liquid water by 4.4 to 4.3 Ga. A heat flow of about 75 mW m^{-2} stands at 0.82 of today’s mean.

A new kind of crust opened a new stage of minerals. The earliest Hadean crust carries 400 species, the earliest hydrosphere 350, the earliest continental crust 2,385. Much of the mineral diversity was in place within 250 million years: as a reading, opened once, filled many times.

The bombardment is read three ways from one lunar record. The middle reading, a quiet time from about 4.4 Ga, an elevated flux from about 4.2 to 3.5 Ga and a tail to 2.0–2.5 Ga, reads as rest and discharge. Of at least 40 basins only Imbrium has a tight age, 3.91–3.94 Ga.

The oldest rocks are small: 50 km² mapped at Acasta, 20 km² at Nuvvuagittuq. Their ages depend on the clock. Zircon gives 4.02–4.03 Ga at Acasta and at most 3.78 Ga at Nuvvuagittuq; the extinct ^{146}Sm gives 4.28 Ga for the same belt, 500 million years older.

The continents grew fast before 3 Ga, 2.9 to 3.4 km³ per year, and slowly after it, 0.6 to 0.9 km³ per year. Generation stayed at about 3 to 4 km³ per year. The difference went into recycling: at least one full volume of the present crust has been destroyed since 3 Ga.

The continents kept their form while their material was replaced. Their area was near 40 % of the surface by 3 Ga and is about 40 % now. Read in the net, that is the form of form and carrier.

The making of crust took other values in the hotter Archaean Earth. Before 3 Ga new crust was 20 km thick or less and held about 48 % SiO_2; after it, about 40 km and 57 %. Read in the net, the same rule in other surroundings is the form of context.

14. The Oceans

The first crust of chapter 13 already carries the mark of water. Its oldest zircon grains hold oxygen that was altered by liquid water at low temperature. From that moment on, the Earth has had an ocean.

This chapter tells the history of that ocean. It begins with the origin of the water, read in the ratio of heavy to light hydrogen.

It follows the first traces of the sea and the rise and fall of sea level over half a billion years. Then come the last great swing of the ice ages and the acid steps of the deep past.

It ends with the ocean of now: its volume and depth, its salt, its overturning, its tides, its acidity and its rising level. Each size and each time stands with its position on the ladder of chapter 11. The ocean is a thin film on a large planet, and it has held for more than four billion years.

Where the water came from

The water of the ocean has a fingerprint. It is the ratio of deuterium to ordinary hydrogen, D/H.

In standard mean ocean water it is $(1.5576 \pm 0.0005) \times 10^{-4}$ [276]. A second measurement gives $(1.558 \pm 0.001) \times 10^{-4}$ for the Earth's water [356].

Every other body that carries water can be set beside this number. Comets carry more deuterium than the ocean, and they differ among themselves. The comet 67P/Churyumov–Gerasimenko, a Jupiter-family comet, was measured in place by the ROSINA instrument on Rosetta [355].

Its D/H is $(5.3 \pm 0.7) \times 10^{-4}$, "approximately three times the value" of the ocean [355]. The exact ratio is 5.3 / 1.5576 = 3.40. The authors conclude that Jupiter-family comets are not made solely of ocean-like water [355].

Another Jupiter-family comet, 103P/Hartley 2, was measured by the Herschel telescope. Its D/H is $(1.61 \pm 0.24) \times 10^{-4}$ [356]. That is 1.03 times the ocean value, the closest match of any comet.

Six comets from the Oort cloud give a mean of $(2.96 \pm 0.25) \times 10^{-4}$, 1.90 times the ocean [356]. Halley, Hyakutake, Hale–Bopp, C/2002 T7 (LINEAR) and 8P/Tuttle all lie "approximately twice that of oceanic water" [276]. Jupiter-family comets alone span a factor of 5.3 / 1.61 = 3.29.

Meteorites tell a different story. Carbonaceous chondrites give $(1.4 \pm 0.1) \times 10^{-4}$, 0.90 times the ocean [356]. Their D/H differs from that of comets and of the moon Enceladus [357].

Alexander and colleagues read this as an argument against a large influx of outer-system ice to the inner Solar System. They name the CI chondrites the "principal source of Earth's volatiles" [357]. Models dominated by asteroids allow at most 10 % of the Earth's water from comets [356].

A second class of meteorites comes from the inner Solar System itself. Enstatite chondrites are isotopically close to the rocks of the Earth. They "contain sufficient hydrogen to be delivered to Earth at least three times the mass of its oceans" [358].

Their nitrogen isotopes match those of the mantle [358]. A third line ties the Earth's water to ancient eucrites from the asteroid Vesta, whose D/H matches the present Earth (Sarafian and others, 2014) [276].

The deep mantle holds its own water. Lavas from Baffin Island and Iceland carry a deep-mantle component with δD "more negative than -218 per mil" [359]. The authors read it as hydrogen inherited from the protosolar nebula.

A δD of −218 ‰ means a D/H of $1.5576 \times 10^{-4} \times (1 - 0.218) = 1.22 \times 10^{-4}$. That is 0.78 times the ocean value.

The primary study gives a deep-mantle δD below −218 ‰ [359]; another account gives the primordial D/H as 218 ‰ higher than now [276].

Since its origin the Earth's D/H may have risen by a factor of 2 to 9 (Genda, 2016) [276]. Icy planetesimals may have accreted about 4.5 Ga (position 69.10), when the Earth had 60–90 % of its present size [276].

Less than 1 % of the Earth's material accreted after the Moon-forming impact of chapter 12 [276]. A molybdenum study of 2019 places most of the water arrival with that collision [276].

Reservoir	D/H (× 10^{-4})	Ratio to ocean	[n]
Deep mantle (Baffin Island, Iceland)	≤ 1.22 (δD < −218 ‰)	0.78	[359]
Carbonaceous chondrites	1.4 ± 0.1	0.90	[356]
Ocean (SMOW)	1.5576 ± 0.0005	1	[276]
Earth's water	1.558 ± 0.001	1.00	[356]
103P/Hartley 2	1.61 ± 0.24	1.03	[356]
Oort-cloud comets, mean of six	2.96 ± 0.25	1.90	[356]
67P/Churyumov–Gerasimenko	5.3 ± 0.7	3.40	[355]

The ocean sits between the chondrites and the comets on one isotope axis. It lies within 10 % of the carbonaceous chondrites and of Hartley 2.

The whole hydrosphere has a mass of 1.4×10^{21} kg [277]. The ocean alone holds about 1.37×10^{21} kg [276]. Against the Earth's mass of 5.9722×10^{24} kg [277], that is $1.37 \times 10^{21} / 5.9722 \times 10^{24} = 0.023$ %.

The other surface water, in ice, lakes, rivers, groundwater and vapour, adds about 5.0×10^{20} kg [276]. The mantle may hold roughly three times the ocean mass. The core could hold hydrogen for four to five oceans [276].

The first oceans

The oldest sign of the sea is a single grain. A detrital zircon from the Jack Hills of Western Australia has a U–Pb age of 4,404 ± 8 Ma (position 69.08) [326]. It is the oldest dated piece of the Earth.

Its oxygen is zoned, with $\delta^{18}O$ from 7.4 to 5.0 ‰. The granitic melt from which it grew had $\delta^{18}O$ of 8.5–9.5 ‰ [326]. Such heavy oxygen forms when crust has been altered by liquid water at low temperature and then melted.

The authors place the window for this water "between its formation about 4,550 Myr ago and 4,030 Myr" [326]. Earlier the oldest grains had been about 4,276 Ma (position 69.06) [326].

A second study in the same issue of Nature measured zircons 3,910–4,280 Ma old (positions 68.97–69.06) [330]. Their $\delta^{18}O$ runs from 5.4 ± 0.6 ‰ to 15.0 ± 0.4 ‰. The magmas included crust reworked in the presence of near-surface water by about 4,300 Ma (position 69.06) [330].

From the Earth's formation at 4,550 Ma (as given in [326]) to the oldest water-marked zircon is 4,550 − 4,404 = 146 Myr (position 65.98). Two independent studies thus place liquid water at the surface 4.4–4.3 Ga.

The first rock made in water follows much later. Pillow basalts of the Isua Greenstone Belt in Greenland show water about 3.8 Ga (position 68.95) [276]. A pillow is a rock form made in water.

The rocks of the Nuvvuagittuq Greenstone Belt are dated 3.8 or 4.28 Ga, depending on

the study [276]. From the oldest isotope signal to the Isua pillows is about 600 Myr (position 67.27).

The Sun gave about 25 % less energy in those first two billion years [380]; chapter 15 tells that story. Liquid water stood all the same. From 4.4 Ga onward the record of water at the surface does not break.

Sea level over half a billion years

The level of the sea is not fixed. It rises and falls with the volume of the ocean basins and with the ice on land. A review by Miller and colleagues covers 543 Ma (position 67.18) to the present [363].

In the Paleozoic, from 542 to 251 Ma (positions 67.18–66.48), Haq and Schutter count 172 documented eustatic events [364]. Their amplitudes run “from a few tens of meters to approximately 125 meters” (125 m, position 19.78) [364].

The highest sea levels came in the middle Paleozoic and in the Cretaceous [365]. A large drop marks the end-Ordovician glaciation [365]. In the Cretaceous the long-term level peaked at 100 ± 50 m (position 19.58) above the present [363].

A second figure gives the mean over the past 100 Myr (position 65.64) as “generally 200 metres above current levels” (position 20.21) [365]. Miller and colleagues read the lower peak as a sign of lower ocean-crust production than once inferred [363].

On scales of 10^4–10^6 years sea level mirrors the oxygen isotopes of the deep sea, a measure of ice volume [363]. The last 100 Myr fall into three phases [363].

From 100 to 33 Ma (positions 65.64–64.63) Antarctic ice sheets were ephemeral. From 33 to 2.5 Ma (position 62.28) large ice sheets stood, mainly on Antarctica.

Since 2.5 Ma large and variable ice sheets have also covered the Northern Hemisphere [363]. Chapter 19 tells the history of that ice.

An acid step: the Paleocene–Eocene Thermal Maximum

About 56 Ma (position 65.11) the ocean took a sudden load of carbon. In the Paleocene–Eocene Thermal Maximum, several thousand Pg of carbon entered the air and sea as methane and/or carbon dioxide [376]. The release took about 10 kyr (position 57.25) [376].

Gutjahr and colleagues give more than 10,000 Pg C, isotopically heavier than earlier estimates [379]. They name the volcanism of the North Atlantic Igneous Province as the main source, rather than methane hydrates [379].

At ODP Site 1209 in the North Pacific, the boron isotopes of planktic foraminifera fell by about 0.8 ‰ at the onset [376]. Their B/Ca ratio fell by 30–40 %. The surface pH dropped by about 0.3 units [376].

A drop of 0.3 in pH means 10^0.3 − 1 = 100 % more hydrogen ions: their concentration doubled. The surface acidification lasted at least 70 kyr (position 59.03) [376]. The whole event lasted about 170 kyr (position 59.83), from an orbital chronology at ODP Leg 208 and Site 690 [381].

As a reading, the form of loading and discharge (chapter 11) shows here in the sea. The load came in 10 kyr; the return took at least seven times longer. Gutjahr and colleagues also find the surface pH “persistently low” [379].

A review of the past 300 Myr (position 66.64) by Hönisch and colleagues gathers several events that joined high carbon dioxide, warming and ocean acidification [377]. Some coincide with extinctions or turnover among marine calcifiers. No past event parallels the present exactly, because of the present speed [377].

The last glacial swing

The deepest fall of the sea in recent time came with the last glacial maximum. Lambeck and colleagues inverted about 1,000 observations from sites far from the former ice sheets [366]. Their record covers the past 35,000 years (position 58.39).

The sea fell about 40 m (position 18.74) in under 2,000 years (position 55.79) to reach the glacial state at about 30 ka (position 58.25) [366]. That is a mean of more than 40 / 2,000 = 0.02 m per year, or 20 mm per year. Then it fell slowly to −134 m (position 19.84) between 29 and 21 ka (positions 58.22–57.93) [366].

At the maximum the land carried about 52 × 10^6 km^3 more grounded ice than today [366]. Melted, with ice at 0.917 times the density of water, and spread over 361.9 × 10^6 km^2 of ocean [311], that is 52 × 10^6 × 0.917 / 361.9 × 10^6 km = 0.132 km. The 132 m of this sum matches the measured 134 m.

Another account gives the glacial sea about 130 m below the present about 20,000 years ago (position 57.88) [365]. The rise began at about 20 mm per year near 19 ka (position 57.84) [365].

The main deglaciation ran from 16.5 to 8.2 ka (positions 57.71–57.07) at about 12 m per 1,000 years, 12 mm per year [366]. Between about 14,000 and 6,500 years ago (positions 57.56–56.86) the sea rose 110 m (position 19.66) [365].

Within this rise one pulse stands out. Meltwater pulse 1A came at the Bølling warming [367]. Corals drilled off Tahiti by IODP Expedition 310 date its start no earlier than 14,650 years ago (position 57.60) and its end before 14,310 years ago (position 57.58) [367].

The sea rose 12–22 m, most probably 14–18 m (positions 17.79–18.02) [367]. The eustatic rate “exceeded 40 millimetres per year” [367]. Over at most 340 years (position 54.18), 14–18 m gives 41–53 mm per year.

Another reconstruction gives 13.5 m over about 290 years (position 54.03), centred on 14.2 ka [365]. That is 13.5 / 290 = 47 mm per year. Lambeck and colleagues give the same pulse, 14.5–14.0 ka, at 40 mm per year or more [366].

The Younger Dryas, 12.5–11.5 ka (positions 57.46–57.38), brought a slower rise [366]. The same study finds no evidence for a second pulse, MWP-1B, at 11.3 ka [366]. Early Holocene rates ran at 6.0–9.9 mm per year, with brief bursts of 30–60 mm per year [365].

After 8.2 ka the rise slowed until about 2.5 ka (position 55.99) [366]. Holocene rates fell from more than 10 to less than 1 mm per year [365]. Then the ocean volume stayed nearly constant until a new rise began 100–150 years ago (positions 53.06–53.43) [366].

Between 6 and 0.15 ka the level oscillated by only 15–20 cm (positions 13.66–13.92), over periods of 200 years (position 53.69) or more [366]. The sea held its level for some 2,500 years.

Interval	Change	Rate	[n]
542–251 Ma	172 events, tens of m to ~125 m	—	[364]
Cretaceous	+100 ± 50 m (mean of last 100 Myr ~+200 m)	—	[363][365]
into ~30 ka	−40 m in < 2,000 yr	> 20 mm/yr	[366]
29–21 ka	slow fall to −134 m	—	[366]
~19 ka	onset of rise	~20 mm/yr	[365]
16.5–8.2 ka	main rise	~12 mm/yr	[366]
14.65–14.31 ka (MWP-1A)	+14–18 m (12–22 m)	> 40 mm/yr	[367]
14,000–6,500 yr ago	+110 m	6.0–9.9 mm/yr early Holocene	[365]
8.2–2.5 ka	slowing rise	> 10 → < 1 mm/yr	[365][366]
6–0.15 ka	±15–20 cm	~0	[366]

As a reading, the sea level of this swing has the form of loading, holding and discharge (chapter 11). Ice loaded slowly for eight thousand years, from 29 to 21 ka.

It discharged in pulses, the fastest 14–18 m in a few centuries. Then the level held for 2,500 years.

The ocean now: volume, depth, area

The size of the ocean was measured anew in 2010. Charette and Smith used bathymetry predicted from satellite altimetry [360]. They found a volume of 1.33238 × 10^9 km³ and a mean depth of 3,682.22 m (position 22.86).

The area is 361.841 × 10^6 km² [360]. The one-sigma uncertainty is 1.2 % for depth and volume and 0.14 % for area. Only 32.4558 × 10^6 km² of the sea floor, 9 % of it, is covered by cells measured with echosounders [360].

Those measured cells have a mean depth of 3,504.49 m (position 22.82). The 329.385 × 10^6 km² estimated from altimetry have 3,699.73 m (position 22.86) [360]. Ninety-one percent of the ocean floor is known from space rather than from a sounding line.

Each survey since 1888 has given a smaller mean depth. The table follows the estimates in the order of their publication [360].

Estimate	Mean depth	Position	Area (10^6 km²)	Volume (10^9 km³)	[n]
Murray 1888	3,797 m	22.89	355.3	1.349	[360]
Kossinna 1921	3,814 m	22.89	362.0	1.370	[360]
Menard & Smith 1966	3,729 m	22.87	362.0	1.350	[360]
Baumgartner & Reichel 1975	3,733 m	22.87	361.1	1.348	[360]
Shiklomanov & Sokolov 1983	3,703 m	22.87	361.3	1.338	[360]
Charette & Smith 2010	3,682.22 m	22.86	361.841	1.33238	[360]

From 3,814 m in 1921 to 3,682 m in 2010 the mean depth fell by 3.5 % over 89 years of estimates. Seamounts and ridges had been undersampled.

Another account gives a volume of “roughly 1.335 billion cubic kilometers” and a mean depth of 3,688 m (position 22.86), after NOAA [311]. The same page gives an area of 361 × 10^6 km², or 361.9 × 10^6 km² with marginal seas. That is 70.8 % of the Earth’s surface [311].

The ocean holds 97.5 % of the Earth’s water [311]. Its mass follows from the volume and the mean density of seawater, 1,025 kg m^{-3} [361]. The product 1.33238 × 10^{18} m³ × 1,025 kg m^{-3} is 1.366 × 10^{21} kg, close to the 1.37 × 10^{21} kg of section one [276].

The ocean is cold on average. Its mean temperature is 3.9 °C, or 4 °C in a rounded figure; the surface averages 20 °C [311]. Deep water stays away from the surface “for hundreds or even a few thousand years” [311].

Seawater at the surface has a density of 1,020–1,029 kg m^{-3} [361]. It freezes at about −2 °C. Sound travels through it at about 1,500 m s^{-1} [361].

The deepest point is the Challenger Deep in the Mariana Trench, at 11°22.3′ N, 142°35.3′ E [362]. Greenaway, Sullivan and Umfress measured 10,935 ± 6 m (position 23.85) in 2021, by acoustics referenced to pressure. The deepest point is 10,935 / 3,682 = 2.97 times the mean depth [362][360].

On the ladder the mean depth stands at 22.86 and the deepest point at 23.85, 0.99 apart.

The record of the Challenger Deep runs across methods and years.

Measurement	Depth	Position	[n]
HMS Challenger 1875, weighted rope, 4,475 fathoms	8,184 m	23.59	[362]

Trieste 1960, pressure	10,911 ± 7 m	23.85	[362]
Sonar 2010	10,994 ± 40 m	23.86	[362]
Gardner et al. 2014, sonar	10,984 ± 25 m	23.86	[362]
PMEL mooring 2015	10,854.7 ± 8.9 m	23.84	[362]
Limiting Factor 2019, eastern basin	10,925 ± 4 m	23.85	[362]
2020, western basin	10,923 ± 4 m	23.85	[362]
Greenaway et al. 2021	10,935 ± 6 m	23.85	[362]

The direct pressure values cluster at 10,911–10,935 m; the sonar values of 2010 and 2014 stand higher, at 10,994 and 10,984 m [362].

Salt

The ocean is salt water. Its mean salinity is about 3.5 %: 35 g per litre, 35 parts per thousand, or 600 mM [361]. Six ions carry nearly all of it.

At salinity 35, chloride stands at 0.546 mol/kg and sodium at 0.469 [361]. Magnesium follows at 0.0528, sulphate at 0.0282, calcium at 0.0103 and potassium at 0.0102. Chloride exceeds sodium by a factor of 0.546 / 0.469 = 1.16.

By mass, seawater is 1.94 % chlorine and 1.08 % sodium [361]. Magnesium makes 0.1292 %, sulphur 0.091 %, calcium 0.04 % and potassium 0.04 %. The whole ocean, 1.366×10^{21} kg at 3.5 %, holds $1.366 \times 10^{21} \times 0.035 = 4.8 \times 10^{19}$ kg of dissolved salt.

The salinity of the ocean “has been stable for billions of years” (Pinet 1996) [361]. Water passes through the ocean in about 3,100 years (position 56.19) on average [382]. Over 4.4×10^{9} years that makes 4.4×10^{9} / 3,100 = 1.4 million passages of the water.

As a reading, this is the form of what closes, stays (chapter 11). The content flows through; the form holds.

The overturning

The ocean turns over. In the Atlantic a vertical loop carries water and heat between the hemispheres [370][371]. It is the Atlantic meridional overturning circulation, AMOC.

Its flow is measured in sverdrups: 1 Sv is 10^{6} m³ per second [369]. Across 26° N the RAPID array has measured it since April 2004 [370]. From April 2004 to February 2017 the mean and standard deviation were 17.0 ± 4.4 Sv [369].

After about April 2008 the transport stood roughly 2.7 Sv lower than in April 2004–April 2008 [369]. A dip of roughly 30 % came in 2009/10 [369]. The RAPID project names a major downturn in 2010–11; the overturning “varies on timescales of days to a decade” [370].

Other arrays measure the same flow at other latitudes [369].

Array	Latitude	Period	Transport	[n]
MOVE	16° N	Feb 2000–Jun 2018	18.0 ± 5.8 Sv	[369]
RAPID	26° N	Apr 2004–Feb 2017	17.0 ± 4.4 Sv	[369]
SAMBA	34.5° S	Mar 2009–Apr 2017	14.6 Sv	[369]
OSNAP	subpolar North Atlantic	Sep 2014–May 2016	14.9 Sv (density space); 8.0 ± 0.7 Sv (depth space)	[369]

From 34.5° S to 26° N the overturning moves 15–18 Sv. Its variability, ±4.4 to ±5.8 Sv, is a quarter to a third of its mean.

The flow carries 1.2 PW of heat northward [370]. That is up to 25 % of the total northward heat transport (Bryden and others, 2001) [371]. About 80 % of the deep

water upwells again in the Southern Ocean [371].

As mass the 17.0 Sv are 17.0×10^6 m³ s⁻¹ × 1,025 kg m⁻³ = 1.74×10^{10} kg per second. The whole ocean volume at this rate passes in $1.33238 \times 10^{18} / 17.0 \times 10^6$ s = 7.84×10^{10} s. That is about 2,480 years (position 55.99).

Deep water is “typically 1,000 years old” [371]. The oldest water rises in the North Pacific after a transit of about 1,000 years (position 55.16) [373]. Conventional radiocarbon ages differ by about 1,000 years between the North Atlantic, the Southern Ocean and the North Pacific [372].

Matsumoto recast them as “circulation ages”, correcting for the surface reservoir and for two sources of deep water [372]. The corrected ages fit centennial times [372].

The overturning has slowed. One estimate gives a slowdown of 0.46 Sv per decade since 1950 (Nature Geoscience, 2024) [371]. Rahmstorf and others (2015) give 15–20 % weakening in 200 years (position 53.69); Caesar and others (2021) give about 15 % [371].

Latif and others (2022) find that a reduction of one sverdrup was not reached until 1980 [371]. Smeed and others (2018) confirm the weaker flow after 2008 [371].

The deep past shows larger swings. The Younger Dryas ran from 12,800 to 11,700 years ago (positions 57.48–57.40) [371]; the sea-level study places it at 12.5–11.5 ka [366].

Dansgaard–Oeschger event 1 came about 14,690 years ago (position 57.60). In Greenland the Dansgaard–Oeschger warmings reached 8–15 °C over several decades (Schmidt and others, 2011) [371].

As a reading, the overturning has the form of metabolism (chapter 11). Its water is replaced in about 2,480 years, while the circulation itself holds its 15–18 Sv. A text of the net puts the closed mesh in these words: “A closed mesh holds its content: what goes round comes back.” [388]

The tides

Twice a day the sea rises and falls. The main lunar tide, M2, has a period of about 12 h 25.2 min, or 44,712 s (position 42.90) [374]. The lunar day lasts about 24 h 50 min (position 43.53) [374].

The solar tidal force is 46 % of the lunar one [374]. The solar tide has a period of 12 h (position 42.87). The two tides beat, and about seven days (position 45.27) pass between springs and neaps [374].

The tidal amplitude in the open ocean is about 54 cm (position 14.83) [374]. The open-ocean range is under 1 m; some coasts exceed 10 m [311]. The Bay of Fundy reaches a maximum range of 16.3 m (position 17.93) (Desplanque and Mossman, 2004) [374]; Ungava Bay reaches up to 16 m [311].

The two clocks of 12 h 25.2 min and 12 h do not close on each other. As a reading, their beat is the form of the remainder (chapter 11): no closure is ever exact, and each depth leaves a remainder.

Tidal friction dissipates energy. The total tidal dissipation is about 3.75 TW [374]. Egbert and Ray mapped it from Topex/Poseidon altimetry [312].

They found about 10^{12} W, 1 TW, in the deep ocean: “25–30% of the total dissipation” [312]. That implies a total of 1 / 0.30 to 1 / 0.25 = 3.3–4.0 TW.

The friction lengthens the day by about 0.002 s per century [374]. The Moon recedes by about 3.8 cm per year [374]. Chapter 12 tells the history of that recession and of the day.

The pH of the sea now

Seawater is slightly basic. Its surface pH before industry stood around 8.2 [361], or 8.17

in 1850 [375].

Between 1950 and 2020 the average surface pH fell from about 8.15 to 8.05 [361]. In 2021 it stood at 8.08 [375].

A change of 0.1 in pH means about 26 % more hydrogen ions: 10^0.1 − 1 = 0.26 [375]. From 8.17 to 8.08 is 10^0.09 − 1 = 23 % more.

Since the late 1980s the open-ocean surface has lost 0.017–0.027 pH units per decade (IPCC AR6) [375]. Three time series show it.

Station	Period	Change per decade	[n]
HOT, Hawaii	1989–2007	−0.019	[375]
BATS, Bermuda	1984–2012	−0.017	[375]
Dyfamed, Mediterranean	1995–2011	−0.03	[375]

The present pH is “unprecedented for at least 26,000 years” (position 58.12), according to AR6 [375]. From 1850 to 2022 the ocean took up 26 % of carbon dioxide emissions [375]. For 2013–2022 the ocean sink was 2.9 ± 0.4 Gt C per year [378].

Projections for 2100 give about 8.0 under SSP1-2.6 and 7.7 under SSP5-8.5 [375]. A pH of 7.7 against 8.08 means 10^0.38 − 1 = 140 % more hydrogen ions.

The present decline of 0.09 is 0.09 / 0.3 = 30 % of the PETM drop. It has come in under two centuries. The PETM drop came over about 10 kyr.

The sea level now

The present rise began 100–150 years ago, after 2,500 years of nearly constant volume [366]. Between 1901 and 2018 global mean sea level rose by 0.20 m (0.15 to 0.25 m) [383]. The rate was about 1.3 mm per year in 1901–1971 and 3.7 mm per year in 2006–2018 [383].

Since 1993 satellites have measured it directly: TOPEX/Poseidon, Jason 1–3 and Sentinel-6 Michael Freilich [368]. The rise since 1993 is 97.8 mm (position 13.27) [368]. The rate was 0.20 cm per year in 1993 and is 0.44 cm per year, 4.4 mm per year, now [368].

Over 1993–2024 the mean rate is 97.8 mm / 31.8 years = 3.1 mm per year. The World Meteorological Organization gives 2.1 mm per year for 1993–2002 and 4.7 mm per year for 2015–2024 [384]. It gives 2.65 mm per year for 1993–2011 and 4.75 mm per year for 2012–2025 [385].

Period	Rate	Ratio late / early	[n]
1901–1971 → 2006–2018	1.3 → 3.7 mm/yr	2.8	[383]
1993 → now	2.0 → 4.4 mm/yr	2.2	[368]
1993–2002 → 2015–2024	2.1 → 4.7 mm/yr	2.2	[384]
1993–2011 → 2012–2025	2.65 → 4.75 mm/yr	1.8	[385]

The present rate stands beside the deep past. Meltwater pulse 1A rose at more than 40 mm per year, nine times faster.

The main deglaciation rose at 12 mm per year, 2.7 times faster. The late Holocene rose at less than 1 mm per year.

The ocean also holds most of the added heat. Ocean warming is 91 % of the heating of the climate system; land takes about 5 %, ice about 3 % and the air about 1 % [383].

The upper 2,000 m of the ocean gained about 23 ± 8 ZJ from 2024 to 2025 [386]. The warming rate was 0.14 ± 0.03 W m^{-2} per decade over 1960–2025 and 0.32 ± 0.14 W m^{-2} per decade over 2005–2025 [386]. About 33 % of the ocean area was in its 1958–2025 top three, and 57 % in its top five [386].

The gain of 23 ZJ was “the largest annual gain on record” [387]. It equals about 23 × 10^{21} / 620 × 10^{18} = 37 years of the world’s primary energy use in 2023 [387]. Ocean heat set a record in each of the past nine years [387].

The sea surface in 2025 stood 0.49 °C above 1981–2010, 0.12 ± 0.03 °C below 2024, the third warmest year [386]. The ocean heat content of 2025 was the highest in the 66-year record [385]. The warming rate of 2005–2025 was “more than twice” that of 1960–2005 [385].

What this part of the history shows

Read in the net, the ocean and its salt have the form of what closes, stays. Water has stood at the surface from 4,404 Ma (position 69.08) to now, and passes through in about 3,100 years (position 56.19), some 1.4 million times in 4.4 billion years. The salinity of 35 g per litre has been stable for billions of years, with chloride and sodium at a ratio of 1.16.

The overturning shows the same form at the size of one basin. From 34.5° S to 26° N it carries 15–18 Sv. At that rate the whole ocean passes in about 2,480 years (position 55.99), while the circulation holds.

As a reading, sea level has the form of loading, holding and discharge. Ice loaded from 29 to 21 ka and took the sea down to −134 m (position 19.84); meltwater pulse 1A discharged 14–18 m in at most 340 years (position 54.18). From 2.5 ka the level held within 15–20 cm.

The acid step of the PETM reads as the same form in the chemistry of the sea. Carbon loaded in about 10 kyr (position 57.25); the pH fell by 0.3 and returned only after at least 70 kyr (position 59.03). The present fall of 0.09 has come in under two centuries.

The ocean takes up the heat of now. In one year, 2024 to 2025, the upper 2,000 m gained 23 ± 8 ZJ. The ocean takes 91 % of the heating of the climate system.

The tide reads as the form of the remainder. The lunar tide of 12 h 25.2 min (position 42.90) and the solar tide of 12 h (position 42.87) never close on each other. Their beat brings springs and neaps about seven days (position 45.27) apart.

On the ladder the ocean is a thin film. Its mean depth of 3,682 m stands at 22.86, against the Earth’s radius at 29.65. Every estimate since 1888 lies between 22.86 and 22.89, and the deepest point, 2.97 times the mean, stands at 23.85.

The water of the Earth lines up on one isotope axis. The deep mantle holds 1.22×10^{-4}, the carbonaceous chondrites 1.4, the ocean 1.558 and the comets 1.61 to 5.3. The ocean lies within 10 % of the chondrites and of Hartley 2.

15. The Air

The ocean of chapter 14 lies under a second, thinner film: the air. Its mass is less than half a percent of the ocean's. Yet its history runs through the same four billion years.

The air of the young Earth held almost no free oxygen. It rose in three steps, separated by plateaus of hundreds of millions of years. Carbon dioxide fell over the same span, from thousands of parts per million to a few hundred, while the Sun grew brighter.

This chapter follows that history and ends with the air of now. Its composition, its layers, its ozone, its winds, its lightning and the resonance that lightning rings in the space between ground and ionosphere close the story. Each size and time stands with its position on the ladder of chapter 11.

The first air

The oldest measured sample of air is trapped in rock. Hydrothermal quartz 3.5 Ga old (position 68.87) holds fluid inclusions with an argon ratio $^{40}Ar/^{36}Ar$ of 143 ± 24 [353]. The present air has 298.6 [353].

The air of 3.5 Ga held less than half of today's share of ^{40}Ar: 143 / 298.6 = 0.48. Pujol and colleagues use the ratio to trace the growth of the continental crust (chapter 13) [353].

Sulphur records the chemistry of the early air. Before 2,450 Ma (position 68.55) sulphur isotopes show mass-independent fractionation in $\delta^{33}S$, $\delta^{34}S$ and $\delta^{36}S$ [389]. Such fractionation needs gas-phase reactions in an air with very low oxygen.

Between 2,450 and 2,090 Ma (position 68.40) the sulphur cycle changed [389]. Before the change, oxygen stood "at just 0.001% of recent atmospheric levels" (PAL) [390]. With the present 20.95 % [277], that is 0.001 % × 20.95 % = 2×10^{-4} % of the air.

The early Earth also lay under a fainter Sun. Models of stellar evolution give "a solar energy input to the climate system which is about 25% lower than today" [380]. With everything else equal, the Earth would have been frozen for its first two billion years (position 68.36) [380].

A secondary source puts the early solar output at "only 70 percent as intense" [398]. The Sun is now 1.4 times as bright as at 4.6 Ga (position 69.12) [398]; 1 / 1.4 = 0.71.

Yet liquid water and life are recorded through the Archean, 3.8–2.5 Ga (positions 68.95–68.57) [380]. The oldest zircon marked by water is 4,404 ± 8 Ma old (position 69.08) [326]. Water stood under the fainter Sun from at least 4,404 Ma.

The proposed compensations centre on more carbon dioxide, methane or ammonia [380]. With a Sun 30 % dimmer at 4.5 Ga, a carbon dioxide pressure of at least 0.1 bar keeps the surface above freezing; 10 bar is a plausible upper limit [398].

About 1,000 times the present carbon dioxide fits the carbon cycle and the Sun's evolution [398]. Feulner concludes that "the faint young Sun problem cannot be regarded as solved" [380].

Read through the net, this has the form of what closes, stays (chapter 11), at the scale of the planet. The Sun changed by a factor of 1.33–1.4, and the liquid ocean held through the change.

The Great Oxidation Event

The first rise of oxygen is the Great Oxidation Event, GOE. Its onset is dated 2,460–2,426 Ma (positions 68.55–68.54) [392]. The key date is a U–Pb age of 2,426 ± 3 Ma from the Ongeluk Formation [392].

The rise oscillated for about 200 Myr (position 66.27), to 2,250–2,240 Ma (position 68.47) or earlier [392]. In multiple sulphur isotopes of drill cores from the Transvaal, Luo and colleagues date the event about 2.33 Ga (position 68.50) [391]. There the transition took roughly 10 Myr (position 63.54) [391].

The Lomagundi carbon-isotope excursion ended about 2,060 Ma (position 68.39) [392]. The GOE ended then too [390].

By its end, oxygen may have reached “as high as 10% of the modern atmospheric level” [390]. That is 10 % × 20.95 % = 2.1 % of the air.

From 2.46 to 2.06 Ga the GOE spanned 400 Myr (position 66.90). Seven published onset estimates range from 2.7 to 2.3 Ga [390].

The makers of the oxygen were older. Cyanobacteria existed at least 2.45–2.32 Ga, and probably by 2.7 Ga (position 68.64) [390]. Oxygenic photosynthesis preceded significant atmospheric oxygen by at least 400 Myr [390].

The oceans changed with the air. Banded iron formations peaked about 2.5 Ga and had largely gone by 1.85 Ga (position 68.29) [390]. The deep ocean stayed anoxic and rich in dissolved iron as late as 580 Ma (position 67.24) [390].

A secondary page divides the oxygen history into four stages: 3.85–2.45 Ga, 2.45–1.85 Ga, 1.85–0.85 Ga and 0.85 Ga to the present [390]. In the second stage oxygen stood at 0.02–0.04 atm [390].

Read through the net, the GOE has the form of loading, holding and discharge (chapter 11). Oxygen was made for at least 400 Myr before the air took it up. Then it rose within about 10 Myr in one record, and oscillated for 200 Myr in another.

The long middle

After the GOE the oxygen fell back. Through the mid-Proterozoic, 1.8–0.8 Ga (positions 68.27–67.53), chromium isotopes show that chromium oxidation was inhibited [393]. Oxygen stood at most 0.1 % of the present level [393].

That is 0.1 % × 20.95 % = 0.02 % of the air. Planavsky and colleagues tie this low level to the delayed rise of animals [393].

One site gives another reading. The Xiamaling Formation of North China, about 1,400 Ma (position 68.04), has trace metals that show oxygenated bottom waters [394]. A carbon–oxygen model makes oxygen above 4 % of the present level consistent with them [394].

That is 4 % × 20.95 % = 0.84 % of the air. The two readings differ by a factor of more than 4.0 / 0.1 = 40 [393][394].

The second and third rise

The second rise is the Neoproterozoic Oxygenation Event, about 850–540 Ma (positions 67.59–67.17) [390]. After the Marinoan glaciation the ocean oxygenated widely, 635–630 Ma (position 67.32) [395]. The black shales of the Doushantuo Formation are enriched in molybdenum and vanadium [395].

The deep ocean, all the same, was still ferruginous at 580 Ma [390].

The third rise came in the Paleozoic. Oxygen stood at 2–11 % of the atmosphere in the Cambrian to mid-Ordovician [396]. It was near modern by the Devonian and above 25 % in the early Mississippian [396].

Charcoal is continuous in the record from 419 Ma (position 66.94) [396]. Oxygen peaked at about 35 % around 280 Ma (position 66.57), in the Carboniferous [397]. Models give 30–35 % [396].

Time	Oxygen	[n]
before 2.45 Ga	~0.001 % PAL	[390]

2.46–2.06 Ga	GOE, to ~10 % PAL	[390][392]
1.8–0.8 Ga	≤ 0.1 % PAL (chromium)	[393]
~1.4 Ga	> 4 % PAL (model, Xiamaling)	[394]
850–540 Ma	Neoproterozoic Oxygenation Event	[390]
635–630 Ma	ocean oxygenation	[395]
Cambrian–mid-Ordovician	2–11 % of the atmosphere	[396]
early Mississippian	> 25 %	[396]
~280 Ma	~35 % peak	[397]
now	20.95 %	[277]

Oxygen rose in three steps across five orders of magnitude, from 2 × 10^{-4} % to 20.95 % of the air. Each step was followed by a long plateau. Read through the net, this is the form of loading, holding and discharge, three times over.

Carbon dioxide over 420 million years

Carbon dioxide leaves its trace in fossil leaves, soils, boron and other proxies. Foster, Royer and Lunt gathered about 1,500 proxy estimates from 112 studies, made with five methods [399]. They kept 1,241 of them.

The highest values, about 2,000 ppm, came in the Devonian, about 400 Ma (position 66.90), and in the Triassic, 220–200 Ma (positions 66.36–66.27) [399]. The single highest estimate is 3,700 ± 1,600 ppm at 215 Ma (position 66.33) [399].

Values near the pre-industrial 278 ppm held in much of the Carboniferous, about 300 Ma (position 66.64), and in the late Cretaceous, about 80 Ma (position 65.43) [399]. Over 420 Myr (position 66.94) the mean decline was 3.4 ppm per Myr [399].

Over the same span the Sun’s irradiance rose by about 50 W m^{-2}, a forcing of about +9 W m^{-2} [399]. The air lost carbon dioxide while the Sun gained strength.

Royer and colleagues set 372 proxy points beside the ice of the past. During long-lived glaciations carbon dioxide stood below 500 ppm; during warm periods above 1,000 ppm [400]. The Permo-Carboniferous glaciation, 340–260 Ma (positions 66.75–66.51), ran at below 500 ppm [401].

The early Paleozoic had more than 2,000 ppm; the Cretaceous about 1,000 ppm [401]. The early Eocene peak reached “1,000+ ppm” [401]. The stomatal proxy loses sensitivity above about 700 ppm [401].

A stomatal-index record over 300 Myr shows two intervals below 1,000 ppmv [402]. They are the Neogene, 1–8 Ma (positions 61.45–63.34), and the early Permian, 275–290 Ma (positions 66.56–66.61) [402].

The Paleocene–Eocene Thermal Maximum and the Eocene

About 56 Ma (position 65.11) a large mass of carbon entered the air. Gutjahr and colleagues give more than 10,000 Pg C [379]. Penman and colleagues give “several thousand” Pg C within about 10 kyr (position 57.25) [376].

Gutjahr and colleagues name the volcanism of the North Atlantic Igneous Province as the main source [379]. The whole event lasted about 170 kyr (position 59.83) [381]. Chapter 14 tells its acid step in the sea.

In the Early Eocene Climate Optimum, carbon dioxide stood “around 1,400 parts per million” [403]. The value comes from boron isotopes of planktonic foraminifera from the Tanzania Drilling Project [403].

Through the Eocene it fell by about 50 %, and further into the Oligocene [403]. The mean surface air temperature of the optimum was more than 10 °C above the pre-industrial [403]. The same study gives an equilibrium climate sensitivity of 2.1–4.6 °C

per doubling (66 % range) [403].

The Azolla interval, about 50–48.5 Ma (positions 65.01–64.98), lasted about 800 kyr (position 61.24) [404]. It drew down 55–470 ppm of carbon dioxide [404].

Eight hundred thousand years of air in ice

Ice sheets hold bubbles of old air. The Vostok core records four glacial cycles over 420 kyr (position 60.66) [407]. The EPICA Dome C core records eight cycles [407].

Lüthi and colleagues extended the record to 800,000 years before the present (position 61.24) [405]. The pre-industrial range of the late Quaternary is “172–300 p.p.m.v.” [405]. The lowest value in all ice cores is 172 ppmv.

Values were lower between 650 and 750 ka (positions 61.05–61.18) [405]. In marine isotope stage 16 carbon dioxide stayed below 180 ppmv for about 3,000 years (position 56.16) [405].

Bereiter and colleagues revised the deepest part of the Dome C record, from 800 to 600 ka [406]. An analytical artefact grew over the deepest 200 m of core and reached 10.1 ± 2.4 ppm in the oldest section [406]. They published a corrected composite record of 800 kyr.

The interglacial after Termination V lasted about 28,000 years (position 58.19) [407]. In the Holocene, carbon dioxide fell by 5 ppmv early on and then rose by 20 ppmv over 11 kyr (position 57.34) [408].

Across eight cycles the air held between 172 and 300 ppmv. Read through the net, this is the form of what closes, stays (chapter 11): the content moved, and the bounds held.

Carbon dioxide now

In 1750 the air held about 278 ppm [378]. The annual mean of 2022 was 417.1 ± 0.1 ppm [378]. One ppm is 2.124 Gt of carbon [378].

The monthly mean at Mauna Loa in September 2026 was 426.07 ppm [409]. A year earlier, in September 2025, it was 424.37 ppm. The rise in one year is 1.70 ppm, and 426.07 / 278 = 1.53 [409].

The global annual growth rates of 2016–2025 were 2.83, 2.14, 2.39, 2.50, 2.32, 2.38, 2.24, 2.69, 3.76 and 2.06 ppm per year [409]. The highest of them fell in 2024.

The annual mean of 2023 was 419.31 ± 0.1 ppm, and 2024 was projected at 422.45 ppm, 52 % above 1750 [423]. The World Meteorological Organization gives 420.0 ± 0.1 ppm for 2023 and 423.9 ± 0.2 ppm for 2024 [384][385].

The same reports give methane at 1,942 ± 2 ppb and nitrous oxide at 338.0 ± 0.1 ppb in 2024 [384][385]. They are “the highest levels in the last 800 000 years” [384]. In 2019 carbon dioxide was “higher than at any time in at least 2 million years” (position 62.08) [383].

From 278 ppm in 1750 to 426.07 ppm in 2026 is a rise of 148 ppm in 276 years (position 53.99). The present value is 426.07 / 300 = 1.42 times the 800-kyr maximum and 2.48 times its minimum.

Time	Carbon dioxide	Method	[n]
~400 Ma; 220–200 Ma	~2,000 ppm	five proxies	[399]
215 Ma	3,700 ± 1,600 ppm	single estimate	[399]
~300 Ma; ~80 Ma	near 278 ppm	proxies	[399]
340–260 Ma	< 500 ppm (glaciation)	proxies	[401]
Cretaceous	~1,000 ppm	proxies	[401]
early Eocene optimum	~1,400 ppm	boron isotopes	[403]
8–1 Ma	< 1,000 ppmv	stomata	[402]
800–0 ka	172–300 ppmv	ice cores	[405]

1750	~278 ppm	ice and firn	[378]
September 2026	426.07 ppm	Mauna Loa	[409]

The net's text on the carbon cycle reads this number as a state of the closures. In its words: "The CO2 number counts the carbon that is not inside a closed mesh at this moment." Read so, the rise of 148 ppm is carbon outside a closed mesh.

The air now: composition and mass

Dry air is three gases. By volume it holds 78.08 % nitrogen, 20.95 % oxygen and 9,340 ppm argon [277]. Together they make 78.08 + 20.95 + 0.934 = 99.96 %.

The NASA fact sheet lists carbon dioxide at 420 ppm, neon at 18.18 ppm and helium at 5.24 ppm [277]. Methane stands at 1.94 ppm, krypton at 1.14 ppm and hydrogen at 0.55 ppm. Water is "highly variable, typically makes up about 1%" [277].

The total mass of the air is 5.1×10^{18} kg [277], or about 5.15×10^{18} kg [397]. Against the ocean's 1.366×10^{21} kg (chapter 14), that is $5.1 \times 10^{18} / 1.366 \times 10^{21} = 0.37$ %. The ocean outweighs the air about 270 times.

With a mean molecular weight of 28.97 g/mol [277], the masses of the gases follow. With molar masses of 28.01, 32.00 and 44.01 g/mol, nitrogen weighs 3.85×10^{18} kg and oxygen 1.18×10^{18} kg. Carbon dioxide at 420 ppm weighs 3.25×10^{15} kg, which holds about 887 Gt of carbon.

The surface pressure is 1,014 mb [277]; the standard sea-level pressure is 101,325 Pa [397]. The surface density is 1.217 kg m^{-3} [277]. The mean surface temperature is 288 K, 15 °C, with a daily range of 283–293 K [277].

The air thins with height. Its scale height is 8.5 km (position 23.62) [277]. Half its mass lies below 5.6 km (position 23.24), and 90 % below 16 km (position 24.20) [397].

From these fractions an e-folding height follows: 5.6 / ln 2 = 8.1 km (position 23.58) from the half, and 16 / ln 10 = 6.9 km (position 23.43) from the nine tenths. The first agrees with the fact sheet. A secondary page gives a scale height "typically 5.5 to 6 km" (positions 23.23–23.30) [397].

Water passes through the air in about 8 days (position 45.39) on average [382]. The ocean's water passes in about 3,100 years (chapter 14). The air is the fast part of the same cycle.

The layers of the air

Temperature turns three times with height. NOAA's account divides the air into five shells [410].

The troposphere reaches 18–20 km (positions 24.30–24.40) at the equator and 9 km (position 23.67) at 50° N and S [410]. At the poles it reaches "just under four miles (6 km)" (position 23.30). The temperature falls from about 17 °C at the surface to −51 °C at the tropopause [410].

The stratosphere runs from 6–20 km to about 50 km (position 25.23) and "holds 19 percent of the atmosphere's gases" [410]. Its temperature rises from −51 °C to about −15 °C at the top.

The mesosphere runs from about 50 to 85 km (position 25.72) [410]. Its temperature falls from about −15 °C to as low as −120 °C at the base of the thermosphere.

The thermosphere runs from about 85 to 600 km (position 27.50) [410]. Its temperature rises from −120 °C to "as high as 3,600°F (2,000°C) near the top". The exosphere runs from about 600 to 10,000 km (position 30.06) [410].

A secondary account gives slightly different values [397]. The troposphere tops out at about 12 km on average (position 23.94), 9 km at the poles and 17 km at the equator. The tropopause reaches about −80 °C (190 K) in places.

The same page gives the stratosphere from 12 to 50 km, with a top just below 0 °C, and the stratopause at 50–55 km [397]. The mesosphere spans 50–80 km at an average of about −85 °C (190 K), the coldest shell. The mesopause lies at 80–85 km.

It gives the thermosphere from 80 to 700 km (position 27.64), up to about 1,500 °C, and the exosphere from 700 to 10,000 km [397]. The exobase lies at 500–1,000 km. The Kármán line at 100 km (position 25.87) marks the edge of space.

The tropopause stands at −51 °C [410] or about −80 °C [397]. The stratopause stands at about −15 °C [410] or just below 0 °C [397]. The thermosphere tops at 600 km and 2,000 °C [410] or at 700 km and 1,500 °C [397].

Shell	Base–top	Positions	Temperature	[n]
Troposphere	0 to 6–20 km (mean 12 km)	to 23.30–24.40	17 → −51 °C	[410][397]
Stratosphere	to ~50 km	25.23	−51 → −15 °C	[410]
Mesosphere	50–85 km	25.72	−15 → −120 °C	[410]
Thermosphere	85–600 km	27.50	−120 → 2,000 °C	[410]
Exosphere	600–10,000 km	30.06	—	[410]

On the ladder the air reaches from the ground through the tropopause at 23.94 to the Kármán line at 25.87. The exosphere reaches 30.06, beyond the Earth’s radius at 29.65. Where the air meets space, at the top of the thermosphere, the temperature is highest.

Ozone

Ozone is measured in Dobson units. One Dobson unit is a layer of pure ozone 0.01 mm thick (position 4.91) at 0 °C and 1 atm, about 2.69×10^{16} molecules per cm² [411]. The atmosphere holds “roughly 300 Dobson Units” on average [411].

That is a layer of 3 mm (position 10.10) [411]. It lies mainly at 15–35 km (positions 24.14–24.91), with a peak of 15 ppm at 32 km (position 24.83) [397].

In 1985 Farman, Gardiner and Shanklin reported that the spring ozone over Antarctica had “now fallen considerably” [414]. They read the loss through the interaction of chlorine and nitrogen oxides [414].

Inside the Antarctic ozone hole ozone drops “to an average of about 100 Dobson Units” [411]. NASA Ozone Watch keeps a yearly record of the hole: its mean area from 7 September to 13 October and its minimum ozone from 21 September to 16 October [412]. The table below stands as of 10 October 2026 [413].

Year	Mean area (10^6 km²)	Minimum (DU)	[n]
1979	0.1	225.0	[412]
1980	1.4	203.0	[412]
1982	4.8	185.0	[412]
1985	14.2	146.5	[412]
1987	19.3	123.0	[412]
1992	22.3	114.3	[412]
1994	23.6	92.3	[412]
1998	25.9	98.8	[412]
2000	24.8	98.7	[412]
2002	12.0	157.4	[412]
2006	26.6	98.4	[412]
2015	25.6	117.2	[412]
2019	9.3	167.0	[412]
2020	23.5	102.6	[412]
2023	23.1	115.2	[412]
2024	19.6	121.0	[412]
2025	18.7	138.3	[412]

From 1979 to 2006 the area grew 26.6 / 0.1 = 266 times. The minimum fell from 225.0 to 92.3 DU, by 132.7 DU or 59 %. The lowest minimum came in 1994 and the largest area in 2006 [412].

The hole grew to more than 20 million km² in 13 years (position 51.21), from 1979 to 1992. It then held at 20–27 million km² until 2023, broken by single small years: 12.0 in 2002 and 9.3 in 2019. In 2025 the minimum of 138.3 DU stood 39 % below 1979.

The hole is a feature of the southern spring, measured each year in September and October. Read through the net, its record has the form of loading, holding and discharge: a fast opening over 13 years, a plateau of three decades, and recent smaller values.

Cells and jets

The air moves in cells. The Hadley cell rises at the equator and descends at about 30°, in the horse latitudes of 30–35° [415].

The Ferrel cell lies between 30° and 60°. The polar cell rises at 60°, under a polar tropopause of about 8 km (position 23.57) [415].

Each hemisphere thus carries three cells, and the globe six. Their heights follow the tropopause, from 18–20 km at the equator to 6–8 km at the poles [410][415].

The energy of the Hadley system is estimated at 200 TW and of the Ferrel system at about 275 TW, with a coefficient of performance of 12.1 (Huang and McElroy, 2014) [415].

The jets sit at the boundaries of the cells. The polar jet flies at about 9.1 km (position 23.68), near 250 hPa, between 30° and 60° and closer to 60° [416]. The subtropical jet lies near 30°, somewhat higher [416].

The polar-night jet lies at about 24 km (position 24.57) near 60° [416]. A typical polar jet moves at about 180 km/h, 50 m s⁻¹, often above 92 km/h; the measured maximum is 400 km/h, 111 m s⁻¹ [416].

A jet is a few hundred kilometres wide and often less than 5 km thick (position 23.14) [416]. Wasaburo Ooishi detected the jets in the 1920s and reported them in 1926, in Esperanto [416].

The power of the jet streams has two estimates: 1,700 TW (Archer and Caldeira, 2009) and 7.5 TW (Miller, Gans and Kleidon, 2011) [416]. They differ by a factor of 1,700 / 7.5 = 227.

The tropical belt has widened over recent decades [417].

Feature	Latitudes	Height	Speed or power	[n]
Hadley cell	0–30°	to the tropopause, 18–20 km	~200 TW	[415][410]
Ferrel cell	30–60°	—	~275 TW	[415]
Polar cell	60–90°	tropopause ~8 km	—	[415]
Polar jet	30–60°, near 60°	~9.1 km, 250 hPa	~180 km/h; max 400 km/h	[416]
Subtropical jet	~30°	above the polar jet	—	[416]
Polar-night jet	~60°	~24 km	—	[416]

Lightning

The air discharges. The Optical Transient Detector, launched in April 1995 into an orbit of 70° inclination, counted flashes from space [418]. It saw most regions more than 400 times a year, for about 2 minutes each (position 37.51), over a field of 1,300 × 1,300 km.

It counted about 1.4 billion flashes a year, 44 ± 5 flashes per second, cloud flashes and

ground strokes together [418]. The arithmetic checks: $1.4 \times 10^9 / 3.156 \times 10^7$ s = 44.4 per second. Thunder records of 1925 had given about 100 per second [418].

Lightning strikes about ten times as often over land as over sea [418]. The Congo basin stands out. The peak mean annual density is 80 flashes per km² per year over Rwanda, and about 3 million km² exceed 30 flashes per km² per year [418].

The rate follows a dominant Northern Hemisphere summer peak and a half-yearly tropical cycle [418].

A merged climatology of the LIS (1998–2010, up to 38° latitude) and OTD (May 1995–March 2000) sensors gives 46 flashes per second [419]. The monthly rate runs from about 35 in February to about 60 in August, a ratio of 60 / 35 = 1.7 [419].

Its peak annual density is 160 flashes per km² per year in one 0.5° cell in the eastern Congo [419]. The peak monthly density is 18 flashes per km² per month in one 2.5° cell in the Brahmaputra valley, in April–May [419].

The two peak densities, 80 over Rwanda and 160 in the eastern Congo, come from grids of different scale [418][419]. About 2,000 thunderstorms are active at any time, producing about 50 flashes per second [420]. Lightning fixes about 5 Tg of nitrogen per year [421].

Quantity	Value	[n]
Global rate (OTD)	44 ± 5 s^{-1}; ~1.4×10^9 per year	[418]
Global rate (LIS/OTD)	46 s^{-1}; 35 (Feb) to 60 (Aug)	[419]
Thunderstorms at any time	~2,000; ~50 s^{-1}	[420]
Land : ocean	~10 : 1	[418]
Peak density	80 (Rwanda); 160 fl km^{-2} yr^{-1} (eastern Congo, 0.5°)	[418][419]
1925 estimate	~100 s^{-1}	[418]
Nitrogen fixed	5 Tg N per year	[421]

Each flash reads as discharge (chapter 11): a storm loads, holds and empties, some 1.4 billion times a year.

The ringing cavity

The ground and the ionosphere form a closed shell around the Earth. Lightning excites it. The cavity rings at “around 8 Hz, 14 Hz, 20 Hz, 26 Hz, etc.” [420].

Schumann predicted these resonances in 1952 [420]. Balser and Wagner first detected them in 1960, using a 10-minute interval (position 38.98) [420]. The modes stand at “around 7.83 Hz (fundamental), 14.1, 20.3, 26.3, and 32.5 Hz” [422].

For an ideal cavity the frequencies follow $f_n = (c / 2\pi a) \sqrt{n(n+1)}$ [420]. Here a is the Earth’s radius, 6.371×10^6 m [277]. The speed of light c is the ratio of the two ladder units of chapter 11, 14.558816×10^{-8} m / 1.520655×10^{-16} s = 2.998×10^8 m s^{-1}.

The ideal values for n = 1 to 5 are 10.59, 18.34, 25.94, 33.49 and 41.02 Hz. Schumann’s idealised first mode was about 10 Hz; the real cavity resonates lower, at 7.8 Hz [420]. The measured modes stand at 0.74, 0.77, 0.78, 0.79 and 0.79 of the ideal.

Mode	Measured	Period	Position	Ideal	Measured / ideal	[n]
1	7.83 Hz	0.128 s	31.28	10.59 Hz	0.74	[422][420]
2	14.1 Hz	0.0709 s	30.74	18.34 Hz	0.77	[422]
3	20.3 Hz	0.0493 s	30.41	25.94 Hz	0.78	[422]
4	26.3 Hz	0.0380 s	30.18	33.49 Hz	0.79	[422]
5	32.5 Hz	0.0308 s	29.98	41.02 Hz	0.79	[422]

The modes are spaced by 6.27, 6.2, 6.0 and 6.2 Hz. Their ratios to the fundamental are 1, 1.80, 2.59, 3.36 and 4.15. For the ideal cavity the ratios $\sqrt{n(n+1)/2}$ are 1, 1.73, 2.45, 3.16 and 3.87.

The resonance is broad. Its quality factor is “Q ranging from 4 to 6” (Nickolaenko and Hayakawa, 2002) [420].

The spectral width is about 20 % [422]. The fields are small: “mV/m for the electric field, and pT for the magnetic fields” [420], about 300 µV/m and 1 pT [422].

The resonance follows the lightning around the globe. At Mitzpe Ramon in Israel, 1999–2002, the first mode peaked at about 9:00 and 20:00 UT in the north–south magnetic field and about 14:00 UT in the east–west field [420]. The vertical electric field peaks at about 9, 14 and 20 UT [422].

These three times belong to the three great lightning centres in turn: Southeast Asia, Africa and South America [422]. The cavity is rung by the 44–50 flashes per second of the section above.

On the ladder the fundamental period of 0.128 s stands at 31.28. The Earth’s equatorial circumference, 2π × 6,378.137 km = 40,075 km [277], stands at 31.32. Light travels once around the circumference in $4.0075 \times 10^{7} / 2.998 \times 10^{8} = 0.134$ s, at the same position 31.32.

The cavity’s ground tone has the size of the Earth’s circumference. The period is 0.955 of the light-circuit time. Read on the ladder, it is the same winding at the size of the planet.

What this part of the history shows

Read through the net, the air has the form of what closes, stays at the scale of the planet. The Sun brightened by a factor of 1.33–1.4 over the Earth’s history. Liquid water is recorded under the air from 4,404 Ma (position 69.08) on.

Oxygen rose in three steps, read as loading, holding and discharge. Oxygenic photosynthesis ran for at least 400 Myr (position 66.90) before the GOE. The GOE took the air from 0.001 % PAL to up to 10 % PAL between 2.46 and 2.06 Ga.

A plateau of at most 0.1 % PAL followed from 1.8 to 0.8 Ga, a hold of 1 Gyr (position 67.73). The second rise came at 850–540 Ma, the third brought modern levels by the Devonian and a peak of about 35 % near 280 Ma.

Carbon dioxide fell by a mean of 3.4 ppm per Myr over 420 Myr, while the Sun’s irradiance rose by about 50 W m^{-2}. During long-lived glaciations it stood below 500 ppm, during warm periods above 1,000 ppm. Through eight glacial cycles the ice-core air held between 172 and 300 ppmv.

Read through the net, the bounds of 172–300 ppmv are the form of what closes, stays at the scale of 800 kyr (position 61.24). The present 426.07 ppm stands 1.42 times above the upper bound. Read through the net’s text, it counts the carbon that stands outside closed forms.

The air is a thin film with an address on the ladder. Its half-mass height of 5.6 km stands at 23.24, its scale height of 8.5 km at 23.62, the tropopause at 23.94 and the Kármán line at 25.87. The ocean’s mean depth stands at 22.86.

The cells of the circulation close each hemisphere with three loops, at boundaries near 30° and 60°. The jets run along those boundaries, at 9–24 km (positions 23.67–24.57).

Read so, lightning has the form of discharge. The air empties 44–46 times a second, ten times as often over land as over sea. The rate follows the northern summer, from 35 to 60 per second.

The cavity between ground and ionosphere rings at 7.83 Hz. Its period of 0.128 s stands at 31.28, the Earth’s circumference at 31.32. The ground tone of the air has the size of the planet that carries it.

16. The Magnetic Field

Under the ocean of chapter 14 and the air of chapter 15 lies a third shell, which cannot be seen. It is the magnetic field. It reaches from the liquid iron of the core out into space, where it meets the wind of the Sun.

The field is made in the core and read in the rocks. Lavas, sediments and single crystals keep its direction and strength [333][435]. From them the history of the field can be told for at least 3.45 billion years.

That history holds a steady dipole, a young solid inner core, and a field that reverses. One polarity once held for 37 million years; in other times the field turned several times in a million.

This chapter tells that history, then the field of the instrumental era, the field in space, and the core and mantle floor that carry it. Each size and time stands with its position on the ladder of chapter 11.

The core that carries the field

The Preliminary Reference Earth Model of Dziewonski and Anderson gives the shells of the deep Earth from seismic waves [280]. The solid inner core reaches from the centre to a radius of 1,221.5 km (position 28.14). The liquid outer core reaches from there to 3,480.0 km (position 29.10) [280].

The core–mantle boundary thus lies at a depth of 6,371 − 3,480 = 2,891 km (position 28.93). A secondary source gives the same depth [449]. The core fills 3,480 / 6,371 = 54.6 % of the Earth's radius, whose position is 29.65.

The inner core and the whole core stand at 28.14 and 29.10 on the ladder. Their radii differ by a factor of 3,480 / 1,221.5 = 2.85. The net's climate text places the Earth at layer 30, its outer core at 29 and its inner core at 28.

The density at the centre is 13.0885 g cm⁻³ [280]. From the PREM polynomials it is 12.76 g cm⁻³ on the inner side of the inner-core boundary and 12.17 on the outer side. At the core–mantle boundary it is 9.90 g cm⁻³ in the core and 5.57 in the mantle.

Across that boundary the density nearly doubles, and the shear waves vanish. On the mantle side the shear speed is 7.26 km s⁻¹ and the P speed 13.77 km s⁻¹; in the core the P speed is 8.06 km s⁻¹ [280]. In the inner core the shear waves return, at 3.50 km s⁻¹ [280].

Boundary	Side	Density (g cm⁻³)	Vp (km s⁻¹)	Vs (km s⁻¹)	[n]
Centre	—	13.0885	—	—	[280]
Inner-core boundary, r = 1,221.5 km	inner	12.76	11.03	3.50	[280]
Inner-core boundary	outer	12.17	10.36	0	[280]
Core–mantle boundary, r = 3,480.0 km	core	9.90	8.06	0	[280]
Core–mantle boundary	mantle	5.57	13.77	7.26	[280]

The inner core has a radius of "about 1221 km", about 19 % of the Earth's radius [448]. Its volume is about 7.6 billion km³, about 0.69 % of the Earth's; from the PREM radii, (1,221.5 / 6,371)³ = 0.70 %. Its mass is about 1.7 % of the Earth's [448].

The pressure in the inner core is "about 330 to 360 gigapascals" [448]. Its surface temperature is "approximately 5,700 K" [448]. Alfè and colleagues (2002) give 5,400–5,700 K; Anzellini and colleagues (2013) give a melting point of iron of 6,230 ± 500 K

[448].

Inge Lehmann found the inner core in 1936 [448]. She inferred a radius of 1,400 km (position 28.27).

The inner core stands at about 6,000 K and the core–mantle boundary at about 3,800 K [425]. Another page gives 4,000 K for the core and 2,000 K for the mantle at the boundary [306]. The top of the outer core is “about 500–1,800 K hotter than the overlying mantle” [449].

In the outer core the mean field is about 25 G, 2.5 mT [425]. That is “50 times stronger than the field at the surface” (Buffett, 2010) [425].

Heat crosses the core–mantle boundary. The Earth loses “46 ± 3 terawatts” through its surface [289]. Lay, Hernlund and Buffett note that estimates of the heat flow across the core–mantle boundary “have generally increased by a factor of 2 to 3” [289].

The core heat flow is “estimated at 5–15 TW” [450]. That is 5 / 46 = 11 % to 15 / 46 = 33 % of the surface flow. A second estimate of the surface flow is 47 ± 2 TW (Davies and Davies, 2010, range 43–49 TW) [450].

About half of the surface flow is radiogenic, after the geoneutrino measurements of Gando and colleagues (2011) [450]. The mantle loses 7–15 TW of primordial heat (Dye, 2012) [450].

In 1995 Glatzmaier and Roberts ran the first self-consistent three-dimensional simulation of a field reversal [451]. Their model “maintains a magnetic field for over 40,000 years” (position 58.52) and reverses [451].

The field is held in moving iron. In the outer core a field would diffuse away in “500 years or less” (position 54.53); in the inner core in about 3,000 years (position 56.16) (Gubbins, 1999) [431]. The field itself has lasted at least 3.45 Gyr (position 68.86), some $3.45 \times 10^9 / 500 = 7$ million times longer.

Read through the net, this is the form of form and carrier (chapter 11). Left to itself, the field in the moving iron would fade within centuries; the form has held for billions of years.

The first field

The oldest claimed record of the field lies in the same Jack Hills zircons that carry the oldest trace of water. The oldest of these grains is 4,404 ± 8 Ma old (position 69.08) [326].

Tarduno and colleagues measured single zircon crystals 3.3–4.2 Ga old (positions 68.82–69.04) from the Jack Hills conglomerate [332]. They found field strengths “between 1.0 and 0.12 times recent equatorial values” [332]. A Hadean field would require a core–mantle heat flow above the adiabatic value [332].

In 2020 they reported “a primary magnetic remanence carried by magnetite in these zircons” [333]. Their record of 4.2 Gy lies “just a few hundred million years after the lunar-forming giant impact” [333]. They find “a period of high geomagnetic field strength at 4.1 to 4.0 billion years ago (Ga)” (positions 69.02–69.00) [333].

Borlina and colleagues read the same zircons differently [334]. In them, “secondary magnetization carriers postdate formation of the zircons” [334]. They conclude that “the existence of the geodynamo before 3.5 Ga ago remains unknown” (position 68.87) [334].

The same rock thus gives a strong field at 4.1–4.0 Ga [332][333], or no established field before 3.5 Ga [334].

In the Isua Supracrustal Belt of southern West Greenland, Nichols and colleagues find that a “3.7-billion-year (Ga) old magnetic field may be preserved” (position 68.92) [348]. They “recover a field strength of >15 μT” [348]. Their age limits come from intrusions emplaced 3.26–3.5 Ga ago and from folding 3.6 Ga ago (position 68.90) [348].

The undisputed record begins in the Kaapvaal craton of South Africa. Rocks of the

Barberton belt, 3.4–3.45 Ga old (positions 68.85–68.86), carry a palaeofield “approximately 50 to 70% that of the present-day field” [430].

From that strength Tarduno and colleagues derive the boundary against the solar wind. The magnetopause then stood at 5 Earth radii or less [430]. A field “since at least about 3,450 million years ago” is recorded in Australia and South Africa [425].

Age	Rock	Finding	Field	[n]
4.2–4.0 Ga	Jack Hills zircons	primary magnetite; strong field at 4.1–4.0 Ga	0.12–1.0 × recent equatorial	[332][333]
before 3.5 Ga	Jack Hills zircons	carriers secondary; dynamo unknown	—	[334]
3.7 Ga	Isua, Greenland	possible record	> 15 µT	[348]
3.45–3.4 Ga	Barberton, Kaapvaal	field present; magnetopause ≤ 5 Earth radii	50–70 % of present	[430]

From the Earth’s formation to the undisputed field at 3.45 Ga is about 1.1 Gyr (position 67.82).

The inner core and the Proterozoic field

The outer core cools by about 100 °C per Gyr [448], and the solid inner core grows. When it first froze is read from the strength of the old field. Biggin and colleagues found a transition “between a billion and 1.5 billion years ago” (positions 67.73–68.10) [286].

At that transition “both average field strength and variability” increased [286]. Earlier estimates of the onset ran from “less than half a billion to nearly two billion years ago” [286].

Bono and colleagues measured the Sept-Îles intrusive suite, about 565 Ma old (position 67.21) [288]. They found a time-averaged dipole moment of “~0.7 × 10^{22} A m^2”, “more than ten times smaller” than the present [288]. Against today’s 7.94 × 10^{22} A m^2, the ratio is 11.3.

The angular dispersion of the directions was about 26° [288]. With 14 other directional data sets, the result suggests frequent reversals.

Bono and colleagues read the weak field as a sign of an Ediacaran onset of the inner core [288]. Predicted onset ages run “from ~0.5 to >2.5 billion years ago” (positions 67.10–68.57) [288].

Nine published ages of the inner core run from 0.5 Ga to below 4.2 Ga [448].

Study	Inner-core age	Method	[n]
Labrosse et al. 2001	1 ± 0.5 Ga	thermal, no radioactivity in core	[448]
Labrosse 2003	~2 Ga	thermal, with radioactivity	[448]
Smirnov et al. 2011	2–3.5 Ga	palaeomagnetism	[448]
Driscoll & Bercovici 2014	0.65 Ga	thermal model	[448]
Labrosse 2015	< 0.7 Ga	—	[448]
Biggin et al. 2015	1–1.5 Ga	palaeointensity	[448][286]
Ohta et al. 2016	< 0.7 Ga	iron resistivity	[448]
Konôpková et al. 2016	< 4.2 Ga	iron conductivity	[448]
Bono et al. 2019	0.5 Ga	palaeointensity	[448][288]

The field grew stronger and more variable at 1.0–1.5 Ga in one record, and was ultra-weak at 565 Ma in another. Each is read as the birth of the inner core.

Reversals and superchrons

The field has two polarities, normal and reverse, as the names of its long intervals show. The field turns from one to the other at irregular intervals, and the rocks keep each turn.

A superchron is “a polarity interval lasting at least 10 million years” (position 63.54) [431]. Three of them stand in the Phanerozoic record.

The oldest is a candidate: the Moyero Reverse Superchron, “lasting more than 20 million years (485 to 463 million years ago)” (positions 67.07–67.03) [431]. It is found only in the section of the Moyero river in Siberia (Pavlov and Gallet, 2005) [431].

The Kiaman Reverse Superchron ran from about 312 to 262 Ma (positions 66.67–66.51), “more than 50 million years” (position 65.01) [431]. A polarity time scale for the Carboniferous by Hounslow counts 33 conventional magnetochrons for the Mississippian and Pennsylvanian, 27 of them in the Pennsylvanian [434]. It rests on 31 U–Pb zircon dates [434].

In the Jurassic the ocean floor older than 160 Ma (position 66.07) was long called the Jurassic Quiet Zone [432]. Tominaga, Tivey and Sager surveyed it at several scales in the Pacific.

They extended the reversal history “from M29 back to M44” [432]. The zone is no longer counted as a superchron [431].

The field was weak about 130 to 170 Ma (positions 65.88–66.12), in the Mesozoic Dipole Low [431]. Its onset lies “from M42 through M39” [432].

The Cretaceous Normal Superchron, C34, “lasted for 37 million years” (position 64.73), from about 120 to 83 Ma (positions 65.80–65.47) [431]. The British Geological Survey gives “about 30 million years around about 100 million years before present” (position 64.54) without a reversal [424].

Since 83 Ma the field has turned often. The Cenozoic record holds “184 polarity intervals in the last 83 million years (and therefore 183 reversals)” (Cande and Kent, 1995) [431].

On average the field reversed “once every ~450,000 years” (position 60.72). The exact mean is 83 Myr / 183 = 454 kyr (position 60.73).

The rate varied [431].

Time	Reversals	Interval	Rate (per Myr)	[n]
about 72 Ma	5	1 Myr	5.0	[431]
centred on 54 Ma	10	4 Myr	2.5	[431]
about 42 Ma	17	3 Myr	5.7	[431]
centred on 24 Ma	13	3 Myr	4.3	[431]
centred on 15 Ma	at least 51	12 Myr	4.25	[431]

Twice the field reversed within 50,000 years (position 58.72) [431].

A new time scale, MM25, covers the magnetochrons C33 to C13, about 83–33 Ma [433]. It combines 23 radioisotopic dates, 128 magnetochron durations and 154 ship tracks over thirteen ridge-flank regions [433].

Read through the net, the field has the form of one direction (chapter 11), with either direction able to win. It holds one polarity at a time, and either polarity holds: for 37 Myr in the Cretaceous and for more than 50 Myr in the Kiaman.

How a reversal runs

A reversal takes time. The last four reversals average about 7,000 years (position 56.93), shorter at low latitude (Clement, 2004) [431]. Glatzmaier and Coe (2015) give 2,000–12,000 years (positions 55.79–57.42) for full reversals [431].

Merrill and colleagues (1998) give 1,000–10,000 years for most estimates [431]. Yamamoto and colleagues (2026) find up to 70,000 years (position 59.03) for some

[431]. Sagnotti and colleagues (2014) describe a reversal “as quick as a human lifetime” [431].

Single lava flows record the fastest change. At Steens Mountain, in lavas of 16.7 Ma (position 64.01), the direction changed “up to 6 degrees per day” (Coe, Prévot and Camps, 1995) [431]. At Battle Mountain, Nevada, about 15 Ma (position 63.91), the direction changed “by over 50 degrees” within several years (Bogue, 2010) [431].

The last reversal

The last full reversal is the Brunhes–Matuyama. Singer and colleagues synchronised volcanic, sedimentary and ice-core records of it [435]. “The final 180° polarity reversal at ~773 ka culminates a complex process” (position 61.21) [435].

The process began about 795 ka (position 61.24) with a weakening of the field [435]. An excursion at about 784 ka (position 61.22) “heralds a >10 ka period” [435]. In all, “the 22 ka evolution of this reversal” ran from 795 to 773 ka (position 57.97) [435].

An older round value gives “about 780,000 years ago” [425]. Since 773 ka the field has held one polarity. That is 773 / 454 = 1.7 times the mean interval of the last 83 Myr.

Excursions

Between reversals the field sometimes swings far and returns. These swings are excursions, read as “failed reversals” (Gubbins, 1999) [431].

The Laschamp excursion is the first known [436]. It fell “between 42,200 and 41,500 years ago” (positions 58.56–58.55) [436]. Cooper and colleagues give “a precisely dated radiocarbon record around the time of Laschamps reversal about 41,000 years ago” (position 58.54) [437].

The transition took “approximately 250 years” (position 53.90) [436]. The field stayed fully reversed for “approximately 440 years” (position 54.41). Its strength fell to “5% of its current strength” in the transition and held “about 25% of its current strength” while reversed [436].

A New Zealand kauri tree “alive from 42,500–41,000 years ago” carries the event in its radiocarbon [436]. From beryllium-10 in Greenland ice the field fell “to an estimated 5% of normal”, and the inverted state lasted “only a few hundred years” (Nowaczyk and colleagues, 2012) [431].

Laj, Kissel and Roberts compared the Iceland Basin excursion and the Laschamp excursion [438]. They gave four new records of the first and five of the second.

The pole paths of both are similar, and “three reach Antarctica” [438]. Each excursion lasted less than 2,000 years (position 55.79) [438].

The excursion of 784 ka came about 784 − 773 = 11 kyr (position 57.34) before the last full reversal [435].

Event	Age	Duration	Field minimum	[n]
Laschamp	42.2–41.5 ka (~41 ka)	transition ~250 yr; reversed ~440 yr	5 % (transition); 25 % (reversed)	[436][437]
Laschamp, beryllium-10	~41 ka	a few hundred years	~5 %	[431]
Iceland Basin and Laschamp	—	< 2,000 yr	—	[438]
Brunhes–Matuyama precursor	~784 ka	—	—	[435]

Read through the net, an excursion has the form of loading, holding and discharge (chapter 11). The field drops to a twentieth, holds the other direction for a few centuries, and returns.

The field in historical time

The field changes from year to year. Over observatory records of hundreds of years, the declination changes by “tens of degrees” [428]. This slow change is the secular variation.

The part of the field beyond the dipole drifts west at “about 0.2 degrees per year” (Dumberry and Finlay, 2007) [428]. At that rate it would turn through 360° in 360 / 0.2 = 1,800 years (position 55.69). At the core–mantle boundary, radius 3,480 km, 0.2° per year is about 12 km per year.

The global mean drift has been westward “since about 1400 AD” [428]. Between about 1000 and 1400 AD it ran eastward. The British Geological Survey traces the westward motion of the declination pattern “using direct observations of the magnetic field over the past 400 years” (position 54.32) [424].

The Levantine Iron Age anomaly had maxima about 950, 750 and 500 BCE (Rivera, Pavón-Carrasco and Osete, 2023) [428]. For the International Geomagnetic Reference Field the secular variation “is assumed to be constant over 5-year intervals” (position 50.34) [424].

The magnetic poles wander. Modelled positions run from 1590 to 2025 [427].

James Clark Ross first reached the north dip pole in 1831 [427]. Natural Resources Canada tracked it from 1948 to 1994, and locations were added in 2001 and 2007 [427]. The south dip poles were observed from 1903 to 2000.

From Cape Adelaide in 1831 the north pole moved north-west to about 600 km (position 27.50) from Resolute Bay by 2001 [425]. It moved about 10 km per year at the beginning of the 1900s, and “up to 40 kilometres (25 mi) per year in 2003” [425].

The geomagnetic reference model gives the speed more exactly. The north dip pole sped up, “peaking at 55.8 km/year in 2002.5 and slowing slightly to 50.6 km/year in 2017.5” [426].

The model “forecasts a speed of 39.8 km/year in 2022.5” [426]. The previous generation of the model had predicted 42.6 km per year for 2017.5 [426].

The latest survey finds the pole moving “approximately north-northwest at 55km per year” [427]. From about 10 km per year near 1900 to 55.8 in 2002.5 is a factor of 5.6. From 55.8 to the forecast 39.8 km per year is a fall of 29 %.

Year	Speed of the north dip pole	[n]
~1900	~10 km/yr	[425]
2002.5	55.8 km/yr (peak)	[426]
2003	up to 40 km/yr	[425]
2017.5	50.6 km/yr (42.6 predicted)	[426]
2022.5	39.8 km/yr (forecast)	[426]
latest survey	~55 km/yr, north-northwest	[427]

In 2025 the North Magnetic Pole stood at “85.762°N and 139.298°E” and the South Magnetic Pole at “63.851°S and 135.078°E” [427]. The geomagnetic north pole stood at 80.85° N, 72.76° W, and the geomagnetic south pole at 80.85° S, 107.24° E [427].

The dipole axis is tilted 90° − 80.85° = 9.15° from the rotation axis (2025). In 2020 the geocentric dipole stood at 80.65° N, 72.68° W, a tilt of 9.35° [277].

Over the South Atlantic the field is weak. Between 1970 and 2020 the minimum there fell “from around 24 000 nanoteslas to 22 000” [429].

The anomaly moved west at “around 20 km per year” [429]. “A second centre of minimum intensity has emerged southwest of Africa” [429].

The fall of 2,000 nT in 50 years (position 52.43) is 40 nT per year, 0.18 % per year of 22,000 nT. The minimum of the anomaly equals the bottom of the surface range given by the British Geological Survey, 22,000 nT [424][429].

The anomaly is bounded where the sea-level field is “less than 32,000 nanotesla” (Pavón-Carrasco and De Santis, 2016) [439]. Its centroid lay near 26.61° S, 49.06° W in January 2021 and drifts “about 0.23°S 0.34°W per year” (Kovář and Sommer, 2021) [439]. Its strongest part drifts west at about 0.3° per year.

Over the anomaly the inner radiation belt dips “down to 200 km” (position 26.50) (Stassinopoulos and others, 2015) [439]. On the Space Shuttle mission STS-94 the dose rates there were 112–175 µGy per day, or 264.3–413 µSv per day (Badhwar and others, 1999) [439]. The reference field model places the anomaly “centered over South America”, “a region of significantly weaker field” [426].

The dipole is weakening. The British Geological Survey gives “a 6% decline in the dipole moment per century” at the present time [424]. A secondary source gives “about 6.3% per century” over the last two centuries [428].

At that rate the dipole “would reach zero in about 1600 years” (position 55.59) [428]. Its present strength is “about average for the last 7 thousand years” (position 56.93) [428]. The reference model shows “a clear downward trend” in its dipole series [426].

The European Swarm mission finds that the field lost “around 9% of its strength on a global average” over the last 200 years (position 53.69) [429]. The dipole moment, at 6–6.3 % per century, loses 12–12.6 % in 200 years [424][428].

The field now

At the Earth’s surface “the total intensity varies from 22,000 nanotesla (nT) to 67,000 nT” [424]. The NASA fact sheet gives a surface field of “0.24 - 0.66 Gauss”, 24,000–66,000 nT [277]. The strength falls from the poles toward the equator [425].

A survey of 2019 gives about 30,000 to 60,000 nT: about 60,000 nT over Siberia and about 30,000 nT over Brazil [425]. “The largest field intensities occur in Siberia in the northern hemisphere” [426].

The dipole has a strength of “0.306 Gauss-Re3”, with an Earth radius of 6,378 km [277]. For a centred dipole this gives 30,600 nT at the dipole equator and twice that, 61,200 nT, at the dipole poles. The dipole is offset from the centre by 0.076 Earth radii [277].

The dipole moment follows as $M = B_0 \cdot 4\pi R^3 / \mu_0$. The inputs are $B_0 = 3.06 \times 10^{-5}$ T, $R = 6.378 \times 10^6$ m and $\mu_0 = 4\pi \times 10^{-7}$. Then $M = 3.06 \times 10^{-5} \times (6.378 \times 10^6)^3 / 10^{-7} = 7.94 \times 10^{22}$ A m².

In 2020 “over 93% of the power in the main geomagnetic field” lay in the three dipole coefficients g_1^0, g_1^1 and h_1^1 [426]. The field is almost all one pair of poles.

Quantity	Value	[n]
Surface total intensity	22,000–67,000 nT	[424]
Surface field (model)	0.24–0.66 G	[277]
Dipole strength	0.306 G·Re³	[277]
Dipole equator / pole	30,600 / 61,200 nT	[277]
Dipole moment	7.94×10^{22} A m²	[277]
Dipole share of power	> 93 %	[426]
Dipole tilt (2025)	9.15°	[427]
Dipole decline	6 % per century (6.3 %)	[424][428]
Global loss over 200 years	~9 %	[429]
Field in the outer core	~25 G	[425]

The field in space

On the side facing the Sun the field holds off the solar wind at “about 10 Earth radii out” [425]. Ten Earth radii are 63,710 km (position 31.74). Typical distances of this boundary, the magnetopause, “range from 6–15” Earth radii (positions 31.28–32.11) (Shue and others, 1997) [440].

Behind the Earth the field trails a tail that “extends beyond 200 Earth radii”, 1.27 × 10^6 km (position 34.47) [425]. During reversals the magnetopause stands at “about three Earth radii” (position 30.65) [431]. At 3.45–3.4 Ga it stood at 5 Earth radii or less, 31,860 km (position 31.11) [430].

The same field holds its boundary at other distances as the solar wind changes: 6–15 Earth radii in typical times, about 3 during a reversal. Read through the net, this is the form of context (chapter 11): the same rule takes other values in other surroundings.

The field traps charged particles in belts. The main belts span “about 640 to 58,000 km” (positions 27.56–31.66) [442].

The inner belt lies at “0.2 to 2 Earth radii”, about 1,000–12,000 km. The outer belt lies at “3 Earth radii … to 10 Earth radii (RE)—13,000 to 60,000 kilometres” (positions 30.30–31.69) [442].

Another page gives the inner belt at “1–2 Earth radii out” and the outer at “4–7 Earth radii” [425].

The inner belt holds protons “exceeding 100 MeV” and electrons of “hundreds of keV” [442]. The outer belt holds electrons of 0.1–10 MeV [442]; ions of 0.1 to 10 MeV are given on another page [425]. Antiprotons of 60–750 MeV are trapped as well [442].

Between the belts, electrons in the slot region live “around one or two days” (positions 43.50–44.13) [442]. A “safe zone” lies at 2–4 Earth radii.

Explorer 1 and Explorer 3 confirmed the belts early in 1958 [442]. The Van Allen Probes, launched on 30 August 2012, saw a transient third belt in 2013 that lasted four weeks (position 46.53) [442].

The solar wind sometimes strikes hard. Storm size is read in the index Dst [443].

Class	Dst	[n]
Quiet	+20 to −20 nT	[443]
Moderate	−50 to −100 nT	[443]
Intense	−100 to −250 nT	[443]
Super-storm	below −250 nT	[443]

In the initial phase Dst rises “by 20 to 50 nT in tens of minutes” (Gonzalez and others, 1994) [443]. The main phase lasts “typically 2–8 hours” (positions 41.24–42.50). The recovery is “as short as 8 hours or as long as 7 days” (positions 42.50–45.27) [443].

The largest storm on record came on 1–2 September 1859. Carrington and Hodgson saw the flare “Just before noon on 1 September 1859” [444]. The mass ejection crossed the 150 × 10^6 km to the Earth in “17.6 hours” (position 43.22) [444].

That is a mean speed of 150 × 10^6 km / 17.6 h = 2,370 km s^{-1}. Telegraph lines threw sparks and caught fire, and aurorae were seen as far as Cuba, Hawaii and Colombia [444].

Tsurutani and colleagues estimate a Dst of about −1,760 nT for the storm [445]; a secondary page gives −0.80 to −1.75 μT [444]. At Colaba in Bombay the horizontal field changed by 1,600 ± 10 nT at local noon [445]. They call it “the most intense in recorded history”.

The storm of March 1989 reached a Dst of −589 nT and brought down the grid of Quebec [443]. The Halloween storms of 2003 reached −151, −353 and −383 nT; on 4–5 November the Dst was −69 nT [443].

On 10–11 May 2024 three mass ejections struck [441]. The Dst reached −412 nT at 03:00 UTC on 11 May; some readings gave −518 nT. The Kp index reached 9, the storm class G5, and Ap stood at 271 [441].

The aurora stood overhead at Onawa, Iowa, at 42° N geographic and 51° N magnetic latitude [441]. It was the most intense storm since 1989 [441]. The subsolar magnetopause was pressed from “higher than 10 RE” to 5 Earth radii [441].

In 2024 the field changed by “over 700 nT/min”, against “350–400 nT/min” for the

extreme of once in 100 years (position 53.06) (Beggan and others, 2024) [444]. In July 2012 a mass ejection missed the Earth “by a margin of roughly nine days” (position 45.50) [444].

Nitrate spikes in ice cores have been read as a storm record. The records of Greenland and Antarctica “do not align” (Wolff and others, 2012; Mekhaldi and others, 2017) [444].

The Sun’s storms follow its own cycles. The solar polarity (Hale) cycle lasts 22 years (position 51.68); the Schwabe cycle 9–14 years (positions 50.87–51.27) [446].

Storm	Date	Dst	[n]
Carrington	1–2 Sep 1859	~−1,760 nT (Colaba ΔH 1,600 ± 10 nT)	[445]
Quebec	Mar 1989	−589 nT	[443]
Halloween	Oct–Nov 2003	−151, −353, −383 nT	[443]
May 2024	10–11 May 2024	−412 nT (−518)	[441]

Read through the net, the magnetopause has the form of the edge (chapter 11). Inside it the field holds; at the boundary it meets the flow of the solar wind. Under a strong storm the edge moves in from 10 to 5 Earth radii.

Below the belts lies the ionosphere, from about 48 km to 965 km above sea level (positions 25.20–27.93) [447]. It has four layers of free electrons [447].

Layer	Height	Electron density (cm⁻³)	[n]
D	60–90 km	10^2–10^4	[447]
E	105–160 km	several × 10^5	[447]
F1	160–180 km	several × 10^5–10^6	[447]
F2	200 to over 800 km; peak near 300 km by day	several × 10^6	[447]

At night only the F layer stays significant [447]. Molecular ions recombine about 1,000 times faster than atomic ions. Sporadic E reflects signals up to 100 MHz, in sheets up to 2 km thick (position 22.30) and hundreds of kilometres long [447].

Marconi sent a signal across the Atlantic on 12 December 1901, at about 500 kHz [447]. Appleton and Barnett detected the E layer in 1924.

Appleton received the Nobel Prize in 1947 [447]. The ionosphere forms the upper wall of the cavity that rings at 7.83 Hz (chapter 15).

The floor of the mantle

Above the core lies the floor of the mantle, through which the core’s heat must pass. Its lowest part is the D″ layer, “approximately 200 km thick” (position 26.50), directly above the core–mantle boundary [449].

Bullen named it in 1949, when he split the lower mantle into D′, about 1,800 km thick (position 28.50), and D″, the bottom 200 km [449]. D″ may consist of post-perovskite [449].

On that floor stand two large provinces where shear waves travel slowly. They lie under Africa and under the Pacific and are named Tuzo and Jason [306]. They “extend approximately 1,000 kilometres upward from the base of the mantle” (position 27.96) [305].

Lau and colleagues weighed them with the tides of the solid Earth. The bottom two-thirds have a mean density “about 0.5 per cent higher than the average mantle density” [305].

Their lateral extent is “thousands of kilometers”; the Pacific province is “3,000 kilometers (1,900 miles) across” (position 28.96) [306]. Together they fill “around 8% of the volume of the mantle”, “6% of the entire Earth” [306].

With an Earth volume of 1.083 × 10^{21} m^3, 6 % is 6.5 × 10^{19} m^3. They may be “over a billion years old” (position 67.73) [306].

Yuan and colleagues propose that they hold remnants of the body that struck the Earth and made the Moon (chapter 12) [307]. That mantle material would be “intrinsically 2.0–3.5% denser than proto-Earth’s mantle”, in “dense TMM blobs with a size of tens of kilometres” [307]. The tides give a density excess of 0.5 % [305]; the impactor model gives 2.0–3.5 % [307].

At the edges of the provinces lie ultra-low velocity zones [453]. They are “tens of kilometers thick” and “a hundred to a thousand kilometers across”. Shear waves slow there by “up to 45%”, typically by 10–30 % [453].

Zone	Size	Velocity and density	[n]
Samoa mega-zone	~800 × 250 km, 10–15 km high	Vs −45 %, Vp −15 %, density +10 %	[453]
Hawaii	~1,000 km across, 20 km high	Vs ~−20 %	[453]

Williams and Garnero studied them in 1996 [453]. The Samoa zone, 10–15 km high, stands at 23.77–24.14 on the ladder; the Hawaii zone, 20 km high, at 24.40.

At the top of the mantle lies the Moho, the base of the crust. It lies 5–10 km (positions 23.14–23.77) below the ocean floor and 20–90 km (positions 24.40–25.77) below the continents, 35 km on average (position 24.91) [452]. The P speed jumps there by “approximately 1 km/s”, from 6.7–7.2 km s^{-1} in basalt to 7.6–8.6 km s^{-1} in peridotite and dunite [452].

Andrija Mohorovičić found it in 1909 from an earthquake near Zagreb, at a depth of “approximately 54 km” (position 25.30) [452]. The PREM places the top of the lid, as a global average, at 24.4 km depth (position 24.58) [280].

The deepest hole ever drilled, the Kola Superdeep borehole, reached 12,260 m (position 23.96) between 1970 and 1992 [452]. It stopped above the continental Moho. Project Mohole was cancelled in 1966 [452].

Feature	Depth or size	Position	[n]
Moho, ocean	5–10 km	23.14–23.77	[452]
Kola borehole	12.26 km	23.96	[452]
Moho, continents (mean)	35 km	24.91	[452]
D″	~200 km thick	26.50	[449]
Large low-shear-velocity provinces	~1,000 km high	27.96	[305]
Pacific province	~3,000 km across	28.96	[306]
Core–mantle boundary	2,891 km deep	28.93	[280]

The turning inner core

The inner core is not uniform. P waves cross it “about 1% faster in the north–south direction” (Poupinet and others, 1983; Morelli and others, 1986) [448].

Frost and Romanowicz (2017) give 0.5–1.5 %. Claims of up to 4.8 % are disputed [448].

A study of 2023 found P waves about 4 % slower at about 50° from the rotation axis [448]. Within the inner core an innermost ball has been proposed, with a radius of 300–750 km (positions 26.87–27.70) [448]. Ishii and Dziewoński (2002) gave about 300 km, Wang and Song (2018) about 500 km, and a study of 2023 a “~650-km thick innermost ball” [448].

The inner core may also turn against the mantle. In 1996 Song and Richards found a change in travel times through it “over the past three decades” [454].

They read a rotation “on the order of 1° per year” faster than the mantle [454]. At the inner-core surface, radius 1,221.5 km, 1° per year is 21.3 km per year.

In 2005 Zhang and colleagues used “18 high-quality waveform doublets with time

separations of up to 35 years” (position 52.11), recorded at “up to 58 stations” [455]. They found a rotation of “about 0.3 degrees to 0.5 degrees per year” faster than mantle and crust [455]. That is 6.4–10.7 km per year at the surface of the inner core.

In 2023 Yang and Song found that the differential rotation “has recently paused”, with little change over “the past decade” [456]. They found “an approximately seven-decade oscillation” (position 52.74), with “another turning point in the early 1970s” [456].

The period “coincides with changes in … the length of day and magnetic field” [456].

In 2024 Wang, Vidale and colleagues used “143 distinct pairs of repeating earthquakes” in “16 multiplets”, from “121 earthquakes between 1991 and 2023” [457]. The inner core “super-rotated from 2003 to 2008” [457]. Then it “sub-rotated two to three times more slowly back through the same path”.

The forward motion lasted 5 years (position 50.34), from 2003 to 2008. The return lasted 15 years (position 51.34), from 2008 to 2023: three times as long.

Year	Finding	Data	[n]
1983–1986	north–south P waves ~1 % faster	travel times	[448]
1996	super-rotation ~1° per year	three decades of travel times	[454]
2005	0.3–0.5° per year	18 doublets, up to 35 years apart, 58 stations	[455]
2023	pause; ~70-year oscillation; turn in the early 1970s	—	[456]
2024	super-rotation 2003–2008, return 2–3 times slower	143 pairs from 121 earthquakes, 1991–2023	[457]

The inner core turns forward and back along one path. Read through the net, its motion has the form of loading and discharge: five years out, fifteen back.

The day and the wobble

The day is not constant. The mean solar day has 86,400 mean solar seconds (position 43.50), “about 0 to 2 ms longer than 86,400 SI seconds” [458]. The sidereal day lasts 86,164.09053083288 s and the stellar day 86,164.098903691 s [458].

The angular velocity of the Earth is $(7.2921150 \pm 0.0000001) \times 10^{-5}$ rad s^{-1} (IERS) [458].

Eclipses record the length of the day over 2,700 years (position 56.06). Stephenson, Morrison and Hohenkerk used ancient and medieval eclipses from 720 BC to AD 2015 [316]. The day lengthened “at an average rate of +1.8 ms per century” (position 27.40) [316].

That is “significantly less than” the “+2.3 ms per century” (position 27.62) predicted from tidal friction [316]. The difference, $2.3 - 1.8 = 0.5$ ms per century, is a non-tidal acceleration. Chapter 12 tells the tidal part of this history.

On scales of 2–30 years (positions 49.50–51.97) the fluctuations follow a power law with an exponent of -1.3 [316]. They show “evidence of increased power at a period of 6 years” (position 50.50). There is “some indication of an oscillation in lod with a period of roughly 1500 years” (position 55.53) [316].

Holme and de Viron found “a 5.9-year period oscillation” (position 50.49) in the length of day [317]. Its jumps are “contemporaneous with geomagnetic jerks” [317].

Roberts, Yu and Russell found a periodicity of about 60 years (position 52.60) in the Earth’s angular velocity [318]. The declination at ten observatories shows a period of “about 62 ± 3 years”; the inclination at five shows “58 ± 5 years” [318]. The correlation is about 0.6.

The annual term of the day has an amplitude of 0.34 ms (position 25.88), peaking about

3 February [319]. The semiannual term has 0.29 ms (position 25.74), peaking about 8 May.

Fluctuations over 10 days (position 45.60) are of order 0.1 ms. The coupling time between core and mantle is about ten years (Rosen, 1993) [319].

In 2022 a day “completed in 1.59 milliseconds under 24 hours” (position 27.29) [458]. The Indian Ocean earthquake of 2004 shortened the day by 3 µs (position 21.58); the Three Gorges Dam lengthened it by 0.06 µs [458].

“Around every 25–30 years Earth’s rotation slows temporarily by a few milliseconds per day” [458]. The modern day is about 1.7 ms longer than a century ago [458].

Rhythm	Period or amount	Position	[n]
Annual term	0.34 ms	25.88	[319]
Semiannual term	0.29 ms	25.74	[319]
Intradecadal	5.9 yr (~6 yr)	50.49	[317][316]
Multidecadal, rotation	~60 yr	52.60	[318]
Declination	62 ± 3 yr	52.63	[318]
Inclination	58 ± 5 yr	52.57	[318]
Inner-core rotation	~70 yr	52.74	[456]
Long term	~1,500 yr	55.53	[316]
Secular trend	+1.8 ms per century (2.3 tidal)	27.40	[316]

The band of 58–70 years appears in three records: the length of day, the direction of the field, and the turning of the inner core. On the ladder they stand at 52.57–52.74. Read through the net, it is the same winding at three depths: mantle rotation, field and inner core.

The axis of rotation wobbles. The Chandler wobble has a period of 433 days (position 49.03) and moves the pole by about 9 m (position 17.39) at the surface [459].

Seth Carlo Chandler found it in 1891. Euler had predicted 305 days (position 48.71) for a rigid Earth [459].

The observed period is 433 / 305 = 1.42 times the rigid value, and 433 / 365.25 = 1.185 years. Without excitation the wobble would decay with a time constant of “about 68 years” (position 52.71) [459]. About two-thirds of its excitation comes from pressure on the ocean bottom and one third from air pressure (Gross, 2000) [459].

Its phase reversed in 1850, 1920 and 2005 (Malkin and Miller, 2009) [459]. Its amplitude has “greatly diminished post-2015” [459].

A second account gives “a period of about 435 days” [460]. The resonance lies at 441 sidereal days, 1.20 sidereal years; the observed free nutation spans 435–445 sidereal days [460].

The amplitude has “never exceeded 230 mas” in the last 100 years and “varies by a factor of three” [460]. At a radius of 6,371 km, 230 mas is 7.1 m (position 17.17). The annual component is “rather constant in amplitude” [460].

Beneath the wobble the mean pole drifts “about 0.10 m per year in the direction of 80° west” [460]. Since 1900 it has moved “about 20 m” (position 18.11).

At 0.10 m per year over 125 years (1900–2025) the drift would be 12.5 m. Since about 2000 it has moved roughly along the central meridian (Chen and others, 2013; Adhikari and Ivins, 2016) [460].

Read through the net, the wobble has the form of what closes, stays. It would die away in about 68 years, yet the pressure of sea and air keeps it going. Its form holds while its excitation is renewed.

What this part of the history shows

Read through the net, the field has the form of form and carrier. In the outer core a

field would diffuse away in 500 years or less (position 54.53). The field itself has held for at least 3.45 Gyr (position 68.86), carried by moving iron.

Read so, it has the form of one direction. It holds one polarity at a time, and either polarity holds. The Cretaceous Normal Superchron held one for 37 Myr (position 64.73); the Kiaman held the other for more than 50 Myr (position 65.01).

Since 83 Ma the field has turned 183 times, once every 454 kyr (position 60.73) on average. Since the last reversal at 773 ka (position 61.21) it has held one direction 1.7 times the mean interval.

Read so, excursions have the form of loading, holding and discharge. The Laschamp field fell to 5 % in about 250 years, held the other direction for about 440 years and returned. The Iceland Basin and Laschamp excursions each lasted less than 2,000 years.

Read so, the magnetopause is the edge of the field. On the day side it stands at about 10 Earth radii (position 31.74), where the field meets the solar wind.

In May 2024 the edge moved in to 5 Earth radii, at 31.11 on the ladder. At 3.45 Ga, under a field of 50–70 % of today’s, it stood at 5 or less.

Read so, the boundary has the form of context. The same field holds the wind at 6–15 Earth radii in typical times, at 5 in a great storm and at about 3 during a reversal.

The inner core at 28.14, the core at 29.10 and the Earth at 29.65 are nested shells. The net’s climate text places them at layers 28, 29 and 30. Across the core–mantle boundary the density nearly doubles, from 5.57 to 9.90 g cm⁻³.

A band of 58–70 years runs through three records: the length of day at about 60 years, the field direction at 58–62 years, and the inner-core rotation at about 70 years. On the ladder they stand together at 52.57–52.74. Read through the net, it is the same winding at three depths.

Read so, the Chandler wobble has the form of what closes, stays. It would decay in about 68 years (position 52.71), yet it has run since its discovery in 1891. Its period of 433 days stands at 49.03.

17. Plates and Continents

The first crust formed in the Hadean (chapter 13). Oceans covered it (chapter 14), and a magnetic field shielded it (chapter 16). This chapter follows what the surface did next: it broke into plates, and the plates began to move.

The history runs in four parts. First comes the start of plate motion, dated from more than 4 Ga (69.00) to about 0.8 Ga (67.53) by different methods. Then come the plates of today, with their number, areas and speeds.

The third part is the ocean floor, made at the ridges and consumed in the trenches. The last part is the long cycle in which the continents gather into one mass and break apart again.

Every size and every age carries its position on the ladder of chapter 11. An age of A years is placed as a duration of A years: $\log_3$ of A × 3.15576 × 10^7 s over 1.520655 × 10^{-16} s.

The first plates

The oldest witnesses are zircon grains from the Jack Hills in Western Australia. More than 400 Hadean zircons are known there [329]. Some of them, aged 4.19–4.02 Ga (positions 69.04–69.00), carry mineral inclusions that record the conditions of their growth.

The inclusions formed at about 700 °C and 7 kbar (7 × 10^8 Pa) [329]. They give a heat flow near the surface of about 75 mW m^{-2}. That is “about three to five times lower than estimates of Hadean global heat flow” [329].

Three to five times 75 mW m^{-2} is 225 to 375 mW m^{-2}. The authors read the low value as melting “largely in an underthrust environment”, “perhaps similar to modern convergent margins” [329]. On that reading, one plate slid under another before 4.0 Ga (69.00).

Other methods give other dates. A summary of the field states that plates have moved “since 3–4 billion years ago”, and that the estimates of onset span “85% of Earth’s history” [354]. Eighty-five per cent of 4.567 Gyr (69.12) is 3.88 Gyr (position 68.97).

The same summary lists the main dates [354]. Subduction may have started “as early as 3.8 billion years ago” (68.95). Modern plate tectonics ran “at least 2.2 billion years ago” (68.45), when the supercontinent Columbia was assembled.

Some authors place the start “800 million years ago” (67.53), from the appearance of blueschists [354]. Others place it “over 4 billion years ago” (69.00), in the Hadean [354]. The Archean mantle was “100 and 250 °C warmer” than today’s [354].

Modern-style subduction ran “at least as early as 1.8 Ga” (68.27) [462]. Eclogite xenoliths show subduction-driven assembly of continents at 1.9–2.0 Ga (68.32–68.36) [462].

A third record is the growth of the continents. Dated zircons show that “Increased rates of crustal destruction starting around 3 billion years ago coincide with the onset of” subduction-driven plate tectonics [352]. The destruction slowed “the overall rate of crustal growth” [352].

The rates of chapter 13 show the same turn. Net growth of continental crust was 2.9–3.4 km^3 per year before 3 Ga (68.73), and 0.6–0.9 km^3 per year after [351]. At least one present volume of continental crust has been destroyed and recycled since 3 Ga [351].

The chemistry of the upper crust changed in the same era. The shift to “contemporary crust composition occurred after the Archean era, suggesting the onset of plate tectonics” [461]. The Archean spans 3.8–2.5 Ga (68.95–68.57) [380].

The minerals keep a record too. A count of mineral species by mode of formation gives a

stage named “initiation of plate tectonics”, at less than 3.5 to 2.5 Ga (68.87 to 68.57) [272]. In that stage 458 species formed by modes first active then [272].

Onset estimate	Method	Age	Position	Source
Underthrust melting	zircon inclusions, 75 mW m^{-2}	4.19–4.02 Ga	69.04–69.00	[329]
Hadean plate motion	various	over 4 Ga	69.00	[354]
Early subduction	various	3.8 Ga	68.95	[354]
Crustal destruction rises	Hf–Pb–O isotopes in zircon	about 3.0 Ga	68.73	[352]
Mineral stage of plate tectonics	paragenetic modes	below 3.5 to 2.5 Ga	68.87–68.57	[272]
Modern upper-crust composition	crust chemistry	after 2.5 Ga	68.57	[461]
Columbia assembled by plates	supercontinent assembly	at least 2.2 Ga	68.45	[354]
Subduction-driven assembly	eclogite xenoliths	1.9–2.0 Ga	68.32–68.36	[462]
Modern-style subduction	various	at least 1.8 Ga	68.27	[462]
Late onset	blueschists	about 0.8 Ga	67.53	[354]

Each method reads a different trace of the plates: heat in a grain, the rate of crustal loss, the chemistry of the upper crust, the first blueschists. The positions run from 69.04 to 67.53. Two independent records, crustal destruction and crust chemistry, both mark a change between 3.0 and 2.5 Ga (68.73–68.57).

The plates of today

The count of plates has grown with the data. In 1967–68 Morgan described “12 rigid plates”, and Le Pichon in 1968 “six major plates” [354]. Today “seven or eight major plates” are named [354].

The finer models count more. The model MORVEL uses “25 tectonic plates that collectively occupy 97 per cent of Earth’s surface” [464]. It rests on 1,696 spreading rates and 133 transform faults [464].

The boundary model PB2002 “includes 52 plates”: 14 large plates and 38 small ones [463]. It treats belts such as Alps–Persia–Tibet as orogens, not as plates [463]. The areas of its small plates follow a power law [463].

The geodetic model GSRM v2.1 rests on GPS. Its authors “determined 6739 velocities” and added “15,772 velocities from 233 (mostly) published studies”, 22,511 in all [465]. “About 14% of the Earth is allowed to deform in 145,086 deforming grid cells” [465].

The rest of the surface in GSRM is “rigid spherical caps representing 50 tectonic plates” [465]. New GPS-derived angular velocities are given for 36 plates [465]. At the finest cut, the crust divides into “roughly 1200 terranes” [354], or “a subdivision of ca. 1200 smaller plates” [466].

The plate list sorts plates by area: major above 20 × 10^6 km^2, minor 1–20 × 10^6 km^2, micro below 1 × 10^6 km^2 [466]. The list gives both the composite Indo-Australian plate and its parts.

Plate	Class	Area (km^2)	Source
Pacific	major	103,300,000	[466]
North American	major	75,900,000	[466]
Eurasian	major	67,800,000	[466]
African	major	61,300,000	[466]
Antarctic	major	60,900,000	[466]
Indo-Australian	major	58,900,000	[466]

Australian	major	47,000,000	[466]
South American	major	43,600,000	[466]
Somali	minor	16,700,000	[466]
Nazca	minor	15,600,000	[466]
Indian	minor	11,900,000	[466]
Philippine Sea	minor	5,500,000	[466]
Arabian	minor	5,000,000	[466]
Caribbean	minor	3,300,000	[466]
Cocos	minor	2,900,000	[466]
Caroline	minor	1,700,000	[466]
Scotia	minor	1,600,000	[466]
Burma	minor	1,100,000	[466]
New Hebrides	minor	1,100,000	[466]
Juan de Fuca	micro	250,000	[466]

The Earth’s mean radius is 6,371.000 km (position 29.65) [277]. Its surface is $4\pi \times 6{,}371^2 = 5.101 \times 10^8$ km². The Pacific plate alone covers $1.033 \times 10^8 / 5.101 \times 10^8 = 20$ % of it.

The small plates follow one power law in area [463]. Read through the net, this has the form of the same winding at every depth (chapter 11): one rule of size across the small plates.

Speeds

The plates move millimetres to centimetres per year. The Mid-Atlantic Ridge “averages about 2.5 centimeters per year (cm/yr)”, “25 km in a million years” [467]. Twenty-five kilometres sits at position 24.60, a million years at 61.45.

Near Easter Island the East Pacific Rise opens at “more than 15 cm/yr” [467]. The Arctic ridge opens at “less than 2.5 cm/yr” [467]. The San Andreas Fault slips at “about 5 cm/yr” [467].

A second account gives the Mid-Atlantic Ridge as “10 to 40 millimetres per year” and the Nazca plate as “160 millimetres per year” [354]. Typical relative motion is up to about 10 cm per year [354].

The ridges sort into classes by spreading rate [468]. The whole range is 10–200 mm per year. Slow ridges open at less than 40 mm per year, fast ones at more than 90, and ultraslow ones, such as the Gakkel Ridge, at less than 20 [468].

In the Miocene the East Pacific Rise opened at more than 200 mm per year [468]. The fastest ridge of the past thus ran at least ten times the ultraslow rate of today: $200 / 20 = 10$.

India moved north at about 20 cm per year before it met Asia, and at about 5 cm per year after [469]. The collision slowed it by a factor $20 / 5 = 4$. Today India converges at 67 mm per year [469].

Between 81 and 43 Ma (65.45–64.87) the Pacific plate moved over the Hawaiian hotspot at “around 60 mm per year” [470]. Against the hotspots, Eurasia moves over Iceland at 5 ± 3 mm per year, North America at 15 ± 5 mm per year [471]. North America moves over Yellowstone at 26 ± 5 mm per year [471].

Motion	Speed (mm/yr)	Source
Ultraslow ridges (Gakkel)	below 20	[468]
Arctic ridge	below 25	[467]
Mid-Atlantic Ridge	about 25; 10–40	[467][354]
San Andreas Fault	about 50	[467]
India today	67	[469]
East Pacific Rise near Easter Island	above 150	[467]
Nazca plate	160	[354]

East Pacific Rise, Miocene	above 200	[468]
India before collision	about 200	[469]
Pacific over Hawaii, 81–43 Ma	about 60	[470]
Eurasia over Iceland	5 ± 3	[471]
North America over Iceland	15 ± 5	[471]
North America over Yellowstone	26 ± 5	[471]

Summed around a circuit of plates, the MORVEL motions do not return exactly to zero. The non-closure is “14 ± 5 and 3 ± 1 mm yr−1” in two plate circuits, and spreading rates needed corrections of “0.6–2.6 mm yr−1” [464].

Read through the net, this has the form of the remainder (chapter 11): no closure is ever exact, and each depth leaves a remainder. The plate circuit, summed around the globe, leaves 3 to 14 mm per year.

The plates also make and destroy surface. In PB2002 the total rate of production and destruction is 0.108 m^2 per second [463]. Over a year that is $0.108 \times 3.15576 \times 10^7 = 3.41 \times 10^6$ m^2, or 3.41 km^2 per year.

The ocean floor: ridges, crust and trenches

The ridges

New ocean floor forms along the mid-ocean ridges. The continuous mountain range of the ridges is 65,000 km long (position 31.76), and the whole oceanic ridge system 80,000 km (31.95) [468]. Other accounts give 50,000 km (31.52) [354] and 60,000 km (31.69) [462].

The crest of a ridge lies at a depth of about 2,600 m (22.54) [468]. It rises about 2,000 m (22.30) above the deepest floor of the basins beside it [468]. Slow ridges carry a rift valley 10–20 km wide (23.77–24.40), with relief up to 1,000 m (21.67) [468].

The ridges make about 2.7 km^2 of new sea floor per year [468]. At a crustal thickness of 7 km (23.45), that is about 19 km^3 of crust per year: $2.7 \times 7 = 18.9$ [468]. The PB2002 rate of 3.41 km^2 per year is 1.26 times larger.

The ocean crust

Ocean crust is “7±1 km” thick, 6–8 km (23.30–23.57) [472]. At very slow ridges such as the Gakkel it is 4–5 km (22.94–23.14). Under Iceland it reaches about 20 km (24.40) [472].

Its density is “about 3.0 grams per cubic centimeter”, against about 2.7 for continental crust [472]. In section the ocean crust has four units [472]. On top lie 0.4 km of sediments (20.84), then 0.5 km of unit 2A (21.04), 1.5 km of unit 2B (22.04), and almost 5 km of unit 3 (23.14).

The base of the crust is the Moho, where the P-wave speed jumps by “approximately 1 km/s” [452]. The speed rises from 6.7–7.2 km/s in basalt to 7.6–8.6 km/s in peridotite and dunite [452]. Andrija Mohorovičić found it in 1909 from a Zagreb earthquake, at a depth of “approximately 54 km” (25.30) [452].

The Moho lies 5–10 km (23.14–23.77) below the ocean floor and 20–90 km (24.40–25.77) below the continents, 35 km (24.91) on average [452]. The global model PREM sets the top of the mantle lid at 24.4 km (24.58) [279].

The rigid plate is thicker than the crust. Oceanic lithosphere is about 6 km (23.30) thick at the ridges and over 100 km (25.87) at the subduction zones [354]. Continental lithosphere is about 200 km (26.50) [354].

Most of the Earth’s heat leaves through the ocean floor. A compilation of 38,347 heat-flow measurements gives “47±2 TW” for the whole surface [138]. The mean flux is 91.6 mW m^{-2}: 105.4 mW m^{-2} through the ocean floor and 70.9 through the continents [150].

The ocean floor thus loses heat 105.4 / 70.9 = 1.49 times faster per square metre than

the continents. The ocean floor covers 58.8 % of the surface, the continents 41.2 % (below). The ocean floor carries 0.588 × 105.4 / (0.588 × 105.4 + 0.412 × 70.9) = 68 % of the heat.

Spread over 5.101×10^{14} m², 47 TW gives 92.1 mW m^{-2}, beside the mean of 91.6 [138] [150].

The age of the ocean floor

The ocean floor is young. The oldest large-scale ocean crust, in the western Pacific and the northwestern Atlantic, is “about up to 180-200 million years old” (66.17–66.27) [472]. Another account dates the oldest sea floor found today to 170 Ma (66.12) [474].

The Jurassic lithosphere at the Mariana Trench is “the oldest on Earth, excluding ophiolites” [462].

One patch is much older. In the Herodotus Basin of the eastern Mediterranean, magnetic data reveal “oceanic crust formed up to 340 million years ago” (66.75) [473]. Other remnants of the Tethys ocean there may be about 270 Ma (66.54) [472].

The age of the floor can be set beside its rate of making. The continents cover 210.4×10^6 km², about 40 % of the surface [349]; against 5.101×10^8 km² that is 41.2 %. The rest is $5.101 \times 10^8 - 2.104 \times 10^8 = 2.997 \times 10^8$ km².

At 3.41 km² per year, that area is made in $2.997 \times 10^8 / 3.41 = 88$ Myr (65.52). At 2.7 km² per year it takes 111 Myr (65.73). The oldest floor in place, 170–200 Ma, is 1.5 to 2.3 times these times: 170 / 111 = 1.53 and 200 / 88 = 2.27.

The Herodotus crust, at 340 Ma, is 3.1 to 3.9 times these times: 340 / 111 = 3.06 and 340 / 88 = 3.86.

The floor as a record of the field

The ridge flanks carry marine magnetic anomalies. They hold the order of the field’s reversals (chapter 16) along the spreading floor.

A time scale for 83–33 Ma (65.47–64.63) combines 23 radioisotopic dates, 128 magnetochron durations and 154 ship tracks across thirteen ridge-flank regions [433]. A survey of the Pacific Jurassic Quiet Zone, older than 160 Ma (66.07), extends the “reversal history from M29 back to M44” [432].

The trenches

The ocean floor returns into the mantle at the subduction zones. They form 55,000 km (31.61) of convergent margins, “almost equal to” the 60,000 km of ridges [462]. About 40 % of these margins are ocean–ocean margins [462].

Convergence reaches “as high as 11 cm/year” [462]. The sinking slabs dip at 25–75°; a flat slab dips less than 30°, a steep one more than 70° [462].

The slabs slow as they sink, from up to about 10 cm per year to about 1 cm per year in the lower mantle [462]. Some reach the core–mantle boundary at 2,890 km (28.93) [462]. At 10 cm per year that depth takes 2,890 km / 0.1 m per year = 28.9 Myr (64.51); at 1 cm per year, 289 Myr (66.60).

The mantle the slabs cross has steps of its own. PREM shows jumps in density at 220, 400 and 670 km depth (26.58, 27.13 and 27.60) [279].

Continental crust can be carried down to about 250 km (26.70) [462]. Earthquakes in the slabs reach about 600–700 km (27.50–27.64) [462]. Volcanic arcs above the slabs produce roughly 0.75 km³ of magma per year, about 10 % of the annual total [462].

Quantity	Value	Position	Source
Ridge, continuous	65,000 km	31.76	[468]
Ridge system, total	80,000 km	31.95	[468]
Subduction margins	55,000 km	31.61	[462]
New sea floor	2.7 km²/yr; 19 km³/yr	–	[468]

Area turnover, PB2002	3.41 km²/yr	–	[463]
Ocean crust	7 ± 1 km	23.45	[472]
Oceanic lithosphere at ridges	about 6 km	23.30	[354]
Oceanic lithosphere at trenches	over 100 km	25.87	[354]
Continental lithosphere	about 200 km	26.50	[354]
Oldest ocean floor in place	170 Ma; 180–200 Ma	66.12; 66.17–66.27	[474][472]
Oldest ocean crust, Herodotus	up to 340 Ma	66.75	[473]
Deepest slabs	2,890 km	28.93	[462]
Deepest slab earthquakes	600–700 km	27.50–27.64	[462]

Ridges and trenches have nearly the same length, 60,000–65,000 km (31.69–31.76) against 55,000 km (31.61). Surface is made and destroyed at the same rate, 3.41 km² per year in PB2002. Read through the net, this is the form of what closes, stays (chapter 11): the ocean basins hold their form while the crust flows through them, from ridge to trench in 88–111 Myr (65.52–65.73).

The continents keep their crust for billions of years, while the ocean floor is replaced within 200 Myr (66.27). Read through the net, this is the form of form and carrier (chapter 11): the closed form persists, its carriers are replaced. The ocean floor lasts at most 340 Myr (66.75).

The continents gather and part

The continents do not stay apart. Several times they have gathered into one or a few large masses, the supercontinents, and broken up again. One account dates the start of this cycle to roughly 3 Ga (68.73), from inclusions in diamonds [474].

The Archean masses

The oldest proposed supercontinent is Vaalbara: the Kaapvaal craton joined to the Pilbara craton [476]. Both cratons carry crust of 3.6 to 2.7 Ga (68.90–68.64) [476].

A palaeomagnetic link between them is possible at 3.87 Ga (68.97) [476]. Both cratons hold spherule layers of about 3.5 Ga (68.87), the “oldest-known terrestrial impact products” [476]. The joined mass “remained stable for 1–0.4 Ga” (67.73–66.90) [476].

By palaeolatitude the two cratons lay 30° of latitude apart at 2.78–2.77 Ga (68.66) [476]. By other events they separated “before 2.05 Ga” (68.39). The Bushveld intrusion of 2.045 Ga (68.38) and the Vredefort impact of 2.025 Ga (68.38) occur in Kaapvaal only, not in Pilbara [476].

A table of supercontinents gives Vaalbara 3,636–2,803 Ma (68.91–68.67), a span of 833 Myr (67.57) [475]. The next masses in that table are Ur, 2,803–2,408 Ma (68.67–68.53), and Kenorland, 2,720–2,114 Ma (68.64–68.41) [475].

Ur lasted 395 Myr (66.89) and Kenorland 606 Myr (67.28). Superia and Sclavia broke off at about 2,480 and 2,312 Ma (68.56 and 68.50) [475].

A second list gives Vaalbara 3.6–2.8 Ga (68.90–68.67), Ur c. 3 Ga (68.73) and Kenorland 2.7–2.1 Ga (68.64–68.41) [474]. Piper (2013) proposes instead a single supercontinent from about 2.7 Ga to its first breakup at about 0.6 Ga (68.64 to 67.27) [474].

Columbia, or Nuna

Columbia was assembled “from 2,100 to 1,800 Ma” (68.41–68.27) [477]. The Transamazonian and Eburnean orogens date to 2.1–2.0 Ga (68.41–68.36). The Trans-Hudson, Penokean and Svecofennian orogens followed at 1.9–1.8 Ga (68.32–68.27) [477].

Final assembly came at about 1.82 Ga (68.28) [477]. The mass then grew along its margins from 1.82 to 1.5 Ga (68.28–68.10). It reached about 12,900 km (30.29) from north to south [477].

Hoffman named it Nuna in 1997 [477].

Fragmentation began at 1.5–1.35 Ga (68.10–68.01) [477]. Final breakup came at 1.3–1.2 Ga (67.97–67.90), marked by the Mackenzie dykes of 1.27 Ga (67.95) and the Sudbury dykes of 1.24 Ga (67.93) [477].

The table gives Nuna/Columbia 1,820–1,350 Ma (68.28–68.01), 470 Myr (67.05) [475]. The second list gives 1.8–1.5 Ga (68.27–68.10) [474].

Rodinia

Rodinia "assembled 1.26–0.90 billion years ago" (67.94–67.64) [478]. Other dates for its formation are c. 1.23 Ga (67.92), 1.3–1.23 Ga (67.97–67.92), and 1.25 Ga (67.94) [478] [474]. It "broke up 750–633 million years ago" (67.47–67.32) [478].

The breakup was "initiated by a superplume around 825–800 Ma" (67.56–67.53) [478]. The table places Rodinia at about 1,000 to 750 Ma (67.73–67.47), a span of 250 Myr (66.47), with breakup "between ~825 and 750 Ma" [475].

The Sturtian glaciation lasted c. 717–660 Ma (67.43–67.36) and the Marinoan c. 650–635 Ma (67.34–67.32) [480]. A study of 2010 reported equatorial ice "at or below sea level", with an onset coeval with a tropical large igneous province [480]. The glaciations are the subject of chapter 19.

Pannotia and Gondwana

Pannotia stands in the table at 633–573 Ma (67.32–67.23), a span of only 60 Myr (65.17) [475]. The second list gives c. 600 Ma (67.27) [474].

Gondwana was assembled by about 608 Ma (67.28) [475]. The table gives it 550–175 Ma (67.19–66.15), a span of 375 Myr (66.84) [475].

Pangaea

Wegener described the joined continents in articles of 1912 and a book of 1915 [479]. Pangaea formed around 335 Ma (66.74) and existed for about 160 Myr (66.07) [479]. Other dates for its formation are 310 Ma (66.67) and 280 Ma (66.57) [479].

The table gives Pangaea 336–175 Ma (66.74–66.15) [475]. Its breakup began at 215 Ma (66.33) by one account [475]. A second account dates the first breakup to the late Ladinian, about 230 Ma (66.40) [479].

The parts then left one by one [479]. North Atlantic rifting came at about 175 Ma (66.15), Gondwana separated at 150–140 Ma (66.01–65.94), and the Norwegian Sea opened at 60–55 Ma (65.17–65.09). The Atlantic opened "about 200 million years ago" (66.27) [467].

At the Mid-Atlantic rate of 25 mm per year, 200 Myr (66.27) of opening give $0.025 \times 2 \times 10^8 = 5 \times 10^6$ m, or 5,000 km (29.43). The next supercontinent, Pangaea Proxima, is expected "within the next 250 million years" (66.47) [475].

Supercontinent	Assembly	Breakup	Span	Position of span	Source
Vaalbara	3,636 Ma (68.91)	2,803 Ma (68.67); or before 2.05 Ga	833 Myr	67.57	[475][476]
Ur	2,803 Ma (68.67); c. 3 Ga	2,408 Ma (68.53)	395 Myr	66.89	[475][474]
Kenorland	2,720 Ma (68.64)	2,114 Ma (68.41)	606 Myr	67.28	[475]
Columbia (Nuna)	2.1–1.82 Ga (68.41–68.28)	1.5–1.2 Ga; table 1,350 Ma (68.01)	470 Myr	67.05	[475][477]

Rodinia	1.26–0.90 Ga (67.94–67.64)	825–633 Ma; table 750 Ma (67.47)	250 Myr	66.47	[475][478]
Pannotia	633 Ma (67.32)	573 Ma (67.23)	60 Myr	65.17	[475]
Gondwana	608–550 Ma (67.28–67.19)	175 Ma (66.15)	375 Myr	66.84	[475]
Pangaea	336–335 Ma (66.74)	230–175 Ma (66.40–66.15)	about 160 Myr	66.07	[475][479]
Pangaea Proxima	within 250 Myr (66.47)	–	–	–	[475]

The rhythm of gathering

The intervals between assemblies in the table shorten with time [475]. Kenorland to Nuna is 2,720 − 1,820 = 900 Myr (67.64). Nuna to Rodinia is about 1,820 − 1,000 = 820 Myr (67.55).

Rodinia to Pannotia is about 1,000 − 633 = 367 Myr (66.82). Pannotia to Pangaea is 633 − 336 = 297 Myr (66.63). “One complete supercontinent cycle is said to take 300 to 500 million years” [474], positions 66.64 to 67.10.

Each supercontinent passes through three phases: the gathering of the cratons, a span as one mass, and the breakup. Read through the net, this is the form of loading, holding and discharge (chapter 11). The holding spans run from 60 Myr (65.17) for Pannotia to 833 Myr (67.57) for Vaalbara.

The cratons outlast each mass. Kaapvaal carries crust of 3.6 Ga, and it still received the Bushveld intrusion and the Vredefort impact at 2.045 and 2.025 Ga, after Vaalbara had parted [476]. This reads as the residue becoming the alphabet (chapter 11): a closed form, the craton, becomes a letter of the next closure.

What this part of the history shows

The start of plate motion is not one date. The measured onsets run from 4.19–4.02 Ga (69.04–69.00) in zircon inclusions to about 0.8 Ga (67.53) in blueschists. Crustal destruction and crust chemistry both mark a change between 3.0 and 2.5 Ga (68.73–68.57).

The plates are counted at many cuts: 25 plates over 97 % of the surface, 50 rigid caps beside 14 % deforming ground, 52 plates in PB2002, about 1,200 terranes. The small plates follow one power law in area. Read through the net, this is the same winding at every depth.

The plate motions, summed around a circuit, leave a non-closure of 14 ± 5 and 3 ± 1 mm per year. Read so, it has the form of the remainder: no closure is ever exact.

Ridges and trenches have almost the same length, 60,000–65,000 km (31.69–31.76) against 55,000 km (31.61). Sea floor is made and destroyed at 3.41 km² per year, and the basins renew their floor in 88–111 Myr (65.52–65.73). The basins hold their form while the crust flows through, read as the form of what closes, stays.

The ocean floor in place is at most 170–200 Ma (66.12–66.27), with one patch of 340 Ma (66.75). The continental cratons carry crust of 3.6 Ga (68.90). Read so, this is the form of form and carrier: the form persists, its carriers are replaced.

The continents gather and part in a cycle of 300–500 Myr (66.64–67.10). The intervals between assemblies shorten from 900 Myr (67.64) to 820, 367 and 297 Myr (66.63). Each mass passes through gathering, holding and breakup, read as loading, holding and discharge; the holding lasts from 60 Myr (65.17) to 833 Myr (67.57).

The cratons outlast the supercontinents: Kaapvaal, with crust of 3.6 Ga, still took the Bushveld intrusion at 2.045 Ga (68.38). This reads as the residue of one depth becoming the alphabet of the next.

18. Mountains, Volcanoes, Earthquakes

The plates of chapter 17 move a few centimetres per year. Where they part, collide or pass over hot mantle, the motion shows at the surface in three ways. Mountains rise, volcanoes erupt, and the ground breaks in earthquakes.

This chapter follows these three expressions in time order. It starts with the great floods of lava of the last 250 Myr (66.47) and the island chains above hotspots. It then takes the Himalaya, the volcanoes of the last 30 Myr (64.54) and of the written record, and the earthquakes of the instrumental age.

It ends with the waves and the slow slips that follow from the earthquakes, and with the deep earthquake in Colombia of 10 August 2026. Every size and every time carries its position on the ladder of chapter 11; an age of A years is placed as a duration of A years.

The great floods of lava

What a large igneous province is

A large igneous province is a vast outpouring of magma. By one definition it covers more than 1×10^5 km² with more than 1×10^5 km³ of rock [481]. It lasts at most about 50 Myr (position 65.01).

Most of the volume comes in short pulses. Pulses of about 1–5 Myr (61.45–62.91) carry more than 75 % of the volume [481]. Their effusion rates are “up to an order of magnitude greater than mid-ocean ridge basalts” [481].

Coffin and Eldholm used an area threshold of 100,000 km² in 1992; Sheth lowered it to 50,000 km² [481].

The provinces, oldest first

The listed provinces span about a fifty-fold range in volume. Their ages run from 253 to 6 Ma (66.48 to 63.08).

Province	Age (Ma)	Position	Area (10^6 km²)	Volume (10^6 km³)	Source
Emeishan	253–250	66.48–66.47	0.25	c. 0.3	[481]
Siberian Traps	250	66.47	1.5–3.9	0.9–2.0	[481]
Central Atlantic (CAMP)	201–197	66.27–66.25	11	2.5 (2.0–3.0)	[481]
Karoo–Ferrar	183–180	66.19–66.17	0.15–2	0.37–0.57	[481]
Paraná–Etendeka	134–129	65.90–65.87	1.5	above 1	[481]
Ontong Java Plateau	c. 122	65.82	1.86	8.4	[481]
Deccan Traps	66	65.26	0.5–0.8	0.5–1.0	[481]
North Atlantic Igneous Province	62–55	65.20–65.09	1.3	6.6	[481]
Columbia River Basalt	17–6	64.02–63.08	0.16	0.175	[481]

The smallest listed volume is 0.175×10^6 km³ (Columbia River), the largest 8.4×10^6 km³ (Ontong Java). Their ratio is 8.4 / 0.175 = 48. The areas run from 0.15 to 11×10^6 km², the largest in the Central Atlantic province.

Siberia and the end of the Permian

The Siberian Traps erupted at the end of the Permian. Other values for them are “about 7 million km2” and “around 4 million km3” [482]. Dated samples near 250 Ma (66.47) cover “5,000,000 square kilometres” [482].

Their duration is given as “roughly two million years” (62.08) and as a “one-million-year-long” episode (61.45) [482]. The Permian–Triassic boundary lies at about 251.9 Ma (66.48) [482].

The table gives 1.5–3.9 × 10^6 km² and 0.9–2.0 × 10^6 km³; the text gives 7 × 10^6 km² and 4 × 10^6 km³ [481][482].

At Meishan the extinction falls between “251.941 ± 0.037” and “251.880 ± 0.031 Mya” [483]. That is “an interval of 60 ± 48 ka” (58.88) [483]. The carbon cycle stayed volatile for about 500 kyr (60.81) [483].

A compilation gives the Permian event a duration of 160 kyr to 2.8 Myr (59.78–62.38) and names “Siberian volcanism” as its cause [484]. The Emeishan province, 253–250 Ma (66.48–66.47), erupted just before [481].

The Central Atlantic and the end of the Triassic

The Central Atlantic Magmatic Province erupted at 201–197 Ma (66.27–66.25), as Pangaea began to break (chapter 17). The end-Triassic boundary and its crisis fall “within <150 ka of the onset of flood volcanism” (59.72) [485].

Its magma was released “in four pulses over about 600,000 years” (60.98) [486]. The province covers 11 × 10^6 km², the largest area in the table [481].

Karoo to the Caribbean

The plume tracks link several provinces to hotspots [471]. Karoo–Ferrar erupted at 183 Ma (66.19) and the Central Atlantic province at about 200 Ma (66.27). Paraná–Etendeka erupted at about 132 Ma (65.89) and Kerguelen at 130 Ma (65.88).

Ontong Java followed at 125–120 Ma (65.84–65.80), the Caribbean province at 95–88 Ma (65.59–65.52) [471]. With 8.4 × 10^6 km³, Ontong Java is the largest province by volume [481].

Deccan and the end of the Cretaceous

The Deccan Traps once covered “about 1.5 million km2”; about 500,000 km² remain [487]. Their volume is “about 1 million km3”, piled “more than about 2 kilometres” (22.30) thick [487].

The eruptions began at “66.25 million years ago” (65.26) [487]. Most fall in a window of “around 66.3 to 65.6 million years ago” (65.26–65.25) [487]. A first pulse is “dated at 67 million years ago” (65.27) [487].

The plume list gives 68.5–66 Ma (65.29–65.26) for the Deccan [471].

The duration is given as “600,000-to-800,000-year” (60.98–61.24), and as “less than 30,000 years” (58.25) [487]. The extinction at the end of the Cretaceous lies near 66 Ma (65.26) [489].

The Chicxulub impact fell “within 33,000 years” (58.34) of the extinction [489]. The carbon cycle was disrupted for “less than 5000 years” (56.62) [489].

Two dating methods order the eruptions against the impact. Argon dating of Deccan ash places most of the flood-basalt eruption after the impact [488]. Uranium–lead dating of zircon gives “four large magmatic pulses”, the first before the impact [488].

The North Atlantic and later provinces

The North Atlantic Igneous Province erupted at 62–55 Ma (65.20–65.09) with 6.6 × 10^6 km³ [481]. At about 56 Ma (65.11) the Paleocene–Eocene Thermal Maximum released more than 10,000 Pg of carbon [379]. Its main source was volcanism of the North Atlantic province rather than methane hydrates [379].

The Afar province, tied to its plume track, dates to 30 Ma (64.54) [471]. The Columbia River Basalt, the youngest listed province, erupted at 17–14 Ma (64.02–63.85) by the plume list, 17–6 Ma (64.02–63.08) by the table [471][481].

In each province the eruptions come in pulses of 1–5 Myr carrying more than 75 % of the volume. Read through the net, this is the form of loading, holding and discharge (chapter 11). The extinctions that follow are shorter still: 60 ± 48 kyr at the end of the Permian, less than 150 kyr after the onset of the Central Atlantic province.

Hotspots and island chains

The Hawaiian–Emperor chain

The Pacific plate carries a line of volcanoes away from the Hawaiian hotspot. The Hawaiian–Emperor chain is “about 6,200 km” long (29.62), with “over 80 identified undersea volcanoes” [470]. The oldest confirmed age in the Emperor chain is “81 million years” (65.45), at Detroit Seamount; Meiji Seamount is probably older [470].

The Hawaiian Islands themselves are 0.4–5.1 Ma (60.61–62.93) [470]. From 81 to 43 Ma (65.45–64.87) the Pacific plate moved over the hotspot at “around 60 mm per year” [470].

The chain bends sharply between its Emperor and Hawaiian limbs. The bend began “near Kimmei seamount about 50 million years ago” (65.01) [490]. It coincides with a realignment of Pacific spreading centres and with early arc magmatism in the western Pacific [490].

A second study finds “an abrupt Pacific plate motion change in the Eocene (~47 Ma)” (64.95) [491]. A third date, 43 Ma (64.87), comes from a “trench jam” account [470].

The hotspot moved too. It “drifted 4–9° south between 80 and 47 Ma” (65.43–64.95), at about 0.2–0.4° per Myr [491]. At 111.2 km per degree that is 22–44 km per Myr, or 22–44 mm per year.

Over the 33 Myr (64.63) from 80 to 47 Ma, 4–9° gives 0.12–0.27° per Myr. The hotspot thus drifted at a speed of the same order as the plate, 22–44 against 60 mm per year.

How many hotspots

Counts of plume-fed hotspots range “from about 20 to several thousand, with most geologists considering a few dozen” [471]. One classification names seven primary plumes: Easter, Iceland, Hawaii, Afar, Louisville, Réunion and Tristan [471].

It adds three likely primary plumes, Galápagos, Kerguelen and Marquesas, and six secondary ones: Samoa, Tahiti, Cook, Pitcairn, Caroline and MacDonald [471]. “Up to 20 or so more” are possible, and the list of hotspots runs to 61 entries [471].

The Hawaiian plume head formed a plateau at about 100 Ma (65.64) [471]. That plateau now lies about 800 km (27.76) deep under eastern Siberia [471]. Over Yellowstone, North America moves at 26 ± 5 mm per year [471].

The base of the mantle

Two large structures sit at the base of the mantle, under Africa and under the Pacific. They “extend approximately 1,000 kilometres upward from the base of the mantle” (27.96) [305]. Their lower two-thirds are “about 0.5 per cent” denser than the average mantle [305].

The Pacific structure is “3,000 kilometers” across (28.96) [306]. Together the two hold “around 8% of the volume of the mantle” [306].

The hotspot persists for 81 Myr (65.45) while each volcano it builds is carried away on the plate: the islands of today are at most 5.1 Ma (62.93) old. Read through the net, this is the form of form and carrier (chapter 11): the form lasts, its carriers are replaced.

The Himalaya and the height of mountains

The highest summits

Mount Everest stands 8,848.86 m (23.66) above sea level, a value announced jointly by Nepal and China on 8 December 2020 [492]. Its summit rock is Ordovician limestone of the Qomolangma Formation [492].

The height has been measured many times [492]. Waugh gave 8,840 m in 1856, the Survey of India 8,847.73 m in 1952–54, and China 8,848.13 m in 1975, on the snow cap. A GPS survey of 1999 gave 8,850 m on the rock head, the Chinese Academy of Sciences 8,844.43 ± 0.21 m in 2005, and an agreement of 2010 8,848 m.

All these values sit at position 23.66. Seven surveys over 164 years (53.51) differ by at most 8,850 − 8,840 = 10 m.

Height depends on where it is counted from. Mauna Kea “rises more than 10,210 meters” (23.79) from its base to its peak [493]. Measured from the Earth’s centre, the summit of Chimborazo lies “over 6,800 feet [2,072 meters]” (22.34) farther out than Everest’s [493].

The same source also gives “over 6,560 feet”, 2,000 m (22.30) [493]. Another account gives 2.1 km (22.35) [494].

The range

The Himalaya forms an arc 2,400 km long (28.76) [469]. It is 350 km wide (27.01) in the west and 151 km (26.24) in the east [469]. “More than 100 peaks exceeding elevations of 7,200 metres” (23.47) rise in it [469].

The ladder of the net’s climate essay names a mountain beside position 23, at 4.3 km (23.00) [29]. Everest, at 23.66, lies two thirds of a step above it.

India meets Asia

The range rose where India met Asia. One account places the collision in the Middle Paleocene, about 60 Ma (65.17) [469]. It gives the closure of the Neotethys ocean as “completed approximately 40 Ma” (64.80) [469].

In the Qumiba section of Tibet, “the youngest marine facies preserved at this locality are 50.6–52.8 Ma” (65.02–65.06) [495]. A palaeomagnetic compilation “indicates initial contact between the continents in the early Eocene” [495]. The same study assesses a claim that collision could not precede about 35 Ma (64.68) [495].

Before contact India moved north at about 20 cm per year, after it at about 5 cm per year [469]. Today it converges at 67 mm per year [469].

Uplift and the monsoon

The two syntaxes, Nanga Parbat and Namche Barwa, rise at “7 millimetres (0.28 in) per year” [469]. That is 7 km per Myr: 7 km sits at 23.45, 1 Myr at 61.45. The Himalaya as a whole rises at about 5 mm per year [469].

Everest rises at about 4 mm per year by two accounts and about 2 mm per year by another [492]. It moves sideways at 3–6 mm per year [492].

The rise of the Himalaya–Tibetan plateau is tied to the Asian monsoons. Asian interior aridity and the onset of the Indian and East Asian monsoons date to “about 9–8 Myr ago” (63.45–63.34) [496]. The East Asian monsoons intensified and dust reached the North Pacific “about 3.6–2.6 Myr ago” (62.61–62.32) [496].

Since “about 2.6 Myr ago” (62.32) the summer monsoons have been more variable, possibly weaker, and the winter monsoon has strengthened [496]. The authors read these steps as phased uplift of the plateau since the Late Miocene [496].

The range still breaks. The Gorkha earthquake of 2015, of Mw 7.8, set off an avalanche

at Everest Base Camp that killed 18 [492]. In 2015 no one reached the summit in spring, for the first time since 1974 [492].

Erosion

A global compilation of ^{10}Be measurements holds “n = 1599” sites: 450 outcrops and 1,149 drainage basins [497]. “Drainage basins erode more quickly (mean = 218 m Myr−1; median = 54 m Myr−1) than outcrops (mean = 12 m Myr−1; median = 5.4 m Myr−1)” [497]. The outcrop median is 5.4 m per Myr in the abstract and 5.3 in the discussion [497].

One metre per Myr is one micrometre per year. The basin mean, 218 m per Myr, is 0.218 mm per year.

The syntaxes rise at 7 mm per year: 7 / 0.218 = 32 times the basin mean and 7 / 0.054 = 130 times the basin median. The means exceed the medians by 218 / 54 = 4.0 for basins and 12 / 5.4 = 2.2 for outcrops.

Quantity	Value	Position	Source
Everest, 2020	8,848.86 m	23.66	[492]
Everest, rock, 2005	8,844.43 ± 0.21 m	23.66	[492]
Mauna Kea, base to peak	above 10,210 m	23.79	[493]
Chimborazo beyond Everest from the centre	2,072 m	22.34	[493]
Himalaya, length	2,400 km	28.76	[469]
Peaks above 7,200 m	more than 100	23.47	[469]
Youngest marine facies, Tibet	50.6–52.8 Ma	65.02–65.06	[495]
Collision, Paleocene account	about 60 Ma	65.17	[469]
Monsoon onset	9–8 Ma	63.45–63.34	[496]
Uplift of the syntaxes	7 mm/yr	–	[469]
Uplift of Everest	2 or 4 mm/yr	–	[492]
Erosion of basins, mean and median	218 and 54 m/Myr	–	[497]
Erosion of outcrops, mean and median	12 and 5.4 m/Myr	–	[497]

The mountains rise faster than they wear down: uplift of 2–7 mm per year against a basin mean of 0.218 mm per year. In erosion a few fast sites carry most of the total, so that means exceed medians by factors of 2.2 to 4.0.

Volcanoes

The scale of eruptions

The size of an explosive eruption is measured on the Volcanic Explosivity Index of Newhall and Self (1982), a logarithmic scale from 0 to 8 [498]. Each step marks a tenfold larger bulk volume of ejecta, from VEI 2 upward.

VEI	Bulk ejecta	Plume height	Position of height	Typical interval	Position of interval
0	below 10^4 m³	below 100 m	19.58	constant	–
1	at least 10^4 m³	0.1–1 km	19.58–21.67	daily	43.50
2	at least 10^6 m³	1–5 km	21.67–23.14	about 2 weeks	45.90
3	at least 10^7 m³	3–15 km	22.67–24.14	about 3 months	47.61
4	at least 0.1 km³	above 10 km	23.77	about 18 months	49.24
5	at least 1 km³	above 20 km	24.40	about 12 years	51.13
6	at least 10 km³	above 30 km	24.77	about 50–100 years	52.43–53.06
7	at least 100 km³	above 40 km	25.03	about 500–1,000 years	54.53–55.16
8	at least 1,000 km³	above 50 km	25.23	above 50,000 years	58.72

Source: [498].

By 2010 the Global Volcanism Program had assigned a VEI to 7,742 Holocene eruptions, about 75 % of those known [498]. About 49 % of them are VEI 2 or less, and about 90 % VEI 3 or less [498]. At least 10 eruptions of VEI 7 occurred in the last 11,700 years (57.40) [498].

The largest class is rare. About 40 eruptions of VEI 8 are counted in the last 132 Myr (65.89), and at least 60 by other authors [498].

From VEI 2 up each step is ten times the volume. The typical interval grows from a day (43.50) at VEI 1 to more than 50,000 years (58.72) at VEI 8.

The largest eruptions, oldest first

The VEI 8 eruptions on record are Wah Wah Springs at about 30 Ma (64.54) and La Garita at 26.3 Ma (64.42) [498]. Then come Yellowstone at 2.1 Ma (62.12) and 640 ka (61.04), Toba at 74 ka (59.08), and the Oruanui eruption of Taupō at 26.5 ka (58.14) [498]. The same page gives Oruanui also as more than 27,000 years ago (58.16) [498].

Yellowstone has had three great eruptions [499]. The Huckleberry Ridge eruption of about 2.08 Ma (62.11) ejected more than 2,450 km³. The Mesa Falls eruption of about 1.30 Ma (61.68) ejected more than 280 km³.

The Lava Creek eruption of about 0.63 Ma (61.03), dated also to 631 or 640 ka (61.03–61.04), ejected more than 1,000 km³ [499]. The intervals are 2.08 − 1.30 = 0.78 Myr (61.22) and 1.30 − 0.63 = 0.67 Myr (61.08). The last lava flow came about 70 ka (59.03) [499].

Yellowstone is restless today. It records 1,000–2,000 earthquakes per year, most of magnitude 3 or less [499].

Its ground has risen at up to 150 mm per year; the rise of about 75 mm per year in 2004–2008 was three times any rate since 1923 [499]. Its magma body measures 80 × 20 km (25.66 × 24.40) [499].

The Youngest Toba Tuff is dated by argon to “73,880 ± 320” years (59.07) and to “73,700 ± 300 years ago” (59.07) [500]. Its volume is “3,800 km3 … dense-rock equivalent”: about 1,800 km³ of ash fall and 2,000 km³ of ignimbrite [500]. Earlier estimates were 2,000–6,000 km³, and Rose and Chesner gave at least 2,800 km³ [500].

Ash at least 1 cm thick (11.19) fell over “more than 38,000,000 km2”, about 7.5 % of the Earth’s surface [500]. As a check, $3.8 \times 10^{7} / 5.101 \times 10^{8} = 7.4$ %. About 5 cm (12.66) of ash fell over India [500].

The eruption released 10^{13}–10^{15} g of sulfur by petrology and about 10^{14} g by ice cores [500]. Models give a maximum cooling of 3.5 °C for 8.5×10^{14} g of sulfur, or 2.3 and 4.1 °C for lower and higher scenarios [500]. If aerosol size limits the effect, the cooling is “less than 1.5 °C” [500].

The South China Sea cooled by 1 °C for a thousand years (55.16) [500]. Some authors propose that the population outside Africa fell to 1,000–3,000 individuals by 50 kyr (58.72) [500]. In the Jurreru Valley stone tools lie both above and below the ash [500].

The written record

The record of volcanoes grew slowly. About 2,000 years ago (55.79) the list held “only the names of nine Mediterranean volcanoes”, plus Mount Cameroon [503]. The next ten centuries added “only 30 names, 18 of them Japanese” [503].

By 1400 CE, 626 years ago (54.73), historically active volcanoes “totaled only 63” [503].

Tambora, 1815

Tambora in Indonesia produced “the largest known historic eruption” [504]. It ejected “about 140 gigatonnes of magma”, about 50 km³ of dense rock [504]. More than 95 % of the ejecta by mass travelled as pyroclastic flows, and the plinian plumes rose to 43 km

(25.10) [504].

The eruption began on 5 April 1815, reached its climax on 10 April and ended on 15 July [505]. That is 101 days (47.70) in all, with the climax 5 days (44.96) after onset. The summit fell from about 4,300 m (23.00) to 2,851 m (22.63) [505].

It is rated VEI 7 [505]. Other volume estimates are 37–45 km³ of dense rock (Kandlbauer and Sparks 2014) and about 41 km³ (Stothers 1984) [505].

More than 71,000 people died on Sumbawa and Lombok [504]. Direct deaths are given as 10,000 to 11,000, and famine and disease as 49,000 [505]. Total estimates run to about 88,000 and 100,000 [505].

About 60 Mt of sulfur reached the stratosphere, “six times” the amount of Pinatubo in 1991 [504]. Ice-core estimates of the sulfur dioxide range from 10 to 120 Mt, on average 25–30 Mt [505].

The next year, 1816, became the “Year without a summer” [504]. The northern summer of 1816 was 0.53 °C cooler by one reconstruction and 0.51 °C by another; the global cooling is given as 0.4 to 0.7 °C [505].

Pinatubo, 1991

Pinatubo reached its climax on 15 June 1991 at 13:42 [506]. It is rated VEI 6. It ejected “over 10 km3”, about 5 km³ of dense rock [506].

The ash cloud rose to 40 km (25.03), or 34 km (24.88) in another section of the same account [506]. The account prints the sulfur dioxide injected as “about 1.7 million t” [506]. Oppenheimer’s ratio gives another figure: Tambora’s 60 Mt of sulfur over six is 10 Mt of sulfur, about 20 Mt of sulfur dioxide [504].

The aerosol optical depth was “nearly twice as great as for the 1982 El Chichon eruption” [507]. Cooling was expected to begin late in 1991 and to peak late in 1992 [507]. Stratospheric ozone reached record lows with the Pinatubo aerosol [508].

The measured cooling is given as 0.5 °C between 1991 and 1993 and as a global decrease of about 0.4 °C [506]. The northern hemisphere cooled 0.5–0.6 °C; a conservative figure is 0.2 °C for 13 months (48.94) [506].

The eruption killed 847 people [506]. About 20,000 people were evacuated by one count, about 60,000 within 30 km (24.77) by another [506].

Hunga Tonga–Hunga Ha’apai, 2022

The volcano Hunga Tonga–Hunga Ha’apai began erupting on 20 December 2021. It reached its climax 26 days (46.47) later, on 15 January 2022; the Plinian phase began at 04:14:45 UTC [511].

Its plume reached “an altitude of 57 kilometers at its highest extent” (25.35), in “the lower mesosphere” [510]. Another account gives 58 km (25.37) [511].

The eruption injected “146 ± 5 Tg” of water, “~10% of the stratospheric burden” [509]. The water was expected to take “several years” to dissipate [509]. It released only about 0.4 Tg of sulfur dioxide [511]: 146 / 0.4 = 365 times more water than sulfur dioxide by mass.

Its VEI is given as at least 5, about 6, and 5.8 [511]. It ejected 1.9 km³, and about 10 km³ of material was displaced overall [511]. The energy is given as 61 Mt of TNT, or 100–200 Mt [511].

The pressure wave went around the Earth up to four times, with amplitudes of about 7 hPa in New Zealand and just over 2 hPa in the United Kingdom [511]. The plume produced 200,000 lightning flashes in one hour (40.61) [511].

The tsunami reached 20 m (18.11) in Tonga, a run-up of 45 m (18.85) on Tofua, and 2 m (16.02) in Peru and Chile [511]. Seven people died: four in Tonga, two in Peru and one in Fiji [511].

The volcanoes of now

The Global Volcanism Program counts 1,214 Holocene volcanoes with 11,089 eruptions [501]. Of these, 853 volcanoes have 9,916 confirmed eruptions, and 557 volcanoes 6,504 confirmed and observed eruptions [501]. The Holocene spans the last 12,000 years (57.42) in this count [502].

Since 1800, 522 volcanoes have had 5,413 confirmed eruptions, 3,783 of them with a known end year [501]. Since 1960, 333 volcanoes have had 2,258 eruptions, 2,066 with a known end year [501].

In 2000–2025 an average of 36 eruptions started each year, at 36 volcanoes, and 36 ended, at 32 volcanoes [501]. In each year 78 eruptions were in progress at 72 volcanoes [501]. In 2026 to 31 March, 6 eruptions started, 7 ended and 41 continued, 47 in all [501].

In 2025 there were 71 eruptions, 29 of them new [502]. There are “40-50 continuing eruptions at any given time”, and 40 were current on 31 March 2026 [502].

The confirmed eruptions since 1960 give 2,258 / 66 years = 34 per year (52.68). Over the whole Holocene the confirmed count gives 9,916 / 11,700 years (57.40) = 0.85 per year. The rate of the record falls by a factor 34 / 0.85 = 40 into the past.

The GVP counts “at least a thousand identified magma systems—on land alone—likely to erupt in the future” [501].

Volcanic gas

The subaerial volcanoes release 51.3 ± 5.7 Tg of CO_2 per year without eruption, and 1.8 ± 0.9 Tg per year in eruptions (2005–2015) [512]. In carbon the quiet flux is 51.3 × 12 / 44 = 14.0 Tg per year. The quiet flux is 51.3 / 1.8 = 28 times the eruptive one.

The volcanoes release 24.9 ± 2.3 Tg of SO_2 per year from 125 persistently degassing volcanoes [512].

Eruption	Date or age	Position	Volume	Gas	Cooling	Deaths
Huckleberry Ridge, Yellowstone	about 2.08 Ma	62.11	above 2,450 km³	–	–	–
Lava Creek, Yellowstone	about 0.63 Ma	61.03	above 1,000 km³	–	–	–
Toba (Youngest Toba Tuff)	73.88 ± 0.32 ka	59.07	3,800 km³ DRE	10^{13}–10^{15} g S	3.5 °C modelled; below 1.5 °C	–
Oruanui, Taupō	26.5 ka	58.14	VEI 8	–	–	–
Tambora	5 April–15 July 1815	–	about 50 km³ DRE	about 60 Mt S	0.4–0.7 °C	above 71,000
Pinatubo	15 June 1991	–	above 10 km³; about 5 km³ DRE	1.7 Mt SO_2 printed; about 10 Mt S by ratio	0.4–0.5 °C	847
Hunga Tonga	15 January 2022	–	1.9 km³	146 ± 5 Tg H_2O; about 0.4 Tg SO_2	–	7

Sources: [498][499][500][504][505][506][509][511].

The measured volumes span three orders of magnitude: 1.9 km³ for Hunga, about 5 km³ for Pinatubo, about 50 km³ for Tambora and 3,800 km³ for Toba. Yellowstone erupted three times in 2.08 − 0.63 = 1.45 Myr (61.78), and its ground still rises. Read through the net, this is the form of loading, holding and discharge, with intervals of 0.78 and 0.67 Myr (61.22 and 61.08).

Earthquakes

The written record of losses

The written record of earthquakes is a record of the dead. The list of events with about 100,000 deaths or more reaches back fifteen centuries [513]. Ages are placed here as years before 2026.

Event	Year	Years before 2026	Position	Deaths	Source
Antioch	526	1,500	55.53	250,000	[513]
Aleppo	533	1,493	55.52	130,000	[513]
Damghan	856	1,170	55.30	200,000	[513]
Aleppo	1138	888	55.05	130,000–230,000	[513]
Ganja	1139	887	55.05	230,000–300,000	[513]
Zhili	1290	736	54.88	7,000–100,000	[513]
Hongdong	1303	723	54.86	200,000	[513]
Shaanxi	1556	470	54.47	100,000	[513]
Messina	1908	118	53.21	120,000	[513]
Haiyuan	1920	106	53.12	273,400	[513]
Kantō	1923	103	53.09	105,385	[513]
Ashgabat	1948	78	52.84	110,000	[513]
Tangshan	1976	50	52.43	300,000+ (official 242,769; local 263,299)	[513]
Indian Ocean	2004	22	51.68	227,898	[513]
Haiti	2010	16	51.39	46,000–316,000	[513]

The earthquake of 6 February 2023 in Turkey and Syria, of M 7.8, killed 59,488–62,013 people [513]. The Noto earthquake in Japan on 1 January 2024, of M 7.5, killed 645 [513].

Measuring the size

The moment magnitude follows the IASPEI relation Mw = (2/3)(log₁₀ M₀ − 9.1), with the seismic moment M₀ in N·m [514]. Each unit of magnitude carries “10^1.5 ≈ 32-fold” more energy [514]; 10^1.5 = 31.6.

Inverted, the relation gives M₀ = 10^(1.5 Mw + 9.1). For Mw 7.4 that is 10^20.2 = 1.58 × 10²⁰ N·m. The USGS moment tensor of the Colombian earthquake of 2026, of Mw 7.4, gives 1.66 × 10²⁰ N·m [516].

The largest earthquakes since 1900

The USGS catalogue holds 17 earthquakes of magnitude 8.5 or more since 1900 [516]. That is 17 in 126 years (53.27), or 0.135 per year.

Date (UTC)	Mw	Depth (km)	Position of depth	Place	Source
1960-05-22	9.5	25	24.60	Valdivia, Chile	[516]
1964-03-28	9.2	25	24.60	Prince William Sound, Alaska	[516]
2004-12-26	9.1	30	24.77	Sumatra–Andaman Islands	[516]
2011-03-11	9.1	29	24.74	Tōhoku, Japan	[516]
1952-11-04	9.0	21.6	24.47	off Petropavlovsk-Kamchatsky	[516]
2025-07-29	8.8	35	24.91	Kamchatka Peninsula	[516]

1906-01-31	8.8	20	24.40	Ecuador–Colombia	[516]
2010-02-27	8.8	22.9	24.52	Maule, Chile	[516]
1965-02-04	8.7	30.3	24.78	Rat Islands, Aleutians	[516]
1946-04-01	8.6	15	24.14	Unimak Island, Alaska	[516]
1950-08-15	8.6	15	24.14	Assam–Tibet	[516]
2012-04-11	8.6	20	24.40	Wharton Basin	[516]
2005-03-28	8.6	30	24.77	off Singkil, Indonesia	[516]
1957-03-09	8.6	25	24.60	Atka, Alaska	[516]
1922-11-11	8.5	70	25.54	off Vallenar, Chile	[516]
1938-02-01	8.5	25	24.60	Banda Sea	[516]
1963-10-13	8.5	35	24.91	Kuril Islands	[516]

All 17 lie at depths of 15–70 km (24.14–25.54). By their place names, all but two lie at subduction margins: Chile, Alaska, the Aleutians, Sumatra, Japan, Kamchatka, the Kurils, Ecuador–Colombia and the Banda Sea [516]. The two others are the Wharton Basin event of 2012, inside a plate, and the Assam–Tibet event of 1950, in the continental collision.

“Nine of the ten largest earthquakes of the last 100 years” (53.06) were subduction megathrust events [462]. Megathrusts release “about 90% of the total seismic moment released worldwide” [517].

Valdivia, 1960

The Valdivia earthquake in Chile is the largest on record. Most studies give Mw 9.4–9.6 [520]. It lasted about 10 minutes (38.98) and ruptured about 800 km (27.76) of fault, from 37° S to 44° S [520].

The average slip was 11 m (17.57) over 27 sub-faults, and 25–30 m (18.32–18.48) offshore [520]. A later analysis splits it into a thrust sub-event of Mw 9.37 and a strike-slip sub-event of Mw 9.07 [520]. Its seismic moment is 1.4–2.8 × 10^{23} N·m [521].

Deaths are given as 1,000–6,000 and as 1,886–6,000 [520]. The local tsunami reached 25 m (18.32). At Hilo it reached 10.7 m (17.54) and killed 61 [520].

The volcano Cordón Caulle erupted 38 hours (43.92) later and stayed active for 59 days (47.21) [520]. Valdivia released “approximately twice” the energy of the Alaska earthquake of 1964 [517]. By the IASPEI relation, Mw 9.5 against 9.2 gives 10^(1.5 × 0.3) = 2.8 times the moment.

Sumatra–Andaman, 2004

The USGS gives the Sumatra–Andaman earthquake Mw 9.1; recent studies give 9.2–9.3 [522]. Its rupture of 1,200–1,300 km (28.13–28.20) is “the longest ever observed” [522]. It lasted at least 10 minutes (38.98), with about 15 m (17.85) of slip along about 1,600 km (28.39) [522].

Its surface-wave energy was “1.1×10^17 joules”, and the tsunami carried about 5 Mt of TNT in energy [522]. The tsunami ran up to 51 m (18.97) at Lhoknga–Leupung [522].

It killed 227,898 people by one count and 229,866 by another [522]. Indonesia lost 130,736 (about 170,000 estimated), Sri Lanka 35,322, India 12,405 and Thailand 5,395 [522].

The earthquake shortened the day by 2.68 µs (21.47) in one model [522], and by 3 µs (21.58) in another account [320].

Tōhoku, 2011

The USGS raised the Tōhoku earthquake in Japan to Mw 9.1 on 11 July 2016 [523]. It

lasted about 6 minutes (38.51) and ruptured an area of 500 × 200 km (27.33 × 26.50) [523].

Early estimates of slip were 20–40 m (18.11–18.74); the sea bed shifted 24 m (18.28) [523]. The tsunami ran up to 40.5 m (18.76) at Miyako and 38.9 m (18.72) at Aneyoshi [523].

There were 19,759 dead and 2,553 missing by 2021 figures [523]. Damage exceeded US$300 billion; another figure is US$360 billion [523].

The coast moved up to 2.4 m (16.18) east, and the Earth's axis shifted 10–25 cm (13.29–14.12) [523]. The day shortened by 1.8 µs (21.11) [523]. The surface-wave energy was 1.9×10^{17} J [523].

Kamchatka, 2025

On 29 July 2025 an earthquake of Mw 8.8 struck the Kamchatka Peninsula at 35 km (24.91) depth [516]. It was the largest of the 16 earthquakes of M 7 or more in 2025 [516].

How often

The USGS counts earthquakes worldwide by magnitude class [515]. For 2000–2021 its tables give 27 events of M 8 or more, 303 of M 7–7.9, 3,021 of M 6–6.9 and 35,492 of M 5–5.9 [515].

Over those 22 years (51.68) the means per year are 1.23, 13.8, 137 and 1,613 [515]. The yearly count of M 7–7.9 ranged from 6 in 2017 to 23 in 2010 [515]. The count of M 8 or more ranged from 0 to 4, the maximum in 2007 [515].

Year	M 8+	M 7–7.9	M 6–6.9	M 5–5.9	Source
2000	1	14	146	1,344	[515]
2004	2	14	141	1,515	[515]
2010	1	23	150	2,209	[515]
2011	1	19	185	2,276	[515]
2017	1	6	104	1,455	[515]
2021	3	16	140	2,047	[515]

The catalogue counts for 2016–2025, ten years (50.97), are 17,561 of M 5 or more, 1,333 of M 6 or more, 134 of M 7 or more and 7 of M 8 or more [516]. Per year that is 1,756, 133, 13.4 and 0.7 [516]. In 2025 alone there were 2,129 of M 5 or more, 145 of M 6 or more and 16 of M 7 or more [516].

About 500,000 earthquakes a year are detectable with current instruments, and about 100,000 of them are felt [517].

The essay of the net on earthquakes gives a yearly ledger [524].

It counts about 1 at M 8 or more, 15 at M 7, 130 at M 6 and 1,300 at M 5. Below come 13,000 at M 4, 130,000 at M 3 and an estimated 1.3 million at M 2. Its steps are 15, 130 / 15 = 8.7 and then 10 at each step down.

One law of frequency

The counts follow the law of Gutenberg and Richter (1944).

The number of earthquakes falls tenfold with each unit of magnitude. For each event of M 4.0 or more there are about 10 of M 3.0 or more and 100 of M 2.0 or more [518]. The exponent b is "commonly close to 1.0 in seismically active regions" [518].

Its range is roughly 0.5–2, and up to about 2.5 in swarms [518]. From the catalogue counts of 2016–2025, $b = \log_{10}(17{,}561 / 1{,}333) = 1.12$ from M 5 to M 6. It is $\log_{10}(1{,}333 / 134) = 1.00$ from M 6 to M 7, and $\log_{10}(134 / 7) = 1.28$ from M 7 to M 8, on 7 events.

The yearly means of 2000–2021, summed upward, give 1,766 events of M 5 or more and 152 of M 6 or more. They give 15.0 of M 7 or more and 1.23 of M 8 or more. These

counts give b = 1.06, 1.01 and 1.09.

One rule of frequency holds from the 1.3 million small events of the ledger to the single great one of a year. The net's earthquake text calls the power law the fingerprint of the machine, and holds that criticality is not an accident of the crust [524].

Where they break

The Ring of Fire around the Pacific holds 90 % of the earthquakes and 81 % of the largest [517]. Megathrusts, the great faults at subduction zones, release about 90 % of the seismic moment [517].

The essay of the net sorts earthquakes by depth [524]. Shallow ones, from 0 to 70 km (25.54), make about three quarters of all. Intermediate ones, from 70 to 300 km (26.87), break where minerals in the sinking plate give up their water under rising pressure.

Deep ones run from 300 to 680 km (27.61) [524]. Below 400 km (27.13) pressure suppresses brittle failure, and near 550 km (27.42) the behaviour changes abruptly [524]. The count has a minimum near 300 km (26.87) and a second peak near 550–600 km (27.42–27.50); near 680 km the earthquakes stop [524].

The deepest great event the essay names is Bolivia 1994, M 8.3 at 630 km (27.54) [524]. Deep-focus earthquakes are placed at 300–700 km (26.87–27.64) [517]. The mantle model PREM has a step in density at 670 km (27.60) [279].

Reid described the loading in 1910, after the San Francisco earthquake of 1906 [524]. Two plates lock, tension loads for decades, and the fault discharges it in seconds [524]. The net's earthquake text names the three phases of its machine: loading, holding and discharge [524].

The essay reads the deep events in the net's terms [524]. In its reading deep earthquakes are reclosures, not fractures: the old winding of the rock no longer fits its context, and reclosure onto the new mesh width is the earthquake. Below 680 km the winding is fully reclosed, with nothing left to store.

After the main shock

The aftershocks fall off in a fixed way. Omori found in 1894 that their frequency "decreases roughly with the reciprocal of time after the main shock" [519]. Utsu (1961) gave the exponent p, which "typically falls in the range 0.7–1.5" [519].

The largest aftershock is about 1.1–1.2 magnitude units below the main shock, by Båth's law of 1965 [519]. In energy that is 10^(1.5 × 1.1) = 45 to 10^(1.5 × 1.2) = 63 times less.

In the essay's reading, Omori is stepwise restoration [524]. A discharge that recloses incompletely leaves residual tension; the deeper the event, the more complete the reclosure [524].

The release of moment

The great events carry most of the moment. Mw 9.5 gives 2.24×10^{23} N·m, 9.2 gives 7.94×10^{22}, 9.1 gives 5.62×10^{22}, 8.8 gives 2.00×10^{22} N·m. The USGS moment of Tōhoku is 3.9×10^{22} N·m [523].

The 16 earthquakes of M 7 or more in 2025 sum to 2.31×10^{22} N·m [516]. The single M 8.8 of Kamchatka carries 2.00 / 2.31 = 86 % of it. Valdivia alone, at 2.24×10^{23} N·m, equals about ten such years: $2.24 \times 10^{23} / 2.31 \times 10^{22} = 9.7$.

At most 10 % of the total energy of an earthquake is radiated as seismic waves [517]. The two largest recent events radiated 1.1×10^{17} J (2004) and 1.9×10^{17} J (2011) as surface waves [522][523].

Deaths do not follow magnitude. Of the 15 deadliest events listed above, only Sumatra 2004 is also among the 17 of M 8.5 or more.

The clocks of the trigger

The essay of the net sets the size of the trigger against the size of the discharge [524]. An earthquake releases a stress drop of 1–10 MPa. The external clocks push with 1–10 kPa [524].

The tides of Moon and Sun deform the solid Earth twice a day, with stresses of 1–5 kPa [524]. Loads of water push with 1–10 kPa: snow in Japan, the yearly water cycle of the Sierra Nevada and groundwater [524]. Changes in the Earth's rotation, of milliseconds per day, appear in the seismic record with a lag of about five years (50.34) [524].

The ratio of discharge to trigger is 1 MPa / 1 kPa = 1,000 and 10 MPa / 10 kPa = 1,000 where the ranges match end to end. Over the full ranges it runs from 1 MPa / 10 kPa = 100 to 10 MPa / 1 kPa = 10,000. The essay concludes that the crust is held near criticality [524].

In the essay's reading, the tension is loaded in the local mesh, while the context in which that mesh hangs is set at solar-system depth. In its words: "The loading is local, the clock is not." The external clocks appear in the timing and never in the energy; read so, this is the form of context (chapter 11).

Tsunamis

In the deep ocean a tsunami travels at "well over 800 kilometres per hour", with a wavelength "up to 200 kilometres" (26.50) [525]. Its height there is "about 1 metre" (15.39) [525].

At a point on the coast the wave cycle lasts "20 or 30 minutes" (39.61–39.98); damaging tsunamis typically last "about twelve minutes" (39.14) [525]. The ladder of the net's climate essay places the tsunami, 10–60 minutes (38.98–40.61), beside position 40 [29].

The speed of a long wave in water of depth h is $\sqrt{(g\,h)}$. With g = 9.82 m s^{-2} [277] and the mean ocean depth of 3,682.22 m (22.86) [360], the speed is $\sqrt{(9.82 \times 3{,}682.22)}$ = 190 m s^{-1}, or 685 km per hour.

"About 80% of tsunamis occur in the Pacific Ocean" [525]. A query of the global tsunami database for 2000–2024, 25 years (51.80), returned at least 175 events [526]. Of 174 complete records, 146 were caused by earthquakes, 146 / 174 = 84 % [526].

The other causes in that set carry the codes 8 (12 events), 3 (7 events), 6 (4 events) and 9 (3 events) [526]. Fifty-two events caused deaths, about 21 per decade [526].

Tsunami	Year	Run-up	Position	Deaths	Source
Messina	1908	–	–	more than 123,000	[525]
Lituya Bay, landslide	1958	524 m	21.09	–	[525]
Valdivia, local	1960	up to 25 m	18.32	–	[520]
Valdivia, at Hilo	1960	10.7 m	17.54	61	[520]
Indian Ocean	2004	51 m	18.97	at least 230,000 in 14 countries	[525][522]
Tōhoku, Miyako	2011	40.5 m	18.76	–	[523]
Tōhoku, Aneyoshi	2011	38.9 m	18.72	–	[523]
Hunga Tonga, Tonga	2022	up to 20 m	18.11	7 in all	[511]
Hunga Tonga, Tofua	2022	45 m	18.85	–	[511]
Hunga Tonga, Peru and Chile	2022	2 m	16.02	–	[511]

The run-ups of the great subduction earthquakes reach 20–51 m (18.11–18.97). A volcano reached 45 m (18.85) on Tofua. A landslide into a fjord reached 524 m (21.09).

Slow slip

Not every slip is sudden. In Cascadia episodic tremor and slip “reoccur cyclically with a period of approximately 14 months” (49.01) [527]. Each episode brings about two weeks (45.90) of tremor and slip, with displacement “over a period of days to weeks” [527].

Other studies give the Cascadia return period as “approximately 14.5 months” (49.04) [528]. They also report that the events “repeat at 13- to 16-month intervals, and last 2 to 4 weeks at any one GPS station” [528]. The intervals sit at 48.94–49.13, the durations at 45.90–46.53.

The event of 1999 “took approximately 35 days” (46.74) and was “equivalent to a magnitude 6–7 earthquake” [528]. Another account gives one episode as “equivalent to a magnitude 7 earthquake” [527].

Slow slip on the deeper Cascadia interface comes with tremor at the same time and place as the slip seen in six years (50.50) of crustal-motion data [529]. Between the slips, tremor is minor or absent [529].

Nonvolcanic tremor was first identified in southwest Japan in 2002 [527]. In Shikoku the slow slips return about every 6 months (48.24) [528]. At Tokai a slow event ran from mid-2000 to 2003, about 3 years (49.87) [528].

Near Wellington in New Zealand a year-long (48.87) slow event recurs “every five years” (50.34): in 2003, 2008 and 2013 [527].

The tectonic low-frequency earthquakes are of magnitude below 3, with a peak at 1–3 Hz, periods of 1 to 0.33 s (33.15–32.15) [528]. They lie at depths of 28–47 km (24.71–25.18) in southern Cascadia and 25–37 km (24.60–24.96) under Vancouver Island [528]. Very-low-frequency events are of magnitude about 3–3.5, with periods of about 20 s (35.88) [528].

For slow events “their seismic moment is proportional to the characteristic duration”, and “their moment rate function is constant” [530]. The family includes tremor, low- and very-low-frequency earthquakes, slow slip events and silent earthquakes [530].

Region	Period	Position	Duration	Position	Source
Shikoku	about 6 months	48.24	–	–	[528]
Cascadia	about 14 (13–16) months	49.01 (48.94–49.13)	2–4 weeks; 35 days in 1999	45.90–46.53; 46.74	[527][528]
Tokai	–	–	about 3 years	49.87	[528]
Wellington	about 5 years	50.34	about 1 year	48.87	[527]

The slow slips load and release on a regular period, from 6 months (48.24) to 5 years (50.34). Read through the net, this is the form of loading, holding and discharge, with the moment growing in step with the duration.

The year 2026 and the Colombian earthquake

On 10 August 2026, at 12:34:28.828 UTC, an earthquake of Mw 7.4 struck 4 km (22.94) south-southwest of San José del Palmar, Colombia [516]. The hypocentre lay at 4.8601° N, 76.2558° W, at a depth of 116.13 km (26.00) [516]. The PAGER system used a depth of 108.2 km (25.94) [516].

The moment tensor gives a scalar moment of 1.66×10^{20} N·m [516]. A second tensor gives 2.22×10^{20} N·m (Mwc 7.5), and the finite-fault model 1.723×10^{20} N·m (Mw 7.424) [516]. The relation of IASPEI turns 2.22×10^{20} into Mw 7.50 and 1.723×10^{20} into Mw 7.42.

The nodal planes have strike 124°, dip 58.6°, rake 158.5° and strike 225.6°, dip 71.8°, rake 33.2° [516]. Both rakes are oblique: the motion combined strike-slip and reverse slip.

The PAGER alert was red, with a maximum shaking intensity of MMI 8 [516]. The ShakeMap gave 8.2, and 1,251 felt reports gave an intensity of 9.1 [516]. No tsunami

was flagged [516].

The essay of the net records more than 220 dead and 33 aftershocks [524]. It places the hypocentre at about 110 km (25.95), in the sinking Nazca plate [524]. In its reading, the load sits in the local mesh, in the plate motions and the sinking Nazca winding [524].

The event was one of 12 of M 7 or more in 2026 to 15 October [516]. In those 288 days (48.65) that is a rate of 12 / (288 / 365.25) = 15.2 per year, against 13.4 per year in 2016–2025.

Date (2026)	Place	M	Depth (km)	Position of depth	Source
22 February	Kota Belud, Malaysia	7.1	629	27.54	[516]
24 March	Tonga	7.5	234	26.64	[516]
30 March	Vanuatu	7.3	121	26.04	[516]
1 April	Bitung, Indonesia	7.4	–	–	[516]
20 April	Miyako, Japan	7.4	–	–	[516]
7 June	Philippines	7.8	57	25.35	[516]
24 June	Venezuela (two events, 31 s apart)	7.2 and 7.5	10	23.77	[516]
17 July	Puerto Madero, Mexico	7.3	–	–	[516]
10 August	San José del Palmar, Colombia	7.4	116	26.00	[516]
14 August	Ende, Indonesia	7.8	–	–	[516]
9 October	Panama	7.7	12.6	23.98	[516]

Four of the twelve lie at 116 km (26.00) or deeper. The two Venezuelan events came 31 s (36.28) apart. The Colombian moment, 1.66×10^{20} N·m, is 0.7 % of the 2025 total for M 7 or more.

What this part of the history shows

Pulses of 1–5 Myr (61.45–62.91) carry more than 75 % of each province. The extinctions beside them last 60 ± 48 kyr (58.88) at the end of the Permian, and less than 150 kyr (59.72) after the Central Atlantic onset. Read through the net, this is the form of loading, holding and discharge.

The Hawaiian hotspot has fed one chain for at least 81 Myr (65.45), while the islands above it are at most 5.1 Myr old (62.93). Read so, this is the form of form and carrier: the form lasts and its carriers are replaced. The hotspot itself drifted at 22–44 mm per year, the plate at 60.

The VEI scale runs from intervals of a day (43.50) to more than 50,000 years (58.72), ten times the volume per step from VEI 2 up. Earthquakes follow one rule of frequency, with b between 1.00 and 1.12 from M 5 to M 7. The net’s earthquake text calls that power law the fingerprint of the machine.

The largest events carry most of the release. One M 8.8 gave 86 % of the moment of 2025, and Valdivia alone equals 9.7 such years. The volumes of the eruptions span 1.9 to 3,800 km³, and Yellowstone discharged three times at intervals of 0.78 and 0.67 Myr (61.22 and 61.08).

A fault loads for decades and discharges in seconds, as Reid described in 1910. The slow slips load and release on periods of 6 months (48.24), 14 months (49.01) and 5 years (50.34), with moment in step with duration. Read through the net, these too have the form of loading, holding and discharge.

The trigger and the discharge differ in size by a factor of 100 to 10,000: 1–10 kPa from

tides and water loads against stress drops of 1–10 MPa. The load is local, while the timing follows clocks of Moon, Sun and rotation. In the net’s text, loading is local and the clock is contextual.

Earthquakes stop near 680 km (27.61), close to the density step of PREM at 670 km (27.60). In the reading of the net’s essay, a deep earthquake is a reclosure onto a new mesh width, and below 680 km nothing is left to store.

The mountains rise faster than they wear. The syntaxes of the Himalaya rise at 7 mm per year, 32 times the mean erosion of drainage basins, 0.218 mm per year. Everest, at 23.66, stands two thirds of a step above the mountain of the ladder at 23.00.

19. Ice and the Climate Cycles

The air and the oceans of the earlier chapters have a temperature. That temperature has never stood still. For 2.5 billion years the Earth has passed between worlds with ice at the Equator and hothouse worlds with a global mean of 36 °C.

The history of the ice runs on many clocks at once. Its states last tens of millions of years, and its rhythms 41,000 and 100,000 years. Its pulses last centuries, and some of its switches take a few years.

This chapter follows the ice in time order, from the first global glaciation 2.46 billion years ago to the two ice sheets, 215,000 glaciers and frozen ground of today. Every duration carries its position on the ladder of chapter 11, as a coordinate.

The first ice: 2.46 to 2.1 billion years ago

The oldest dated ice age falls with the rise of oxygen. A U–Pb age of 2.426 ± 0.003 billion years for the magmatism of the Ongeluk Formation, on the Kaapvaal craton of South Africa, fixes the window [392].

The first global glaciation and the onset of the Great Oxidation Event fall between about 2.460 and 2.426 billion years ago [392]. That window is at most 34 million years long (position 64.66).

As an age, 2.46 billion years stands at position 68.55 and 2.426 billion years at 68.54. A wider estimate places global glaciation between 2.5 and 2.2 billion years ago [480]. Those two ages stand at 68.57 and 68.45.

The rocks of this ice age are the Huronian Supergroup, north of Lake Huron in Canada. They run between Sault Ste. Marie and Rouyn-Noranda and were laid down around 2.4 to 2.1 billion years ago [531].

They hold at least three ice ages in three glacial diamictites. From oldest to youngest these are the Ramsay Lake, the Bruce and the Gowganda formations; the Gowganda is about 2.3 billion years old [531].

Deposits of similar age lie in Michigan, Wyoming, Quebec and Nunavut. Others lie in the Griquatown Basin of South Africa, in India and in Australia [531]. A. P. Coleman inferred the ice age from these rocks in 1907 [531].

The Huronian span, 2,400 − 2,100 = 300 million years, has position 66.64. In South Africa the Makganyene Formation is about 2.25 billion years old (position 68.47) and may have been laid down at tropical latitudes [480].

Snowball Earth: the Cryogenian, 717 to 635 million years ago

The next dated global ice falls in the Cryogenian. It came in two long glaciations that reached the Equator.

Re–Os ages on three palaeocontinents bracket them [532]. At the base of the Callison Lake Formation in Yukon an age of 752.7 ± 5.5 million years shows sediment laid down without ice. Western Laurentia was free of ice between about 753 and 717 million years ago [532].

On the Congo craton an age of 727.3 ± 4.9 million years lies just below the Grand Conglomerate. That age argues against a global “Kaigas glaciation” near 740 million years ago [532].

In Mongolia an age of 659.0 ± 4.5 million years lies directly above the Maikhan-Uul diamictite. It supports “a long 717–660 Ma glacial epoch” [532].

This is the Sturtian glaciation, 717 to 660 million years ago. It lasted 717 − 660 = 57 million years (position 65.13); with the Mongolian age, 717 − 659.0 = 58 million years (65.14). As ages, 717 and 660 million years stand at 67.43 and 67.36.

The second glaciation is the Marinoan. Two U–Pb zircon ages on ash beds within the Ghaub Formation of Namibia are 639.29 ± 0.26 and 635.21 ± 0.59 million years [533].

The glaciation lasted at least 4 million years; 639.29 − 635.21 = 4.08 million years (position 62.73). Another dating gives the Marinoan as about 650 to 635 million years ago, 15 million years (63.91) [480].

The interval without ice between the two glaciations lasted at most 20 million years [533]. From 660 to 639.29 million years ago is 20.7 million years (position 64.20). For about the last 4 million years of the Marinoan the ice ground and laid down sediment, with at least some open water [533].

A Re–Os age of 632.3 ± 5.9 million years at the base of the Sheepbed Formation in north-western Canada dates the end of the Marinoan in Laurentia [532]. It is the first direct radiometric limit there.

It matches U–Pb zircon ages from China, Australia and Namibia [532]. The two glaciations were synchronous within error across three to four palaeocontinents.

Both reached the sea at the Equator. Equatorial glacial ice stood “at or below sea level”, and its onset was coeval with a tropical large igneous province [480].

The Elatina deposit of Australia is the one deposit the summary page calls indubitably low-latitude. Palaeomagnetic data put some glacial sediments within 10 degrees of the Equator [480].

Between 717 and 635 million years ago lie 82 million years (position 65.46). Ice covered about 57 + 4 = 61 of them (65.19): 61 / 82 = 74 percent.

Model studies give the exit from such a state [480]. A thaw needed about 350 times the present carbon dioxide, about 13 percent of the atmosphere (Crowley 2001).

The gas built up over 4 to 30 million years (positions 62.71 to 64.54). The melting then took as little as a millennium (55.16).

The meltwater formed a lid on the ocean up to 2 kilometres thick (size position 22.30) [480]. Above the glacial deposits lie cap carbonates, metres to tens of metres thick, with $\delta^{13}C$ near −5 ‰.

The Doushantuo cap of China reaches $\delta^{13}C$ as low as −48 ‰ [480]. An iridium anomaly at the base of a cap has been used to argue a duration of at least 3 million years (62.45) [480].

Read through the net, the history here has the form of loading, holding and discharge. The gas loads over millions of years while the ice holds; the discharge of the ice takes about a thousand years.

A review by Hoffman and co-authors adds the life of the Snowball [534]. Its ice sheets lose mass and grow sensitive to orbital forcing. Meltwater on the ice holds ecosystems with cyanobacteria and some eukaryotes.

Under the ice the ocean circulates, moved by the heat of the interior and the loss of heat through the ice. Cap carbonates are unique to the Cryogenian glaciations [534].

The Gaskiers glaciation follows. It lasted 350,000 years (position 60.49) and was not global (Pu et al. 2016) [480].

Within 5 million years after the Marinoan, about 635 to 630 million years ago, the ocean took up oxygen. Black shales of the Doushantuo show it in their enrichment of molybdenum and vanadium [395].

Episode	Start	End	Duration	Position (duration)	Source
First global glaciation	2,460 Ma	2,426 ± 3 Ma	≤ 34 Myr	64.66	[392]

Huronian (three diamictites)	~2,400 Ma	~2,100 Ma	300 Myr span	66.64	[531]
Sturtian	717 Ma	660 Ma (659.0 ± 4.5)	57 Myr	65.13	[532]
Cryogenian interlude	660 Ma	639.3 Ma	≤ 20 Myr	64.20 (20.7 Myr)	[533]
Marinoan	≥ 639.29 ± 0.26 Ma	635.21 ± 0.59 Ma	≥ 4 Myr	62.73 (4.08 Myr)	[533]
Gaskiers	—	—	0.35 Myr	60.49	[480]

The Phanerozoic: 485 million years of temperature

The reconstruction PhanDA covers the last 485 million years (position 67.07) [535]. It joins proxy data and climate model simulations by data assimilation.

Its database, PhanSST, holds over 150,000 proxy estimates from five proxy systems for sea-surface temperature [535]. Eighty-five time slices were assimilated. Each stage used an 80-member ensemble drawn from over 850 simulations across more than 100 time slices, and each stage was assimilated 420 times [535].

Global mean surface temperature ranged from 11 °C to 36 °C [535]. The coldest value, 11 °C, falls in the Late Pleistocene, 129,000 to 11,700 years ago. The warmest, 36 °C, falls in the Turonian, 93.9 to 89.39 million years ago (positions 65.58 to 65.54).

Each era had its hothouse peak: 34 °C in the Paleozoic, 36 °C in the Mesozoic and 34 °C in the Cenozoic [535]. The time-weighted mean is 24 ± 5 °C, against 20 ± 2 °C for the model prior. The range is 36 − 11 = 25 °C.

The Earth spent more time warm than cold [535]. The reconstruction divides its states by quintile of global temperature: hothouse 28–36 °C, warmhouse 25–28 °C, transitional 22–25 °C, coolhouse 18–22 °C and coldhouse 11–18 °C.

Greenhouse states hold 41 percent of the time, icehouse states 31 percent and transitional states 27 percent [535]. The coldhouse alone holds 13 percent.

The tropics changed less than the globe. Tropical temperatures ran from 22 to 42 °C: 22–31 °C in icehouse worlds (median 27 °C) and 32–42 °C in greenhouse worlds (median 36 °C) [535]. Peak tropical sea-surface temperature reached about 40 °C in the Turonian and 38 °C at the Paleocene–Eocene boundary.

The gradient from the tropics to the poles was 30–48 °C in coldhouse worlds and 14–25 °C in hothouse worlds [535]. Warmer worlds have weaker gradients; global temperature and gradient correlate at r = −0.90.

Temperature follows carbon dioxide [535]. Against the logarithm of carbon dioxide the correlation is r = 0.72 over the Phanerozoic.

It is 0.97 in the Cenozoic and 0.73 in the Paleozoic, and −0.37, not significant, in the Mesozoic. The apparent Earth system sensitivity is 7.7 ± 0.3 °C per doubling over the Phanerozoic, 8.2 ± 0.4 °C in the Cenozoic and 7.8 ± 1.5 °C in the Paleozoic [535].

A second model covers the last 540 million years (position 67.17) [536]. It combines oxygen-isotope temperatures with climate-sensitive rocks: coals, evaporites and bauxites. It adds indicators of polar ice: tillites, dropstones and glendonites [536].

It finds 8 major climate modes, each with 3 to 4 pairs of warming and cooling episodes, which it calls chronotemps [536]. It does not reproduce the very high Early Paleozoic temperatures of studies based on isotopes alone. It links warming to the eruption of large igneous provinces [536].

A summary page counts about 4 climate optima separated by roughly 140 million years (position 65.94) [537]. It places the Phanerozoic ice ages in the late Ordovician to early Silurian and in the Permian–Carboniferous.

It gives a Sun about 30 percent dimmer at 4.5 billion years ago, its output rising about 10 percent per billion years [537]. For the Archean and Paleoproterozoic it reports

ocean temperatures of 55–85 °C (Knauth 2005), an estimate other work disputes [537].

Three icehouses are dated in the Phanerozoic. The first is the late Ordovician glaciation, under way by about 444 million years ago (as an age, position 66.99) [538]. The spread of non-vascular land plants has been proposed to have speeded chemical weathering.

That would have drawn down carbon dioxide enough to start the ice sheets [538]. Models require at most 1,500 ppm of carbon dioxide for this glaciation [401].

The second is the late Paleozoic ice age, 340 to 260 million years ago (ages at 66.75 and 66.51; span 80 million years at 65.43) [401]. Carbon dioxide then stood below 500 ppm [401]. It is the longest icehouse of the Phanerozoic and the only recorded passage from icehouse to greenhouse [539].

Its glacial periods were discrete and separated by brief warm intervals. Moderate ice sheets grew from several centres across southern Gondwana [539].

Across 372 published observations binned in steps of 10 million years, carbon dioxide stays below 500 ppm during long, widespread continental glaciations [540]. It rises above 1,000 ppm in the warm periods. The threshold for growing ice sheets under a Sun about 4 percent fainter lies likely at 2,000–4,000 ppm [401].

The third icehouse is the present one, begun about 34 million years ago. It is the subject of the next sections.

The same relation between gas and heat takes other values in other eras: r = 0.97 in the Cenozoic and no significant relation in the Mesozoic. Read through the net, this has the form of context: the same rule takes other values in other surroundings.

Quantity	Value	Position	Source
Span of PhanDA	485 Myr	67.07	[535]
Global mean surface temperature	11–36 °C; mean 24 ± 5 °C	—	[535]
Coldest	11 °C, 129–11.7 ka	—	[535]
Warmest	36 °C, Turonian 93.9–89.39 Ma	—	[535]
Time shares	greenhouse 41 %, icehouse 31 %, transitional 27 %	—	[535]
Earth system sensitivity	7.7 ± 0.3 °C per doubling	—	[535]
Span of Scotese model	540 Myr	67.17	[536]
Spacing of climate optima	~140 Myr	65.94	[537]
Late Paleozoic ice age	80 Myr (340–260 Ma)	65.43	[401]

The Cenozoic: from hothouse to icehouse, 66 to 2.6 million years ago

The last 66 million years (position 65.26) carry an astronomically dated record. CENOGRID is a continuous composite of benthic $\delta^{18}O$ and $\delta^{13}C$ over this span, dated astronomically and built from the records of several laboratories [541].

It defines four climate states by their response to orbital forcing: Hothouse, Warmhouse, Coolhouse and Icehouse [541]. Polar ice volume is key to how predictable each state is.

The Cenozoic climate varies in three kinds [542]. Gradual trends run over 10^5 to 10^7 years (positions 59.35 to 63.54) and follow the movement of plates.

Rhythmic cycles run over 10^4 to 10^6 years (57.25 to 61.45) and follow the orbit. Rare rapid aberrations last about 10^3 years (55.16) [542].

Over the Cenozoic global temperature follows the logarithm of carbon dioxide at r = 0.97 [535]. The era’s hothouse maximum is 34 °C.

The Paleocene–Eocene Thermal Maximum, 56 million years ago

One aberration, the Paleocene–Eocene Thermal Maximum, began around 55.8 million years ago (Bowen 2015; as an age, position 65.11) [543]. It lasted about 200,000 years (59.98) on one estimate. An orbital chronology gives about 170,000 years (59.83) [543].

A precession chronology of the Walvis Ridge sites of Ocean Drilling Program Leg 208 also gives a total of about 170,000 years [381]. The onset took less than 20,000 years (57.88), by helium-3 (Farley 2003) [543].

The globe warmed by 5 to 8 °C; an alternative estimate gives 3 to 6 °C (Evans 2016) [543]. Global mean surface temperature stood at 27.2–34.5 °C during the event and at 22.3–28.3 °C in the latest Paleocene (a 2020 study, 66 percent confidence) [543]. Peak tropical sea-surface temperature reached about 38 °C [535].

The carbon added is given as 2,000 to 7,000 Gt (Zeebe 2009 and others) [543]. Another study gives more than 10,000 Pg C, isotopically heavier on average than earlier estimates [379].

It finds surface pH persistently low and names the volcanism of the North Atlantic Igneous Province as the main source, rather than methane hydrates [379]. Peak emission ran at 0.3–1.7 Pg C per year [543].

The carbon-isotope excursion is about 2 ‰ in bulk carbonate and more than 6 ‰ on land [543]. It has been found at more than 130 locations. The lysocline of the ocean rose about 2 kilometres (size position 22.30) within a few thousand years (Zachos 2005) [543].

The Early Eocene optimum and the Azolla interval

The Early Eocene Climatic Optimum ran from 53.3 to 49.1 million years ago, 4.2 million years (position 62.75) [543]. Global mean temperature stood at 23.2–29.7 °C (a 2020 study, 66 percent confidence).

Around the start of the middle Eocene, about 50 million years ago, the free-floating fern *Azolla* grew and reproduced in the Arctic Ocean [544]. Freshwater microfossils show the surface diluted episodically over about 800,000 years (61.24). Local sea-surface temperature rose from about 10 °C to 13 °C at the end of the phase [544].

The bloom is dated about 48.5 million years ago, in sediments of the Lomonosov Ridge [545]. Carbon stored in the interval amounts to 0.9–3.5 × 10^{18} g, that is 900–3,500 Pg C. The estimated drawdown of carbon dioxide is roughly 55–470 ppm under Eocene conditions [545].

The Eocene–Oligocene transition: Antarctica freezes, 34 million years ago

The large Antarctic ice sheet grew at the Eocene–Oligocene transition, about 34 million years ago (as an age, 64.66) [546]. The transition lasted about 790,000 years (61.23); an earlier estimate of 500,000 years (60.81) has been superseded. The top of the earliest Oligocene oxygen-isotope step lies at 33.65 million years ago [546].

The benthic $\delta^{18}O$ shifted by about 1.5 ‰, joining deep-sea cooling and ice growth [546]. Tropical surface and bottom water cooled by a permanent 2.5 °C at the first step, by Mg/Ca in Tanzania. Surface waters cooled by 1–5 °C in both hemispheres and by 4–8 °C in some subantarctic records [546].

The best-fit models need a fall of carbon dioxide of about 40 percent, about 325 ppm, called an upper estimate [546]. Sea level fell by the order of 70 metres (size position 19.25).

The ice came in steps. In the equatorial Pacific the calcite compensation depth deepened by more than 1 kilometre near the boundary [547]. It did so “in two jumps of about 40,000 years each” (58.52), in step with the growth of Antarctic ice.

The modern compensation depth lies near 4,500 metres (size position 23.04) [547]. The $\delta^{18}O$ change is too large for Antarctic ice growth alone [547].

A summary page gives the first Antarctic ice between 60 and 45.5 million years ago (ages at 65.17 and 64.92) [548]. It places the escalation at about 34 million years ago, with carbon dioxide then about 760 ppm and a tipping point near 600 ppm [548].

The sea-level record gives three phases of ice over the last 100 million years [363]. Ephemeral Antarctic ice sheets came and went from 100 to 33 million years ago. Large, mainly Antarctic ice sheets stood from 33 to 2.5 million years ago.

Large and variable ice sheets in the Northern Hemisphere followed from 2.5 million years ago to the present [363]. Long-term sea level peaked at 100 ± 50 metres above the present in the Cretaceous (size position 19.58) [363].

Greenland and the northern ice

Greenland has carried glaciers and ice caps for at least 18 million years (Thiede 2011; position 64.08) [549]. A coherent ice sheet existed from about 10 million years ago (63.54). A single ice sheet over most of the island formed about 2.6 to 2.7 million years ago (62.32 to 62.35), when carbon dioxide fell to 280–320 ppm [549].

In the Pliocene warm period, about 3 million years ago, ice was limited to the highest peaks [549]. The oldest ice in the 3-kilometre summit core is about 1,000,000 years old (61.45). The soil under the ice has been covered for about 2.7 million years [549].

South Greenland was largely free of ice about 400,000 years ago, in Marine Isotope Stage 11 (60.61). The ice at Camp Century melted at least once in the past 1.4 million years (61.75) [549].

The sheet is older than its oldest ice: 2.6 million years against about 1 million. Read through the net, this has the form of form and carrier: the form lasts while its carriers are replaced.

Event	Age	Duration	Position (duration)	Source
PETM	~55.8–56 Ma	~170,000–200,000 years; onset < 20,000 years	59.83–59.98; 57.88	[543][381]
Early Eocene optimum	53.3–49.1 Ma	4.2 Myr	62.75	[543]
Azolla interval	~50–48.5 Ma	~800,000 years	61.24	[544][545]
Eocene–Oligocene transition	~34 Ma	~790,000 years	61.23	[546]
Steps in the compensation depth	~34 Ma	2 × ~40,000 years	58.52	[547]
Greenland glaciers and caps	since ≥ 18 Ma	18 Myr	64.08	[549]
Greenland single ice sheet	2.6–2.7 Ma	—	62.32–62.35 (as age)	[549]

The rhythm of the ice ages: 41,000 and 100,000 years

The ice ages of the last 2.7 million years follow the Earth’s orbit. Three orbital periods set the pace [550]. The tilt of the axis moves between 22.1° and 24.5° over about 41,000 years (position 58.54).

The eccentricity of the orbit has a main component of 405,000 years (60.62), with components of 95,000 (59.30) and 124,000 years (59.55) [550]. The climatic precession runs about 21,000 years now (57.93). Over 300,000 years it varies from 20,800 to 29,000 years (57.92 to 58.22), with a mean of 23,000 years (58.01) [550].

The rhythm is old. A rhythmite sequence of about 1.4 billion years ago (as an age, 68.04) records Milankovitch cycles [324].

Its precession constant is 85.79 ± 2.72″ per year. The Earth–Moon distance was then 340,900 ± 2,600 km and the day 18.68 ± 0.25 hours long [324].

In 1976 the orbital pace of the ice was measured in Southern Ocean cores spanning 450,000 years (60.72) [551]. Their spectra show peaks at about 23,000, 42,000 and 100,000 years (58.01, 58.56, 59.35).

These carry about 10, 25 and 50 percent of the variance [551]. The 42,000-year component is in phase with the tilt, and the 100,000-year component is close to the eccentricity.

The stack LR04 joins 57 benthic $\delta^{18}O$ records from around the globe over 5.3 million years (62.96) [552]. It is coherent with the 41,000-year tilt throughout. The response to the tilt lags by about 3,400 years before 3 million years ago (56.27) and by about 6,800 years in the Pleistocene (56.90) [552].

In the late Pleistocene, 0 to 780,000 years ago, the band from 88,000 to 120,000 years (59.23 to 59.52) carries about 45 percent of the variance [552]. The phase of the precession response jumps at about 1.6 million years ago (as an age, 61.87) [552].

The Mid-Pleistocene Transition

From about 1,250,000 to 700,000 years ago the dominant cycle changed from about 41,000 to about 100,000 years [553]. The orbital forcing did not change substantially. Antarctic ice volume rose abruptly at about 900,000 years ago (as an age, 61.35) [553].

The transition lasted around 550,000 years (60.90) [554]. Before it the ice sheets were thin and of low amplitude; after it they were thick.

The tilt paced West Antarctic ice volume until about 400,000 years ago (Ohneiser 2022) [554]. Tropical Africa changed as early as 1.05 million years ago (Dupont 2001) [554].

The 41,000-year world ran from about 2.7 to 1.25 million years ago: 1,450,000 / 41,000 = 35 cycles. The 100,000-year world since 700,000 years ago holds 700,000 / 100,000 = 7 cycles. The Antarctic ice core of Dome C counts eight glacial cycles [555].

The same orbit gives thin ice every 41,000 years before the transition and thick ice every 100,000 years after it. Read through the net, this has the form of context: the same rule takes other values in other surroundings.

The terminations

The ends of the last glacial periods are dated [556]. Termination II falls about 130,000 years ago, III about 243,000 years ago and IV about 337,000 years ago (Chen 2006). Termination V falls about 430,000 years ago [555].

The spacings are 430 − 337 = 93,000 years, 337 − 243 = 94,000 years and 243 − 130 = 113,000 years. From Termination II to the base of the Holocene at 11,700 years ago is 118,300 years. The mean of the four spacings is 104,600 years (59.39).

The interglacial after Termination V lasted about 28,000 years (58.19) [555]. Between 740,000 and 430,000 years ago the interglacials were weaker, but warm conditions took a larger share of each cycle [555].

Rhythm	Period	Position	Source
Climatic precession, now	21,000 years	57.93	[550]
Climatic precession, mean	23,000 years	58.01	[550][551]
Tilt	41,000 years	58.54	[550][552]
Eccentricity components	95,000 / 124,000 years	59.30 / 59.55	[550]
Late-Pleistocene band	88,000–120,000 years	59.23–59.52	[552]
Glacial cycle	100,000 years	59.35	[551][553]
Mean spacing of terminations	104,600 years	59.39	[556][555]
Eccentricity, main	405,000 years	60.62	[550]
Mid-Pleistocene Transition	550,000 years	60.90	[554]

Interglacial after Termination V	28,000 years	58.19	[555]

The ice cores

The air of the glacial cycles is kept in the ice. At Vostok in Antarctica a core covers four glacial–interglacial cycles over “the past 420,000 years” (60.66) [557].

Its carbon dioxide and methane move with Antarctic air temperature [557]. The present levels have no precedent in the record.

The Vostok ice reaches 420,000 years at a depth of 3,310 metres (size position 22.76) [558]. The deepest Vostok core reached 3,769 metres (22.88). The core Vostok 5 was begun in 1990 and reached 3,661 metres in 2007 (22.86) [558].

At Dome C the European core EPICA holds eight glacial cycles [555]. The 2004 paper reports a record of about 740,000 years (61.17). The core reached bedrock at 3,260 metres (22.75), and usable data reach back 800,000 years (61.24) [558].

Over these 800,000 years carbon dioxide stayed between 172 and 300 ppmv before industry [405]. In Marine Isotope Stage 16 it stood below 180 ppmv for about 3,000 years (56.16) [405]. At the Last Glacial Maximum it was 30 percent below its level just before industrialisation [558].

Dome Fuji in Antarctica has two holes [558]. The first reached 2,503 metres in 1996 (22.51), with a bottom age of about 330,000 years (60.44). The second reached 3,035 metres in 2006 (22.68), with ice 720,000 years old (61.15) [558].

Greenland’s cores are shorter in time [558]. GRIP reached bedrock at 3,029 metres in 1992 (22.68) and GISP2 at 3,053 metres in 1993 (22.69).

Each holds about 100,000 years of climate (59.35). NGRIP reached 3,085 metres in 2003 (22.70) and holds data to 123,000 years (59.54) [558].

In the Allan Hills of Antarctica, blue ice retrieved in 2016 is dated by potassium–argon to 2.7 million years (62.35) [558]. It is not a continuous record.

The mean years of ice per metre of core differ by a factor of six. Vostok holds 420,000 / 3,310 = 127 years per metre and EPICA 800,000 / 3,260 = 245 years per metre. NGRIP holds 123,000 / 3,085 = 40 years per metre.

Read through the net, the cores have the form of reading. The ice keeps the relation of gas and temperature through eight cycles and drops the rest.

Core	Depth	Position (depth)	Age span	Position (age span)	Source
Vostok (420,000 years)	3,310 m	22.76	420,000 years	60.66	[557][558]
Vostok, deepest	3,769 m	22.88	—	—	[558]
EPICA Dome C	3,260 m	22.75	800,000 years	61.24	[555][558]
Dome Fuji, first hole	2,503 m	22.51	330,000 years	60.44	[558]
Dome Fuji, second hole	3,035 m	22.68	720,000 years	61.15	[558]
GRIP	3,029 m	22.68	~100,000 years	59.35	[558]
GISP2	3,053 m	22.69	~100,000 years	59.35	[558]
NGRIP	3,085 m	22.70	123,000 years	59.54	[558]
Allan Hills blue ice	—	—	2.7 Myr	62.35	[558]

The Last Glacial Maximum, 33,000 to 19,000 years ago

The last glacial period reached its peak between 33,000 and 19,000 years ago. A compilation of 5,704 ages by radiocarbon, beryllium-10 and helium-3 dates its ice

margins [559].

The ice sheets reached their maximum between about 33,000 and 26,500 years ago (as ages, 58.34 and 58.14). Nearly all stood at their maximum positions at 19,000–20,000 years ago (57.84–57.88) [559].

A summary page gives the maximum as 26,000 to 20,000 years ago [560]. The ice sheets of the whole world stood at their limits together.

Sea level records the ice. About 1,000 observations far from the former ice margins cover the past 35,000 years [366].

Around 30,000 years ago, at the onset of the glacial maximum, sea level fell about 40 metres (size position 18.74) in under 2,000 years (55.79). That is more than 40 / 2,000 = 20 mm per year [366].

Then followed a “slow fall to -134 m from 29 to 21 ka BP” [366]. The further 134 − 40 = 94 metres (19.52) fell over 8,000 years (57.05), about 12 mm per year. The low stand of 134 metres has size position 19.84.

Other records give about 125 metres lower at 21,000 years ago (Fairbanks 1989), and about 125 metres in the Bonaparte Gulf (Yokoyama et al. 2001) [560], against 134 metres [366].

The grounded ice at the maximum held about 52 × 10^6 km^3 more than today [366]. As water at a density of 0.917 this is 52 × 10^6 × 0.917 = 47.7 × 10^6 km^3.

Spread over the ocean area of 361.9 × 10^6 km^2 [311], it gives 47.7 × 10^6 / 361.9 × 10^6 = 0.132 km, that is 132 metres. That agrees with the −134 metres of the sea-level record.

The present ice and snow hold 24.06 × 10^6 km^3 [561]. At the maximum the ice held 24.06 + 52 = 76 × 10^6 km^3, 3.2 times today.

The Laurentide ice sheet over North America reached a maximum volume of about 26.5 to 37 million km^3 [560]. It stood 3.2 km high near the Keewatin Dome (size position 22.73).

Permanent summer ice covered about 8 percent of the Earth’s surface and 25 percent of its land, against 3.1 and 10.7 percent today [560]. Land ice covered 25 / 10.7 = 2.3 times today’s share.

The globe was about 6 °C colder than today (Tierney et al. 2020; Seltzer et al. 2021) [560]. Land at low elevation in low and middle latitudes was 5.8 °C colder (Seltzer 2021). The Late Pleistocene holds the coldest global temperature of the last 485 million years, 11 °C [535].

Permafrost reached as far as Beijing and Szeged [560]. Tundra and steppe spread widely [562]. The northern forest zones moved south, and the boreal and temperate deciduous forests broke apart.

The steppes of Europe and East Asia expanded, and the tropical moist forest contracted [562]. In south-western North America open conifer woodland replaced desert.

The end of the ice: deglaciation, 19,000 to 11,700 years ago

The main deglaciation ran from 16,500 to 8,200 years ago, 8,300 years (position 57.08) [366]. Sea level rose by about 12 metres per thousand years, 12 mm per year on average.

A summary page gives about 20 mm per year at the onset of deglaciation, about 19,000 years ago [365]. It gives 110 metres of rise (size position 19.66) between about 14,000 and 6,500 years ago. Early-Holocene rates were 6.0–9.9 mm per year, with brief accelerations to 30–60 mm per year [365].

The ice margins drew back in sequence. The Fennoscandian ice still stood at its maximum extent about 17,000 years ago (Stroeven 2016; as an age, 57.74) [560].

The West Antarctic ice declined between 15,000 and 14,000 years ago. Sea level rose abruptly at about 14,500 years ago (Clark 2009) [560].

Meltwater pulse 1A

At Tahiti the corals of the Bølling warming record the fastest rise [367]. The pulse "started no earlier than 14,650 years ago" and "ended before 14,310 years ago".

Sea level rose between 12 and 22 metres, with a most probable value of 14 to 18 metres (size positions 17.79 to 18.02) [367]. The rate "exceeded 40 millimetres per year".

The window is at most 14,650 − 14,310 = 340 years (position 54.18). A rise of 14–18 metres in 340 years is 41–53 mm per year, or 4.1–5.3 metres per century. Against the 3.7 mm per year of 2006–2018 [563] that is 11 to 14 times faster.

A summary page gives the window as 14,700 to 13,500 years ago, narrowed by several authors to 14,650–14,300 [564]. It gives a total rise of 16–25 metres over about 400–500 years (54.32–54.53), at a mean rate of 30–60 mm per year.

Antarctic iceberg discharge supplied at least 50 percent of it (Weber et al. 2014). The Fennoscandian and Barents ice supplied 4.5–7.9 metres of sea-level equivalent over half a millennium [564].

Another reconstruction gives 13.5 metres over about 290 years centred on 14,200 years ago [365]. That is 13.5 / 290 = 47 mm per year (position of 290 years: 54.03).

A second pulse, meltwater pulse 1B near 11,300 years ago, is not found in the sea-level inversion of the far field [366]. A summary page ties a pulse 1B to superfloods of the Mississippi 9,900–9,100 years ago [564].

The Younger Dryas

One cold interruption broke the warming. The Younger Dryas ran from about 12,900 to 11,700 years ago (Rasmussen 2006) [556].

Cooling in the Northern Hemisphere began around 12,870 ± 30 years ago (Cheng 2020). Its end is set at 11,700 years ago; some work places it closer to 11,550 [556].

It lasted 1,150 to 1,300 years (positions 55.29 to 55.40) [556]. In Greenland temperatures fell by 4–10 °C (Buizert 2014). At the summit it was up to 15 °C colder than in the early twenty-first century (Alley 2000) [556].

It began "over just 3 years or less" (Partin 2015; position 49.87) [556]. Its end warmed the climate over 50–60 years (Alley 1993; 52.43–52.60).

The net global cooling was 0.6 °C (Carlson 2013), and sea level changed little (Shakun 2012) [556]. Over the whole deglaciation carbon dioxide rose from about 210 to about 275 ppm (Shakun 2012) [556].

The end of the Younger Dryas is the base of the Holocene. It is fixed at 11,700 years before 2000 in the Greenland core NGRIP2 [565].

Read through the net, the glacial cycle of the last 100,000 years has the form of loading, holding and discharge. The ice loaded over a cycle of about 100,000 years (59.35), held at its maximum from 26,500 to 19,000 years ago, and discharged in 8,300 years (57.08).

Event	Age	Duration	Position (duration)	Size	Rate	Source
Ice sheets at maximum	33,000–26,500 years ago; all at maximum 20,000–19,000	—	—	—	—	[559]
Fast fall	~30,000 years ago	< 2,000 years	55.79	−40 m	> 20 mm/yr	[366]
Slow fall	29,000–21,000 years ago	8,000 years	57.05	to −134 m	~12 mm/yr	[366]

Main deglaciation	16,500–8,200 years ago	8,300 years	57.08	~100 m	~12 mm/yr	[366]
Meltwater pulse 1A	≤ 14,650 to ≥ 14,310 years ago	≤ 340 years	54.18	14–18 m	> 40 mm/yr	[367]
Younger Dryas	12,900–11,700 years ago	1,150–1,300 years	55.29–55.40	—	onset ≤ 3 yr; end 50–60 yr	[556]

The Holocene, 11,700 years ago to now

The present interglacial has a measured temperature history. A reconstruction from 73 records spread over the globe covers 11,300 years (position 57.37) [566]. The early Holocene, 10,000 to 5,000 years ago, was the warmest part.

The middle and late Holocene cooled by about 0.7 °C, much of it tied to a change of about 2 °C in the North Atlantic [566]. The coolest interval was the Little Ice Age, about 200 years ago.

A second reconstruction uses 1,319 temperature records from 470 sites on land and 209 at sea [567]. Its warmest 200-year interval (53.69) lies “around 6500 years ago”, 0.7 °C (0.3 to 1.8) warmer than the nineteenth century. The cooling after it ran at −0.08 °C per 1,000 years (−0.24 to −0.05) [567].

The decade 2011–2019 stood about 1 °C above 1850–1900 [567]. In 80 percent of the ensemble members no 200-year interval of the Holocene exceeded it.

The decade before 2013 was warmer than about 75 percent of the Holocene [566]. Global surface temperature for 2011–2020 stood 1.09 °C (0.95 to 1.20) above 1850–1900 [563].

The Holocene is divided into three stages [565]. The Greenlandian runs from 11,700 to 8,236 years before 2000, the Northgrippian from 8,236 to 4,250, and the Meghalayan from 4,250 to the present.

The stage lengths are 3,464, 3,986 and 4,250 years (56.29, 56.42, 56.48) [565]. The Meghalayan boundary is set in a speleothem of Mawmluh Cave in north-eastern India.

Two short events mark the stage boundaries. The 8.2 ka event lasted about 150 years (53.43), its coldest core about 60 years (52.60) [568].

In Greenland the cooling reached 3.3 °C below the decadal mean in less than 20 years (51.60). The glacial lakes Agassiz and Ojibway drained into the North Atlantic at its start [568].

The 4.2 ka event falls about 2200 BC and fills the twenty-second century BC, about 100 years (53.06) [569]. In the Habur Plains of Syria aridity and wind rose abruptly at 2200 BC, after four centuries of urban life [570].

Off the Indus delta the largest shift of planktonic $\delta^{18}O$ in the last 6,000 years falls at 4.2 ka [571]. Later drought cycles there vary between 200 and 800 years (53.69 to 54.95) [571].

Carbon dioxide moved little [572]. It fell by 5 ppmv in the early Holocene, when land took up about 290 Gt C. It then rose by 20 ppmv over 11,000 years [572].

The ocean volume stood almost still. From about 2,500 years ago (55.99) until a renewed rise 100–150 years ago it was nearly constant [366]. Between 6,000 and 150 years ago sea level oscillated by no more than 15–20 cm over intervals of 200 years or more [366].

Quantity	Value	Position	Source
Span of the 73-record reconstruction	11,300 years	57.37	[566]
Holocene thermal maximum	~6,500 years ago, +0.7 °C (0.3–1.8)	56.86 (as age)	[567]

Cooling after the maximum	−0.08 °C per 1,000 years	—	[567]
Greenlandian	3,464 years	56.29	[565]
Northgrippian	3,986 years	56.42	[565]
Meghalayan	4,250 years	56.48	[565]
8.2 ka event	~150 years (core 60)	53.43 (52.60)	[568]
4.2 ka event	~100 years	53.06	[569][570][571]
South Asian drought cycles	200–800 years	53.69–54.95	[571]

The millennial pulses: Dansgaard–Oeschger and Heinrich events

Within the last glacial period the climate jumped. Dansgaard–Oeschger events "occurred 25 times during the last glacial period" [573]. Another count gives 25 or 26 events over the past 120,000 years (Nye 2014; position 59.52) [556].

Each event warms in decades and cools gradually [573]. One warming reached about 8 °C in 40 years (52.23). A warming of 5 °C in 30–40 years (51.97–52.23) is more common [573].

The spacing of the events is measured two ways. In the GISP2 core a spacing of about 1,470 years (55.51) is "stable within a few percent" [574]. It holds to better than 12 percent over at least 23 cycles.

Under the NGRIP dating the recurrence is "indistinguishable from a random occurrence" [575].

In the Holocene the ice-rafted debris of the North Atlantic shows a cycle of "1470 ± 500 years" [576]. Cool waters bearing ice from north of Iceland then reached as far south as Britain. The cycle runs independent of the glacial or interglacial state [576].

Nine Bond events are listed, at about 11.1, 10.3, 9.4, 8.2, 5.9, 4.2, 2.8, 1.4 and 0.5 thousand years ago [577]. The gaps between these ages run from 800 to 2,300 years (54.95 to 55.92), with a mean of (11.1 − 0.5) / 8 = 1,325 years (55.41) [577]. A later reading puts the primary period at about 1,000 years (55.16) [577].

Heinrich events are layers of rock debris in the North Atlantic, carried by icebergs from around Hudson Strait [578]. Each layer was laid down over about "500 ± 250 years" (54.53; range 53.90 to 54.90). Three origins have been proposed: the binge–purge of the Laurentide ice, a jökulhlaup from Hudson Bay, and the build-up and collapse of an ice shelf [578].

The events appear in five of the last seven glacial periods, over 640,000 years (61.04) [579]. The events H3 and H6 are minor and of European ice. Their lithic peaks reach 3,000 grains per gram, against 6,000 for the others [579].

For H4 the fresh-water flux was 0.29 ± 0.05 Sv for 250 ± 150 years (53.90) [579]. That is about 2.3×10^6 km³ of fresh water and a sea-level rise of 2 ± 1 metres (Roche, Paillard & Cortijo 2004). Spread over the ocean area of 361.9×10^6 km², 2.3×10^6 km³ gives 6.4 metres, against the 2 ± 1 metres of the study.

The binge–purge cycle has a spacing of about 7,000 years (56.93) [579]. Heinrich events fall only in the cold spells before some Dansgaard–Oeschger warmings (Bond & Lotti 1995) [573].

Read through the net, the Heinrich cycle has the form of loading, holding and discharge. The ice loads for about 7,000 years and discharges its icebergs in 250 to 750 years.

The durations nest inside each other. A Dansgaard–Oeschger warming takes decades (51.97–52.23).

A Heinrich discharge takes centuries (53.90–54.90), the spacing of Dansgaard–Oeschger events a millennium and a half (55.51). The spacing of Heinrich events is

about 7,000 years (56.93) and the glacial cycle 100,000 years (59.35).

The net's own texts give a rule for layers of different speed [580]. "The slow layer sets the frame for the fast layer, never the reverse." Read through the net, the history here has the same form at every depth: each pulse sits inside a slower one.

Phenomenon	Count or spacing	Duration	Position	Source
Dansgaard–Oeschger events	25–26 in the last glacial (120,000 years)	warming in 30–40 years	51.97–52.23 (warming)	[573][556]
D-O spacing, GISP2	1,470 years ± 12 %, 23 cycles	—	55.51	[574]
D-O spacing, NGRIP	random	—	—	[575]
Bond cycle	1,470 ± 500 years	—	55.51	[576]
Bond gaps	800–2,300 years, mean 1,325	—	54.95–55.92; 55.41	[577]
Heinrich layer	—	500 ± 250 years	54.53	[578]
H4 discharge	2 ± 1 m; 2.3 × 10^6 km³	250 ± 150 years	53.90	[579]
Heinrich spacing	~7,000 years	—	56.93	[579]

The ice now: the two ice sheets

Two ice sheets remain. Together they hold "more than 99 percent of the land ice" and "over 68 percent of the fresh water on Earth" [581].

Antarctica

The Antarctic ice sheet covers almost 14 million km² [581]. Its thickest point is nearly 4.9 km (size position 23.12). Its volume is about 30 million km³, and its sea-level equivalent about 58 metres (19.08) [581].

The ice-thickness grid Bedmap2 rests on 25 million measurements [582]. It gives 27 million km³ of ice and a potential sea-level contribution of 58 metres. Its mean thickness is 4.6 percent greater than in Bedmap1, and the mean bed under grounded ice 72 metres lower (19.28) [582].

The area grounded below sea level is 10 percent larger than in Bedmap1. A summary page gives 26.5 × 10^6 km³ [548], against 27 × 10^6 km³ in Bedmap2 and 30 × 10^6 km³ at NSIDC.

The East Antarctic ice sheet holds 53.3 metres of sea-level equivalent (19.01) [548]. The West Antarctic sheet holds 4.3 metres on full melt (16.71). A collapse that leaves the mountain ice gives 3.3 metres (16.47; Bamber 2009) [548].

The mean thickness is 2.2 km (22.39) [548]. Parts of the bed of West Antarctica lie more than 2,500 metres below sea level (22.51). The Antarctic ice equals 61 percent of all fresh water on Earth by the Bedmap2 count [548].

The mapping BedMachine Antarctica corrects the bed elevation by up to 1 km at the margins (21.67) [583]. It shows deep glacial troughs and stabilising ridges beneath the edges of the sheet.

Greenland

The Greenland ice sheet covers 1.7 million km², about 80 percent of the island [581]. Its thickest point is over 3 km. Its volume is about 2.9 million km³ and its sea-level equivalent about 7.4 metres (17.21) [581].

A summary page gives 1,710,000 km², about 12 percent of the Antarctic sheet's area [549]. It gives 2,900,000 km³ (2,850,000 km³ in IPCC 2001), a mean thickness of 1,673 metres (22.14) and a maximum of 3,488 metres (22.81).

It gives a sea-level equivalent of about 7.4 metres (7.2 metres in IPCC 2001) [549]. The

annual mean temperature at the summit is about −31 °C.

The two sheets hold 58 + 7.4 = 65.4 metres of sea level (19.19). Antarctica holds about 30 / 2.9 = 10 times Greenland’s volume on 14 / 1.7 = 8.2 times its area.

Mass loss

Both sheets now lose ice. The IMBIE assessment of 2023 joins 50 independent estimates [584].

Over 1992–2020 the ice sheets added 21.0 ± 1.9 mm to global mean sea level (size position 11.87). Their combined loss was 105 Gt per year in 1992–1996 and 372 Gt per year in 2016–2020 [584].

Greenland lost 169 ± 9 Gt per year on average over 1992–2020 [584]. Its lowest loss was 86 Gt in 2017 and its highest 444 Gt in 2019.

West Antarctica lost 82 ± 9 Gt per year and the Antarctic Peninsula 13 ± 5 Gt per year. East Antarctica gained 3 ± 15 Gt per year [584].

The gravity satellites GRACE (2002–2017) and GRACE-FO (from June 2018) weigh the ice [585]. Since 2002 “Antarctica is losing ice mass at an average rate of about 135 billion tons per year”. Greenland is losing about 264 billion tons per year [585].

One millimetre of global sea level is 361.9×10^{12} m² × 10^{-3} m × 1,000 kg/m³ = 362 Gt of water. The gravity total of 135 + 264 = 399 Gt per year is 399 / 362 = 1.10 mm per year.

The IMBIE mean, 21.0 mm over 29 years (51.94), is 0.72 mm per year. The combined loss grew 372 / 105 = 3.5 times in 24 years (51.76).

Antarctica lost 2,720 ± 1,390 Gt over 1992–2017, 109 ± 56 Gt per year, 7.6 mm of sea level (IMBIE 2018) [548]. Greenland gained about 47 Gt per year in the 1970s [549]. It lost 51 Gt per year in the 1980s, 41 in the 1990s, 187 in the 2000s and 286 in 2010–2018.

Its net loss over 1992–2018 was 3,902 Gt, 0.13 percent of its mass [549]. In July 2012 melt covered over 97 percent of its surface.

Its last year of net gain was 1996. Since 1972 it has added 13.7 mm to sea level (Mouginot 2019; 11.48) [549].

At present loss rates the mass of each sheet would turn over slowly. Antarctica holds 27 × 10^6 km³ × 0.917 = 24.8 × 10^6 Gt; divided by 135 Gt per year this is 1.8 × 10^5 years (59.88). Greenland holds 2.9 × 10^6 × 0.917 = 2.66 × 10^6 Gt; divided by 264 Gt per year this is 1.0 × 10^4 years (57.25).

Quantity	Antarctica	Greenland	Source
Area	~14 × 10^6 km²	1.7 × 10^6 km²	[581]
Volume	27 × 10^6 km³ (30 × 10^6 NSIDC)	2.9 × 10^6 km³	[582][581]
Maximum thickness	~4.9 km (position 23.12)	3,488 m (22.81)	[581][549]
Mean thickness	2.2 km (22.39)	1,673 m (22.14)	[548][549]
Sea-level equivalent	58 m (19.08)	7.4 m (17.21)	[582][581]
Loss, gravity, since 2002	~135 Gt/yr	~264 Gt/yr	[585]
Loss, IMBIE, 1992–2020	West 82, Peninsula 13, East −3 Gt/yr	169 Gt/yr (86–444)	[584]
Turnover at present loss	1.8 × 10^5 years (59.88)	1.0 × 10^4 years (57.25)	computed

Glaciers and frozen ground

Outside the two ice sheets lie about 215,000 glaciers [586]. Together they hold 158 ± 41 × 10^3 km³ of ice. After removing the roughly 15 percent that lies below present sea level, they hold 0.32 ± 0.08 metres of sea-level equivalent (size position 14.35) [586].

High Mountain Asia holds about 27 percent less ice than earlier estimates. The mean glacier holds 158,000 / 215,000 = 0.73 km³.

Glaciers lost “267 ± 16 gigatonnes per year” in 2000–2019 [587]. That is 21 ± 3 percent of the observed rise of sea level, and 267 / 362 = 0.74 mm per year.

The loss accelerated by 48 ± 16 Gt per year per decade [587]. That accounts for 6 to 19 percent of the observed acceleration of sea-level rise.

Since 1971 glaciers supplied 22 percent and the ice sheets 20 percent of the rise of sea level [563]. Sea level rose 1.3 mm per year in 1901–1971, 1.9 in 1971–2006 and 3.7 in 2006–2018, in total 0.20 metres over 1901–2018 (13.92) [563]. The 78 water towers of glaciers and snow supply about 1.9 billion people [588].

The glaciers hold 0.32 / 65.4 = 0.5 percent of the ice sheets’ sea level. Their loss, 267 Gt per year, is two-thirds of the ice sheets’ 399 Gt. Their mass is 158 × 10^3 km³ × 0.917 = 1.45 × 10^5 Gt; at 267 Gt per year it would last about 540 years (54.60).

Frozen ground underlies much of the north. A map of the Northern Hemisphere for 2000–2016 at 1 km² resolution finds 13.9 × 10^6 km² with mean annual ground temperature below 0 °C [589]. That is about 15 percent of the exposed land area.

All classes of permafrost probability together cover about 21 × 10^6 km², 22 percent of the exposed land, about 2 × 10^6 km² less than earlier estimates [589]. The modelled ground temperature lies within ±2 °C of boreholes.

The water in ground ice and permafrost is given as 300,000 km³ [561]. Another budget gives 22 × 10^3 km³ [590]. The two estimates differ by a factor of 14.

The soils of the permafrost region hold about 1,300 Pg of organic carbon, in a range of about 1,100 to 1,500 [591]. Of this, 1,035 ± 150 Pg lies in the top 3 metres.

Below 3 metres deltaic deposits hold 91 ± 52 Pg and Yedoma 181 ± 54 Pg. About 800 Pg is perennially frozen and about 500 Pg is not [591].

Quantity	Value	Position	Source
Glaciers, count	~215,000	—	[586]
Glacier volume	158 ± 41 × 10^3 km³	—	[586]
Glacier sea-level equivalent	0.32 ± 0.08 m	14.35	[586]
Glacier loss, 2000–2019	267 ± 16 Gt/yr; +48 Gt/yr per decade	—	[587]
Glacier lifetime at present loss	~540 years	54.60	computed
Permafrost, mean ground temperature < 0 °C	13.9 × 10^6 km² (15 % of land)	—	[589]
Permafrost, any probability	~21 × 10^6 km² (22 %)	—	[589]
Permafrost-region soil carbon	~1,300 Pg (800 frozen)	—	[591]

What this part of the history shows

Read through the net, the ice comes and goes in the form of loading, holding and discharge. In the Snowball the gas built up over 4 to 30 million years (positions 62.71 to 64.54) and the ice melted in as little as a millennium (55.16). In the last glacial cycle the ice built over about 100,000 years (59.35), held at its maximum from 26,500 to 19,000 years ago, and went in 8,300 years (57.08).

The Heinrich ice reads the same way: about 7,000 years between events (56.93) and 250 to 750 years of iceberg discharge (53.90 to 54.90). Meltwater pulse 1A raised the sea 14 to 18 metres in at most 340 years (54.18), at more than 40 mm per year.

The switches are fast against the loading. The Younger Dryas began in 3 years or less (49.87) and ended in 50 to 60 years (52.43 to 52.60). A Dansgaard–Oeschger warming

of 5 °C takes 30 to 40 years, and the cooling after it takes centuries.

After the discharge the sea came to rest. From about 2,500 years ago until 100 to 150 years ago the ocean volume stood nearly constant, moving no more than 15 to 20 cm over 200 years or more. Holocene carbon dioxide fell by 5 ppmv and then rose by 20 ppmv over 11,000 years.

The durations nest. Zachos counts aberrations of 10^3 years (55.16), rhythms of 10^4 to 10^6 years (57.25 to 61.45) and trends of 10^5 to 10^7 years (59.35 to 63.54). At 34 million years ago two jumps of 40,000 years (58.52) sit inside a transition of 790,000 years (61.23), inside a decline of 66 million years (65.26).

Inside the last glacial, decadal warmings (51.97 to 52.23) sit inside centennial Heinrich discharges, millennial spacings (55.51), Heinrich spacings of 7,000 years and the cycle of 100,000 years. Read as the same form at every depth, each pulse sits inside a slower one.

The orbital rhythms of the ice stand on the ladder as coordinates. The precession runs from 57.92 to 58.22, the tilt at 58.54, the eccentricity components at 59.30 and 59.55 and the main eccentricity at 60.62. The ice-age period since the full Greenland sheet, 2.6 million years, stands at 62.32; the Precambrian glaciations last 4 to 57 million years (62.71 to 65.13).

Read as the form of context, the same rule takes other values in other surroundings. The same orbit paced thin ice every 41,000 years before 1.25 million years ago and thick ice every 100,000 years after 700,000 years ago. Temperature follows carbon dioxide at r = 0.97 in the Cenozoic and 0.73 in the Paleozoic, and at r = −0.37, not significant, in the Mesozoic.

Read as form and carrier, an ice sheet lasts while its ice is replaced. Greenland’s single sheet has stood for 2.6 to 2.7 million years, while its oldest ice is about 1 million years old. At today’s loss rates the mass of Greenland would turn over in 1.0×10^4 years (57.25) and of Antarctica in 1.8×10^5 years (59.88).

Read as the form of reading, the cores keep a relation and drop the rest. Across eight cycles and 800,000 years the ice keeps carbon dioxide between 172 and 300 ppmv, moving with Antarctic temperature.

20. Water on the Land

The oceans of chapter 14 hold almost all the Earth’s water; a small part stands on and under the continents. It falls as rain, runs in rivers, rests in lakes and soil, and sinks into rock. Some of it has stayed in the rock for more than a billion years.

The water on the land has a history of its own. Deserts formed at different times, from 80 million to 2 million years ago. The Sahara turned green more than 230 times, and the monsoons began 9 to 8 million years ago and follow the 23,000-year precession of chapter 19.

This chapter tells that history in time order. It begins with the oldest water held in the crust and with the oldest deserts. It ends with the cycle of today: the stores, the yearly flows, the rivers and lakes, and the times water stays in each.

The oldest water on the land

The oldest water known stands in the deep crust of Canada. At Timmins, Ontario, fluids fill fractures 2.4 km deep (size position 22.47) in rocks 2.7 billion years old (as an age, 68.64) [592].

Their xenon isotopes give a minimum mean residence time of “about 1.5 billion years” (68.10) [592]. Some pockets have stayed between 1.5 and 2.64 billion years (68.10 to 68.62).

This water has been sealed in the rock for more than half the age of the Earth. It is the far end of a range of residence times that begins with days.

The dry land: deserts and their ages

The great deserts are of very different ages. The Namib of south-western Africa has been arid or semi-arid for roughly 55 to 80 million years (positions 65.09 to 65.43) [593].

Its driest parts receive 2 mm of rain a year and its escarpment 200 mm. Its coast has more than 180 days of thick fog a year, and its dunes stand 300 metres high (size position 20.58) [593].

Its area is given as 80,950 km² in the text of one summary page and 160,000 km² in its table [593].

The Atacama of South America became hyperarid “ca. 33 million years ago” (64.63), with a proto-Humboldt current (citing Dunai 2005) [594]. A humid interval interrupted it between around 10.86 and 6.4 million years ago, a span of 4.46 million years (62.81), recorded by the Tiliviche palaeolake [594].

Mean rainfall there is around 15 mm a year, and some places receive only 1 to 3 mm [594]. Periods of up to four years pass without rain (50.13). The desert covers about 105,000 km², or 128,000 km² with the lower Andean slopes [594].

The Sahara is the youngest of the three. Aeolian dune deposits in the northern Chad Basin are about 7 million years old (63.22), the oldest known evidence of the desert [595]. The conventional age is “no more than ~2–3 million years” (62.08 to 62.45), and the 7-million-year dunes have been “hotly challenged” [596].

A model finds that the shrinking of the Tethys Sea in the Tortonian, about 7 to 11 million years ago, weakened the African summer monsoon drastically [596]. On that model the shrinking set the aridity of the Sahara, about 7 million years ago by the dunes against 2–3 million years by the conventional count.

Desert	Onset of aridity	Position (as age or duration)	Rainfall	Source

Namib	55–80 Myr	65.09–65.43	2–200 mm/yr	[593]
Atacama (hyperarid)	~33 Ma	64.63	~15 mm/yr; 1–3 mm/yr in places	[594]
Atacama humid interval	10.86–6.4 Ma (4.46 Myr)	62.81	—	[594]
Sahara, dunes	~7 Ma	63.22	—	[595]
Sahara, conventional	2–3 Ma	62.08–62.45	—	[596]

The monsoons

The monsoons of Asia share a dated history with the phased uplift of the Himalaya and Tibet [496]. Asian interior aridity and the onset of the Indian and East Asian monsoons date to “about 9–8 Myr ago” (63.45 to 63.34) [496]. The East Asian summer and winter monsoons strengthened about 3.6 to 2.6 million years ago (62.61 to 62.32), and dust reached the North Pacific [496].

Since about 2.6 million years ago the summer monsoon has been more variable and possibly weaker, while the winter monsoon strengthened [496]. The change falls at the start of the full Greenland ice sheet of chapter 19.

A summary page gives a strong Indian monsoon from around 8 million years ago, in the view of many geologists; newer studies give a start 15 to 20 million years ago (63.91 to 64.17) [597].

The monsoon follows the orbit. A record of $\delta^{18}O$ in Chinese caves “covers the past 224,000 years” (60.08) [598].

It is “dominated by 23,000-year-long cycles” (58.01), following summer insolation at 65° N [598]. The East Asian monsoon peaked around 6,000 years ago (56.79) [597].

Today the Indian monsoon brings nearly 80 percent of India’s rain, from June to September [597]. It reaches Kerala about 1 June. Some areas receive up to 10,000 mm a year (size position 17.48) [597].

The West African monsoon reaches West Africa on or near 22 June [597]. Over three-quarters of the rain of northern Australia falls in the monsoon [597].

After the 4.2 ka event of chapter 19 the monsoon of South Asia ran in drought cycles of 200 to 800 years (53.69 to 54.95) [571]. They track the production of radiocarbon.

The Green Sahara

The Sahara has not stayed a desert. Its record holds “over 230 GSPs within the last 8 million years” (63.34), green Sahara periods [599].

Each “took 2–3 kyr to develop, peaked over 4–8 kyr” and ended within 2 to 3 thousand years [599]. One period thus lasted 8 to 14 thousand years (57.05 to 57.56).

Over 8 million years, 230 periods give a mean spacing of at most 8,000,000 / 230 = 34,800 years (58.39). The periods form “400-kyr and 100-kyr clusters” (60.61 and 59.35) [599]. They grow less frequent after about 900,000 years ago (61.35).

The most recent green periods fall about 6–10, 77–81, 102–108 and 122–128 thousand years ago [599].

The last of them is the African Humid Period. It began about 15,000 to 14,500 years ago (57.62 to 57.59), at the end of Heinrich event 1 [600].

It ended 6,000 to 5,000 years ago, about 5,500 years ago in the Sahel, in steps that include the 4.2 ka event [600]. From about 14,500 to 5,500 years ago it lasted 14,500 − 5,500 = 9,000 years (57.16).

Summer insolation was at least 4 percent higher than today from 15,000 to 5,000 years ago [600]. Lake Megachad then covered 330,000 km² [600]. That is 330,000 / 371,000 =

0.89 of the present area of the Caspian Sea.

Maps of vegetation for 6,000 radiocarbon years ago show the Sahara and the Sahel shrunk [562]. Monsoon forest extended in China, and the Arctic forest limit lay further north in some sectors [562].

Read through the net, the Green Sahara has the form of loading, holding and discharge. Each period builds over 2–3 thousand years (55.79 to 56.16), holds for 4–8 thousand years (56.42 to 57.05), and ends within 2–3 thousand years.

Item	Age or period	Position	Source
Asian monsoon onset	9–8 Ma	63.45–63.34 (as age)	[496]
East Asian monsoon strengthening	3.6–2.6 Ma	62.61–62.32 (as age)	[496]
Green Sahara periods	> 230 in 8 Myr	63.34 (8 Myr)	[599]
Mean spacing	≤ 34,800 years	58.39	[599]
One green period	8–14 kyr	57.05–57.56	[599]
Clusters	100 kyr; 400 kyr	59.35; 60.61	[599]
East Asian monsoon pacing	23,000 years over 224,000	58.01; 60.08	[598]
Last African Humid Period	~14,500–5,500 years ago (~9,000 years)	57.16	[600]
South Asian drought cycles	200–800 years	53.69–54.95	[571]

Where the water is now

The Earth holds about 1,386 × 10^6 km³ of water [561]. The oceans hold 1,338 × 10^6 km³, 96.54 percent. Ice caps, glaciers and permanent snow hold 24,064,000 km³, 1.74 percent of all water and 68.7 percent of the fresh [561].

Groundwater holds 23,400,000 km³ [561]. Of this 10,530,000 km³ is fresh, 30.1 percent of all fresh water, and 12,870,000 km³ is saline. Ground ice and permafrost hold 300,000 km³ [561].

The smaller stores follow [561]. Lakes hold 176,400 km³: 91,000 fresh and 85,400 saline. Soil moisture holds 16,500 km³, the atmosphere 12,900, swamps 11,470, rivers 2,120 and living things 1,120 km³ [561].

A second budget gives other stores, in thousands of km³ [590]. The ocean holds 1,335,040, ice 28,740, soil moisture 121.8, permafrost 22 and the atmosphere 12.7. The two budgets differ most for soil moisture and permafrost: 16,500 against 121,800 km³, and 300,000 against 22,000 km³.

The ocean holds roughly 1.335 billion km³ over 361.9 × 10^6 km², 70.8 percent of the Earth’s surface [311]. Its mean depth is 3,688 metres (size position 22.86).

Groundwater in the upper 2 km of the crust (size position 22.30) amounts to “approximately 22.6 million km3” [601]. Of this “0.1–5.0 million km3 is less than 50 years old” (52.43). Less than 6 percent of the groundwater in the upper crust is modern [601].

The modern groundwater equals “a body of water with a depth of about 3 m spread over the continents” (size position 16.39) [601].

Lakes are counted one by one. There are 1.42 million natural lakes of 10 hectares or more [602].

They cover 2.67 × 10^6 km², 1.8 percent of the land. Their shoreline runs 7.2 × 10^6 km (size position 36.05), about four times the ocean coastline [602].

Their volume is 181.9 × 10^3 km³, 0.8 percent of the non-frozen water on land [602]. Their mean depth is 3.9 metres (size position 16.63).

Store	Volume (km³)	Share	Source

Ocean	1,338 × 10^6	96.54 % of all water	[561]
Ice caps, glaciers, permanent snow	24.064 × 10^6	68.7 % of fresh water	[561]
Groundwater, total	23.4 × 10^6	fresh 30.1 % of fresh water	[561]
Groundwater, upper 2 km	22.6 × 10^6	modern 0.1–5.0 × 10^6	[601]
Ground ice and permafrost	300,000 (22,000)	—	[561][590]
Lakes	176,400 (181,900)	fresh 91,000; saline 85,400	[561][602]
Soil moisture	16,500 (121,800)	—	[561][590]
Atmosphere	12,900 (12,700)	—	[561][590]
Swamps	11,470	—	[561]
Rivers	2,120	—	[561]
Living things	1,120	—	[561]

The yearly cycle

Each year 486.9 ± 2.9 × 10^3 km³ of water falls as rain and snow (GPCP, 1988–2004) [590]. Over the ocean fall 372.8 ± 2.7 × 10^3 km³ and over the land 112.6 ± 1.4 × 10^3 km³. The ocean receives 372.8 / 486.9 = 77 percent of the fall.

Of the 112.6 × 10^3 km³ that falls on land, 72.6 × 10^3 km³ returns to the air by evaporation and transpiration [590]. Rivers carry 40.0 × 10^3 km³ back to the sea. The net transport of vapour from ocean to land is about 40 × 10^3 km³, and the ocean evaporates about 413 × 10^3 km³ [590].

On land 72.6 / 112.6 = 64 percent of the fall returns to the air and 40.0 / 112.6 = 36 percent runs to the sea. The fluxes are counted per year (position 48.87).

A second budget from the USGS, after Abbott et al. 2019, gives other values [603]. Ocean evaporation is 420,500 km³ a year (350,000–510,000).

Precipitation is 380,500 on the ocean and 110,600 on land. Evapotranspiration from land is 68,900 and river discharge 46,000 km³ a year (36,000–56,000) [603].

Plants move most of the water that rises from land. Transpiration is 80 to 90 percent of the evapotranspiration from land, 62,000 ± 8,000 km³ a year [604].

The runoff of the world’s rivers to the oceans is given as 38,500 to 44,200 km³ a year [605].

Read through the net, the cycle has the form of what closes, stays: the water passes through each store while the stores hold. The net’s own texts state the form of a closed mesh [388]. “A closed mesh holds its content: what goes round comes back.”

Flux	Trenberth 2007 (10^3 km³/yr)	USGS after Abbott 2019 (km³/yr)	Source
Precipitation, total	486.9 ± 2.9	—	[590]
Precipitation on ocean	372.8 ± 2.7	380,500	[590][603]
Precipitation on land	112.6 ± 1.4	110,600	[590][603]
Evapotranspiration from land	72.6	68,900	[590][603]
River discharge	40.0	46,000 (36,000–56,000)	[590][603]
Ocean evaporation	~413	420,500 (350,000–510,000)	[590][603]
Transpiration	62 ± 8	—	[604]

How long water stays

Each store holds its water for its own time [606]. Water stays in the atmosphere for 8

days (position 45.39) and in rivers for 12 to 20 days (45.76 to 46.23). It stays in soil moisture for 280 days (48.63) [606].

It stays in fresh lakes for 1 to 100 years (48.87 to 53.06) and in salt lakes for 10 to 1,000 years (50.97 to 55.16) [606]. Groundwater holds it for 300 years (54.06), and deep aquifers far longer. The ocean holds it for 3,100 years (56.19) and glaciers for 16,000 years (57.68) [606].

The budget of the stores checks these times. The atmosphere holds 12.7 × 10³ km³ against a fall of 486.9 × 10³ km³ a year [590]: 12.7 / 486.9 of a year is 9.5 days (45.55). The ocean holds 1,335,040 × 10³ km³ against an evaporation of 413 × 10³ km³ a year: 1,335,040 / 413 = 3,200 years (56.22).

The lakes counted one by one have a mean residence time of 1,834 days, 5.0 years (50.34) [602]. Their median is 456 days, 1.25 years (49.07).

Most groundwater is old. Water that infiltrated before the Holocene, more than 11,700 years ago (57.40), makes up 42 to 85 percent of the aquifer storage in the upper kilometre of the crust (size position 21.67) [607]. This fossil water dominates what is pumped from wells deeper than 250 metres (20.41).

Half of the wells dominated by fossil water contain detectable tritium, a sign of modern water [607]. The study sampled 6,455 wells.

People now draw down the stores. Groundwater depletion rose from 126 ± 32 km³ a year in 1960 to 283 ± 40 km³ a year in 2000 [608]. The 2000 rate adds 0.8 mm a year to sea level; 283 / 362 = 0.78 mm, at 362 Gt per millimetre.

The times range from 8 days in the air (45.39) to 2.64 billion years in sealed rock (68.62). That is 23 positions on the ladder.

Store	Residence time	Position	Source
Atmosphere	8 days (9.5 computed)	45.39 (45.55)	[606][590]
Rivers	12–20 days	45.76–46.23	[606]
Soil moisture	280 days	48.63	[606]
Lakes, counted	median 456 days; mean 1,834 days	49.07; 50.34	[602]
Fresh lakes	1–100 years	48.87–53.06	[606]
Salt lakes	10–1,000 years	50.97–55.16	[606]
Modern groundwater	< 50 years	52.43	[601]
Groundwater	300 years	54.06	[606]
Ocean	3,100 years (3,200 computed)	56.19 (56.22)	[606][590]
Glaciers	16,000 years	57.68	[606]
Fossil groundwater	> 11,700 years	57.40	[607]
Deep fracture fluid	1.5–2.64 billion years	68.10–68.62	[592]

The rivers

River flow is concentrated in a few great rivers. The mean discharges below are given in cubic metres per second, with their basins [605].

The Amazon carries 209,000 m³/s near its mouth (1973–1990) and 223,700 m³/s at the Amazon Delta [605]. Its basin with the Rio Pará covers 6,925,674 km². The Ganges–Brahmaputra–Meghna carries 43,704 m³/s (1921–1985) from 1,731,334 km² [605].

The Congo carries 40,500 m³/s (1902–2021, at Kinshasa and Brazzaville) [605]. The Rio Negro carries 30,641 and the Madeira 30,173 m³/s. The Paraná carries 19,706 m³/s from 2,630,667 km² [605].

The St. Lawrence carries 17,600, the Tapajós 12,800, the Tocantins 11,800 and the Xingu 9,680 m³/s [605]. The Ob carries 7,428 m³/s above the Irtysh. The Amazon alone carries 15 to 18 percent of the fresh water that runs off to the oceans [605].

Over a year of 3.15576 × 10⁷ seconds, 209,000 m³/s is 6,596 km³. That is 6,596 / 40,000 = 16.5 percent of the river discharge of the global budget [590]. The Congo, 1,278 km³ a year, carries 3.2 percent; the Amazon carries 209,000 / 40,500 = 5.2 times as much.

Four of the ten largest rivers by discharge, the Negro, Madeira, Tapajós and Xingu, are tributaries of the Amazon.

River	Discharge (m³/s)	km³ per year (computed)	Basin (km²)	Source
Amazon	209,000 (delta 223,700)	6,596 (7,059)	6,925,674 (with Rio Pará)	[605]
Ganges–Brahmaputra–Meghna	43,704	1,379	1,731,334	[605]
Congo	40,500	1,278	—	[605]
Rio Negro	30,641	967	—	[605]
Madeira	30,173	952	—	[605]
Paraná	19,706	622	2,630,667	[605]
St. Lawrence	17,600	555	—	[605]
Tapajós	12,800	404	—	[605]
Tocantins	11,800	372	—	[605]
Xingu	9,680	305	—	[605]
Ob (above Irtysh)	7,428	234	—	[605]

The lakes

Lake water is concentrated too. The volumes below come from a 1990 base dataset, in km³ with areas in km² [609].

The Caspian Sea holds 78,200 km³ over 371,000 km², at a salinity of 1.2 percent [609]. Baikal holds 23,610 km³ over 31,722 km², and Tanganyika 18,750 over 32,900. Superior holds 12,070 km³ over 82,100 km², and Malawi 8,640 over 29,600 [609].

Under the Antarctic ice, Lake Vostok holds 5,400 ± 1,600 km³ over 12,500 km² [609]. Michigan holds 4,930 km³, Huron 3,520 and Victoria 2,420 over 59,940 km². Great Bear holds 2,234, Issyk-Kul 1,736 at a salinity of 0.6 percent, and Ontario 1,631 km³ [609].

Baikal holds 23,610 / 91,000 = 26 percent of the fresh lake water of the Shiklomanov budget [561]. Of all lake water in the lake count, 181,900 km³ [602], it holds 13 percent. The Caspian holds 78,200 / 85,400 = 92 percent of the saline lake water, and 78,200 / 181,900 = 43 percent of all lake water.

One salt lake and one rift lake thus hold more than half of all lake water. The 1.42 million lakes of 10 hectares or more average only 3.9 metres deep [602].

Lake	Volume (km³)	Area (km²)	Source
Caspian Sea	78,200	371,000	[609]
Baikal	23,610	31,722	[609]
Tanganyika	18,750	32,900	[609]
Superior	12,070	82,100	[609]
Malawi	8,640	29,600	[609]
Vostok (subglacial)	5,400 ± 1,600	12,500	[609]
Michigan	4,930	—	[609]
Huron	3,520	—	[609]
Victoria	2,420	59,940	[609]
Great Bear	2,234	—	[609]
Issyk-Kul	1,736	—	[609]
Ontario	1,631	—	[609]
Megachad (African Humid Period)	—	330,000	[600]

Water, ice and soil on the land

The ice on land is part of the same store. The glaciers outside the two ice sheets hold 158 ± 41 × 10³ km³ [586].

Their 78 water towers of glaciers and snow supply about 1.9 billion people [588]. The two ice sheets hold over 68 percent of the fresh water on Earth [581].

Water moves soil. Soil erosion by water reached 35.9 Pg in 2012, on a model at 250 m resolution [610].

That is at least two times lower than earlier estimates. It rose 2.5 percent from 2001 to 2012, and cropland, about 11 percent of the land studied, gave about half of it [610].

Rivers carry the soil to the sea, and people have changed both ends of that flow. Soil erosion raised river sediment transport “by 2.3 +/- 0.6 billion metric tons per year” [611].

Reservoirs cut the flux reaching the coasts “by 1.4 +/- 0.3 billion metric tons per year”. More than 100 billion tonnes of sediment and 1 to 3 billion tonnes of carbon now lie in reservoirs built mostly in the last 50 years [611].

The net’s Climate text names layer 23 as the water beneath and beside the ground where people live, with the mean depth of the ocean, 3.7 km (22.86), beside it [29]. The groundwater of the upper 1 to 2 km stands at 21.67 to 22.30, and the sealed fracture water at 22.47.

What this part of the history shows

Read through the net, the water cycle has the form of what closes, stays: the content flows through while the form holds. Each year 486,900 km³ falls, while the atmosphere holds only 12,900 km³; its water is replaced every 8 to 9.5 days (45.39 to 45.55). The rivers hold 2,120 km³ and carry about 40,000 km³ a year, and river water stays 12 to 20 days (45.76 to 46.23).

Read as form and carrier, the stores last while their water is replaced. The 1.42 million lakes keep their basins, while their water turns over in a median of 1.25 years (49.07). The ocean keeps its volume, nearly constant for the last 2,500 years (chapter 19), while each of its waters stays 3,100 years (56.19).

Read as the same form at every depth, each store holds while its content passes. Water stays 8 days in the air (45.39), 280 days in soil (48.63), 1 to 100 years in fresh lakes and 300 years in groundwater (54.06). It stays 3,100 years in the ocean, 16,000 years in glaciers (57.68) and 1.5 to 2.64 billion years in sealed rock (68.10 to 68.62), a span of 23 positions.

Read through the net, the Green Sahara has the form of loading, holding and discharge. Each of more than 230 green periods builds over 2–3 thousand years, holds for 4–8 thousand years and ends within 2–3 thousand. The last ran about 9,000 years (57.16), from 14,500 to 5,500 years ago, and ended in steps.

The orbital rhythms of chapter 19 return on the land. The East Asian monsoon follows the 23,000-year precession (58.01) over 224,000 years, and the green periods of the Sahara cluster at 100,000 and 400,000 years (59.35 and 60.61). The last green period and the East Asian monsoon peak fall together, near 6,000 years ago.

Read as the form of context, the same rule takes other values in other surroundings. The green periods of the Sahara grow less frequent after about 900,000 years ago (61.35), inside the Mid-Pleistocene Transition of chapter 19. Since 2.6 million years ago the East Asian summer monsoon has been more variable and the winter monsoon stronger.

The stores of water are concentrated. The Amazon carries 209,000 / 43,704 = 4.8 times the flow of the next river, the Ganges–Brahmaputra–Meghna, and 5.2 times the Congo. The Caspian holds 43 percent of all lake water and Baikal about a quarter of the fresh.

The water under the land is mostly old. Water from before the Holocene makes up 42 to 85 percent of aquifer storage in the upper kilometre, and less than 6 percent of the upper crust’s groundwater is younger than 50 years.

21. The Minerals

The chapters before this one told how the Earth was assembled, how its crust, oceans and air formed, and how its plates, mountains, ice and rivers move. All of it is made of minerals. Each kind approved by the International Mineralogical Association (IMA) counts as one species.

The count of species has a history of its own. About a dozen kinds existed before the Sun; in July 2026 the IMA listed 6,226 [270][613]. Between those two numbers lie the nebula, the first crust, the first continents, the rise of oxygen, life on land and people.

This chapter follows that count in time order. Then it turns to the minerals of the deep interior, the elements of the crust, the growth of single crystals, the slow cycle of rock and the ores.

Ages are given in Ga, Ma or ka, with their position on the ladder of chapter 11 in parentheses; the year stands at 48.87, 4.567 Ga at 69.12. Sizes carry their position on the ladder of sizes in the same way.

Before the Sun

The oldest minerals are older than the Solar System. They condensed around other stars and in the gas between them. Hazen and colleagues counted “about a dozen” refractory minerals in the molecular clouds before the Sun [270].

A later count by paragenetic mode, the process by which a mineral forms, sets these “Ur-minerals” as Stage 0, older than 4.57 Ga (69.12). Its table lists 23 species with a mode first active in this stage; its text gives 296 pre-terrestrial species approved by the IMA [272].

Two modes belong to the stars. Condensates in stellar atmospheres hold 22 species, one of them unique to that mode. Condensates in interstellar space hold one approved species; seven further ice phases are excluded because the IMA has not approved them [272].

Some of these grains survive in meteorites. Presolar grains of silicon carbide were dated by the neon isotopes made in them by cosmic rays.

About 60 % of the grains spent less than 3×10^8 years in interstellar space (66.64); at least 8 % spent more than 10^9 years (67.73) [267]. “Presolar grains are the oldest datable solid samples available” [267].

The nebula and the first bodies

The Solar System’s first solids formed between 4.567 and 4.561 Ga (69.12–69.11), a span of 6 Myr (63.08). This is Stage 1, the primary nebular phases: 86 species in the 2022 count [272]. The 2008 count gave about 60 primary phases in chondrites [270].

Stage 2 followed from 4.566 to 4.550 Ga (69.12–69.11), a span of 16 Myr (63.97). The small bodies of the young system differentiated and were altered. The 2022 count assigns 261 species to this stage; the 2008 count gave about 250 minerals in unweathered meteorites [272][270].

Both stages are short against what followed. From 4.567 to 4.550 Ga, 17 Myr (64.02), the two stages opened 86 + 261 = 347 species. Every later stage belongs to a planet.

The Hadean crust and the first water

On the young Earth the count rose again. Stage 3a, the earliest Hadean crust, is older than 4.50 Ga (69.10) and opened 400 species.

Stage 3b, the earliest hydrosphere, is older than 4.45 Ga (69.09) and opened 350 [272]. The 2008 count gave 350 to 420 species for the Hadean, with “over 100 more that were rare” [612].

The oldest piece of the Earth that survives is a mineral grain. A detrital zircon from the Jack Hills, in the Narryer Gneiss Terrane of the Yilgarn Craton in Western Australia, has “an age as old as 4,404 ± 8 Myr” (69.08). It is about 130 Myr older than any terrestrial zircon known before it [326].

Its oxygen isotopes run from $\delta^{18}O$ 7.4 ‰ to 5.0 ‰, and the melt it grew from had 8.5–9.5 ‰. The authors read this as “the earliest evidence for continental crust and oceans on the Earth” [326]. Chapter 13 tells the other Hadean zircons and the water they record.

Atom-probe tomography looked inside a “4.4-Gyr-old Hadean zircon” (69.08) with an overgrowth formed about 1 Gyr after its core (67.73). Inside it lie nanoclusters about 10 nm across (−1.38), spaced 10–50 nm apart (−1.38 to 0.08), enriched in incompatible elements. The study places the mixing of the silicate Earth before 4.4 Ga, consistent with a Moon-forming impact about 4.5 Ga (69.10) [297].

Hazen and Morrison sum up the early count: “Much of Earth’s mineral diversity was established within the first 250 million years” (66.47) [272].

Granites, pegmatites and the first continents

The largest single opening of new species came with the continental crust. Stage 4a, the earliest continental crust, runs from before 4.4 Ga to 3.0 Ga (69.08–68.73) and opened 2,385 species. Stage 4b, highly evolved igneous rocks older than 3.0 Ga (68.73), opened 1,476 [272].

The 2008 count gave this step in a different frame. Its Stage 4, the granitoids and pegmatites of 4.0–3.5 Ga (69.00–68.87), brought the total to about 1,000, with 500 new minerals [612]. Crustal processes in all, volcanism, crystallisation, metamorphism, plate tectonics and fluid–rock interaction, account for an estimated 1,500 species [270].

Five further large modes of the 2022 survey are of crustal rocks and fluids. Each is given with its species and the species unique to it [272]:

Mode (number in the 2022 survey)	Species	Unique	Source
#33 hydrothermal deposition from metal-rich fluids	797	496	[272]
#35 ultra-alkali and agpaitic rocks	726	377	[272]
#34 complex granite pegmatites	564	238	[272]
#32 Ba/Mn/Pb/Zn deposits	412	185	[272]
#31 thermally altered carbonate, phosphate and iron formations	356	89	[272]

The abstract of the same paper gives 859 species for subsurface hydrothermal deposition, against 797 in its table [272].

Plate tectonics

Stage 5, the initiation of plate tectonics, runs from less than 3.5 Ga to 2.5 Ga (68.87–68.57) and opened 458 species [272]. The 2008 count placed plate tectonics after 3.0 Ga (68.73) and brought the total to 1,500, including 150 new sulfosalts [612].

In the 2008 frame, Stage 6 is the anoxic biological world of 3.9–2.5 Ga (68.97–68.57). The cumulative total stayed at 1,500 [612]. Before 2.45 Ga (68.55) the air held about

0.001 % of its present oxygen [390], and chapter 15 tells how that changed.

Oxygen

The Great Oxidation Event is dated to about 2.33 Ga (68.50) by one study; another places its onset at 2.460–2.426 Ga (68.55–68.54) [391][392].

Stage 7 of the 2022 count, the Great Oxidation Event after 2.4 Ga (68.53), opened 2,328 species [272]. The 2008 count put the step at 2.5–1.9 Ga (68.57–68.32) with “about 2500 new minerals”, among them more than 200 new uranyl minerals. Its cumulative total passed 4,000 [612].

The largest single mode of the whole survey needs free oxygen and water. Mode #47, low-temperature oxidative hydration and weathering at the surface, has 1,998 species, 1,119 of them found in no other mode [272]. Two smaller modes share the same open air:

Mode	Species	Unique	Source
#47 low-temperature subaerial oxidative hydration, weathering	1,998	1,119	[272]
#45 oxidised fumarolic minerals	424	168	[272]
#23 subaerial aqueous alteration, not redox-sensitive	398	79	[272]

The abstract gives 459 species for fumarole condensates, against 424 in the table [272].

The quiet billion years and the snowball

After the oxidation the count stood still. Stage 8, the intermediate ocean of 1.85–0.85 Ga (68.29–67.59), and Stage 9, the Snowball Earth of 0.85–0.542 Ga (67.59–67.18), opened no new paragenetic modes [272][612].

From 1.85 Ga to 0.6 Ga is 1.25 Gyr (67.94) without a new mode. Chapter 19 tells the ice of the Cryogenian.

Life on land

Stage 10a, the Neoproterozoic oxygenation and the terrestrial biosphere, began after 0.6 Ga (67.27). It opened 597 species [272].

The 2008 count gives Stage 10 as the time after 0.542 Ga (67.18) [612]. Its framing claim is that “Over two-thirds of mineral species owe their existence to life” [612]. The 2022 survey gives other shares, set out below.

Water, life and the modes of formation

The 2022 survey sorted 5,659 IMA-approved species into 57 paragenetic modes [272][617]. About 12,000 links connect the minerals to the modes that form them [617]. Most species are tied to one way of forming:

Measure	Count	Share	Source
Species known from one paragenetic mode only	3,349	59.2 %	[272]
Species known from two modes	1,372	24.2 %	[272]
Species that involve biological processes	≥2,707	47.8 %	[272]
Species that form only through biological	–	~34 %	[272]

processes			
Species that arise through water–rock interaction	≥4,583	81 %	[272]

The share for biology is computed: 2,707 / 5,659 = 47.8 %. Lu gives the same survey as water in more than 80 % of species, life in a direct or indirect role in about 50 %, and about a third formed only through biological activity [617].

The 2008 framing gave “over two-thirds” owing their existence to life [612], against about 50 percent and about a third in 2022 [272][617].

The survey’s own conclusion names water: “By far the most significant factor in enhancing Earth’s mineral diversity has been its dynamic hydrological cycle” [272].

A few minerals form in many ways. Pyrite has the most modes of any mineral [617]. Pyrite, albite, hornblende, corundum, magnetite, calcite, hematite, rutile and baryte each have 15 or more [272].

Rare elements carry much of the diversity. Forty-one rare elements make up 1 in every 10,000 atoms of the crust, yet they are essential constituents of 42 % of known minerals [617]. In 1997 the IMA widened the definition of a mineral from the product of a “geological process” to that of a “natural process” [617].

Many species are rare in place as well. Of 4,933 approved species counted in 2015, 34 % are known from only one or two localities [616].

Minerals made with people

The newest stage is the shortest. Stage 10b, anthropogenic minerals of the last 10 ka (57.25), is assigned 603 species in the 2022 table [272].

A count of 2017 gives 208 IMA-approved species that occur mainly or exclusively as a consequence of human activities, in mine workings, waste dumps and similar places [618]. The two counts use different definitions.

Zalasiewicz and co-authors proposed in 2015 an eleventh stage of mineral evolution for the minerals made by people [612]. Outside the mineral list stand the synthetic compounds: the Inorganic Crystal Structure Database holds over 180,000 inorganic crystalline compounds [612]. That is 180,000 / 6,226 = 29 times the number of valid mineral species.

The minerals of the deep

The most abundant mineral of the Earth was named only in 2014. Magnesium silicate, $MgSiO_3$, in the perovskite structure is “the most abundant solid phase in Earth” [619]. It is stable only at the pressures of the lower mantle, and the search for a natural sample took half a century (52.43).

In 2014 Tschauner and colleagues found it in the Tenham L6 chondrite, a meteorite shocked to about 24 GPa and 2,300 K. The IMA approved it as specimen IMA 2014-017 and it was named bridgmanite. The find “concludes a half century of efforts” [619].

Bridgmanite is stable between about 670 km (27.60) and 2,700 km (28.87) depth, a span of 2,030 km (28.61). It makes up about 80 % of the mineral assemblage in pyrolitic and harzburgitic rock at those depths.

Above it, ringwoodite breaks down at about 24 GPa, near 660 km (27.58). Its calcium counterpart, $CaSiO_3$, was named davemaoite in 2021 [620].

The seismic model of the Earth sets these boundaries in its own numbers. In PREM the transition zone begins at 400 km (27.13) at 13.4 GPa; the lower mantle begins at 670 km (27.60) at 23.8 GPa, where the density jumps from 3.99 to 4.38 g cm^{-3}.

The core–mantle boundary lies at 2,891 km (28.93) at 135.8 GPa [279]. Another division gives the upper mantle to 410 km (27.15), the transition zone at 410–660 km and the

lower mantle from 660 km to 2,891 km [282].

The pressure at which ringwoodite gives way, about 24 GPa, is the pressure PREM gives for the top of the lower mantle, 23.8 GPa [620][279]. The same mantle rock holds ringwoodite above that depth and bridgmanite below it. Read through the net, this has the form of context: the same rule takes other values in other surroundings.

Earthquakes in sinking slabs reach depths of about 600–700 km (27.50–27.64) [628]. That lies near the depth where bridgmanite begins.

The net's text on earthquakes reads the deep event as a rock that changes its winding [524]. "The old winding of the rock no longer fits its context." Chapter 18 tells the earthquakes themselves.

The elements of the crust

The crust that carries the oceans and continents is made of a few elements. By mass the continental crust holds [621]:

Element	Share by mass	Source
Oxygen	46.1 %	[621]
Silicon	28.2 %	[621]
Aluminium	8.23 %	[621]
Iron	5.63 %	[621]
Calcium	4.15 %	[621]
Sodium	2.36 %	[621]
Magnesium	2.33 %	[621]
Potassium	2.09 %	[621]
Titanium	0.565 %	[621]
Hydrogen	0.14 %	[621]
Phosphorus	0.105 %	[621]
Manganese	0.095 %	[621]
Fluorine	0.0585 %	[621]
Barium	0.0425 %	[621]
Strontium	0.037 %	[621]

Oxygen and silicon together make 46.1 + 28.2 = 74.3 %. The first eight elements make 46.1 + 28.2 + 8.23 + 5.63 + 4.15 + 2.36 + 2.33 + 2.09 = 99.1 %.

The rarest elements of the crust are mostly siderophile, the elements that bind with iron. Rhenium stands at 0.0007 ppm, osmium at 0.0015 ppm, and iridium, ruthenium and rhodium at 0.001 ppm each [621]. Oxygen, at 461,000 ppm, is 461,000 / 0.0007 = 6.6×10^8 times as abundant as rhenium.

The rarity of an element and the number of its minerals do not go together. The 41 rare elements that make 1 in 10,000 atoms of the crust are essential in 42 % of all minerals [617].

Single crystals: Naica

Minerals grow as crystals, and some grow very large. In the Cave of the Crystals at Naica, Chihuahua, 300 m below the surface (20.58), gypsum crystals fill a cave 109 m long (19.66) with a volume of 5,000–6,000 m³ [622]. The cave was discovered in April 2000 [622].

The largest crystal is 11.40 m long (17.60), about 5 m³ in volume, with an estimated mass of 12 t. The air reaches 58 °C at a humidity of 90–99 % [622]. Uranium–thorium dating by Lauritzen gives the crystals a maximum age of about 500,000 years (60.81) [622].

Van Driessche and colleagues measured the growth of Naica gypsum. On the {010}

face the rate was 1.4 ± 0.2 × 10⁻⁵ nm/s at 55 °C, the slowest crystal growth measured.

At 50 °C there was neither growth nor dissolution. Growth appeared only between 55 and 58 °C, close to the transition between gypsum and anhydrite, and the rate rose exponentially with temperature [623].

In a year that rate adds 1.4 × 10⁻⁵ nm/s × 3.15576 × 10⁷ s = 442 nm (2.07) to the face. To grow 0.5 m (14.76) normal to one face takes 0.5 m / 442 nm per year = 1.13 × 10⁶ years (61.56).

The secondary account gives “about 1 million years” (61.45) for the largest crystals, against the uranium–thorium maximum of about 500,000 years (60.81) [622].

A crystal has the form of the closed window that holds one value three times (chapter 11). At Naica the form shows in its slowest state, a lattice that adds less than half a micrometre a year and holds for hundreds of thousands of years.

The cycle of rock

Minerals are worn from the land, carried to the sea, buried and made into rock again. The rates of that cycle are measured in metres per million years. Wilkinson and McElroy derived them from the volumes of preserved sedimentary rock [626]:

Rate	Lowering of the land	Mass per year	Source
Mean subaerial denudation, Phanerozoic	16 m/Myr	about 5 Gt	[626]
Pliocene	53 m/Myr	16 Gt	[626]
Present natural denudation, ice-free land	about 62 m/Myr	about 21 Gt	[626]
Erosion of cropland	about 600 m/Myr	about 75 Gt	[626]
Accumulation of post-settlement alluvium	about 12,600 m/Myr	–	[626]

About 83 % of river sediment comes from the highest 10 % of the land surface [626]. At the Phanerozoic mean, 1 m of land is removed in 62,500 years (58.92). Over the 542 Myr of the Phanerozoic (67.18) the same rate adds up to 16 × 542 = 8,672 m (23.64).

At the present natural rate 1 m goes in 16,100 years (57.69). On cropland it goes in 1,670 years (55.62), ten times faster than the natural rate (600 / 62 = 9.7) and 37.5 times the Phanerozoic mean [626]. Chapter 23 returns to the land that people work.

Soil forms more slowly than it is now removed from fields. On mantled hillslopes the median rate of soil formation is about 0.026 mm per year (n = 252), and 0.023–0.064 mm per year at a site in the United Kingdom [627].

At the median, a centimetre of soil takes 385 years (54.29). The natural denudation rate of 62 m/Myr is 0.062 mm per year, 2.4 times the median soil formation.

Ores

Some minerals are gathered into ores, and people mine them. Two metals show the scale [624][625].

Copper: world mine production was 22,600 kt in 2023 and 23,000 kt in 2024 (estimated). Reserves are 980 Mt. Identified resources hold 1.5 billion t not yet extracted, 2.1 billion t with the 0.6 billion t already produced, and undiscovered resources “an estimated 3.5 billion tons of copper” [624].

Chile produced 5,300 kt in 2024, 5.3 / 23 = 23 % of the world [624]. Reserves divided by production give 980 / 23 = 43 years (52.29).

Iron ore: usable ore production was 2,530 Mt in 2023 and 2,500 Mt in 2024 (estimated), holding 1,560 and 1,600 Mt of iron. Reserves are 200 Gt of crude ore with 88 Gt of iron.

World resources are “greater than 800 billion tons of iron ore containing more than 230 billion tons of iron” [625]. Australia produced 930 Mt in 2024 [625].

By mass of ore, iron outweighs copper 2,500 / 23 = 109 times; by mass of metal, 1,600 / 23 = 70 times. Chapter 22 tells where most of that iron was laid down: in the banded iron formations of the Archaean and Palaeoproterozoic.

The count now

The count of known species has grown steadily since the 2008 survey. Its milestones:

Date	Valid or known species	Source
2008	more than 4,300 known	[270]
2015	4,933 approved (mineral ecology survey)	[616]
November 2018	5,413 officially recognised	[612]
2022	5,659 IMA-approved (paragenetic survey)	[272]
May 2024	6,050 valid (IMA Master List)	[614]
July 2026	6,226 valid (IMA Master List)	[613]

From May 2024 to July 2026, 26 months (49.57), the list grew by 6,226 − 6,050 = 176 species, about 81 a year. From 2008 to 2026, 18 years (51.50), it grew by 6,226 − 4,300 = 1,926, about 107 a year.

In 2015 Hazen and colleagues estimated how many minerals the Earth holds in all. They found that more than 1,563 species were still to be described, “approximately one fourth of the 6394 estimated total” [615]. About 25 % of the minerals of aluminium, boron, carbon, chromium, phosphorus, silicon and tantalum remained undiscovered, and almost 35 % of those of sodium.

More than 50 % of sodium minerals are white, poorly crystallised or soluble in water. For copper, magnesium, nickel, sulfur, tellurium, uranium and vanadium fewer than 20 % remained [615].

In July 2026 the known species stood at 6,226 / 6,394 = 97.4 % of that estimate, a gap of 168 species.

What this part of the history shows

Read through the net, the count of minerals has the form of a depth opened once and filled many times. The 2022 count gives 23 species before the Sun, 86 in the nebula and 261 in the first bodies. It gives 400 and 350 in the Hadean crust and water, and 2,385 with the first continental crust [272].

Each opened mode then fills. The mode of oxidative weathering, opened with free oxygen after 2.4 Ga (68.53), now holds 1,998 species [272]. Most species stay with the mode that formed them: 3,349 of 5,659, 59.2 %, are known from one mode only [272].

The count also pauses. From 1.85 to 0.6 Ga, 1.25 Gyr (67.94), no new mode opened [272]. Then life on land opened 597 species after 0.6 Ga (67.27), and people 603 in the last 10 ka (57.25) [272].

Read as the residue that becomes the alphabet, the minerals of one stage are the material of the next. Weathering, hydrothermal fluids and metamorphism make new minerals out of older ones, and 81 % of all species arise through water working on rock [272]. Pyrite, albite, hornblende, corundum, magnetite, calcite, hematite, rutile and baryte are letters in many words: each forms in 15 or more ways [272].

The rare elements carry a large share of the diversity. Forty-one rare elements make 1 in 10,000 atoms of the crust, and they are essential in 42 % of all minerals [617].

A crystal has the form of the closed window that holds one value three times (chapter 11). Naica shows it in its slowest state: gypsum adding 442 nm a year (2.07), growing only between 55 and 58 °C, holding for up to 500,000 years (60.81) [622][623]. A single grain of zircon has held its form for 4,404 ± 8 Myr (69.08), presolar silicon carbide for

more than 10^9 years (67.73) [326][267].

Read as form and carrier, the crust holds while its minerals move. On Phanerozoic average the land is lowered by 16 m per million years, 8,672 m over 542 Myr (23.64) [626]. The minerals are worn, carried and buried; the continental crust remains.

Read as the form of context, the same rock takes other minerals at other depths. $MgSiO_3$ is bridgmanite only between about 670 and 2,700 km (27.60–28.87), and ringwoodite gives way at about 24 GPa, near 660 km (27.58) [620]. The deepest earthquakes, at about 600–700 km (27.50–27.64), lie near the same depth [628].

The count is close to its estimate. In July 2026, 6,226 species were valid, 97.4 % of the 6,394 estimated in 2015 [613][615]. The list grows by about 81 species a year [613] [614].

22. Earth and Life Together

Chapter 21 counted the minerals. About half of them involve life, and about a third form only through it [272]. This chapter turns the count around and follows what life did to the planet’s rock, water and air.

Iron was laid down in bands across the ancient sea floor. Life changed the speed at which rock weathers and so the amount of carbon dioxide in the air. It holds the carbon, nitrogen and phosphorus of the surface in cycles that turn in years to millennia, and it lives kilometres down inside the crust.

The chapter runs from the first traces of life in the rock to the soils of today. Ages carry their position on the ladder of chapter 11 in parentheses; sizes and depths do the same on the ladder of sizes.

The first traces in the rock

The oldest traces of life are carbon and shapes held in minerals. Among more than 10,000 detrital zircons from the Jack Hills, one grain dated 4.10 ± 0.01 Ga (69.02) holds graphite with $\delta^{13}C$ of −24 ± 5 ‰ [331]. Its authors call it “potentially biogenic carbon” [331].

In the Nuvvuagittuq belt of Quebec, putative microfossils in hydrothermal vent precipitates are “at least 3,770 million and possibly 4,280 million years old” (68.94–69.06) [345]. In the Isua belt of Greenland, banded iron formation about 3,800 Myr old (68.95) holds isotopically light carbonaceous inclusions; at Akilia the rock may be older than 3,850 Myr (68.96) [347].

The nitrogen of the early sea carries the same signature. Sediments 3.2–2.75 Gyr old (68.79–68.65) show $\delta^{15}N$ of 0.0 ± 1.2 ‰, the oldest record of biological nitrogen fixation [629]. Chapter 13 tells the rocks that hold these traces.

Iron in bands: the banded iron formations

For two billion years the sea floor received layers of iron.

A banded iron formation is defined as sediment with more than 15 % iron, typically about 30 % [346]. Its bands are “a few millimeters to a few centimeters in thickness” (1 mm stands at 9.10, 1 cm at 11.19) [346]. In its iron, Fe^{3+} makes up 0.3–0.6 of the total [346].

The record begins at Isua, Greenland, 3,700–3,800 Ma (68.92–68.95). Deposition peaked in the late Archaean, 2,800–2,500 Ma (68.67–68.57). A second peak came in the Orosirian, about 1,850 Ma (68.29), and the main deposition ended about 1.85 Ga [346].

After a long gap, minor deposits formed in the Neoproterozoic about 750 Ma (67.47). The youngest known banded iron formation is of Early Cambrian age, in western China [346]. From 3.8 to 1.85 Ga the main record spans 1.95 Gyr (68.34).

Two kinds are distinguished. Algoma-type formations are tied to submarine volcanic rocks in greenstone belts; Superior-type formations lie in successions of passive continental margins [630]. Banded iron formation dominates in the Archaean and earliest Palaeoproterozoic, granular iron formation in the Palaeoproterozoic [630].

The great deposits are measured in hundreds of metres and thousands of square kilometres [346]:

Deposit	Region	Age	Size	Position (age)	Source
Isua	Greenland	3,700–3,800 Ma	–	68.92–68.95	[346]
Temagami	Canada	2,736–2,687 Ma	up to 60 m thick (19.11)	68.65–68.63	[346]

Hamersley	Western Australia	2,470–2,450 Ma	>900 m thick (21.58); originally ~150,000 km²; ~300 Gt iron	68.56–68.55	[346]
Itabirites	Brazil	–	≥80,000 km²; up to 600 m (21.21)	–	[346]

Hamersley was laid down in about 20 Myr (64.17), Temagami over 49 Myr (64.99). Typical deposition rates are 19–270 m per million years [346].

The formations now hold more than 60 % of the world's iron reserves [346]. The iron of Hamersley alone, about 300 Gt, equals 300 / 1.6 = 188 years (53.64) of the iron mined worldwide in 2024 [346][625].

Oxygen and the end of the bands

The main bands span the rise of oxygen. The Great Oxidation Event is dated to about 2.33 Ga (68.50), with the transition within roughly 10 Myr (63.54) in one record [391]. Another study places the onset at 2.460–2.426 Ga (68.55–68.54) and an oscillating rise for about 200 Myr (66.27) [392].

Before 2.45 Ga (68.55) the air held about 0.001 % of the present level of oxygen. By the end of the event, about 2.06 Ga (68.39), it held up to 10 %, and the banded iron formations were largely gone by 1.85 Ga (68.29) [390]. Chapter 15 tells the rise of oxygen in full.

Through the middle Proterozoic, 1.8–0.8 Ga (68.27–67.53), chromium isotopes give oxygen at most 0.1 % of the present level [393]. At 1,400 Ma (68.04) in North China, trace metals give oxygenated bottom water and a model above 4 % [394]. The two estimates differ by a factor of more than 40.

The deep ocean stayed anoxic and rich in iron as late as 580 Ma (67.24) [390]. After the Marinoan glaciation the ocean was oxygenated at 635–630 Ma (67.32–67.31) [395]. Oxygen reached 2–11 % of the atmosphere in the Cambrian to mid-Ordovician and near-modern levels by the Devonian; charcoal is continuous from 419 Ma (66.94) [396].

Life and the weathering of rock

The weathering of silicate rock draws carbon dioxide from the air. Life on land changed its speed. In two measured settings trees raise the weathering of calcium about 10-fold (Hubbard Brook) and 5–10-fold (Iceland) [631].

The fungi that live with plant roots take part. In field experiments the hyphae of mycorrhizal fungi colonised basalt preferentially, and angiosperms released calcium from basalt at twice the rate of gymnosperms [632].

Incubations of moss, scaled to the first plants on land in the Ordovician, give about 5 °C of cooling from the weathering of calcium and magnesium silicates. The release of phosphorus and iron adds another 2–3 °C [538].

Over the last 420 Myr (66.94) carbon dioxide in the air fell by about 3.4 ppm per million years. In that time the Sun brightened by about 50 W m^{-2}, a forcing of about +9 W m^{-2}, and the decline of carbon dioxide offset it [399]. The authors attribute the decline to the feedback of silicate weathering and the spread of the land biosphere [399].

Between about 400 Ma (66.90) and 300 Ma (66.64), as forests spread, carbon dioxide fell from near 2,000 ppm to near 278 ppm [399]. That is a fall by a factor 2,000 / 278 = 7.2 in about 100 Myr (65.64).

The weathering of basalt consumes about 4.08×10^{12} mol of CO_2 a year, 30–35 % of all continental silicate weathering. Indonesia and Central America supply about 40 % of the basalt flux [633].

In carbon that is $4.08 \times 10^{12} \times 12$ g = 0.049 Gt C a year. The implied total silicate drawdown is 0.049 / 0.35 to 0.049 / 0.30 = 0.14–0.16 Gt C a year.

The volcanoes return carbon to the air. Subaerial volcanoes emit 51.3 ± 5.7 Tg of CO_2 a year without eruption, plus 1.8 ± 0.9 Tg in eruptions (2005–2015). They also emit 24.9 ± 2.3 Tg of SO_2 a year from 125 persistently degassing volcanoes [512].

In carbon the volcanic flux is 51.3 × 12 / 44 = 14.0 Tg C a year. The silicate drawdown of 0.14–0.16 Gt C a year is 10–12 times that output, which excludes submarine and diffuse sources.

The carbon cycle

Carbon moves between rock, sea, life and air. Most of it lies in rock. A table for the year 2000 gives these reservoirs, in Gt C [634]:

Reservoir	Carbon (Gt C)	Source
Sedimentary carbonates	>60,000,000	[634]
Kerogens	15,000,000	[634]
Ocean, total	38,400	[634]
of which dissolved inorganic carbon	37,400	[634]
of which dissolved organic carbon	1,000	[634]
of which surface layer; deep layer	670; 36,730	[634]
Fossil fuels: coal, oil, gas, peat	4,130 (3,510; 230; 140; 250)	[634]
Terrestrial biosphere: living; dead	2,000 (600–1,000; 1,200)	[634]
Soils	~1,500	[634]
Atmosphere (2000)	720	[634]
Marine biota	1–2	[634]

Of the carbon in rock, carbonates hold about 80 % and kerogens about 20 % [634]. In 2023 the air held 419.31 ppm of CO_2 [423]; at 2.124 Gt C per ppm [378] that is 891 Gt C.

Living things hold a small share. All life holds about 550 Gt C: plants about 450, bacteria about 70 and archaea about 7 [635]. Bacteria and archaea are “concentrated in the deep subsurface” [635].

Global net primary production is 104.9 Pg C a year: 56.4 on land and 48.5 in the sea [636]. The biological pump exports about 9 Pg C a year from the surface ocean [637]; a model ensemble gives 6.08 ± 1.17 Pg C [638]. That is 9 / 48.5 = 18.6 % or 6.08 / 48.5 = 12.5 % of ocean production.

Soil respiration returned 98 ± 12 Pg C in 2008, rising by 0.1 Pg C a year [639]. Rivers export 0.50–0.70 Pg C a year as dissolved inorganic carbon and 0.15–0.35 Pg C as organic carbon [634]. The slow cycle through rock moves 10–100 Mt C a year [634].

The turnover times follow from pool and flux. The air’s 891 Gt C over land production of 56.4 Gt C a year gives 15.8 years (51.38). The soil’s carbon to 1 m, 1,462–1,548 Pg [640], over soil respiration of 98 Pg a year gives 14.9–15.8 years (51.33–51.38).

The carbon in rock, more than 7.5×10^7 Gt C, over the slow cycle of 0.01–0.1 Gt C a year gives 7.5×10^8 to 7.5×10^9 years (67.47–69.57). The longest of these times is longer than the age of the Earth.

The net’s text on the carbon number reads carbon by closure [388]. “A closed mesh holds its content: what goes round comes back.”

In that reading leaf and air close within a season, soil over decades to centuries, peat over millennia, and coal, oil and gas over hundreds of millions of years. The measured turnover times run in the same order, from 15.8 years in the air to 7.5×10^8 years and

more in rock.

Nitrogen and phosphorus

Nitrogen enters life through fixation. The oldest record of biological fixation is 3.2–2.75 Gyr old (68.79–68.65) [629]. Before industry, land plants and their partners fixed about 58 Tg N a year, with a range of 40–100 Tg [642].

All sources of reactive nitrogen together now create about 413 Tg N a year, about half of it, 210 Tg, made by people. Marine biological fixation gives about 140 Tg [641]. The Haber–Bosch process makes about 120 Tg N a year, lightning about 5, and the human share reached 220 Tg N in 2010 [421].

Haber–Bosch alone is 120 / 58 = 2.07 times the pre-industrial fixation on land and 120 / 5 = 24 times lightning. Human fixation now equals all natural fixation.

The ocean loses nitrogen by denitrification. Four budgets give the terms in Tg N a year [643]:

Term	Gruber & Sarmiento 2002	Galloway 2004	Codispoti et al. 2001	Codispoti 2007
Water-column denitrification	80 ± 20	50 ± 20	150	150+
Benthic denitrification	95 ± 20	180 ± 50	300	300+
Nitrogen fixation	132 ± 41	135 ± 51	132	135+
Atmospheric input	30 ± 5	50	86	30
Riverine input	76–80 ± 14	–	–	–
Net balance	+34 ± 53	+5 ± 78	−188	−234

The two sinks add to 80 + 95 = 175 Tg N a year in the first budget and 150 + 300 = 450 in the last, a factor 2.6 apart [643]. The soils of the world hold 133–140 Pg N to a depth of 1 m [640].

The phosphorus of soil starts in the minerals of rock. On the Hawaiian islands, a sequence of soils from 300 years (54.06) to 4.1 Myr (62.73) shows its fate [644]. Mineral phosphorus falls from 82 % to 1 % of soil phosphorus between 300 and 20,000 years (54.06–57.88), and organic phosphorus reaches its maximum at about 150,000 years (59.72) [644].

People now move more phosphorus than the natural flows. Fertiliser supplies about 15 Mt P a year, and human mobilisation by 2000 was about three times the natural flows [645]. Net storage of phosphorus on land and in fresh water rose by at least 75 % over pre-industrial levels [646].

Animals carry phosphorus back from the sea. Breeding seabird colonies excrete 591 Gg N and 99 Gg P a year [647]. Seabirds and anadromous fish once moved about 150 Gg P a year from sea to land, and now “less than 4 %” of that [648].

Life inside the rock

Life is not confined to the surface. Below the sea floor, sediments hold about 2.9×10^{29} cells with about 4.1 Pg C, about 0.6 % of the Earth’s living biomass [649]. Their abundance varies by about five orders of magnitude between sites and follows the rate of sedimentation and the distance from land [649].

The 2012 count of sea-floor cells was 50–78 % lower than earlier estimates, and their biomass 10–45 % lower [649]. Earlier counts had given the oceanic subsurface 3.5×10^{30} cells [652]; a 2019 synthesis gives 4×10^{29} for the deep oceanic subsurface and 3×10^{29} for the deep continental subsurface [653]. From 3.5×10^{30} to 2.9×10^{29} or 4×10^{29} the estimate fell by a factor of 9–12.

The continents hold as many again. Magnabosco and colleagues count 2–6 $\times 10^{29}$ cells in the continental subsurface and about 23–31 Pg C in all subsurface prokaryotes,

“roughly 4 to 10 times less than previous estimates” [650]. Bacteria outnumber archaea there [650].

The continental count is 0.7–2.1 times the sea-floor count.

The Deep Carbon Observatory gave its synthesis in December 2018. Deep life holds 15–23 billion tonnes of carbon, “245 to 385 times greater” than the carbon of all humans [651]. It fills a volume of 2–2.3 billion km³, and “about 70% of Earth’s bacteria and archaea live in the subsurface” [651].

Life was found about 5 km down in the continents (23.14) and 2.5 km into the sea floor (22.51). In culture it survives up to 122 °C [651]. The deep carbon of the synthesis is 15 / 4.1 to 23 / 4.1 = 3.7–5.6 times the carbon of the sea-floor sediments alone.

The whole count of prokaryotes stands at 4–6 × 10^{30} cells in the 1998 estimate and 1.2 × 10^{30} in the 2019 estimate [652][653]. In the subsurface they turn over in 1,000–2,000 years (55.16–55.79) [652].

Subsurface carbon is 4.1 Pg C in sea-floor sediment [649], 23–31 Pg C in all subsurface prokaryotes [650] and 15–23 Pg C by the Deep Carbon Observatory [651]. A fourth estimate places most of the 77 Gt C of bacteria and archaea in the deep [635].

Soils

The top 30 cm (14.29) of the world’s soils hold about 680 billion t of carbon, by the FAO’s Global Soil Organic Carbon Map of 5 December 2017 [654]. Ten countries hold over 60 % of it. The FAO gives it as almost double the carbon of the atmosphere, and more than the 560 billion t in all vegetation [654].

Against the 891 Gt C of the air in 2023, 680 Gt C is 680 / 891 = 0.76 of it.

Deeper soil holds more [640][655]:

Depth	Soil organic carbon (Pg)	Position (depth)	Source
0–30 cm	684–724	14.29	[640]
0–1 m	1,462–1,548	15.39	[640]
0–2 m	2,376–2,456	16.02	[640]
0–2 or 3 m	2,270–2,770	16.02–16.39	[655]
below 3 m	>500	16.39	[655]
carbonate carbon, 0–1 m	695–748	15.39	[640]

The frozen soils of the north hold about 1,300 Pg of organic carbon, with a range of about 1,100–1,500 [591]. Of that, 1,035 ± 150 Pg lie within 3 m; below 3 m lie 91 ± 52 Pg in deltas and 181 ± 54 Pg in Yedoma, 74 ± 20 Pg of it intact. About 800 Pg are perennially frozen and about 500 Pg are not [591].

The median rate of soil formation on mantled hillslopes is about 0.026 mm a year (n = 252), and 0.023–0.064 mm a year at a site in the United Kingdom [627]. At the median a centimetre takes 385 years (54.29). Chapter 23 gives the rates at which soil is now lost.

What this part of the history shows

Read through the net, the carbon cycle has the form of metabolism: the content flows through while the form holds. Life holds about 550 Gt C, yet production moves 104.9 Pg C through it every year [635][636]. The air’s carbon over land production gives 15.8 years (51.38), the soil’s carbon over soil respiration 14.9–15.8 years (51.33–51.38).

Read as rest and discharge, the cycle holds longest in rock. Rock holds more than 7.5 × 10^{7} Gt C, and the slow cycle moves 10–100 Mt C a year, a holding time of 7.5 × 10^{8} to 7.5 × 10^{9} years (67.47–69.57) [634]. Volcanoes return 14.0 Tg C a year above sea level, and weathering takes back 0.14–0.16 Gt C a year [633][512].

In the net’s reading leaf and air close within a season, soil over decades to centuries, peat over millennia, and coal, oil and gas over hundreds of millions of years [388]. The

measured turnover times run in the same order, from 15.8 years in the air to 7.5×10^8 years and more in rock.

Read as form and carrier, the iron bands keep one form through changing carriers. The same layered form was laid down from 3.8 to 1.85 Ga, through 1.95 Gyr (68.34), and returned in minor deposits at about 750 Ma (67.47) [346]. The sea water and the iron it carried were replaced again and again; the banded form held.

Read through the net, the oxygenic world has the form of a depth opened once and filled many times. The Great Oxidation Event opened it at 2.460–2.33 Ga (68.55–68.50) [391][392].

Oxygen then filled it in steps. It reached up to 10 % of the present level by about 2.06 Ga (68.39) and stood at most 0.1 % or above 4 % in the middle Proterozoic [390][393][394]. The ocean was oxygenated at 635–630 Ma, the air near-modern by the Devonian [395][396].

Nitrogen fixation is old, and people have now matched it. Biological fixation was under way by 3.2–2.75 Ga (68.79–68.65) [629]. Of the 413 Tg N of reactive nitrogen created each year, people now make about 210, as much as all natural sources together [641].

Read as the form of context, the same life takes other numbers in other surroundings. Sea-floor abundance varies by five orders of magnitude between sites [649]. Life reaches 5 km into the continents (23.14) and 2.5 km into the sea floor (22.51), and survives in culture to 122 °C [651].

Life sets the rate of the rock’s own reaction. Trees raise the weathering of calcium 5- to 10-fold, and angiosperms release calcium from basalt at twice the rate of gymnosperms [631][632]. Over 420 Myr (66.94) the air’s carbon dioxide fell by 3.4 ppm per million years while the Sun brightened by 50 W m^{-2} [399].

23. The Earth Now

The chapters before this one followed the Earth through 4.567 billion years (69.12). This chapter stands in the present: the decades since 1950 and the years 2023 to 2026. It gives the state of the land, the carbon, the temperature, the sea and the ice as they are measured now.

The Earth of now is also the Earth of 8 billion people. They live on the ground and in the first kilometre or two of air above it; on the ladder of sizes 1.5 km stands at 22.04. The chapter counts the people who live where the Earth now changes.

Durations and lengths carry their position on the ladder of chapter 11 in parentheses; the year stands at 48.87. Temperatures are given above the mean of 1850–1900, the reference that the measuring bodies use.

The people on the Earth

In 2023 the world held 8,091,734,933 people [656]. The United Nations dates the eighth billion to 15 November 2022 [657]. The count stood at 0.98 billion in 1800, 1.63 billion in 1900, 2.49 billion in 1950 and 6.17 billion in 2000 [656].

The UN page gives 1950 as “around 2.6 billion” [657]. From 1800 to 2023, 223 years (53.79), the population grew by a factor 8.23.

The steps now come further apart. The world passed 5 billion in 1987, 6 billion in 1999 and 7 billion in October 2011 [657]. From 7 to 8 billion took 12 years (51.13); to 9 billion is expected to take about 15 years (51.34), until 2037 [657].

The UN projects a peak of about 10.3 billion in the mid-2080s and about 10.2 billion by 2100 [657]. One person in four already lives in a country whose population has peaked [657].

Most people now live in towns and cities. By national definitions the urban share rose from 34.3 % in 1960 to 57.8 % in 2025, and urban dwellers passed rural ones in 2007 [658]. By the harmonised Degree of Urbanisation, 45 % of 8.2 billion people live in cities, against 20 % of 2.5 billion in 1950 [659].

The great cities stand mostly in Asia. Cities of 10 million or more rose from 8 in 1975 to 33 in 2025, 19 of them in Asia, and 37 are expected by 2050 [659]. Jakarta has nearly 42 million residents, Dhaka almost 40 million and Tokyo 33 million; Cairo is the only city outside Asia among the ten largest [659].

Of 12,000 cities analysed, 96 % have fewer than one million inhabitants and 81 % fewer than 250,000 [659]. Two thirds of population growth to 2050 is projected to occur in cities [659].

The land

Forests cover 4.14 billion ha, “about one-third of the planet’s land area”, by the FAO assessment of 2025 [660]. That is 41.4 million km². The 2020 assessment gave 4.06 billion ha, 40.6 million km² [661]; the two assessments differ by 0.8 million km².

Deforestation ran at 10.9 million ha a year in 2015–2025, against 17.6 million in 1990–2000. The net loss was 4.12 million ha a year in 2015–2025, against 10.7 million in the 1990s [660]. The difference, $10.9 - 4.12 = 6.78$ million ha a year, is forest gained; the net loss is $4.12 / 4{,}140 = 0.10$ % of the forest a year.

Forests hold 714 Gt of carbon [660]. Primary forest covers at least 1.18 billion ha, about a third of all forest; planted forest covers 312 million ha, about 8 % [660]. Fire affects 261 million ha of land a year on average, nearly half of it forest [660].

The assessment covers 236 countries and areas [660].

Of all land, about 10 % lies under glaciers and 14 % is desert or other barren land; the rest is called habitable [662]. Agriculture uses 44 % of the habitable land, about 48 million km² [662].

Four fifths of that farmland, 80 %, feeds livestock through grazing and feed. Crops for people take 16 % and non-food crops 4 %; cropland is one third of farmland and grazing two thirds [662].

The wild land shrank over three centuries (54.06). In 1700 nearly half of the terrestrial biosphere was wild; by 2000 a quarter was wild and less than 20 % seminatural [663]. Agriculture and settlements covered almost 39 % of the ice-free land in 2000, and another 37 % lay embedded within them, 76 % in all [663].

Since 1961 the area of cropland grew by 11 % while the population about doubled. Cropland per person fell by 44 % [626].

What people move

The things people make now weigh as much as all life. Human-made mass was about 35 Gt in 1900, 3 % of the living biomass. By 2020 it was about 1.1 Tt, a factor 1,100 / 35 = 31 [664].

It grows by about 30 Gt a year and doubles roughly every 20 years (51.60) [664]. Spread over 7.8 billion people that is 30×10^{12} kg / 7.8×10^{9} / 52 = 74 kg per person per week.

The two masses crossed around 2020. Buildings and infrastructure weigh about 1,100 Gt against 900 Gt of trees and shrubs; plastic weighs 8 Gt against 4 Gt (dry) of all animals [664]. The living biomass itself fell from about 2 Tt to about 1 Tt since the start of agriculture [664].

Human-made mass passed the dry biomass “in the year 2020 (± 6)”, or in 2013 ± 5 when waste is counted. Against wet biomass the crossing falls in 2031 ± 9 with waste or 2037 ± 10 without, and the mass may pass 3 Tt by 2040 [664].

The mammals of the Earth are now mostly people and their animals. By wet mass livestock weigh about 630 Mt and humans about 390 Mt; wild land mammals weigh about 20 Mt and marine mammals about 40 Mt [665]. Humans hold 0.06 Gt C of the roughly 550 Gt C of all life [635].

People move more rock and soil than the rivers. Mineral extraction gave a direct human sediment production of “conservatively some 316 Gt (150 km3)” in 2015 [666]. That is “more than 24 times greater” than the sediment the world’s major rivers supply each year, which puts the rivers near 316 / 24 = 13.2 Gt a year [666].

The human flux overtook the natural flux of the rivers “in the mid-1950s”, after an acceleration “just after the Second World War” [666]. A single gold wedding ring needs “between 4 and 20 metric tons of rock” [667].

The rivers themselves were changed. Soil erosion raised the sediment carried by rivers “by 2.3 +/- 0.6 billion metric tons per year”. Reservoirs cut the flux that reaches the coasts “by 1.4 +/- 0.3 billion metric tons per year” [611].

Over 100 billion t of sediment and 1–3 billion t of carbon now lie in reservoirs, most of them built in the past 50 years (52.43) [611].

Soil goes faster than it forms. Water eroded 35.9 Pg of soil in 2012, at least two times less than earlier estimates gave, and 2.5 % more than in 2001 [610]. Cropland covers about 11 % of the land studied but supplies about half of the erosion, and about 0.86 Pg a year of the increase comes from changes in land use [610].

Cropland erodes at about 600 m per million years, about 75 Gt a year, against natural denudation of about 62 m per million years, about 21 Gt a year [626]. Human sediment production of 316 Gt is 316 / 35.9 = 8.8 times the soil eroded by water.

A third of the land is degraded. The FAO’s Status of the World’s Soil Resources, released on 4 December 2015, found “33 percent of land is moderately to highly

degraded” [668].

People also draw down the water under the land. Groundwater depletion rose from 126 ± 32 km³ a year in 1960 to 283 ± 40 km³ a year in 2000, about 0.8 mm a year of sea level [608]. The 78 mountain water towers of glaciers and snow supply about 1.9 billion people [588].

The minerals record the same change. Between 208 and 603 mineral species owe their existence mainly to human activity, by the definition used [618][272]. Chapter 21 tells them.

Carbon in the air

The Global Carbon Budget gives the carbon of 2023. Fossil CO_2 emissions were 10.1 ± 0.5 Gt C, 1.3 % more than in 2022, and 10.3 Gt C before the cement carbonation sink is counted. Changes in land use added 1.0 ± 0.7 Gt C, for a total of 11.1 ± 0.9 Gt C, or 40.6 ± 3.2 Gt CO_2 [423].

The net’s text on the carbon number gives the same fossil flow: carbon closed for some 300 million years, now unwound at 10.3 Gt C a year [388].

Of that carbon, 5.9 ± 0.2 Gt C stayed in the air, 2.79 ± 0.1 ppm. The ocean took up 2.9 ± 0.4 Gt C and the land 2.3 ± 1.0 Gt C, leaving an imbalance of −0.02 [423]. The airborne share is 5.9 / 11.1 = 53 %; the ocean took 26 % and the land 21 %.

From 1750 to 2019, 269 years (53.96), fossil fuels and land-use change released 700 ± 75 Pg C, and less than half of it remains in the air [669]. In 2010–2019 the budget of 10.9 ± 0.9 Pg C a year split into 5.1 for the air (46 %), 2.5 for the ocean (23 %) and 3.4 for the land (31 %) [669].

The ocean took up 105 ± 20 Pg C from 1960 to 2019, 23 % of the 450 ± 50 Pg C emitted. Its interior stored 140 ± 18 Pg C between 1800 and 2007 [669].

Against these flows the volcanoes are small. Their subaerial output of 51.3 Tg CO_2 a year is 14.0 Tg C [512], 14 / 10,100 = 0.14 % of the fossil emissions of 2023.

The air’s carbon dioxide stood at 419.31 ± 0.1 ppm in 2023, by the Global Carbon Budget, and was projected to rise by 2.87 ppm to 422.45 ppm in 2024. That is 52 % above the pre-industrial value of about 278 ppm in 1750 [423].

The WMO gives 420.0 ± 0.1 ppm for 2023, 151 % of 1750, and 423.9 ± 0.2 ppm for 2024 [384][385]. At Mauna Loa the monthly mean reached 426.07 ppm in September 2026, against 424.37 a year before; the global monthly mean for July 2026 was 426.10 ppm [409].

The annual growth ran at 2.06–3.76 ppm a year in 2016–2025, with 3.76 in 2024 [409]. At 426.07 ppm the air holds 426.07 / 278 = 1.53 times its carbon dioxide of 1750.

The other greenhouse gases rose with it. In 2024 methane stood at 1,942 ± 2 ppb and nitrous oxide at 338.0 ± 0.1 ppb, “the highest levels in the last 800 000 years” (61.24) [384][385]. Carbon dioxide in 2019 was “higher than at any time in at least 2 million years” (62.08) [383].

Over the glacial cycles of 800,000 years carbon dioxide moved between 172 and 300 ppm [405]. The present 426.07 ppm is 1.42 times the top of that range.

The ocean grows more acid as it takes up the carbon. Its surface pH was 8.17 in 1850 and 8.08 in 2021, 171 years (53.55), an increase of 10^0.09 − 1 = 23 % in hydrogen ions [375]. The open-ocean surface has lost 0.017–0.027 pH units per decade since the late 1980s, and the present pH is “unprecedented for at least 26,000 years” (58.12) [375].

The temperature

Three datasets give the global mean temperature of 2025. HadCRUT5 gives 1.41 ± 0.09 °C above 1850–1900, the third warmest year since 1850 after 2024 and 2023 [670].

Berkeley Earth gives 1.44 ± 0.09 °C, and the WMO's consolidated value is 1.43 ± 0.13 °C [671][385].

The three differ by 0.03 °C, within the uncertainty of each. The mean of 2023–2025 was 1.47 °C [670].

The year 2024 was warmer. The WMO gives 1.55 ± 0.13 °C, "the warmest year in the 175-year observational record" (53.57) [384]. Berkeley Earth's report gives about 1.52 °C for 2024 and about 1.47 °C for 2023 [671].

The long-term human-induced warming stands at 1.37 °C, with a range of 1.34–1.41 °C [670][384]. For 2011–2020 the IPCC gives 1.09 °C (0.95–1.20) above 1850–1900 [383]. Since 1980 the trend has been about +0.20 °C per decade [671].

The land warms faster than the sea. In 2025 the land stood 2.03 ± 0.17 °C above 1850–1900, its second warmest year, and the ocean surface 1.03 ± 0.05 °C, its third [671]. For 2011–2020 the IPCC gives 1.59 °C over land and 0.88 °C over the ocean [383].

The warmth reaches people where they live. In 2025, 9.1 % of the Earth's surface had its locally warmest year on record: 10.6 % of the land and 8.3 % of the ocean [671]. About 770 million people, 8.5 % of humanity, lived in those places, and 16 countries set national records, against 104 in 2024 [671].

Berkeley Earth gives 2026 a 51 % chance of being the fourth warmest year [671]. Hot extremes have become more frequent and more intense since the 1950s [383].

Over the past 485 Myr (67.07) the global mean surface temperature ranged from 11 to 36 °C. The coldest stretch, at 11 °C, was the late Pleistocene, 129–11.7 ka (59.58–57.40) [535].

The sea and the ice

The sea rose 0.20 m (13.92) between 1901 and 2018, with a range of 0.15–0.25 m (13.66–14.12) [383]. Its rate was about 1.3 mm a year in 1901–1971, 1.9 mm a year in 1971–2006 and 3.7 mm a year in 2006–2018 [383].

The satellites give the recent rise. Since 1993 the altimeters of TOPEX/Poseidon, Jason 1–3 and Sentinel-6 Michael Freilich record a rise of 97.8 mm (13.27) [672]. The rate rose from 0.20 cm a year in 1993 to 0.44 cm a year now, without correction for the rebound of the land after the ice [672].

The WMO gives 2.1 mm a year for 1993–2002 and 4.7 mm a year for 2015–2024 [384]. Its 2025 summary gives 2.65 mm a year for 1993–2011 and 4.75 mm a year for 2012–2025, with 2025 close to the record of 2024 [385].

Every measure shows the rate grown by a factor of 1.8 to 2.8. The ratios are 4.7 / 2.1 = 2.2, 4.75 / 2.65 = 1.8, 4.4 / 2.0 = 2.2 and 3.7 / 1.3 = 2.8.

The ocean holds most of the heat. It takes 91 % of the heating of the climate system; the land takes about 5 %, the ice about 3 % and the air about 1 % [383].

The upper 2,000 m of the ocean gained about 23 ± 8 ZJ from 2024 to 2025 [386]. The Institute of Atmospheric Physics calls it "the largest annual gain on record", a new record in "each of the past nine years" (50.87) [387]. It equals about 37 years of the world's primary energy use of 2023, about 620 EJ a year: 23×10^{21} J / 620×10^{18} J = 37 [387].

The warming of the upper ocean ran at 0.14 ± 0.03 W m^{-2} per decade over 1960–2025 and 0.32 ± 0.14 W m^{-2} per decade over 2005–2025 [386]. About 33 % of the ocean area stood in its three warmest years of 1958–2025, and 57 % in its five warmest [386].

The sea surface was 0.49 °C above 1981–2010 in 2025, 0.12 ± 0.03 °C below 2024, the third warmest [386]. The ocean heat content of 2025 was the highest of the 66-year record (52.68), and the rate of 2005–2025 "more than twice" that of 1960–2005 [385].

The ice retreats with the heat. The Arctic sea ice minimum of 2024 was 4.28 million km^2, the seventh lowest in 46 years (52.36); the Antarctic minimum fell below 2 million

km² for the third year in a row [384]. The Arctic maximum of 2025 was “the lowest annual maximum in the observed record” [385].

The glaciers had their most negative three-year mass balance on record in 2022–2024 [384]. In 2000–2019 they lost “267 ± 16 gigatonnes per year”, “21 ± 3 per cent of the observed sea-level rise” [587]. At 362 Gt per mm of sea level, 267 / 362 = 0.74 mm a year.

Extremes and the people they reach

The WMO counted 11,778 disasters from weather, climate and water between 1970 and 2021, 52 years (52.47). They caused “just over 2 million deaths” and US$4.3 trillion of losses [673]. On average that is 227 disasters and about 38,000 deaths a year.

Over 90 % of the reported deaths were in developing countries [673].

The database EM-DAT counted 393 disasters from natural hazards in 2024 [674]. They killed 16,753 people, against a mean of 65,566 for 2004–2023, “primarily due to the absence of mass disasters” [674]. The mean is 65,566 / 16,753 = 3.9 times the toll of 2024.

The same disasters affected 167.2 million people and caused US$241.95 billion of losses [674]. New displacements in 2024 were the highest since 2008 [384].

The Anthropocene vote

In 2009 the Anthropocene Working Group was set up to examine a new epoch of geological time for the present. It deliberated for about 15 years (51.34) and reported in late October 2023 [675].

The proposal set the base of the epoch in a lake-sediment section 15 cm thick (13.66) at Crawford Lake, southern Ontario, with a start “(~1950)” marking the “Great Acceleration” [675]. It went to a vote of the Subcommission on Quaternary Stratigraphy from 4 February to 4 March 2024 [675].

The result was 4 in favour, 12 against and 3 abstentions; three members did not vote [675]. Against were 12 / 19 = 63 %, in favour 4 / 19 = 21 %.

The executive of the International Commission on Stratigraphy recognised the vote as valid. The chairs of its 17 subcommissions supported that with 15 votes, 1 abstention and 1 conflict of interest [675].

The reasons given include human impacts that predate the mid-twentieth century, a unit shorter than a human lifetime, and effects that vary from place to place and begin at different times [675]. The statement adds that the term “will remain an invaluable descriptor in human-environment interactions” [675].

The year of the proposed start, about 1950, matches the mid-1950s in which the human flux of sediment overtook the rivers [666][675].

What this part of the history shows

Read through the net, the human part of the Earth has the form of a depth opened once and filled many times. People numbered 0.98 billion in 1800 and 8.09 billion in 2023 [656].

Their made mass grew from 35 Gt in 1900 to 1.1 Tt in 2020, doubling every 20 years (51.60) [664]. Cities of 10 million rose from 8 in 1975 to 33 in 2025 [659].

Read as form and carrier, the forest holds while its trees are replaced. Each year 10.9 million ha are cleared, yet the net loss is 4.12 million ha; the difference, 6.78 million ha, is forest gained [660]. The cover of 4.14 billion ha shrinks by 0.10 % a year.

In the net’s reading, fossil carbon was closed for some 300 million years and is now

unwound at 10.3 Gt C a year [388][423]. Of the 700 ± 75 Pg C released since 1750, less than half stays in the air; the ocean and the land take the rest [669].

Read through the net, the ocean has the form of loading. It takes 91 % of the heat of the climate system [383], and its upper 2,000 m gained 23 ± 8 ZJ in 2025, a record in each of the past nine years (50.87) [386][387]. The sea rises with it, now 4.4–4.75 mm a year, about twice the rate of the 1990s [672][385].

Read as the form of context, the same warming takes other values in other surroundings. In 2025 the land stood 2.03 °C above 1850–1900 and the ocean surface 1.03 °C [671]. Of the surface, 9.1 % had its warmest year on record, home to 770 million people [671].

In the net’s reading, the global numbers are readings of a state that has its places. Three datasets give the temperature of 2025 within 0.03 °C of each other [670][671] [385], and one number of ppm gives the carbon of the whole air [409].

The net’s text on the carbon number places the state where people live [388]. “A balance is restored where it can be read by the people who live on it.” The net’s Climate text names the ground where people live as layer 22 and the water beneath and beside them as layer 23 [29].

On that ground cropland, 11 % of the land, supplies half of the soil eroded by water [610]. There groundwater is drawn down by 283 km³ a year, and 1.9 billion people depend on the water of the mountains [608][588].

The changes reach people unevenly. Over 90 % of the deaths in 11,778 weather and climate disasters since 1970 fell in developing countries [673]. In 2024 the disasters affected 167.2 million people, and new displacements were the highest since 2008 [674] [384].

Part III — The Sky

24. The First Moments

The history of the sky begins with the universe itself. Its age is measured at 13.787 ± 0.020 billion years [238][676]. The matter whose light reaches the Earth now lies up to 46.5 billion light-years away in every direction [677].

The earliest moment that measurement reaches is about one second after the beginning. Then neutrinos stopped interacting and the ratio of neutrons to protons was fixed [202]. By about 180 seconds the light nuclei were made, and their amounts are measured today in old gas and in old stars [202].

Before that second lie transitions known from lattice computation, from the laboratory and from limits on the first fluctuations. This chapter first sets the frame: the age, the size, the rate of expansion and the contents of the universe. Then it tells the first moments in order, up to the end of the first three minutes.

The age of the universe

The Planck satellite measured the microwave background over the whole sky. Its 2018 analysis gives an age of 13.787 ± 0.020 billion years, or 4.351×10^{17} s [238][676]. The Particle Data Group lists 13.797 ± 0.023 billion years for the same data without the galaxy-clustering ruler [25].

The two values are two data combinations of one analysis. They differ by 0.010 billion years, inside one standard deviation. The age is a derived parameter of the fit of the six-parameter standard model to the background light [25].

Earlier fits give nearly the same number. Planck 2015 gave 13.813 ± 0.038 billion years, and the nine-year WMAP analysis 13.772 ± 0.059 billion years [676]. Four fits from 2013 to 2020 span 0.041 billion years, about the size of the WMAP error.

Supernovae gave an age before the microwave fits did. In 1999 the Supernova Cosmology Project found $14.9\ (+1.4, -1.1) \times (0.63/h)$ billion years from 42 exploding white dwarfs [678]. The value scales with the inverse of the Hubble constant.

Stars give the age without the fit. The metal-poor halo star BD +17°3248 is dated by its radioactive isotopes at 13.8 ± 0.4 billion years [676]. The subgiant HD 140283, with iron at [Fe/H] = −2.40 and a parallax of 17.15 ± 0.14 mas, is 14.46 ± 0.31 billion years old, ± 0.8 billion years with all uncertainties [679].

The PDG review states that the fitted age agrees with the oldest globular clusters and with radioactive dating [680]. The HD 140283 study compared its star with an age of the universe of 13.77 ± 0.06 billion years and found agreement within the errors [679].

Every size and every time in this book has a position on the ladder of the net. The position is the logarithm, base 3, of a size over 4.558816×10^{-8} m, or of a time over 1.520655×10^{-16} s. The time unit is the reciprocal of the Rydberg frequency counted in half-cycles, 6.576115×10^{15} per second; the length unit is that time multiplied by the speed of light [681].

One step on the ladder is a factor of three. One second sits at 33.15, the day at 43.50 and the year at 48.87. The age of the universe, 4.351×10^{17} s, sits at 70.12; HD 140283 at 70.17 and the supernova age of 14.9 billion years at 70.19.

The ladder counts in threes, as the net does. Every crossing of the strand holds one of three values: +1, 0 or −1. Three in a row form a window, and a window is closed when its three values add to zero, counted in threes.

Of the 27 possible windows, 9 close [702]. Three hold one value three times; six hold all three values, so the content changes while the window stays closed. The open part is tension [682].

The positions are depths. Each depth n is one layer, a layer holds n trits, and layer n has

the time $3^{n} \cdot T_{0}$ and the length $3^{n} \cdot S_{0}$ [29]. The sky is told at depths from 33 for the first second to 70 for the present age.

Case	Method	Age (billion years)	Position	Source
Planck 2018	microwave background fit	13.787 ± 0.020	70.12	[238][676]
Planck 2018, without ruler	microwave background fit	13.797 ± 0.023	70.12	[25]
Planck 2015	microwave background fit	13.813 ± 0.038	70.12	[676]
WMAP nine-year	microwave background fit	13.772 ± 0.059	70.12	[676]
Supernova Cosmology Project 1999	42 type Ia supernovae, flat	14.9 (+1.4, −1.1) × 0.63/h	70.19	[678]
BD +17°3248	radioactive dating	13.8 ± 0.4	70.12	[676]
HD 140283	subgiant isochrone with parallax	14.46 ± 0.8	70.17	[679]

The size of the observable universe

Light has travelled for 13.8 billion years, but the matter that sent it is now farther away because space has grown in the meantime. The comoving radius of the observable universe is about 14.26 Gpc, 46.5 billion light-years or 4.40×10^{26} m [677]. It sits at 71.23 on the ladder.

The diameter is about 28.5 Gpc, 93 billion light-years or 8.8×10^{26} m, at 71.86 [677]. 93 billion light-years of 0.946073×10^{16} m each give 8.80×10^{26} m. This diameter is the largest length in this book.

The volume is about 1.22×10^{4} Gpc³, 4.22×10^{5} cubic billion light-years or 3.57×10^{80} m³ [677]. The sphere of radius 4.40×10^{26} m has $4/3 \cdot \pi \cdot (4.40 \times 10^{26})^{3} = 3.57 \times 10^{80}$ m³. The radius is 3.4 times the light-travel age in light-years: 46.5 / 13.8 = 3.37.

The surface that sent the microwave background lies about 14.0 Gpc or 45.7 billion light-years away, at 71.21 [677]. That is 98 % of the radius of the observable universe: 45.7 / 46.5 = 0.983. The cosmic event horizon, the farthest distance from which light sent today can still arrive, is about 16 billion light-years, at 70.26 [677].

The Hubble length, the speed of light divided by the expansion rate, is 1.372×10^{26} m with the Planck rate and 1.267×10^{26} m with the local rate [25]. These are 14.5 and 13.4 billion light-years, at 70.17 and 70.10. The radius of the observable universe is 3.21 Hubble lengths: 4.40 / 1.372 = 3.21.

The observable universe holds about 1.5×10^{53} kg of ordinary matter [677]. Estimates of the number of galaxies run as high as 2 trillion; other estimates give hundreds of billions [677]. It holds as many as 10^{24} stars and about 10^{80} hydrogen atoms [677].

Case	Value	Metres	Position	Source
Radius of the observable universe	46.5 billion light-years	4.40×10^{26}	71.23	[677]
Diameter	93 billion light-years	8.8×10^{26}	71.86	[677]
Distance to the surface of last scattering	45.7 billion light-years	4.32×10^{26}	71.21	[677]
Event horizon	16 billion light-years	1.51×10^{26}	70.26	[677]
Hubble length (Planck)	14.5 billion light-years	1.372×10^{26}	70.17	[25]
Hubble length (local ladder)	13.4 billion light-years	1.267×10^{26}	70.10	[25]

The ladder of three meets the ladder of two only nearly. Powers of three come close to powers of two at depths 1, 2, 5, 12, 41, 53 and 306: these are the denominators of the best fractions for $\log_2 3 = 1.58496$ [29][682]. No closure is exact, and each depth leaves a remainder: $3/2^2 = 0.75$, $3^2/2^3 = 1.125$, $3^5/2^8 = 0.94922$, $3^{12}/2^{19} = 1.01364$, $3^{41}/2^{65} = 0.98860$, $3^{53}/2^{84} = 1.00209$ and $3^{306}/2^{485} = 0.99898$.

The remainder at depth 12, 1.01364, is the Pythagorean comma: twelve pure fifths overshoot seven octaves by that factor. The remainders shrink along the series and fall alternately below and above one, at every step.

The closure depths are positions. Depth 1 is 136.8 nm and 0.46 fs; depth 2 is 410.3 nm and 1.37 fs; depth 5 is 11.08 µm and 37.0 fs; depth 12 is 24.23 mm and 80.8 ps. These sit below the sizes of this book.

Two closure depths fall inside this book. Depth 41 is 11.1 AU and 92.4 minutes; depth 53 is 93.4 light-years and 93.4 years. Length and time agree at depth 53 because the length unit is the time unit times the speed of light, so one light-year matches one year.

Depth 306 lies far beyond the observable universe, at 4.8×10^{122} light-years and 4.8×10^{122} years. The age at 70.12 and the radius at 71.23 sit between the rungs 53 and 306. The net's texts read rung 306 as the address of the universe as a whole, with a capacity of $3^{306} \approx 10^{146}$ [682].

The net's texts give each knot a rim of its own: the solar knot ends where its own stretch thins to the stretch around it [701]. This book meets that rim at the reach of the Sun and at the outskirts of galaxies.

The rate of expansion

Galaxies recede at a speed that grows with their distance. The constant of proportion, the Hubble constant H_0, is given in kilometres per second per megaparsec. Its inverse, $1/H_0$, is a time close to the age of the universe, and each value here is placed by that time on the ladder.

Edwin Hubble's own value of 1929 was about 500 km s^{-1} Mpc^{-1}, far above today's values because of errors in his distance calibration [683]. Its inverse is 1.96 billion years, at 68.34. Every later value lies between 66 and 77 km s^{-1} Mpc^{-1}, with inverses from 12.7 to 14.7 billion years.

The early universe gives one group of values. The Planck fit of the background light gives 67.4 ± 0.5 km s^{-1} Mpc^{-1} [238][25]. With the galaxy-clustering ruler added it gives 67.7 ± 0.4 [680]; another Planck data combination is listed at 67.66 ± 0.42 [683].

The Atacama Cosmology Telescope, combined with Planck, lensing and the first DESI clustering data, gives 68.22 ± 0.36; with the second DESI release, 68.43 ± 0.27 [684]. DESI clustering with the light-element baryon density and the angular scale of the background gives 68.52 ± 0.62 for its first release [124]. Its second release gives 68.51 ± 0.58 and 68.45 ± 0.47 [685].

The South Pole Telescope gives 68.3 ± 1.5 [683]. The inverse distance ladder, which anchors supernovae to the clustering ruler, gives 67.8 ± 1.3 [680], and with DES supernovae 67.77 ± 1.30 [683].

The local distance ladder gives a second group. SH0ES measured Cepheid stars in the host galaxies of 42 type Ia supernovae and found 73.04 ± 1.04 km s^{-1} Mpc^{-1} [686]. The team found a 5σ difference from the value that Planck and the standard model predict [686][680].

Earlier SH0ES work on Cepheids in the Large Magellanic Cloud gave 74.03 ± 1.42 (2019), and Pantheon+ with SH0ES 73.4 (+0.99, −1.22) (2022) [683]. A community report on the local distance network gave 73.50 ± 0.81 on 1 April 2026 [683]. SH0ES and the Chicago-Carnegie programme together, with all three JWST methods, gave 72.6 ± 2.0 [683].

JWST tested whether crowded Cepheid images had biased the result. In 5 hosts of 8 supernovae, with more than 150 Cepheids per galaxy on average, the crowding

explanation was rejected at 8.2σ [687].

The Chicago-Carnegie Hubble Program used red giants at the tip of their branch and carbon stars instead of Cepheids. With HST and JWST and 24 supernova calibrators it found 70.39 ± 1.22 (stat) ± 1.33 (sys) ± 0.70 (supernova scatter) [688]. Combined, the errors give 70.39 ± 1.94 [683].

From JWST alone the red giants give 68.81 ± 1.79 (stat) ± 1.32 (sys), and the carbon stars 67.80 ± 2.17 (stat) ± 1.64 (sys) [688]. The same study finds its distances in agreement with the Cepheid distances at just over the 1 % level [688]. An earlier red-giant value was 69.8 ± 0.6 (stat) ± 1.6 (sys) [680], listed as 69.8 ± 1.9 (2019) and 69.8 ± 1.7 (2021) [683].

One-step methods carry larger errors. The time delays of gravitationally lensed quasars give 67.4 (+4.1, −3.2) for TDCOSMO [680], 73.3 (+1.7, −1.8) for six H0LiCOW quasars, 76.8 ± 2.6 for SHARP/H0LiCOW and 74.2 (+2.7, −3.0) for STRIDES [683]. Water masers give 73.9 ± 3.0 [683].

The lensed supernova Refsdal gives 66.6 (+4.1, −3.3), and the lensed supernova H0pe seen with JWST 75.7 (+8.1, −5.5) [683]. The neutron-star merger GW170817 gave 70.0 (+12.0, −8.0) as a standard siren, 70.3 (+5.3, −5.0) with its radio counterpart, and 67.0 ± 3.6 from the blackbody of its kilonova [683].

In the table the statistical and systematic errors of the Chicago-Carnegie values are combined in quadrature.

Case	Kind	H_0 (km s^{-1} Mpc^{-1})	$1/H_0$ (billion years)	Position	Source
Hubble 1929	first distances	~500	1.96	68.34	[683]
Planck 2018	background fit	67.4 ± 0.5	14.51	70.17	[238]
Planck + clustering ruler	background fit	67.7 ± 0.4	14.44	70.16	[680]
Planck, other combination	background fit	67.66 ± 0.42	14.45	70.16	[683]
ACT + Planck + DESI DR1	background fit	68.22 ± 0.36	14.33	70.16	[684]
ACT + Planck + DESI DR2	background fit	68.43 ± 0.27	14.29	70.15	[684]
DESI DR1 + light elements + angle	inverse ladder	68.52 ± 0.62	14.27	70.15	[124]
DESI DR2 + light elements	inverse ladder	68.51 ± 0.58	14.27	70.15	[685]
DESI DR2 + angle + light elements	inverse ladder	68.45 ± 0.47	14.28	70.15	[685]
SPT-3G	background fit	68.3 ± 1.5	14.32	70.16	[683]
Inverse distance ladder	inverse ladder	67.8 ± 1.3	14.42	70.16	[680]
DES supernovae + clustering	inverse ladder	67.77 ± 1.30	14.43	70.16	[683]
SH0ES 2022	Cepheids, 42 hosts	73.04 ± 1.04	13.39	70.09	[686]
SH0ES LMC 2019	Cepheids	74.03 ± 1.42	13.21	70.08	[683]
Pantheon+ with SH0ES	Cepheids and supernovae	73.4 (+0.99, −1.22)	13.32	70.09	[683]
Local distance network 2026	combined ladder	73.50 ± 0.81	13.30	70.09	[683]
SH0ES + CCHP JWST	three ladders	72.6 ± 2.0	13.47	70.10	[683]
CCHP HST + JWST	red giants	70.39 ± 1.94	13.89	70.13	[688]
CCHP JWST	red giants	68.81 ± 2.22	14.21	70.15	[688]
CCHP JWST	carbon stars	67.80 ± 2.72	14.42	70.16	[688]
CCHP earlier	red giants	69.8 ± 1.7	14.01	70.14	[680]

TDCOSMO	lens time delays	67.4 (+4.1, −3.2)	14.51	70.17	[680]
H0LiCOW, six quasars	lens time delays	73.3 (+1.7, −1.8)	13.34	70.09	[683]
SHARP/H0LiCOW	lens time delays	76.8 ± 2.6	12.73	70.05	[683]
STRIDES DES J0408−5354	lens time delay	74.2 (+2.7, −3.0)	13.18	70.08	[683]
Megamaser Cosmology Project	water masers	73.9 ± 3.0	13.23	70.08	[683]
Supernova Refsdal	lensed supernova	66.6 (+4.1, −3.3)	14.68	70.18	[683]
Supernova H0pe	lensed supernova	75.7 (+8.1, −5.5)	12.92	70.06	[683]
GW170817	standard siren	70.0 (+12.0, −8.0)	13.97	70.13	[683]
GW170817 with radio	standard siren	70.3 (+5.3, −5.0)	13.91	70.13	[683]
Kilonova blackbody	standard candle	67.0 ± 3.6	14.59	70.17	[683]

The values group in two clusters. Fits of the early universe give 67.4 to 68.5 with errors of 0.3 to 0.6; the Cepheid ladder gives 73.0 to 73.5 with errors of 0.8 to 1.0. The ratio of the central values of SH0ES and Planck is 73.04 / 67.4 = 1.084.

On the ladder the two clusters sit at 70.09 and 70.17, less than a tenth of a step apart. Read in the net’s terms, this is context: constants are state functions of the local vacuum [29].

What the universe holds

The standard model of the universe has six free parameters, fitted to the background light. They are the baryon density, the cold dark matter density, the angular size of the sound horizon, the optical depth to reionization, and the amplitude and tilt of the first fluctuations [680]. All other quantities in this section are derived from them.

Ordinary matter, the baryons, has $\Omega_b h^2 = 0.02237 \pm 0.00015$, so $\Omega_b = 0.0493 \pm 0.0006$ [25]. With the clustering ruler, $\Omega_b h^2 = 0.02242 \pm 0.00014$ [680]. Baryons make 4.93 % of the energy of the universe today.

Cold dark matter has $\Omega_c h^2 = 0.1200 \pm 0.0012$, so $\Omega_c = 0.265 \pm 0.007$ [25]. With the ruler it is 0.1193 ± 0.0009 [680]. Dark matter outweighs ordinary matter by 0.1200 / 0.02237 = 5.36 to 1.

All matter together has $\Omega_m = 0.315 \pm 0.007$, or 0.311 ± 0.006 with the ruler [238] [680]. The combination $\Omega_m h^2$ is 0.1428 ± 0.0011 [689]. DESI clustering alone gives 0.295 ± 0.015 in its first release and 0.2975 ± 0.0086 in its second [124][685], in mild tension with the background light at 2.3σ [125].

Dark energy has $\Omega_\Lambda = 0.685 \pm 0.007$, listed elsewhere as 0.6847 ± 0.0073, and 0.689 ± 0.006 with the ruler [25][689][680]. Its density is 5.83×10^{-27} kg m^{-3} and the cosmological constant $\Lambda = 1.088 \times 10^{-52}$ m^{-2} [25]. A rounder value is 7×10^{-30} g cm^{-3}, or 6×10^{-10} J m^{-3}, 68 % of the total [690].

The critical density is $1.87834 \times 10^{-29}\ h^2$ g cm^{-3}, or $2.77536627 \times 10^{11}\ h^2$ solar masses per cubic megaparsec [25]. With h = 0.674 it is $1.87834 \times 10^{-29} \times 0.674^2 = 8.53 \times 10^{-30}$ g cm^{-3} = 8.53×10^{-27} kg m^{-3}. Dark energy alone is 5.83 / 8.53 = 0.683 of it.

Space is flat. In an extended fit the curvature is $\Omega_K = 0.0007 \pm 0.0019$ [25], and with the ruler 0.001 ± 0.002 [238]. Flatness holds to 0.4 % at 95 % confidence [691].

Light is the smallest part of the budget today. The photons of the background have $\Omega_\gamma = 5.38 \times 10^{-5}$, or 0.005 % [25]. There are 410.73 photons per cubic centimetre, with a density of 4.645×10^{-34} g cm^{-3}, about 0.260 eV cm^{-3}, and an entropy density of 2,891.2

per cubic centimetre [25].

The baryons are far fewer. The ratio of baryons to photons is $\eta = 6.04 \times 10^{-10}$, so there are $1 / 6.04 \times 10^{-10} = 1.66 \times 10^{9}$ photons for every baryon [25]. The baryon number density is 2.515×10^{-7} cm^{-3} from the background light and 2.48×10^{-7} cm^{-3} from the light elements [25].

Relativistic species that decoupled early are counted as N_eff. The background light with the ruler gives 2.99 ± 0.17 [238][25]. The light elements give 2.898 ± 0.141, and helium in metal-poor galaxies with deuterium gives 3.11 (+0.34, −0.31) [202][692].

The neutrinos have a summed mass below 0.12 eV at 95 % confidence from Planck with the ruler [238]. DESI's first release with the background light gives below 0.072 eV, or 0.113 eV in a wider analysis [124]. The second release gives below 0.064 eV in the standard model and below 0.16 eV with evolving dark energy [125]; neutrino oscillations require at least 0.06 eV [25].

The clumping of matter on a scale of 8 h^{-1} Mpc is $\sigma_8 = 0.811 \pm 0.006$ [25]. The combination $\sigma_8(\Omega\_m/0.3)\text{^}0.5$ is 0.832 ± 0.013 from Planck and 0.812 ± 0.008 from the Dark Energy Survey's third year [680]. Weak-lensing surveys each give lower values than Planck, and the joint KiDS and DES analysis brings the difference to 1.7σ [680].

Case	Planck 2018	With clustering ruler	Other	Source
Baryon density Ω_b h²	0.02237 ± 0.00015	0.02242 ± 0.00014	light elements 0.02205 ± 0.00043	[25][680][202]
Cold dark matter Ω_c h²	0.1200 ± 0.0012	0.1193 ± 0.0009	—	[25][680]
Baryons Ω_b	0.0493 ± 0.0006	—	—	[25]
Cold dark matter Ω_c	0.265 ± 0.007	—	—	[25]
Matter Ω_m	0.315 ± 0.007	0.311 ± 0.006	DESI DR1 0.295 ± 0.015	[25][124]
Dark energy Ω_Λ	0.685 ± 0.007	0.689 ± 0.006	—	[25][680]
Curvature Ω_K	0.0007 ± 0.0019	0.001 ± 0.002	—	[25][238]
Photons Ω_γ	5.38×10^{-5}	—	—	[25]
Baryons per photon η	6.04×10^{-10}	—	light elements $\eta_{10} = 6.040 \pm 0.118$	[25][202]
Relativistic species N_eff	2.99 ± 0.17 (with ruler)	—	light elements 2.898 ± 0.141	[25][202]
Summed neutrino mass	< 0.12 eV	—	DESI DR2 + background < 0.064 eV	[238][125]
Clumping σ_8	0.811 ± 0.006	0.810 ± 0.006	DES Y3 $S_8 = 0.812 \pm 0.008$	[25][680]

Before the nuclei

The tabulated chronology of the universe begins above the Planck scale [693]. The Planck length is 1.616255×10^{-35} m, at −57.53 on the ladder, and the Planck mass 1.220890×10^{19} GeV, or 2.176434×10^{-8} kg [25]. The Planck length is the smallest size in this book.

The net's texts describe the ground before every form as full but without form [694]. They describe the whole as an equilibrium in motion that turns around zero, a rewriting machine whose sum is always zero [168]. Read in the terms of the window, that is the zero sum to which every closed window adds.

In the standard chronology a grand-unified epoch follows, at temperatures above 10^{15} GeV [693]. Then comes inflation, a rapid growth of space by a factor of the order of 10^{26} [693]. On the ladder that factor is $26 / \log_{10}3 = 54.49$ steps.

The times of inflation are model values. One table gives 10^{-36} to 10^{-32} s; the accompanying text gives 10^{-33} to 10^{-32} s [693]. On the ladder these are −42.30, −36.01

and −33.92.

Inflation is measured through limits. The share of primordial gravitational waves, the tensor-to-scalar ratio r, is below 0.10 at 95 % confidence from Planck alone [691]. With the BICEP2 and Keck Array data the limit falls to 0.056 [691].

BICEP and Keck observed at frequencies from 23 to 353 GHz. In 2021 they set r below 0.036 at 95 % confidence, with an uncertainty σ(r) = 0.009 [695]. The standard model table lists r below 0.06 [689].

The first fluctuations have an amplitude ln(10¹⁰ A_s) = 3.044 ± 0.014, so A_s = e^3.044 / 10¹⁰ = 2.10 × 10⁻⁹ [25]. Its square root, 4.6 × 10⁻⁵, is the amplitude of the curvature ripples from which all structure grew.

The ripples are slightly stronger on large scales than on small ones. Their tilt is n_s = 0.9649 ± 0.0042 from Planck [691], 0.965 ± 0.004 in the PDG table and 0.966 ± 0.004 with the ruler [25][680]. ACT with Planck gives 0.974 ± 0.003 [684].

The tilt lies (1 − 0.965) / 0.004 = 8.75 standard deviations below exact scale invariance. Its running with scale is −0.004 ± 0.007 [25]. Read in the net's terms, the tilt is a remainder: the ripples are nearly, not exactly, the same on every scale.

The first transition that lattice physics computes is the electroweak crossover. Its temperature is T = 159.5 ± 1.5 GeV, found from the peak of the susceptibility of the Higgs condensate [696]. In the chronology this falls near 10⁻¹¹ s, at 10.10, at about 10¹⁵ K [693].

The second is the crossover of quarks and gluons into hadrons. The HotQCD collaboration found T_c = 156.5 ± 1.5 MeV at zero baryon chemical potential [70]. In the chronology it falls near 10⁻⁵ s, at 22.67, at about 10¹² K, and the quark epoch ends there [693].

The two crossovers lie 159.5 GeV / 156.5 MeV = 1,019 times apart in energy. In time they lie a factor of 10⁶ apart, 6 / log₁₀3 = 12.58 steps on the ladder. Both are smooth crossovers in the lattice results, not sharp transitions [696][70].

The ALICE experiment collided lead nuclei at 2.76 TeV per nucleon pair. In the 20 % most central collisions, direct photons of 0.9 to 2.1 GeV/c show an inverse slope of 297 ± 12 (stat) ± 41 (syst) MeV [103]. That is 297 / 156.5 = 1.9 times the lattice crossover.

At about one second, at 33.15, the temperature had fallen to about 1 MeV, or 10¹⁰ K [202][693]. Neutrinos then decoupled from matter. N_eff = 2.99 counts the relativistic species that decoupled in this epoch [25].

Electrons and positrons then annihilated, between 1 MeV and 100 keV, or 10¹⁰ to 10⁹ K. One table gives 6 s, at 34.78; the text gives about 10 s, at 35.25 [693]. The lepton epoch ends about 10 seconds after inflation [693].

Event	Time	Position	Energy or temperature	Kind	Source
Planck scale	—	−57.53 (length 1.616 × 10⁻³⁵ m)	1.22 × 10¹⁹ GeV	constants	[25]
Grand unification	—	—	> 10¹⁵ GeV	model	[693]
Inflation	10⁻³⁶ or 10⁻³³ to 10⁻³² s	−42.30 / −36.01 to −33.92	factor ~10²⁶	model	[693]
Tensor modes	—	—	r < 0.036	limit	[695]
Electroweak crossover	~10⁻¹¹ s	10.10	159.5 ± 1.5 GeV	lattice	[696][693]
Quark-hadron crossover	~10⁻⁵ s	22.67	156.5 ± 1.5 MeV	lattice	[70][693]
Quark-gluon matter in lead collisions	laboratory	—	inverse slope 297 ± 43 MeV	direct	[103]
Neutrino decoupling	~1 s	33.15	~1 MeV	model	[202][693]

Electron-positron annihilation	6 to 10 s	34.78 to 35.25	1 MeV to 100 keV	model	[693]

The first three minutes

At one second, at about 1 MeV, the weak reactions that turn neutrons into protons and back fell out of balance [202]. The neutron fraction froze at n/p = e^(−Q/T_fr) ≈ 1/6 [202].

Free neutrons decay. By the time nuclear reactions began, the ratio had dropped to n/p ≈ 1/7 [202]. Every neutron that was not bound in a nucleus by then went on decaying.

The first step of the chain is deuterium. It was held back until T ≈ 0.1 MeV, where this bottleneck broke [202]. At that time photons outnumbered baryons by 1.66×10^{9} to one, as they do today [25].

Then the neutrons were taken up within minutes. The abundances were essentially fixed by t ≈ 180 s, at 37.88: the light elements were made by the end of the first three minutes [202]. One table gives a window of 10 s to 1,000 s, at 35.25 to 39.44; its text gives 3 to 20 minutes, at 37.88 to 39.61, at 10^{9} to 10^{7} K [693].

Nearly every surviving neutron ended in helium-4 [202]. With n/p = 1/7 the helium mass fraction is 2 · (1/7) / (1 + 1/7) = 2/8 = 0.25. The measured value is 0.245.

This history has a form the net's texts name [701]: "What fits, stays."

Read in the net's terms, the free neutron belongs to the unclosed class: it decays, and while it lasts it carries tension on to the closure that holds it. Helium-4 is the closed form that keeps the neutrons from then on.

Helium is measured in the ionized hydrogen regions of galaxies with very few heavy elements. Its recombination lines, extrapolated to zero heavy-element content, give the primordial mass fraction Y_p = 0.245 ± 0.003 [202].

The dwarf galaxy Leo P, measured in the helium line at 10,830 Å, gives Y_p = 0.2453 ± 0.0034 [697]. The EMPRESS survey raised the number of extremely metal-poor galaxies in such fits from 3 to 8, with 51 moderately metal-poor ones, and found Y_p ≈ 0.2370 [692]. That is 0.008 below the adopted value, 2.7 times its error; EMPRESS reads it as a lepton asymmetry ξ_e ≈ 0.05 [692].

The background light gives Y_p = 0.2448 ± 0.0033 [202], and the standard model fit consistent with the light elements gives about 0.2454 [238].

Deuterium is measured in absorption. Clouds of metal-poor gas in front of quasars show deuterium and hydrogen lines of the Lyman series. The adopted ratio is D/H = (25.47 ± 0.29) × 10^{-6} [202].

The most precise single study used eight deuterium lines in one new system, together with six earlier high-precision systems. It found D/H = (2.527 ± 0.030) × 10^{-5}, or $\log_{10}$(D/H) = −4.5974 ± 0.0052, a 1 % determination [698].

The review judges helium-3 unsuitable as a measure of the first minutes [202]. Lithium-7 is seen in the oldest stars of the halo, where its abundance forms a plateau. There Li/H = (1.6 ± 0.3) × 10^{-10} [202].

The calculation of the first minutes predicts Li/H = (4.72 ± 0.7) × 10^{-10} [202]. That is 4.72 / 1.6 = 2.95 times the observed value; the review gives a factor of 3.1 at 4.4σ, the lithium problem [202].

Deuterium fixes the number of baryons per photon. The light elements give η_{10} = 6.040 ± 0.118, and the background light η_{10} = 6.12 ± 0.04 [202]. With helium and deuterium together the light elements give η_{10} = 6.088 ± 0.054 and N_ν = 2.898 ± 0.141 [202].

Two epochs far apart give the same amount of ordinary matter. The light elements, made in the first minutes, give Ω_b h^2 = 0.02205 ± 0.00043 [202]. The background light, released after 372,000 years, gives 0.02237 ± 0.00015; the difference, 0.00032, is

0.7 times the error of the first [25].

DESI uses a light-element prior of $\Omega_b h^2 = 0.02218 \pm 0.00055$, or 0.02196 ± 0.00063 with the number of neutrino species free [125].

About 74 % of the matter in the universe, even today, is hydrogen made in these minutes, with about 24 % helium and a trace of lithium [699]. For 100 million years after the beginning there was nothing but hydrogen, helium and lithium [700]. That span ends at 65.64 on the ladder.

Case	Measured	Method	Calculated or fitted	Source
Helium-4, Y_p (adopted)	0.245 ± 0.003	H II regions, zero metals	background 0.2448 ± 0.0033; fit ≈ 0.2454	[202][238]
Helium-4, Leo P	0.2453 ± 0.0034	He I 10,830 Å	—	[697]
Helium-4, EMPRESS	≈ 0.2370	8 extremely and 51 moderately metal-poor galaxies	—	[692]
Deuterium D/H (adopted)	$(25.47 \pm 0.29) \times 10^{-6}$	quasar absorbers	consistent with $\eta_{10} = 6.12$	[202]
Deuterium D/H, Cooke	$(2.527 \pm 0.030) \times 10^{-5}$	8 lines plus 6 systems	—	[698]
Lithium-7 Li/H	$(1.6 \pm 0.3) \times 10^{-10}$	halo star plateau	$(4.72 \pm 0.7) \times 10^{-10}$	[202]
Baryons per photon η_{10}	6.040 ± 0.118	deuterium	background 6.12 ± 0.04	[202]
Baryon density $\Omega_b h^2$	0.02205 ± 0.00043	light elements	background 0.02237 ± 0.00015	[202][25]
Neutrino species N_ν	2.898 ± 0.141	helium and deuterium	3 species	[202]

Event	Time	Position	Temperature	Source
Weak freeze-out, n/p ≈ 1/6	~1 s	33.15	~1 MeV	[202]
Electron-positron annihilation	6 to 10 s	34.78 to 35.25	1 MeV to 100 keV	[693]
Deuterium bottleneck breaks, n/p ≈ 1/7	minutes	—	≈ 0.1 MeV	[202]
Abundances fixed	~180 s	37.88	—	[202]
Nucleosynthesis window (table)	10 to 1,000 s	35.25 to 39.44	10^9 to 10^7 K	[693]
Nucleosynthesis window (text)	3 to 20 min	37.88 to 39.61	—	[693]
Only hydrogen, helium, lithium	to 100 million years	65.64	—	[700]

What this part of the history shows

Sizes run from the Planck length at −57.53 to the diameter of the observable universe at 71.86, a span of 129.39 steps. The measured first moments fill the short stretch from 33.15 to 37.88, from the freeze-out at one second to the fixing of the light nuclei at 180 seconds. The age of the universe sits at 70.12.

Depths 1, 2, 5 and 12 sit below the sizes of the sky. Depths 41 and 53 sit inside it, at 11.1 AU and 92.4 minutes and at 93.4 light-years and 93.4 years; depth 306 sits far beyond the observable universe. The age and the radius of the observable universe sit between the rungs 53 and 306.

The first minutes have the form of what fits, stays. The neutron fraction froze at 1/6 and fell to 1/7 as free neutrons decayed. The neutrons that were bound by then ended in helium-4, which holds a mass fraction of 0.245 ± 0.003, close to the 0.25 that n/p = 1/7 gives.

Read in the net’s terms, the free neutron is a carrier. It decays, and while it lasts it carries tension on to the closure that holds it. The photons stay unbound throughout, 1.66×10^{9} for every baryon, and carry the heat of the first minutes into the next part of the history.

Read in the net’s terms, what closed in the first minutes became the alphabet of everything later. About 74 % of the matter is still hydrogen and about 24 % helium, with deuterium at 2.527×10^{-5} of hydrogen and lithium at 1.6×10^{-10}. For 100 million years, to 65.64 on the ladder, these were the only letters; every heavier element is a later word written in stars.

Read in the net’s terms, the same amount of ordinary matter is seen at two depths. The light elements, fixed at 37.88, give $\Omega_b h^2 = 0.02205 \pm 0.00043$. The background light, released at 60.55, gives 0.02237 ± 0.00015: one quantity seen at two places on the ladder, 22.67 steps apart.

The rate of expansion reads as context. The early universe gives 67.4 to 68.5 km s^{-1} Mpc^{-1}, the local ladder 73.0 to 73.5, a ratio of 1.084 between Planck and SH0ES. On the ladder the two groups sit at 70.17 and 70.09: the same rule, read in two surroundings.

The remainder appears in the first fluctuations. Their amplitude is 4.6×10^{-5}, and their tilt $n_s = 0.965$ lies 8.75 standard deviations from exact equality on all scales.

The universe is flat to 0.4 %, with $\Omega_K = 0.0007 \pm 0.0019$. Read in the net’s terms, the whole adds to zero curvature, while its parts never close exactly.

25. Light Set Free

After the first three minutes the universe held hydrogen, helium and a trace of lithium, all ionized, in a bath of light. For the next 372,000 years light and gas stayed together [25].

Two events mark this part of the history. At about 51,000 years matter began to weigh more than radiation. At about 372,000 years the electrons joined the nuclei, the gas became neutral, and the light went free [25].

That light is the microwave background, measured today at 2.7255 K over the whole sky [25]. It carries the imprint of sound waves that ran through the young gas, and the same imprint returns later in the spacing of galaxies. After the release came a long dark interval, and then the first sources ionized the gas again.

Matter overtakes radiation

As space expanded, the density of matter overtook the density of radiation. In the Planck fit the two were equal at redshift $z_{eq} = 3{,}402 \pm 26$ [25]. The age then was $t_{eq} = 51.0 \pm 0.8$ thousand years, or 1.609×10^{12} s, at 58.74 on the ladder [25].

Older tables give 47,000 years, at 58.66, and $z = 3{,}600$ [693]. These values are rounder and older; the Planck values are a fit fixed by $\Omega_m h^2$ and the radiation content.

The temperature of the light scales with $1 + z$. At equality it was $2.7255 \text{ K} \times 3{,}403 = 9{,}275$ K. The photons alone contribute $\Omega_\gamma h^2 = 2.473 \times 10^{-5}$ today; the neutrinos add their share through N_{eff} [25].

Equality came 371.8 / 51.0 = 7.3 times earlier in time than the release of the light. In $1 + z$ it lies 3,403 / 1,090.92 = 3.1 times higher.

Recombination: the atoms close

The atoms closed in stages. Helium took its first electron back near $z \approx 6{,}000$ and its second near $z \approx 2{,}000$ [703]. Hydrogen began to recombine at roughly 4,000 K, near $z = 1{,}500$ [703].

The ionization energy of hydrogen is 13.6 eV [703]. With 1.66×10^9 photons for every baryon, one of the many photons would at once ionize any new atom [703][25]. Recombination therefore waited until the light had cooled far below 13.6 eV.

The universe was 90 % neutral at $z \approx 1{,}070$ [703]. The moment of release is defined where the optical depth to scattering falls to one. Planck places it at $z^* = 1{,}089.92 \pm 0.25$, a precision of 0.02 % [25].

The age at that moment is $t^* = 371.8 \pm 1.0$ thousand years, or 1.173×10^{13} s, at 60.55 [25]. Other pages give approximately 379,000 years, about 378,000 years at $z = 1{,}100$, and around 400,000 years, at 60.56 and 60.61 [704][703]. One table gives 290,000 to 370,000 years, at 60.32 to 60.54, with redshifts 1,090 to 1,270 [693].

The temperature at last scattering is given as around 3,000 K [704]. The Nobel committee wrote that the universe was almost 3,000 degrees Celsius when the light was emitted [705]. Today’s 2.7255 K times $1 + z^* = 1{,}090.92$ gives 2,973 K.

The release took time. Decoupling ran over roughly 115,000 years, the width of the visibility function, at 59.48 [704]. That is 115 / 371.8 = 31 % of the age at that moment.

The same moment fixes the sound horizon, the distance a pressure wave in the gas had travelled. At z^* it is $r^* = 144.43 \pm 0.26$ Mpc in comoving measure, 4.457×10^{24} m, at 67.05 [25].

Read in the net’s terms, the form here is what fits, stays. Free electron and proton are

open; the neutral atom is the closed form, and it holds from then on. The light that was bound in scattering is left as the unclosed part, free to travel.

Event	Redshift	Age	Position	Temperature	Source
Matter–radiation equality	3,402 ± 26	51.0 ± 0.8 thousand years	58.74	9,275 K (computed)	[25]
Equality, older table	3,600	47,000 years	58.66	—	[693]
Helium, first recombination	≈ 6,000	—	—	—	[703]
Helium, second recombination	≈ 2,000	—	—	—	[703]
Hydrogen begins to recombine	≈ 1,500	—	—	≈ 4,000 K	[703]
Last scattering (optical depth one)	1,089.92 ± 0.25	371.8 ± 1.0 thousand years	60.55	2,973 K (computed)	[25]
Last scattering, other values	≈ 1,100	378,000 to 400,000 years	60.56 to 60.61	≈ 3,000 K	[704][703]
Recombination span, table	1,090 to 1,270	290,000 to 370,000 years	60.32 to 60.54	4,000 K	[693]
Hydrogen 90 % neutral	≈ 1,070	—	—	—	[703]
Width of decoupling	—	≈ 115,000 years	59.48	—	[704]

The background light

The light released at last scattering was found by Penzias and Wilson. Their first measurement, on 20 May 1964, showed an excess antenna temperature of 4.2 K [704].

The COBE satellite was launched on its own rocket on 18 November 1989 [705]. Its FIRAS instrument measured the spectrum and found a perfect blackbody [705]. The Nobel Prize in Physics 2006 went to Mather and Smoot for this work [705].

The full FIRAS data of 1996 gave T = 2.728 ± 0.004 K at 95 % confidence [706]. The deviations from a blackbody are less than 50 parts per million of the peak [706]. The two kinds of spectral distortion are bounded at $|y| < 15 \times 10^{-6}$ and $|\mu| < 9 \times 10^{-5}$ [706].

In 2009 the FIRAS data were recalibrated with WMAP, giving 2.7260 ± 0.0013 K [707]. The adopted value is 2.7255 ± 0.0006 K, or 2.72548 ± 0.00057 K, fixed to 0.02 % [25] [704]. The three FIRAS-based values agree within their errors.

The net’s ladder text lists the peak of the background spectrum at 1.06 mm, at 9.15 on the ladder [29]. The 21-cm line of hydrogen, the probe of the dark gas that follows, sits at 13.97 [29].

The background holds 410.73 photons per cubic centimetre, about 411 per cubic centimetre in round numbers [25][704]. Their energy density is about 0.260 eV cm^{-3}, and they make $\Omega_\gamma = 5.38 \times 10^{-5}$ of the critical density [25].

The light is the same in every direction to high precision. The text of the net names light in its own words: “Light is the first appearance of the bottom: vacuum-resonance in transit” [694]. Read in those terms, the background is that transit, sent from 45.7 billion light-years, at 71.21, and still arriving [677].

The largest variation across the sky is a dipole. Its amplitude is 3.3621 ± 0.0010 mK, from the motion of the Sun at 369.82 ± 0.11 km s^{-1} against the background [25]. The Local Group moves at 620 ± 15 km s^{-1} [25].

FIRAS measured the dipole at 3.372 ± 0.007 mK toward galactic longitude 264.14° ± 0.30 and latitude 48.26° ± 0.30 [706]. The direction is towards the constellation Crater [704]. The dipole is $3.3621 \times 10^{-3} / 2.7255 = 1.2 \times 10^{-3}$ of the temperature.

The net's texts give this motion as the Earth's own, at about 370 km s⁻¹ against the oldest light there is [708]. The same text counts at least four windings turning above the Earth: turning within turning within turning [708].

Below the dipole lie the ripples of the first fluctuations. The background is isotropic to roughly one part in 25,000, with root-mean-square variations of just over 100 μK [704]. The Nobel committee gave the variations as about a hundred-thousandth of a degree [705].

100 μK over 2.7255 K is 3.7×10^{-5}. One part in 25,000 is the root mean square over all angular scales; a hundred-thousandth of a degree is the Nobel wording. The amplitude of the curvature ripples is $\sqrt{A_s} = 4.6 \times 10^{-5}$, from $\ln(10^{10} A_s) = 3.044 \pm 0.014$ [25].

The strongest ripples have a characteristic size on the sky of about one degree [704]. The angle of the sound horizon is $100\,\theta^* = 1.0411 \pm 0.0003$, so $\theta^* = 0.010411$ rad = 0.5965° [238]. With the sampled parameter it is $100\,\theta_{MC} = 1.04092 \pm 0.00031$ [25], and DESI uses a prior of $100\,\theta^* = 1.04110 \pm 0.00053$ [125].

Read in the net's terms, this is a remainder. The light closed into a blackbody to 50 parts per million, yet it differs from place to place by 3.7×10^{-5}.

Case	Value	Method	Source
First measurement, 20 May 1964	excess 4.2 K	antenna temperature	[704]
COBE launch	18 November 1989	—	[705]
Temperature, FIRAS 1996	2.728 ± 0.004 K	FIRAS	[706]
Temperature, recalibrated 2009	2.7260 ± 0.0013 K	FIRAS with WMAP	[707]
Temperature, adopted	2.7255 ± 0.0006 K	combined	[25]
Deviation from a blackbody	< 50 ppm of peak	FIRAS	[706]
Distortion y	$< 15 \times 10^{-6}$	FIRAS	[706]
Distortion μ	$< 9 \times 10^{-5}$	FIRAS	[706]
Photon number density	410.73 cm⁻³	from temperature	[25]
Dipole	3.3621 ± 0.0010 mK	combined	[25]
Dipole, FIRAS	3.372 ± 0.007 mK toward (264.14°, 48.26°)	FIRAS	[706]
Speed of the Sun against the background	369.82 ± 0.11 km s⁻¹	dipole	[25]
Speed of the Local Group	620 ± 15 km s⁻¹	dipole	[25]
Anisotropy	just over 100 μK, about 1 part in 25,000	rms	[704]
Acoustic angle θ*	0.5965°	Planck	[238]
Distance to the surface of last scattering	45.7 billion light-years, position 71.21	model	[677]

The sound waves frozen in

Before last scattering, sound waves ran through the gas at slightly over half the speed of light [709]. When the light went free, the distance the waves had run remained in the matter as a standard ruler [709].

At recombination that distance was about 450,000 light-years, or 0.14 Mpc, in radius [709]. These sit at 60.72 and 60.73 on the ladder. In today's universe the same length is about 490 million light-years, or about 150 Mpc, at 67.08 [709].

The length grew by 150 / 0.14 = 1,071, close to the growth of space since then, $1 + z^* = 1{,}090.92$. The precise comoving sound horizon at last scattering is $r^* = 144.43 \pm 0.26$ Mpc, at 67.05 [25].

The ruler for galaxies, r_d, is set at the drag epoch of the baryons, which follows the last scattering of the photons, and is slightly larger than r*. DESI's reference value is r_d = 147.05 Mpc, 4.537 × 10^{24} m, at 67.06 [125].

The ruler was first seen in 2005. Among 46,748 luminous red galaxies of the Sloan Digital Sky Survey, at redshifts 0.16 to 0.47, the correlation function shows a well-detected peak at 100 h^{-1} Mpc separation [710]. With h = 0.674 that is 148.4 Mpc, at 67.07.

The survey covered 3,816 square degrees [709]. It fixed the ratio of distances to z = 0.35 and z = 1,089 to 4 % [710]. The 2dF Galaxy Redshift Survey detected the same feature in its power spectrum in the same year [680].

The Dark Energy Spectroscopic Instrument took the method to millions of objects. It works with 5,000 robotic fibres on the Mayall 4 m telescope at Kitt Peak, and its survey began on 14 May 2021 [711]. Its five-year survey was completed by April 2026 [711].

The first DESI analysis used more than 6 million extragalactic objects at redshifts 0.1 to 4.2 [124]. From the ruler alone it found Ω_m = 0.295 ± 0.015 [124]. Its public release of 19 March 2025 held 18.7 million objects: about 4 million stars, 13.1 million galaxies and 1.6 million quasars [711].

The second analysis, of March 2025, used more than 14 million galaxies and quasars [125]. Bright galaxies cover z = 0.1 to 0.4, luminous red galaxies 0.4 to 1.1, emission-line galaxies 0.8 to 1.6 and quasars 0.8 to 3.5 [125]. The precision improved by 30 to 50 % over the first release [125].

The forest of hydrogen absorption in quasar spectra, at an effective redshift of 2.33, gives the ruler to 0.64 %, or 0.7 % with systematic errors [125]. One combined bin of red and emission-line galaxies gives the isotropic scale α_iso = 0.9886 ± 0.0046 against the reference [125]. More than 47 million galaxies and quasars were expected by 2026 [711].

The ruler is a small fraction of the visible universe. 147.05 Mpc over the radius of 14,260 Mpc is 1.0 × 10^{-2}.

The net's ladder text names a fixed scale in the distribution of galaxies at depth 67, beside Laniakea [29]. The measured ruler, at 67.05 to 67.08, lies on that layer.

Read in the net's terms, this is the same winding at two depths. One length was laid down in the gas at 60.73 and is read again in the galaxies at 67.06. It shows as an angle of 0.5965° on the background and as a separation of 147 Mpc between galaxies at z = 0.1 to 4.2.

Case	Value	Metres	Position	Source
Ruler at recombination	450,000 light-years (0.14 Mpc)	4.26 × 10^{21}	60.72	[709]
Sound horizon at last scattering r*	144.43 ± 0.26 Mpc	4.457 × 10^{24}	67.05	[25]
Ruler at the drag epoch r_d	147.05 Mpc	4.537 × 10^{24}	67.06	[125]
First detection, SDSS 2005	100 h^{-1} Mpc = 148.4 Mpc	4.578 × 10^{24}	67.07	[710]
Ruler today, round	about 150 Mpc, 490 million light-years	4.63 × 10^{24}	67.08	[709]

Survey	Objects	Redshift	Result	Source
SDSS luminous red galaxies, 2005	46,748	0.16 to 0.47	peak at 100 h^{-1} Mpc; distance ratio to 4 %	[710]
2dFGRS, 2005	—	—	detection in the power spectrum	[680]
DESI DR1	> 6 million	0.1 to 4.2	Ω_m = 0.295 ± 0.015	[124]
DESI DR1 public release, 19 March	18.7 million (4 million stars, 13.1	—	—	[711]

2025	million galaxies, 1.6 million quasars)			
DESI DR2, March 2025	> 14 million	0.1 to 3.5; Lyα forest at 2.33	0.64 % precision; gain of 30 to 50 %	[125]
DESI by 2026	> 47 million	—	—	[711]

The dark ages

After the release the gas was neutral and the light was cooling. One table places the dark ages from 370,000 years to about 150 million years, at 60.54 to 66.01; another entry lets them last to about 1 billion years, at 67.73 [693]. Over that span the redshift fell from 1,100 to 20 and the temperature from 4,000 K to 60 K [693].

The background itself at z = 20 had 2.7255 K × 21 = 57 K, close to the 60 K of the table. The interval is dark. Its proposed direct probe is the 21-cm line of neutral hydrogen, stretched by the expansion to radio wavelengths [693].

In 2018 the EDGES experiment reported an absorption in the radio sky averaged over all directions. It is centred at 78 MHz, with a full width at half maximum of 19 MHz and an amplitude of 0.5 K [712]. The depth is more than a factor of two greater than the largest predictions [712].

A wave of 78 MHz has a wavelength of 3.84 m, at 16.61 on the ladder. The half-maximum band runs from 68.5 to 87.5 MHz.

EDGES read the profile as light from the first stars. Lyman-α photons from stars would be present by 180 million years after the beginning, at 66.17, and the gas heated less than 100 million years later [712]. 180 million years is 5.68×10^{15} s.

The SARAS 3 radiometer observed from 55 to 85 MHz. It rejected the best-fitting EDGES profile with 95.3 % confidence [713]. The interval thus holds one reported signal and one rejection of it.

Read in the net’s terms, the dark ages have the form of rest. The gas held still and cooled from 4,000 K to about 60 K for 150 million years or more. The discharge followed with the first light.

Reionization

The first sources ionized the gas again. Planck measures the optical depth of the reionized gas to the background light as $\tau = 0.054 \pm 0.007$ [238][25]. The low-multipole polarization alone gives 0.0506 ± 0.0086, and with the ruler the value is 0.056 ± 0.007 [238][680].

In the Planck fit half the gas was ionized at $z_i = 7.7 \pm 0.7$ [25]. The age then was $t_i = 690 \pm 90$ million years, 2.18×10^{16} s, at 67.40; the range 600 to 780 million years spans 67.27 to 67.51 [25]. Another table gives $z_{re} = 7.68 \pm 0.79$ [689].

Quasars measure the neutral gas directly. The quasar ULAS J1342+0928 at z = 7.54 shows a damping wing of the Lyman-α line [714]. The neutral fraction there is more than 0.33 at 68 % probability and more than 0.11 at 95 % [714].

The gamma-ray burst GRB 090423 at z = 8.23, about 630 million years after the beginning, at 67.31, showed the Lyman-α break [715].

The end of reionization is seen in the forest of absorption lines in quasar spectra. The XQR-30 study used 67 quasar sightlines at $z > 5.5$, including 30 quasars at $z > 5.7$ with a signal-to-noise ratio above 20 per pixel [716]. It measured the Lyman-α transmission over $4.9 < z < 6.1$ [716].

Neutral islands persist in the gas between galaxies until at least z = 5.3, at 1.1 billion years, at 67.82 [716]. From the midpoint at 690 million years to that end, reionization ran over at least $1.1 - 0.69 = 0.41$ billion years.

One table gives the whole of reionization from 200 million to 1 billion years, at 66.27 to 67.73, over redshifts 20 to 6 and temperatures 60 K to 19 K [693]. The background at z = 6 had 2.7255 K × 7 = 19 K.

The ionizing light came from the first galaxies, which the next chapter tells.

Three methods line up on one sequence. The background places the midpoint at 690 million years, and a quasar at z = 7.54 still sees more than a third of the gas neutral. The forest closes the epoch at 1.1 billion years.

Case	Redshift	Age	Position	Measure	Source
Dark ages begin	1,100	370,000 years	60.54	4,000 K	[693]
Dark ages end (table)	20	about 150 million years	66.01	60 K	[693]
Dark ages end (other entry)	—	about 1 billion years	67.73	—	[693]
EDGES absorption	—	180 million years	66.17	78 MHz, 19 MHz wide, 0.5 K deep	[712]
Gas heated (EDGES)	—	by about 280 million years	66.57	—	[712]
SARAS 3	—	—	—	EDGES profile rejected at 95.3 %	[713]
Optical depth τ	—	—	—	0.054 ± 0.007	[238]
Half reionization	7.7 ± 0.7	690 ± 90 million years	67.40	Planck fit	[25]
GRB 090423	8.23	about 630 million years	67.31	Lyman-α break	[715]
ULAS J1342+0928	7.54	690 million years	67.40	neutral fraction > 0.33	[714]
End of reionization	≤ 5.3	≥ 1.1 billion years	67.82	67 quasar sightlines	[716]
Reionization (table)	20 to 6	200 million to 1 billion years	66.27 to 67.73	60 K to 19 K	[693]

What this part of the history shows

On the ladder this part of the history runs from equality at 58.74 to the end of reionization at 67.82, just over nine steps. The release of the light, at 60.55, sits near its start; the long dark interval fills most of the span.

Read in the net’s terms, recombination has the form of what fits, stays. Helium closed first, near z ≈ 6,000 and z ≈ 2,000, then hydrogen from z ≈ 1,500, 90 % neutral by z ≈ 1,070. The neutral atom held, and the release at z* = 1,089.92 took about 115,000 years.

Read in the same terms, the light set free is the carrier. It left the closed atoms behind and has been in transit since, through 45.7 billion light-years of comoving distance. Its temperature fell from 2,973 K to 2.7255 K by the factor 1,090.92, while 410.73 photons still fill each cubic centimetre.

Read in the same terms, the background shows the remainder. It is a blackbody to better than 50 parts per million of its peak, with distortions below 15×10^{-6} and 9×10^{-5}. Yet it varies across the sky by 3.7×10^{-5}: the closure is close, never exact.

Read in the same terms, the sound ruler is the same winding at two depths. It was laid down at about 0.14 Mpc, at 60.73, and is read today at 147.05 Mpc, at 67.06. It appears as a 0.5965° angle in the background and as the preferred separation of galaxies from z = 0.1 to 4.2, and the net’s ladder text places it at depth 67.

The dipole reads as turning within turning. The Sun moves at 369.82 km s^{-1} against the background and the Local Group at 620 km s^{-1}; the oldest light reads as the frame in which each smaller winding turns.

Read in the net’s terms, the dark ages and reionization have the form of rest and discharge. The gas held neutral and cooled to about 60 K for at least 150 million years. The first light then ionized it, half by 690 ± 90 million years and all by about 1.1 billion years, a discharge of at least 0.41 billion years.

26. The First Stars and Galaxies

The dark ages ended with the first light made by matter itself. Stars formed in the neutral gas, gathered into galaxies, and fed black holes at their centres. Their light ionized the gas between them, as Chapter 25 told.

The first stars are known from models and from the traces they left. The first galaxies are seen directly: the James Webb Space Telescope has confirmed galaxies at 280 to 300 million years after the beginning [717][718]. Black holes of a billion solar masses already shone at 670 million years [719].

The chapter then follows the expansion itself. For about 7.7 billion years it slowed; then it began to speed up [25]. The last section measures what speeds it up and sets the whole sequence of the first three chapters on the ladder.

The first stars

The first stars, called Population III, formed from the hydrogen, helium and lithium of the first minutes. Their masses are model results. One model family gives several hundred solar masses and possibly up to 1,000, with lifetimes of only 2 to 5 million years [720].

Those lifetimes sit at 62.08 to 62.91 on the ladder. Another model family, fitted to the abundance patterns of metal-poor stars, gives 20 to 130 solar masses [720]. The two families differ in mass by about a factor of ten.

A first-generation star of 0.8 solar masses or less, ejected early, could survive to the present day [720]. Models give the first stars the making of the first 26 elements [720].

The time of their birth is set from several sides. The chronology places the first stars within a few hundred million years, and a Planck analysis suggests around 300 million years [693]. The EDGES radio absorption places Lyman-α photons from stars by 180 million years, at 66.17 [712].

By 290 million years the first galaxies already held oxygen at 5 to 20 % of the solar value [721]. Earlier stars had already made that oxygen.

The net’s texts give stars the form of loading and discharge: “Stars — loading for millions of years, discharging as supernovae” [694]. Read in those terms, a first star of 2 to 5 million years has that form at its shortest.

The traces of the first stars survive in old stars of the Milky Way. SMSS J031300.36−670839.3 has iron below $10^{-7.1}$ of the solar fraction, that is below 7.9×10^{-8} [722]. Its metals fit a single low-energy supernova of a star of about 60 solar masses [722].

That star is one of a series. SDSS J102915+172927, Caffau’s star, was the most metal-poor known when it was found in 2012; SMSS J0313−6708 went lower in 2014 [720]. A candidate in the dwarf galaxy Pictor II, reported in 2026, holds iron below 1/43,000 and calcium below 1/160,000 of the Sun [720].

Read in the net’s terms, this is the residue that becomes the alphabet. The few heavy atoms of one supernova of 60 solar masses became the letters with which the next star was written.

Direct candidates for Population III stars are seen much later. The source CR7 lies at z = 6.60, around 800 million years after the beginning, at 67.53 [720]. A possible detection of Population III stars in RX J2129–z8He II was reported on 8 December 2022 [720].

LAP1-B, at z = 6.6, holds a total mass of up to 2,700 solar masses [720]. CR7 and LAP1-B both lie near z ≈ 6.6, at about 800 million years.

Case	Value	Kind	Position	Source

Mass, first model family	several hundred, up to 1,000 solar masses	model	—	[720]
Lifetime	2 to 5 million years	model	62.08 to 62.91	[720]
Mass, from abundance patterns	20 to 130 solar masses	model	—	[720]
Survival limit	≤ 0.8 solar masses	model	—	[720]
Elements made	the first 26	model	—	[720]
First stars (chronology)	around 300 million years	Planck analysis	66.64	[693]
Starlight by (EDGES)	180 million years	21-cm absorption	66.17	[712]
Oxygen in JADES-GS-z14-0	5 to 20 % of solar at 290 million years	ALMA [O III]	66.61	[721]
SMSS J0313−6708	[Fe/H] < −7.1; one supernova of ~60 solar masses	spectroscopy	—	[722]
Pictor II candidate	Fe < 1/43,000, Ca < 1/160,000 of solar	spectroscopy	—	[720]
CR7	z = 6.60, ~800 million years	candidate	67.53	[720]
RX J2129–z8He II	possible detection, 8 December 2022	candidate	—	[720]
LAP1-B	z = 6.6, ≤ 2,700 solar masses	candidate	67.53	[720]

The earliest galaxies

The James Webb Space Telescope confirms galaxies by their spectra. The redshift comes from the Lyman break in the spectrum or from emission lines such as those of oxygen [718][721].

In 2024 the JADES survey confirmed two luminous galaxies near z = 14 [718]. JADES-GS-z14-0 has a Lyman-break redshift of z = 14.32 (+0.08, −0.20); JADES-GS-z14-1 has z = 13.90 ± 0.17 [718]. They were already in place 300 million years after the beginning, at 66.64 [718].

JADES-GS-z14-0 is resolved, with a radius of 260 parsecs [718]. 260 pc is 8.02×10^{18} m, at 55.01 on the ladder.

The ALMA telescope then detected oxygen in JADES-GS-z14-0 at 88 μm. The [O III] line, at 6.6σ, gives z = 14.1793 ± 0.0007, a mere 300 million years after the beginning [721]. The line redshift lies 0.14 below the break redshift, within its lower error of 0.20.

The galaxy is surprisingly rich in metals, at Z ≈ 0.05 to 0.2 of the solar value [721]. Its dust is below 2×10^{-3} of its stellar mass [721]. The record list gives it z = 14.18 and about 290 million years, at 66.61 [715].

In 2025 MoM-z14 took the record. Five rest-ultraviolet emission lines, each at about 3σ, give z_spec = 14.44, a mere 280 million years after the beginning, at 66.57 [717]. Its absolute ultraviolet magnitude is −20.2 and its ultraviolet slope β = −2.5 ± 0.2 [717].

MoM-z14 is compact, with a circularized effective radius of 74 (+15, −12) parsecs [717]. 74 pc is 2.28×10^{18} m, at 53.86; the range 62 to 89 pc spans 53.70 to 54.03. Its nitrogen exceeds its carbon, [N/C] > 1, and its star formation rose about tenfold in its last 5 million years, at 62.91 [717].

Bright galaxies at this distance are far more common than expected. Their density is 182 (+329, −105) times the pre-JWST consensus models, more than a factor of 100 [717].

The list of spectroscopically confirmed objects holds 16 galaxies at z ≥ 10.38, all

confirmed with JWST or ALMA [715]. GN-z11, at z = 10.60 and 430 million years, was confirmed by JWST in February 2023 [715]. The ages of the three oldest systems lie within 20 million years of each other, from 280 to 300 million years.

Rank	Object	z	Million years after the beginning	Position	Confirmation
1	MoM-z14	14.44	280	66.57	NIRSpec Lyman break and lines
2	JADES-GS-z14-0	14.18	290	66.61	ALMA [O III]
3	JADES-GS-z14-1	13.90	300	66.64	NIRSpec
4	PAN-z14-1	13.53	310	66.67	NIRSpec
5	JADES-GS-z13-0	13.20	330	66.72	NIRSpec
6	UNCOVER-z13	13.08	330	66.72	NIRSpec
7	JADES-GS-z13-1	13.0	330	66.72	Lyman-α emitter (2025)
8	JADES-GS-z12-0	12.63	350	66.78	break and carbon lines
9	UNCOVER-z12	12.39	350	66.78	NIRSpec
10	GLASS-z12 (GHZ2)	12.33	367	66.82	ALMA [O III]
11	UDFj-39546284	11.58	380	66.85	NIRSpec
12	EGS-z11-R0	11.45	386	66.87	NIRSpec
13	Maisie’s Galaxy	11.44	390	66.88	JWST
14	CEERS2-588	11.04	410	66.92	JWST
15	GN-z11	10.60	430	66.97	JWST (February 2023)
16	JADES-GS-z10-0	10.38	450	67.01	NIRSpec
17	JD1	9.793	480	67.07	NIRSpec
18	Gz9p3	9.313	510	67.12	JWST, merger
19	CAPERS-LRD-z9	9.288	500	67.10	JWST, little red dot
20	MACS1149-JD1	9.110	500	67.10	hydrogen line (VLT), oxygen line (ALMA)
21	EGSY8p7	8.683	570	67.22	Keck Lyman-α
22	SMACS-4590	8.496	—	—	NIRSpec
23	A2744 YD4	8.38	600	67.27	ALMA
24	MACS0416 Y1	8.312	600	67.27	ALMA
25	GRB 090423	8.23	630	67.31	gamma-ray burst Lyman-α break

The list is drawn from the record table of spectroscopic redshifts [715]. The most distant single star seen is Earendel, at z = 6.2 ± 0.1, reported in March 2022 [715].

Read in the net’s terms, the galaxies have the form of a depth opened once and then filled many times. The first galaxies appear within 20 million years of one another near 66.6 on the ladder. From there the list fills densely toward 67.3, and the observable universe today holds up to 2 trillion galaxies [677].

The first black holes

Black holes grew in the first galaxies within a few hundred million years.

GN-z11, at z = 10.6 and about 430 million years, at 66.97, holds a black hole of log(M/M☉) = 6.2 ± 0.3, about 1.6 million solar masses [723][715]. It accretes at about five times the Eddington rate [723]. It is the most distant black hole in the record list, at z = 10.6034 [715].

UHZ1, behind the cluster Abell 2744, was found by JWST at z ≈ 10.3 and detected in X-rays by Chandra [724]. Its luminosity is about 5×10^{45} erg s^{-1}, or 5×10^{38} W [724]. Assuming the Eddington limit, its black hole holds 10^7 to 10^8 solar masses, about 500 million years after the beginning, at 67.10 [724].

In UHZ1 the black hole weighs about as much as all the stars of its host. In nearby galaxies the black hole holds about 0.1 % of the stellar mass [724]. The record list gives UHZ1 at z ≅ 10.0 [715].

The quasar J0313−1806 lies at z = 7.642, about 670 million years after the beginning, at 67.37 [719]. Its black hole holds $(1.6 \pm 0.4) \times 10^9$ solar masses, $1.6 \times 10^9 \times 1.98841 \times 10^{30}$ kg = 3.2×10^{39} kg [719][25]. Its luminosity is 3.6×10^{13} solar luminosities, its host forms about 200 solar masses of stars per year, and its outflow reaches about 0.2 times the speed of light [719].

The Eddington luminosity is $1.2570651798 \times 10^{31}$ W per solar mass [25]. For J0313−1806 that is $1.257 \times 10^{31} \times 1.6 \times 10^9 = 2.0 \times 10^{40}$ W. Its luminosity, $3.6 \times 10^{13} \times 3.828 \times 10^{26}$ W = 1.38×10^{40} W, is 0.69 of that limit.

ULAS J1342+0928, at z = 7.54, holds a black hole of 8×10^8 solar masses, 1.6×10^{39} kg, when the universe was only 690 million years old, at 67.40 [714]. The gas around it is still at least one-third neutral [714]. ULAS J1120+0641 lies at z = 7.085, about 770 million years, at 67.50 [715].

CAPERS-LRD-z9, a little red dot at z = 9.288 and about 500 million years, was confirmed by JWST [715].

The black holes rose in step with time. A million solar masses stood at 430 million years, 10^7 to 10^8 at about 500 million years, and 10^9 at 670 million years. On the ladder these are 66.97, 67.10 and 67.37, within half a step.

The net’s texts set black holes and neutron stars at the two limits of the medium: its two limiting states of tension [694]. They read the early universe, with its vacuum state far from today’s, as able to form such saturated regions directly, fully grown a few hundred million years after the beginning [725]. This is a reading of context: the same rule with other values in other surroundings.

Object	z	Million years	Position	Black hole (solar masses)	Method	Source
GN-z11	10.6	~430	66.97	10^(6.2 ± 0.3), ~1.6×10^6	JWST, local virial relations; 5 × Eddington	[723]
UHZ1	≈ 10.3	~500	67.10	~10^7 to 10^8	Chandra X-ray with JWST, Eddington assumed	[724]
CAPERS-LRD-z9	9.288	~500	67.10	—	JWST, little red dot	[715]
J0313−1806	7.642	~670	67.37	$(1.6 \pm 0.4) \times 10^9$	deep spectroscopy; 0.69 of Eddington	[719]
ULAS J1342+0928	7.54	690	67.40	8×10^8	spectroscopy	[714]
ULAS J1120+0641	7.085	~770	67.50	—	—	[715]

The first stars of the Milky Way

The Milky Way keeps stars from this early time. The thick disk of the Galaxy began to form stars 13 billion years ago, at 70.07, only 0.8 billion years after the beginning, at 67.53 [726]. Most of its stars formed 11 billion years ago, at 69.92 [726].

The oldest globular clusters have ages as old as 12.7 billion years, at 70.05 [727]. Their later history belongs to Chapter 34.

The expansion turns

For its first 7.7 billion years the expansion slowed. In 1998 the High-z Supernova Search Team measured type Ia supernovae out to z = 0.62 [728]. It used 10 supernovae at 0.16 < z < 0.62, 16 at high redshift and 34 nearby in the combined set [728].

The team found a positive cosmological constant at 3.0σ and 4.0σ, and a negative deceleration parameter, $q_0 < 0$, at 2.8σ and 3.9σ [728]. A universe of matter alone, $\Omega_M = 1$, was excluded at 7 to 8σ [728].

The Supernova Cosmology Project published 42 supernovae at 0.18 < z < 0.83 in 1999. It found $0.8\,\Omega_M - 0.6\,\Omega_\Lambda \approx -0.2 \pm 0.1$, and for a flat universe $\Omega_M = 0.28$ (+0.09, −0.08) [678]. The probability of a positive Λ was 99 %, including the identified systematic errors [678].

In 2004 HST supernovae reached beyond z = 1. Sixteen new type Ia supernovae included 6 of the 7 most distant known, all at z > 1.25 [729]. They showed past deceleration at more than 99 % confidence and placed the turn at $z_t = 0.46 \pm 0.13$ [729].

The Planck fit puts the turn at $z_q = 0.656 \pm 0.018$ [25]. The universe was then $t_q = 7.70 \pm 0.10$ billion years old, 2.43×10^{17} s, at 69.59 [25]. That was 13.797 − 7.70 = 6.10 billion years before now, at 69.38.

Another account gives about 5 billion years ago, at 69.20 [690]. The supernova turn, 0.46 ± 0.13, lies (0.656 − 0.46) / 0.13 = 1.5 of its errors below the fitted 0.656.

Dark energy took over the density later than it took over the acceleration. It has dominated since the universe was about 9.8 billion years old, at 69.81, below z = 0.4 and a background temperature of 4 K [693]. Today its density is 0.685 / 0.315 = 2.17 times that of matter.

In a flat universe of matter and dark energy the deceleration parameter today is $q_0 = \Omega_m / 2 - \Omega_\Lambda = 0.1575 - 0.685 = -0.53$. The negative sign means acceleration.

The net’s texts read the expansion as the remainder paid out: the Hubble flow is the comma, paid out [682]. They label this spiral reading a hypothesis [682].

Case	Value	Method	Position	Source
Deceleration parameter $q_0 < 0$	2.8σ and 3.9σ	type Ia supernovae, 1998	—	[728]
$\Omega_\Lambda > 0$	3.0σ and 4.0σ	type Ia supernovae, 1998	—	[728]
$\Omega_M = 1$ excluded	7 to 8σ	type Ia supernovae, 1998	—	[728]
$P(\Lambda > 0)$	99 %	42 supernovae, 1999	—	[678]
Flat Ω_M	0.28 (+0.09, −0.08)	42 supernovae, 1999	—	[678]
Turn, supernovae	$z_t = 0.46 \pm 0.13$	16 HST supernovae to z > 1.25	—	[729]
Turn, Planck fit	$z_q = 0.656 \pm 0.018$; 7.70 ± 0.10 billion years	background fit	69.59	[25]
Turn, years before now	6.10 billion years (computed)	—	69.38	[25]
Turn, other account	about 5 billion years ago	—	69.20	[690]

Dark energy dominates the density	after 9.8 billion years; z < 0.4; < 4 K	model	69.81	[693]
q_0 today	−0.53 (computed)	flat ΛCDM	—	[25]

What speeds the expansion

If dark energy is a constant, its equation of state is w = −1. Fits that hold w fixed in time give w = −1.028 ± 0.031 [25]. The 2004 supernovae gave w = −1.02 (+0.13, −0.19) [729], and an encyclopaedia summary gives w ≈ −1 ± 0.1 (stat) ± 0.1 (sys) [690].

DESI let w change with the scale factor, as w_0 today and a slope w_a. Its first release preferred $w_0 > -1$ and w_a < 0 at 2.6σ with the background light [124]. With supernova samples added, the preference was 2.5σ, 3.5σ and 3.9σ [124].

DESI DR1 combination	w_0	w_a	Significance against Λ	Source
DESI + background	−0.45 (+0.34, −0.21)	−1.79 (+0.48, −1.0)	2.6σ	[124]
+ Pantheon+	−0.827 ± 0.063	−0.75 (+0.29, −0.25)	2.5σ	[124]
+ Union3	−0.65 ± 0.10	−1.27 (+0.40, −0.34)	3.5σ	[124]
+ DES-SN5YR	−0.727 ± 0.067	−1.05 (+0.31, −0.27)	3.9σ	[124]

The second release, of March 2025, again favoured the quadrant $w_0 > -1$, w_a < 0. The preference is 3.1σ for DESI with the background light, and 2.8 to 4.2σ depending on the supernova sample [125]. The trend comes particularly from low redshift, $z \lesssim 0.3$, and is stable under different modelling choices [730].

DESI DR2 combination	w_0	w_a	Significance against Λ	Source
DESI + background	−0.42 ± 0.21	−1.75 ± 0.58	3.1σ	[731]
+ Pantheon+	−0.838 ± 0.055	−0.62 (+0.22, −0.19)	2.8σ	[731]
+ Union3	−0.667 ± 0.088	−1.09 (+0.31, −0.27)	3.8σ	[731]
+ DES-SN5YR	−0.752 ± 0.057	−0.86 (+0.23, −0.20)	4.2σ	[731]

From the first to the second release the error on w_0 with supernovae shrank by 12 to 15 %, from 0.067 to 0.057 with DES-SN5YR. At the redshift where it is best fixed, w = −0.954 ± 0.024 from DESI, supernovae and the background together [732]. An encyclopaedia summary of the result gives 3.2 to 3.4σ [711].

Held constant, w is −1 within 3 %. Allowed to change, it lies at $w_0 \approx -0.42$ to −0.84 and w_a ≈ −0.6 to −1.8 in every combination of both releases.

Read in the net's terms, this is context. The same quantity reads −1 in one frame and departs from it at low redshift in another, the same rule with other values in other surroundings.

The sequence from the first second to now

The first three chapters follow one sequence. On the ladder it runs from the first measured second at 33.15 to the present at 70.12.

#	Event	Age	Position	Redshift	Temperature or energy	Source
1	Inflation (model)	10^{-36} or 10^{-33} to 10^{-32} s	−42.30 to −33.92	—	—	[693]
2	Electroweak crossover	~10^{-11} s	10.10	—	159.5 ± 1.5 GeV	[696][693]
3	Quark–	~10^{-5} s	22.67	—	156.5 ± 1.5	[70][693]

	hadron crossover				MeV	
4	Neutrino decoupling; n/p ≈ 1/6	~1 s	33.15	—	~1 MeV	[202]
5	Electron–positron annihilation	6 to 10 s	34.78 to 35.25	—	1 MeV to 100 keV	[693]
6	Deuterium bottleneck breaks; n/p ≈ 1/7	minutes	—	—	≈ 0.1 MeV	[202]
7	Light elements fixed	~180 s	37.88	—	—	[202]
8	Matter–radiation equality	51.0 ± 0.8 thousand years	58.74	3,402 ± 26	9,275 K	[25]
9	Last scattering	371.8 ± 1.0 thousand years	60.55	1,089.92 ± 0.25	2,973 K (computed)	[25]
10	Dark ages	0.37 to ~150 million years	60.54 to 66.01	1,100 to 20	4,000 to 60 K	[693]
11	First starlight (EDGES)	~180 million years	66.17	—	0.5 K absorption	[712]
12	MoM-z14	280 million years	66.57	14.44	—	[717]
13	JADES-GS-z14-0	~290 to 300 million years	66.61	14.1793	—	[721]
14	GN-z11, 10^6.2 solar-mass black hole	~430 million years	66.97	10.6	—	[723]
15	UHZ1 X-ray quasar	~500 million years	67.10	≈ 10.3	—	[724]
16	10^9 solar-mass quasar J0313−1806	~670 million years	67.37	7.642	—	[719]
17	Half reionization	690 ± 90 million years	67.40	7.7 ± 0.7	—	[25]
18	Thick disk of the Milky Way begins	0.8 billion years	67.53	—	—	[726]
19	Reionization ends	≥ 1.1 billion years	67.82	≤ 5.3	—	[716]
20	Deceleration turns to acceleration	7.70 ± 0.10 billion years	69.59	0.656 ± 0.018 (fit); 0.46 ± 0.13 (supernovae)	—	[25][729]
21	Dark energy dominates the density	> 9.8 billion years	69.81	< 0.4	< 4 K	[693]
22	Today	13.787 ± 0.020 billion years	70.12	0	2.7255 K	[238][25]

The measured sequence before one billion years has two dense clusters. The nuclear epoch fills 33.15 to 37.88, and the release of the light 58.74 to 60.55. From 66.57 to 67.82 galaxies, black holes and reionization are all seen together.

What this part of the history shows

Read in the net’s terms, the first stars have the form of loading and discharge at its shortest. Models give them 2 to 5 million years, at 62.08 to 62.91 on the ladder. One

supernova of about 60 solar masses left its metals in SMSS J0313−6708, and by 290 million years the first galaxies held oxygen at 5 to 20 % of solar.

Read in the same terms, the residue of the first stars became the alphabet of the next. SMSS J0313−6708 carries iron below 7.9×10^{-8} of the solar fraction, all from one explosion. MoM-z14, at 280 million years, already shows nitrogen above carbon, [N/C] > 1.

Read in the same terms, the galaxies have the form of a depth opened once and filled many times. The three oldest appear within 20 million years of each other, from 280 to 300 million years, near 66.6 on the ladder. The record list then holds 16 galaxies at $z \geq 10.38$, bright galaxies are 182 times more common than the older models, and the universe today holds up to 2 trillion.

The black holes rose by three orders of magnitude within half a step of the ladder. About 1.6 million solar masses stood at 430 million years, 10^{7} to 10^{8} at 500 million and 1.6×10^{9} at 670 million, at 66.97, 67.10 and 67.37. The net’s texts place black holes at one of the two limiting states of tension of the medium.

The early universe reads as context. In UHZ1 the black hole weighs about as much as its host’s stars, against about 0.1 % in nearby galaxies. The same kind of object takes another proportion in other surroundings.

The expansion turned at 7.70 billion years, at 69.59, 6.10 billion years before now. Dark energy now holds 2.17 times the density of matter, and $q_0 = -0.53$. The net’s texts read this growth, as a hypothesis, as the comma paid out.

The measure of dark energy reads as context as well. Held constant, $w = -1.028 \pm 0.031$; allowed to change, it reads $w_0 \approx -0.42$ to -0.84 with $w_a < 0$, at 2.8 to 4.2σ, with the change at $z \lesssim 0.3$.

27. The Life of Stars

The first stars lit the young universe within a few hundred million years (chapter 26). Stars have formed ever since, and they still form now.

In the Milky Way every stage of a star's life can be seen at the same time. There are cold clouds, newborn stars, stars burning hydrogen, giants, white dwarfs, explosions, neutron stars and black holes.

This chapter tells that life in its order. It begins in the cold clouds and ends at the black holes in the centres of galaxies.

The masses are given in solar masses. One solar mass, M☉, is 1.9884 × 10^{30} kg; the Sun's radius, R☉, is 695,700 km; its luminosity, L☉, is 3.828 × 10^{26} W [733].

Every size and every time carries its position on the ladder of chapter 24. The position is the base-3 logarithm of the size over 4.558816 × 10^{-8} m, or of the time over 1.520655 × 10^{-16} s. One parsec (pc) is 3.0857 × 10^{16} m, one light-year (ly) 9.4607 × 10^{15} m, one astronomical unit (AU) 1.495978707 × 10^{11} m, and one year 3.15576 × 10^{7} s.

The cold clouds

Stars are born in molecular clouds, the coldest and densest part of the gas between the stars. A catalogue of the whole Milky Way disk counts 8,107 of them [734]. Together they hold 1.2 × 10^{9} M☉ of molecular hydrogen, or 2.4 × 10^{39} kg (computed) [734].

The most common cloud radius is about 30 pc (position 53.04) [734]. Mass grows with size as M ∝ R^2.2±0.2, and the surface density runs from 2 to 300 M☉ per square parsec [734]. The catalogue holds 98% of the carbon-monoxide emission within 5° of the Galactic plane [734].

The giant clouds weigh 10^{4} to 10^{7} M☉ [735]. Their diameters run from 5 pc (51.41) to 200 pc (54.77) [735]. Inside them lie clumps of about 1 pc (49.95) and cores a factor of ten smaller, about 0.1 pc (47.85) [735].

The molecular disk of the Galaxy is thin. Its scale height is 50 to 75 pc (53.51 to 53.88) [735]. Along the dense filaments, cores sit 0.15 pc apart (48.22) [735].

The clouds fill less than 1% of the volume of the interstellar medium but hold about half of its gas [735]. Only about 2% of a cloud's mass ends up in stars [735]. A cloud is dispersed after about 10 million years (position 63.54) [735].

Most molecular gas lies in a ring between 3.5 kpc (57.37) and 7.5 kpc (58.07) from the Galactic centre [735]. A typical giant cloud has 100 particles per cubic centimetre, a diameter of 100 ly (53.06), and a temperature of 10 K inside [736].

The largest reach 6 × 10^{6} M☉ [736]. The Galaxy holds an estimated 6,000 clouds of more than 10^{5} M☉ each [736].

The smallest dark clouds are the Bok globules. They are up to about 1 ly across (48.87) and hold a few solar masses [736]. Most prestellar cores lie within 0.1 pc (47.85) of dense, supercritical filaments [736].

Read in the net's terms, the cloud is a carrier of a lasting form. Each cloud lives about ten million years and gives only 2% of its gas to stars, yet the Galaxy keeps forming stars without pause. The form lasts while its carriers are replaced.

Collapse

A cloud core collapses when its mass exceeds the Jeans mass, the mass at which gravity overcomes the gas pressure. For a typical molecular cloud the Jeans mass is thousands to tens of thousands of solar masses [736]. The calculation uses a mean particle mass of

3.9×10^{-24} g, fitting molecular hydrogen with 20% helium by number [737].

The collapse runs through fixed stages [736]. First the dust warms to 60–100 K. A first hydrostatic core forms when the density reaches about 10^{-13} g cm^{-3}.

When the core reaches about 2,000 K, the hydrogen molecules begin to break apart. After the infalling gas reaches about 10^{-8} g cm^{-3}, a second core forms: the star itself.

The youngest stars seen are very young. MWC 349 is estimated at only 1,000 years old (55.16) [736]. VLA 1623 may be younger than 10,000 years (57.25) [736].

Stars form in clusters of dozens to tens of thousands, almost at once [736].

The lightest stars take longest to settle. A star below 0.13 M☉ needs 5×10^8 years (67.10) to reach the main sequence, the long stable phase of hydrogen burning [738].

How many stars, and of what mass

The Milky Way turns 1.65 ± 0.19 M☉ of gas into stars each year [739]. That is 3.28×10^{30} kg per year, or 1.04×10^{23} kg per second (computed). The same study puts the Galaxy's total stellar mass at $(6.08 \pm 1.14) \times 10^{10}$ M☉ [739].

Earlier estimates ranged from 1 to 10 M☉ per year [740]. Brought onto one scale, they converge to 1.9 ± 0.4 M☉ per year [740].

Rates from counts of single young stars exceed those from mid-infrared and radio calibrations by factors of about 2 to 3 [740]. A secondary source gives about 3 M☉ per year, with about 150 M☉ per year of gas gathered into clouds [735].

Newborn stars come in a fixed spread of masses, the initial mass function. Above a few solar masses their number falls with the Salpeter slope: the number per unit mass goes as m^−2.35 [741]. A critical review of the variations finds no clear evidence that this spread changes strongly and systematically with the conditions of birth [741].

The spread is a broken power law. In the Galactic field the slope α (number per unit mass ∝ m^−α) takes four values [742]:

Mass range (M☉)	Slope α	Source
0.01–0.08	+0.3 ± 0.7	[742]
0.08–0.50	+1.3 ± 0.5	[742]
0.50–1.00	+2.3 ± 0.3	[742]
above 1.00	+2.3 ± 0.7	[742]

The mean stellar mass between 0.01 and 50 M☉ is 0.36 M☉ [742]. Brown dwarfs, from 0.01 to 0.08 M☉, are 37% of all objects but only 4.3% of the mass [742]. In young clusters the slope between 0.1 and 1 M☉ is steeper than in the field by 0.5 [742].

Another form is log-normal in mass up to 1 M☉: the logarithm of the mass follows a bell curve [738]. The broken form places its breaks at 0.08 and 0.5 M☉, and an upper limit of 150 M☉ is used [738].

A full-sky census of about 3,600 stars and brown dwarfs within 20 pc (52.67) gives the same picture [743]. Its slopes are α = 2.3 from 0.55 to 8.00 M☉, 1.3 from 0.22 to 0.55 M☉, 0.25 from 0.05 to 0.22 M☉ and 0.6 from 0.01 to 0.05 M☉ [743]. Stars outnumber brown dwarfs four to one, and the mean mass per object is 0.41 M☉ [743].

Above half a solar mass the slope is 2.3 to 2.35 in three independent measurements, made in 1955, 2001 and 2024 [738][742][743]. The same form of the mass spread holds in the field, in the 20-pc census and in most populations studied [741]. Read in the net's terms, it is the same winding at another place.

The lightest and the heaviest stars

The lightest star with a directly measured mass and radius is EBLM J0555-57Ab. It weighs 85 ± 4 Jupiter masses, or 0.081 M☉ [744].

Its radius is 0.84 Jupiter radii, 0.084 R☉ or 58,400 km (computed; position 31.66) [744]. It is the size of Saturn, and its surface gravity is log g = 5.50 [744].

This star sits at the floor of the stars. Sustained hydrogen fusion needs about 0.08 M☉, or 80 Jupiter masses [745]. A secondary source gives the minimum as 0.080 ± 0.008 M☉ [746].

Below the floor lie the brown dwarfs, from about 13 to 80 Jupiter masses [746]. Objects below 65 Jupiter masses never burn lithium [746].

The lower edge of the brown dwarfs is the deuterium-burning limit: half of the initial deuterium burns at (13.0 ± 0.8) Jupiter masses under most conditions [747]. The limit runs from about 11.0 Jupiter masses at three times solar metallicity to about 16.3 at zero metallicity [747].

Teide 1 was found in 1994 and confirmed in 1995 by its lithium [746]. Gliese 229B, confirmed in 1995, was the first T dwarf and showed methane [746]. The spectral types run M (2,100–3,500 K), L (1,300–2,100 K), T (600–1,300 K) and Y (below 600 K) [746].

Over 1,800 brown dwarfs have been identified, and 25 to 100 billion are estimated in the Milky Way [746]. The nearest, Luhman 16 AB, lies about 6.5 ly away (50.57) [746].

The net’s texts draw a line between a body that reads and a body that opens: “Planets read; stars open.” [26] In a star the central stretch reaches closure for the heaviest knots present [26]. Read in those terms, the hydrogen-burning limit at 0.08 M☉ is where that line falls.

At the top, the heaviest stars stand in the young cluster R136 in the Large Magellanic Cloud and in NGC 3603. Three systems in NGC 3603 have initial masses of 105–170 M☉, and four stars in R136 have 165–320 M☉ [748]. They are about 1.5 million years old (61.81) [748].

The R136 stars have surface temperatures of about 53,000 ± 3,000 K [748]. They lose 2–5 × 10^{-5} M☉ per year [748]. One star, R136a1, supplies about 7% of the ionising photons of the whole 30 Doradus region [748].

The study sets a tentative upper mass limit near 300 M☉ [748]. Stars in the Arches cluster approach 200 M☉ at birth [748].

The mass of R136a1 differs between models [749]. One UV study gives a current mass of 315 M☉ and an initial mass of 325 M☉ (2016). Others give 256 M☉ (2014), 251 M☉ initial with rapid rotation (2020), about 291 M☉ (2025) and 215 M☉ from visual spectra [749].

R136a1 shines with 7,244,000 L☉ [749]. Its temperature is 46,000 K in one model and 53,000–56,000 K in others [749]. Its radius is 42.7 R☉, 2.97 × 10^{7} km or 0.20 AU (computed; position 37.34) [749].

R136a1 is 1.02 ± 0.16 million years old (61.46) [749]. It loses 1.6 × 10^{-4} M☉ per year, which is 1.0 × 10^{19} kg per second (computed) [749]. It lies about 49,970 pc away (59.79), or 163,000 ly (computed) [749].

From 0.081 M☉ to about 300 M☉, the masses of stars span a factor of 3,700 (computed). The floor is sharp; the ceiling spreads over a range of models. The heaviest stars are all about a million years old.

The main sequence

A star spends most of its life fusing hydrogen into helium in its core. In that phase it sits on the main sequence of the diagram of colour against brightness. About 90% of observed stars above 0.5 M☉ are on the main sequence [745].

Brightness rises steeply with mass [745]. Luminosity goes as M^2.3 below 0.5 M☉, as about M^4 below 10 M☉, and as M^3 for high masses [745]. Lifetime is the energy store divided by the luminosity, so the heavy stars burn out fast [745].

The most massive stars last a few million years: 3 million years sits at position 62.45

[745]. Stars of less than a tenth of a solar mass may last more than 10^{12} years (74.02) [745]. That is longer than the present age of the universe, 13.8 billion years (70.12; chapter 24).

The Sun's main-sequence life is about 10^{10} years (69.83), with about 12 billion years (70.00) of hydrogen burning [745]. About 4.5 billion years of it (69.10) have passed [745]. Its centre is at 1.571×10^{7} K, its central density 1.622×10^{5} kg m^{-3}, its surface 5,772 K [733].

Hydrogen burns in two ways. In the proton–proton chain, protons fuse directly. In the CNO cycle, carbon, nitrogen and oxygen act as catalysts.

The two are equally efficient at a core temperature of 18 million K, found in a star of about 1.5 M☉ [745]. Stars of 1.8 M☉ and more draw almost all their energy from the CNO cycle [745].

The Gaia satellite drew the diagram of colour against brightness from its own parallaxes in 2018 [750]. It was the first such diagram to show the white-dwarf sequence split cleanly into hydrogen and helium white dwarfs [750]. It also separates two populations in the kinematic halo [750].

Read in the net's terms, the main-sequence star has the form of metabolism: what fits, stays. Hydrogen flows into the core and leaves it as helium, while the star keeps its size and brightness for billions of years. Nine in ten stars above half a solar mass are seen in this phase.

The giants

When the core hydrogen is used up, the star swells into a red giant. Stars of about 0.3 to 8 M☉ pass through this phase [751]. On the red-giant branch they reach radii of about 200 R☉ (1.39×10^{11} m; 38.74) and luminosities of about 3,000 L☉ [751].

Giants of types K and M have surfaces of 3,000–4,000 K [751]. Helium ignites in the core at about 10^{8} K; in light stars it starts as a flash [751].

Stars then burning helium on the horizontal branch shine with about 75 L☉ [751]. For a star of one solar mass the red-giant phase lasts about 1 billion years (67.73) [751].

The Sun will leave the main sequence in about 5 billion years (69.20) [751]. It will grow to about 256 R☉, about 1.2 AU (computed 1.19 AU; position 38.97), and lose 38% of its mass [751]. The Earth's orbit, 1 AU, sits at 38.81.

White dwarfs

Most stars end as white dwarfs: the bare, hot cores left after the giant sheds its outer gas. White dwarfs are the endpoint of over 97% of the stars in the Milky Way [753]. Eight white dwarfs lie among the hundred star systems nearest the Sun [753].

A white dwarf holds itself up by the pressure of its electrons, and that pressure has a ceiling. The Chandrasekhar limit is about 1.44 M☉ [752].

Edmund Stoner derived about 2.19×10^{30} kg (1.10 M☉, computed) in 1930, and an earlier model by Anderson gave about 1.37×10^{30} kg (0.69 M☉, computed) [752]. Chandrasekhar's papers appeared from 1931 to 1935, begun on a voyage in 1930; he shared the Nobel Prize of 1983 with Fowler [752].

Some exploding white dwarfs appear to exceed the limit. Their progenitors are inferred at 2.4–2.8 M☉, and that of SN 2003fg at about 2 M☉ [752].

Observed white-dwarf masses lie mostly between 0.5 and 0.7 M☉, strongly peaked at 0.6 M☉ [753]. The known range runs from 0.17 to 1.33 M☉ [753]. Their density is 10^{4} to 10^{7} g cm^{-3}, and their radii are 0.8 to 2% of the Sun's (5,600 to 13,900 km; positions 29.52 to 30.36, computed) [753].

White dwarfs make no new energy; they cool. Cooling to 7,140 K takes about 1.5 billion years (68.10) [753].

The coolest known are near 3,050 K [753]. The cooling clock of the white dwarfs dates the Galactic disk at about 8 billion years (69.63) [753].

In old white dwarfs the core freezes. Gaia shows this crystallisation in the white dwarfs within 100 pc (54.14) [754]. Their cores reach 10^{7} g cm^{-3}, and the freezing delays the cooling by about one billion years (67.73) [754].

Gaia’s third data release evaluated about 1.3 million sources [755]. It lists about 359,000 high-confidence white-dwarf candidates between magnitudes 8 and 21 [755]. More than 30,000 white dwarfs and look-alikes are confirmed by spectra, and the catalogue is at most 93% complete within its limits [755].

Sirius B is a white dwarf in a nearby binary. Its mass is 1.018 ± 0.011 M☉, and that of its companion Sirius A 2.063 ± 0.023 M☉ [756].

The pair orbit each other every 50.13 years (52.43) [756]. Sirius B has been cooling for about 126 million years (65.85) [756].

The radius of Sirius B is 5,634 ± 34 km, or 0.008098 R☉ (29.54) [757]. That is 0.88 of the Earth’s radius (computed), with a solar mass inside.

Its mean density is 2.7 × 10^{9} kg m^{-3} (computed). Its surface is at about 25,000 K [757].

Alvan Graham Clark first saw Sirius B on 31 January 1862 [757]. The system lies 2.639 ± 0.010 pc away, 8.61 ly (50.83) [757]. It is about 228–230 million years old (66.39), and Sirius B began as a star of about 5 M☉ [757].

Supernovae

Stars heavier than about eight solar masses end in a core collapse: the core falls in, and the star explodes as a supernova. The Milky Way has 1.63 ± 0.46 core-collapse supernovae per century [758].

The mean interval is 61 years (52.61), with a range of 47 to 85 years (52.37 to 52.91) [758]. A secondary source gives 1.6 to 4.6 per century [760].

The closure depth 53 of the ladder, 93.4 years, lies just above that range. In 93.4 years the Galaxy has on average 1.5 core-collapse supernovae (computed).

The last supernova seen in the Milky Way was Kepler’s, in 1604 [760]. That is 422 years ago (54.37, computed).

The youngest known remnant, G1.9+0.3, dates from the late nineteenth century; Cassiopeia A from about 1680 [760]. SN 1006 reached magnitude −7.5 ± 0.4, and Chinese astronomers recorded SN 1054, whose remnant is the Crab [760].

About 2,000 supernovae are now found each year in other galaxies [760]. The Lick Observatory Supernova Search considered about 1,000 nearby ones [759]. Its optimal sample of 726 holds 274 of type Ia, 116 of type Ibc and 324 of type II; the three classes named add up to 714 [759].

Types II and Ibc are core collapses of massive stars. Type Ia is the thermonuclear explosion of a white dwarf, with a peak absolute magnitude of −19.3, or 5 × 10^{9} L☉ [760].

A core collapse releases 1–2 × 10^{44} J, enough to unbind the star [760]. The ejecta fly at 5,000 to 20,000 km s^{-1}, 1.7% to 6.7% of the speed of light (computed) [760].

Most of the energy leaves as neutrinos. They carry about 99% of the gravitational energy of the collapsing star, in a burst lasting tens of seconds [761]. The typical energies are 10 to 20 MeV, and about 10^{58} neutrinos and antineutrinos leave [761].

One supernova has been seen in neutrinos. SN 1987A exploded in the Large Magellanic Cloud, about 51.4 kpc away, 168,000 ly (59.82) [762].

On 23 February 1987 at 07:35 UT, Kamiokande II detected 12 antineutrinos [762].

IMB detected 8 events and Baksan 5 [762]. The 25 events arrived within about 13

seconds (35.49) [761]. The light was found the next day, 24 February 1987, by Shelton and Duhalde [762].

The star that exploded was Sanduleak −69 202, a blue supergiant of type B3 [762]. The supernova peaked in May 1987 at magnitude about 3 [762].

Models give a total neutrino energy of about 10^{46} J [762]. In 2024 the James Webb Space Telescope found argon lines that point to radiation from a neutron star inside [762].

The supernova has the form of rest and discharge. In the net's reading, stars load for millions of years and discharge as supernovae [694]. The loading of a massive star lasts a few million years; the discharge of the neutrinos takes about 13 seconds.

Neutron stars

The collapsed core of a massive star becomes a neutron star. Walter Baade and Fritz Zwicky proposed such stars at the December 1933 meeting of the American Physical Society, published in January 1934 [767]. The first pulsar, PSR B1919+21, was found in 1967 by Jocelyn Bell Burnell and Antony Hewish [767].

A neutron star packs more than a solar mass into a ball of order 10 km in radius (23.77) [767]. Its mean density is 3.7 to 5.9 × 10^{17} kg m^{-3}, its surface gravity 10^{12} to 10^{13} m s^{-2}, and its escape velocity more than half the speed of light [767]. Its surface magnetic field runs from 10^{4} to 10^{11} T [767].

The masses have a ceiling, and the heaviest stars measured press against it. PSR J0952−0607 weighs 2.35 ± 0.17 M☉ [763].

It is also the fastest-spinning known neutron star in the Galaxy [763]. Its mass sets the maximum neutron-star mass above 2.19 M☉ at 1σ and above 2.09 M☉ at 3σ [763].

PSR J0740+6620 weighs 2.08 ± 0.07 M☉, measured by the delay of its radio pulses as they pass its companion [764]. The maximum mass of a non-rotating neutron star appears on one secondary page as about 2.2 to 2.9 M☉ and as about 2.17 M☉ [767].

The NICER X-ray telescope measured radii by modelling the hot spots on spinning stars. PSR J0030+0451 has a mass of 1.34 M☉ and an equatorial radius of 12.71 km (+1.14/−1.19; position 23.99) [765]. Its compactness, $GM/(Rc^2)$, is 0.156 [765].

PSR J0740+6620 has an equatorial radius of 13.7 km (+2.6/−1.5; 24.06) [766]. A neutron star of 1.4 M☉ has a radius of 12.45 ± 0.65 km (23.97), known to ± 4% [766]. Its mean density is 3.4 × 10^{17} kg m^{-3} (computed).

The Milky Way is thought to hold about a billion neutron stars [767]. About 3,200 are known in the Milky Way and the Magellanic Clouds, most of them as pulsars [767].

Pulsars and magnetars

A pulsar is a spinning neutron star whose beam sweeps past the Earth. The first pulses were resolved on 28 November 1967, evenly spaced every 1.337 seconds (33.42) [771]. The ATNF Pulsar Catalogue, version 2.9.0 of 6 October 2026, lists 4,503 pulsars, 110 of them new in that version [768].

The first binary pulsar was found in 1974 by Hulse and Taylor, who received the Nobel Prize in 1993 [771]. The first millisecond pulsar followed in 1982, with a period of about 1.6 ms (27.29) [771]. In 1992 the first planets beyond the Solar System were found around the pulsar PSR B1257+12 [771].

The fastest pulsar spins 716 times per second, a period of 1.397 ms (27.17, computed) [769]. It is PSR J1748−2446ad in the globular cluster Terzan 5, eclipsed for about 40% of its orbit [769].

If its mass is below 2 M☉, its spin limits its radius to less than 16 km (24.20) [769]. It took the record from B1937+21, at 642 Hz (27.27), which had held it for 23 years [769].

The slowest radio-emitting neutron star is PSR J0901−4046 [770]. It turns once every 75.88554711 seconds (37.09) [770]. It was found on 27 September 2020 in MeerKAT data, lies 400 ± 100 pc away (55.40), and has a characteristic age of 5.3 million years (62.96) [770].

Spin periods thus span from 1.397 ms to 75.9 s, a factor of 54,000 (computed). The positions run from 27.17 to 37.09.

Pulsars age along two roads [771]. Ordinary radio pulsars fall silent after 10 to 100 million years (63.54 to 65.64).

Millisecond pulsars, spun up by a companion, live for billions of years and are the oldest pulsars known [771]. Their magnetic fields are weaker by a factor of 10^3 to 10^4 [771].

The ages in the pulsar list run from 11,300 years for the Vela pulsar, PSR J0835−4510 (57.37), to 7,580 million years for PSR J0030+0451 (69.58) [771].

Magnetars are neutron stars with the strongest fields: about 10^9 to 10^{11} T [772]. Their fields decay after about 10,000 years (57.25) [772]. Most turn once every 2 to 10 seconds (33.78 to 35.25), and they are about 20 km across (24.40) [772].

The first giant flare of a soft gamma repeater was seen on 5 March 1979, from SGR 0525−66 [772]. The count of magnetars differs on one page: 24 known with six candidates (July 2021), and 31 confirmed (January 2021) [772].

On 27 December 2004 the magnetar SGR 1806−20 released 1.0×10^{40} J in about a tenth of a second (31.06) [773]. That is more than the Sun releases in 150,000 years [773].

At the Sun’s 3.828×10^{26} W it equals 8.3×10^5 years of sunlight (computed). The magnetar lies about 13 kpc away (58.57), turns every 7.5 seconds (34.99) and has a field of more than 10^{15} G [773].

Read in the net’s terms, the magnetar shows the form of rest and discharge at its sharpest. Field energy is held for thousands of years and leaves in a tenth of a second.

The net reads the neutron star as the network of knots pressed to its packing limit [725]. Read in those terms, the measured stars show how narrow that limit is. Their masses run from 1.34 to 2.35 M☉, yet their radii stay between 12 and 14 km.

Black holes of stellar mass

The heaviest stars leave black holes. Cygnus X-1 holds a black hole of 21.2 ± 2.2 M☉ at a distance of 2.22 kpc (56.96) [774]. The mass was found from the radio parallax and the orbit of the companion star [774].

Gaia BH3 is a dormant black hole of 32.70 ± 0.82 M☉, found from the wobble of its companion in Gaia astrometry [775]. The orbit takes 11.6 years (51.10), and the system lies 590 pc away (55.75) [775]. The companion is an old, very metal-poor giant of the Galactic halo [775].

Black holes also reveal themselves when they merge, by the gravitational waves they send out. The first detection, GW150914, came on 14 September 2015 at 09:50:45 UTC [776]. The signal swept from 35 to 250 Hz, periods of 28.6 to 4.0 ms (29.92 to 28.13, computed) [776].

The peak strain of GW150914 was 1.0×10^{-21}, with a signal-to-noise ratio of 24 [776]. Its false-alarm rate is below one per 203,000 years (59.99), more than 5.1σ [776]. The source lay at 410 Mpc (+160/−180; position 68.00), at redshift 0.09 [776].

Two black holes of 36 (+5/−4) and 29 ± 4 M☉ merged into one of 62 ± 4 M☉ [776]. The waves carried away 3.0 ± 0.5 M☉c² [776]. That is 5.4×10^{47} J (computed with $c^2 = 8.988 \times 10^{16}$ m² s⁻²), or 4.6% of the initial mass (computed).

GW190521 joined black holes of 85 (+21/−14) and 66 (+17/−18) M☉ into a remnant of 142 (+28/−16) M☉ [777]. It lay at 5.3 Gpc (70.33), redshift 0.82 [777]. The heavier black hole has only a 0.32% probability of lying below 65 M☉ [777].

The heaviest pair so far is GW231123. Its black holes weighed 137 (+23/−18) and 101 (+22/−50) M☉, a total of 190–265 M☉ [778]. They spun at 0.9 and 0.80 of the maximum [778].

The source lay at 0.7–4.1 Gpc (68.48 to 70.09), redshift 0.40, with a signal-to-noise ratio of about 20.7 [778]. A summary announced on 14 July 2025 gives the final black hole about 225 M☉ [779].

The catalogue grows fast. The first part of the fourth observing run lasted from 24 May 2023, 15:00 UTC, to 16 January 2024, 16:00 UTC: 237 days (48.48, computed) [780]. It added 128 new candidates, bringing the catalogue to 218 [780][781].

In that run 1,697 alerts went out online, and two candidates were a neutron star with a black hole [780]. The black holes in the binary mergers range from 5.79 M☉ (GW230627_015337) to 137 M☉ (GW231123_135430) [780].

The one confirmed merger of two neutron stars is GW170817, on 17 August 2017 at 12:41:04 UTC [782]. Its signal-to-noise ratio was 32.4, its false-alarm rate below one per 80,000 years (59.15) [782]. The total mass was 2.74 (+0.04/−0.01) M☉, with components of 1.17–1.60 M☉ [782].

GW170817 lay at 40 Mpc (+8/−14; 65.88) [782]. The Fermi satellite caught a gamma-ray burst, GRB 170817A, 1.7 seconds (33.64) after the coalescence [782]. Chapter 28 follows the elements made in that merger.

The measured masses form a ladder. The heaviest neutron star weighs 2.35 M☉ [763]; the lightest merging black hole in the catalogue 5.79 M☉ [780].

The net reads the neutron star and the black hole as the two limiting states of tension of its medium [694]. In the first the knots are pressed to their packing limit; in the second a region has turned into a saturated phase [725].

Read in the net’s terms, a merger has the form of rest and discharge in its pure state. The two bodies circle for a long time, and the last orbits pass in a fraction of a second. In GW150914 about one twentieth of the mass left as waves while the signal swept from 35 to 250 Hz [776].

The great black holes in the centres of galaxies

In the centre of the Milky Way sits Sagittarius A*. Its mass is 4.30×10^{6} M☉, known to about ± 0.25% [783]. It is weighed by the stars that orbit it: S2, S29, S38, S55 and thirteen more [783].

Any extended mass inside the farthest point of S2’s orbit is at most 3,000 M☉, 0.1% of the black hole [783]. That point lies 0.23 arcseconds from the centre, 2.4×10^{4} Schwarzschild radii [783]. At the Galactic Centre’s distance this is 2.8×10^{14} m, or 1,880 AU (computed; position 45.67).

The distance to the Galactic Centre is 8,178 ± 13 (statistical) ± 22 (systematic) pc (58.15) [784]. The star S2 orbits the black hole every 16 years (51.39), and it has been followed for 27 years (51.87) [784]. The positions are measured to 20 micro-arcseconds, and the gravitational redshift of S2’s light is detected at 20σ, with a factor f = 1.04 ± 0.05 against general relativity [784].

The Event Horizon Telescope imaged Sagittarius A* at a wavelength of 1.3 mm in 2017 [785]. It shows a bright, thick ring with a diameter of 51.8 ± 2.3 micro-arcseconds [785]. At 8,178 pc that ring is 6.3×10^{10} m across, 0.42 AU (computed; position 38.03).

The same telescope imaged M87*, the black hole in the centre of the galaxy M87, earlier [786]. Its ring is 42 ± 3 micro-arcseconds across, and its mass is $(6.5 \pm 0.7) \times 10^{9}$ M☉ [786]. The ring is about ten times brighter than the dark centre, and it held over four observations on different days [786].

M87* is about 1,500 times heavier than Sagittarius A* (computed), yet both rings span a similar angle. Both match general relativity across that factor in mass [785][786].

The masses measured in this chapter run 5.79, 33, 225, 4.3×10^{6} and 6.5×10^{9} M☉.

Read in the net’s terms, the black hole is the same form at every depth. A ring around a dark centre appears at four million and at six and a half billion solar masses.

What this part of the history shows

The life of a star runs from a cloud at 10 K to a remnant pressed to the density of nuclear matter. Every stage is present in the Galaxy now. The durations run from a tenth of a second (31.06) for a magnetar flare to more than 10^{12} years (74.02) for a red dwarf on the main sequence.

Read in the net’s terms, the cloud has the form of form and carrier. The star-forming disk of the Galaxy lasts and turns 1.65 to 1.9 M☉ of gas into stars each year [739][740]. Each cloud in it lasts about ten million years (63.54) and gives only 2% of its gas to stars [735].

Read in the net’s terms, the line between reading and opening falls at 0.08 M☉. Below it lie the brown dwarfs, from 13 to 80 Jupiter masses; above it lies EBLM J0555-57Ab, at 0.081 M☉, with fusion in its centre [746][747][744]. The line is sharp; the top of the mass range, near 300 M☉, is spread over models [748][749].

Read in the same terms, the main-sequence star has the form of what fits, stays. Hydrogen flows through the core as fuel and leaves as helium, while the star keeps its shape for up to 10^{10} years (69.83) in the Sun’s case [745]. About 90% of the stars above 0.5 M☉ are seen in this phase [745].

Read as context, the same rule takes other values in other surroundings. Hydrogen burns by the proton–proton chain in cool cores and by the CNO cycle in hot ones, with the switch at 18 million K in a star of about 1.5 M☉ [745]. Lifetime falls from more than 10^{12} years at 0.1 M☉ to a few million years at the top (62.45) [745].

Read in the net’s terms, the spread of masses at birth is the same winding in the field and in the census. Above half a solar mass its slope is 2.3 to 2.35 in the field, in the 20-pc census and in Salpeter’s count [741][742][743]. Below half a solar mass it flattens to 1.3 in both the field and the census [742][743].

Read in the net’s terms, rest and discharge mark the end of the heavy stars. A massive star loads for a few million years; at core collapse 99% of the energy leaves as neutrinos, and SN 1987A sent its 25 events within 13 seconds (35.49) [761]. The magnetar SGR 1806−20 released 10^{40} J in a tenth of a second, and GW150914 lost 3 M☉ of mass-energy as its signal swept to 250 Hz [773][776].

The neutron star and the black hole read as the two limits of the medium [725][694]. The neutron stars sit in a narrow band: masses of 1.34 to 2.35 M☉, radii of 12 to 14 km (23.97 to 24.06) [763][765][766]. The black holes reach from 5.79 M☉ in merging pairs to 6.5×10^{9} M☉ in M87 [780][786].

Read in the same terms, the black hole is the same form at every depth. A ring around a dark centre was imaged at 4.30×10^{6} M☉ and at 6.5×10^{9} M☉, a factor of 1,500 apart, both at 1.3 mm [783][785][786].

The mean interval between core-collapse supernovae in the Milky Way, 61 years (52.61), lies below the closure depth 53, 93.4 years [758]. The upper end of its range, 85 years, lies at 52.91.

28. The Elements Made in Stars

The first minutes left the universe with hydrogen, helium and a trace of lithium (chapter 24). The primordial helium mass fraction is Y_p = 0.245 ± 0.003 [202]. “For 100 million years after the Big Bang, there was nothing but hydrogen, helium and lithium” [700].

Every heavier element was made later, inside stars or in their deaths. Burbidge, Burbidge, Fowler and Hoyle set out in 1957 how stars build most elements heavier than lithium [33]. In 1952 technetium was seen in red giant stars, which showed that stars make elements [33].

This chapter follows that making in its order. It runs from the burning of hydrogen to the mergers of neutron stars, then to the mixture of the Sun and the oldest stars. Times and sizes carry their positions on the ladder of chapter 24; the units are those of chapter 27.

Hydrogen into helium

A star of the Sun’s kind burns hydrogen through the proton–proton chain, which builds helium-4. One whole chain yields 26.73 MeV, of which 2.2%, or 0.59 MeV, is carried off by neutrinos [787].

The chain has three branches, which lose 2.0%, 4.0% and 28.3% of their energy to neutrinos [787]. In the Sun the first branch makes 83.3% of the helium, the second 16.68% and the third 0.02% [787]. The first branch dominates at 10 to 18 million K, the second at 18 to 25 million K, the third above 25 million K [787].

The first step is slow. The average proton in the Sun’s core waits 9 billion years (69.73) before it fuses with another [787]. About 99% of the Sun’s energy comes from the proton–proton chains [787].

The Borexino detector measured the flux of the neutrinos from the first step in 2014. It found $(6.6 \pm 0.7) \times 10^{10}$ per cm² per second, against a solar-model value of $(5.98 \pm 0.04) \times 10^{10}$ [787]. The measured flux is 1.10 times the model value (computed).

In heavier stars hydrogen burns through the CNO cycle, with carbon, nitrogen and oxygen as catalysts. The two ways are equally efficient at 18 million K, in a star of about 1.5 M☉ [745]. From 1.8 M☉ upward, almost all the energy comes from the CNO cycle [745].

In 2020 Borexino found the first experimental evidence of CNO neutrinos from the Sun [132]. They show as an excess of a few counts per day per 100 tonnes of target [132]. The CNO cycle supplies of the order of 1% of the Sun’s energy [132].

As a reading, hydrogen burning has the form of the residue that becomes the alphabet. Helium, the ash of this stage, is the fuel of the next.

Helium into carbon

When the core hydrogen is gone, the star becomes a giant, and near 10^8 K helium ignites [788]. Its burning is the triple-alpha process: three helium nuclei, or alpha particles, become one carbon-12 nucleus.

Two helium nuclei form beryllium-8, and beryllium-8 does not last. Its half-life is 8.19×10^{-17} s, about half a unit of the ladder’s time (position −0.56, computed) [788]. Only when a third helium nucleus arrives within that time does carbon form.

The step runs through an excited state of carbon-12, the Hoyle state. Fred Hoyle predicted this state in 1953 from the cosmic abundance of carbon [788]. It was found in Fowler’s laboratory a few months later, near 7.65 MeV above the ground state [788].

The net energy release of the triple-alpha process is 7.274 MeV [788]. The rate rises as

the temperature to the 40th power and as the square of the density [788].

As a reading, the triple-alpha process has the form of what closes, stays. The pair of helium nuclei falls apart within about half a time unit. The triple stays as carbon.

Iron, and the explosions

The iron group is made in explosions. In the words of one survey, “Basically all the iron in the Universe is made in explosive nucleosynthesis” [789]. An exploding white dwarf, a type Ia supernova, makes about half a solar mass of nickel-56, between 0.4 and 0.8 M☉ [760].

White-dwarf explosions are a main source of calcium and iron, and the supernovae of massive stars of the elements from oxygen to selenium [700].

In the Milky Way a core-collapse supernova occurs on average every 61 (+24/−14) years (52.61) [758].

A model of the Galaxy’s chemical history covers every stable element from carbon to uranium [790]. In it, stars of more than 30 M☉ can end as failed supernovae, without an explosion [790]. Strontium, yttrium and zirconium come from electron-capture supernovae together with giant stars [790].

In the same model europium comes from magneto-rotational supernovae [790]. These are about 3% of the hypernovae of 25 to 50 M☉ [790].

The slow neutron capture

Beyond iron the nuclei grow by capturing neutrons. The slow process, the s-process, makes about half the nuclei heavier than iron [791].

In the s-process a nucleus meets a neutron flux of about 10^{5} to 10^{11} neutrons per cm² per second [791]. Captures come decades apart and go on over thousands of years [791]. Ten years sits at position 50.97, a hundred at 53.06, a thousand at 55.16 (computed).

The neutrons come from carbon-13, the main source, and from neon-22, the weak source [791]. The weak component builds from the iron-group seeds up to strontium and yttrium [791]. The main component carries on beyond strontium and yttrium up to lead [791].

The chain ends in a cycle among the stable lead isotopes 206, 207 and 208 and bismuth-209 [791]. Galactic models need about 25% more for the solar isotopes from mass 90 to 130 than the main s-process gives [792].

The s-process runs in giant stars on the asymptotic giant branch [790]. Paul Merrill found technetium in S-type and carbon stars in 1952 [791]. Technetium has no isotope with a half-life longer than 4.2 million years (62.75) [791].

Such giants reproduce the barium and lead peaks of the solar mixture [790]. Low-mass stars make most of the lead in the Solar System [789].

As a reading, the s-process has the same form of the residue that becomes the alphabet. Its seeds are the iron nuclei left by earlier explosions. Each nucleus it builds is the seed of the next capture.

The rapid neutron capture and the kilonova

The rapid process, the r-process, makes the other half of the nuclei heavier than iron [793]. An early estimate puts its conditions at 10^{24} free neutrons per cm³ at about 10^{9} K, almost 1 g of free neutrons per cm³ [793].

The r-process needs up to 100 captures per second, against one capture every 10 to 100 years in the s-process [793]. One hundredth of a second sits at position 28.96

(computed). Its abundance peaks lie near mass 82 (selenium, bromine, krypton), 130 and 196 [793].

In the r-process the nuclei hold their neutrons with separation energies down to 2 MeV [793]. A single neutron-star merger may make between 3 and 13 Earth masses of gold [793].

On 17 August 2017 two neutron stars merged in the event GW170817 (chapter 27) [782]. The light of the explosion, the kilonova AT2017gfo, was followed from the ultraviolet to the near infrared [794]. It is fitted by three components of ejected matter [794]:

Component	Ejected mass (M☉)	Speed	Source
blue, poor in lanthanides	0.020	0.27 c	[794]
purple, intermediate	0.047	0.15 c	[794]
red, rich in lanthanides	0.011	0.14 c	[794]

Together the three components carry about 0.078 M☉, or 1.6×10^{29} kg (computed). Another analysis finds two components, a light r-process below mass 140 and a heavy r-process above it [795]. With the merger rate from GW170817, such mergers are a dominant mode of r-process production in the universe [795].

In 2019 a re-analysis of the spectra identified strontium [796]. It was the first single neutron-capture element named in a merger. The lower limit on its mass in the outer ejecta is 1 to 5×10^{-5} M☉ [33].

The lower figure is 2×10^{25} kg [33]. That is 3.3 Earth masses of one element, made in one event (computed with an Earth mass of 5.972×10^{24} kg) [33].

As a reading, the two neutron captures have the form of loading, holding and discharge. The s-process loads one neutron at a time over thousands of years. The r-process loads a hundred per second, and the merger throws its matter out at up to 0.27 c.

In one model, neutron-star mergers make r-process elements up to thorium and uranium [790]. Their delay is too long, however, for the stars poorest in metals [790].

Johnson called the site of the r-process “currently in dispute” in 2017 [789]. By the mid-2020s mergers of two neutron stars were believed to be its main source [699].

The table of origins

The elements of the Solar System come from a few channels. The Big Bang made hydrogen, helium and some lithium [789][699]. Low-mass stars, massive stars, exploding white dwarfs and merging neutron stars made the rest, with cosmic rays splitting heavier nuclei [789].

Channel	Elements	Source
Big Bang	about 74% hydrogen and 24% helium by mass; some lithium-7	[699][789]
Cosmic-ray splitting	lithium-6; almost all helium-3; most lithium, beryllium, boron	[789][699]
Low-mass stars	most lithium-7; most of the Solar System’s lead; s-process barium	[789][790]
Massive-star supernovae	oxygen to selenium	[700]
Exploding white dwarfs	calcium, iron	[700]
Merging neutron stars	most of the r-process; most gold; rhodium, xenon	[789][700]

One source gives most lithium to cosmic rays, another most lithium-7 to low-mass stars [699][789]. Technetium and promethium have no stable isotopes; the chart shows them grey and leaves out the elements beyond uranium [789]. The mix changes over time, because the channels work on different timescales [700].

Models of the first stars give them the first 26 elements [797]. Model masses for those stars run from 20–130 M☉ to several hundred, possibly up to 1,000 M☉ [797].

The Sun’s mixture

The mixture of the Sun is read in its surface. The latest full analysis covers all 83 long-lived elements, using three-dimensional models of the solar atmosphere without the assumption of local equilibrium [798].

By mass the present photosphere is X = 0.7438 ± 0.0054 hydrogen, Y = 0.2423 ± 0.0054 helium and Z = 0.0139 ± 0.0006 heavier elements [798]. The ratio Z/X is 0.0187 ± 0.0009 [798].

An analysis twelve years earlier gave X = 0.7381, Y = 0.2485 and Z = 0.0134, with Z/X = 0.018 [799]. For the bulk of the young Sun it gave X = 0.7154, Y = 0.2703 and Z = 0.0142 [799]. The two analyses agree within 0.006 in X and 0.0005 in Z (computed).

The abundances are written as log ε, the base-10 logarithm of the number of atoms per 10^{12} hydrogen atoms. Carbon stands at 8.46 ± 0.04, nitrogen at 7.83 ± 0.07, oxygen at 8.69 ± 0.04 [798]. The earlier analysis gave 8.43, 7.83 and 8.69, and iron 7.52 (from Fe I) and 7.50 (from Fe II) [799].

Element	log ε	Atoms per hydrogen atom (computed)	Source
Carbon	8.46 ± 0.04	2.9×10^{-4}	[798]
Nitrogen	7.83 ± 0.07	6.8×10^{-5}	[798]
Oxygen	8.69 ± 0.04	4.9×10^{-4}	[798]
Iron	7.52 ± 0.05	3.3×10^{-5}	[799]

Oxygen is the most common element after hydrogen and helium in this table. There are 1.7 oxygen atoms per carbon atom and 15 per iron atom (computed).

The surface of the Sun and the meteorites give the same mixture. Across 45 elements, the mean difference between the photosphere and the meteorites is 0.00 ± 0.05 dex [799]. Carbon, nitrogen, oxygen and neon came out clearly lower than the values of a decade before [799].

Helioseismology gives the helium in the Sun’s convection zone as Y = 0.2485 ± 0.0034 [800]. The Hyades cluster, 625 ± 50 million years old (67.31), has Y = 0.26 ± 0.02 [801]. Its metallicity is +0.14 relative to the Sun [802].

Against the Big Bang mixture, the gas of the young Sun held 0.025 more helium by mass and 0.0142 in heavier elements (computed from [202] and [799]). The added helium is 1.8 times the heavier elements by mass (computed).

As a reading, the Sun’s mixture has the form of form and carrier: the form lasts while its carriers differ. The pattern of the elements is the same in the Sun’s surface and in the meteorites, two carriers of different kind.

The first metals and the oldest stars

The oldest stars hold almost no elements heavier than helium. The poorest known star in iron is SMSS J031300.36−670839.3 [722]. Its iron is less than $10^{-7.1}$ of the solar fraction, one part in 12.6 million (computed) [722].

The metals of SMSS J0313−6708 fit the matter of one single, low-energy supernova [722]. The exploding star weighed about 60 M☉ [722].

When Caffau’s star, SDSS J102915+172927, was found in 2012, it was the most metal-poor star known [797]. SMSS J0313−6708 went lower in 2014 [797]. A candidate in the Pictor II dwarf galaxy, reported in 2026, has iron below 1/43,000 and calcium below 1/160,000 of the Sun’s [797].

HD 140283 is a nearby star from the earliest times. Its parallax is 17.15 ± 0.14 milli-arcseconds, which places it at 58.3 pc, 190 ly (computed; position 53.65) [679]. Its iron is [Fe/H] = −2.40, 1/250 of the Sun’s (computed), and its oxygen [O/H] = −1.67 [679].

Its age is 14.46 ± 0.31 billion years from the statistics alone (70.17), and ± 0.8 billion years with all uncertainties [679]. The study compares it with an age of the universe of

13.77 ± 0.06 billion years (70.12) and finds no conflict within the errors [679].

The ultra-metal-poor binary 2MASS J18082002−5104378 holds a companion of 0.14 M☉, near the hydrogen-burning limit [803]. The pair orbit each other every 34.757 ± 0.010 days (46.73) [803]. The system moves on an orbit in the thin disk of the Galaxy [803].

The first metals came early. The galaxy JADES-GS-z14-0, seen about 300 million years after the Big Bang (66.64), already holds 0.05 to 0.2 of the Sun’s metals [721]. Earlier stars had made its oxygen by that time.

In the Milky Way the stars of the thick disk began to form 13 billion years ago (70.07), 0.8 billion years after the Big Bang (67.53) [726]. Most of them formed by 11 billion years ago (69.92) [726]. Over the next 5 to 6 billion years the metallicity rose by a factor of ten [726].

As a reading, the first metals have the form of a depth opened once and filled many times. One supernova of about 60 M☉ supplied the metals of SMSS J0313−6708 [722]. In the thick disk the metallicity then rose tenfold in 5 to 6 billion years [726].

The clocks of spin and cycles

A star’s spin slows with age, so its period is a clock. The Kepler satellite measured rotation periods for 34,030 of 133,030 main-sequence stars cooler than 6,500 K, 25.6% [804].

The periods run from 0.2 days (42.03) to 70 days (47.37) [804]. Their distribution has two peaks, less clear above 0.6 M☉ [804].

Gyrochronology reads a star’s age from its period and its colour, calibrated on the Sun [805]. For late-F, G, K and early-M stars the age error is about 15% [805]. One sample of active stars has a median age of 365 million years (66.82), another a median of 1.2 billion years (67.90) [805].

Stars have magnetic cycles like the Sun’s. Olin Wilson began the Mount Wilson programme in 1966, sixty years ago (52.60, computed), and about 2,000 stars were watched over its life [806].

Of its core sample of 111 dwarf stars, 60% show cyclic or apparently cyclic behaviour, 25% vary irregularly and 15% are flat [806]. In cycle length against rotation period, the stars group into an active and an inactive branch [806].

Of 65 solar-type stars and cooler dwarfs watched for decades, about half show cycles of 7 to 18 years (50.64 to 51.50) [807]. Cool dwarfs that turn in less than 5 days (44.96) show brightness cycles of up to 80 years (52.86) [807].

The Sun’s magnetic cycle recurs in other stars. Cycles of 7 to 18 years appear in half of the solar-type stars, and they fall on two branches of cycle length against spin [806] [807].

Elements from nearby explosions

The elements made in supernovae reach the Earth. The Local Bubble, the cavity of thin gas around the Sun, has a radius of 165 ± 6 pc (54.59) [808].

It is 14.4 million years old (63.87), and its making needed 15 (+11/−7) supernovae [808]. Every well-known molecular cloud within about 200 pc lies on its surface, except the Perseus cloud [808].

Iron-60 lies in deep-sea sediments, in Antarctic snow and in lunar soil [809]. Iron-60 and manganese-53 peak 1.7 to 3.2 million years ago (61.93 to 62.50), and iron-60 again 6.5 to 8.7 million years ago (63.15 to 63.41) [809]. The star ζ Ophiuchi and the pulsar PSR B1706−16 come from one supernova 1.78 ± 0.21 million years ago (61.97) [809].

The cycle of matter through stars

The life of a star (chapter 27) is also the path of its matter. The stages run in this order:

Stage	Threshold	Duration	Position	Source
Cold cloud	about 10 K	about 10 million years	63.54	[736][735]
Collapse of a core	above the Jeans mass; first core at about 10^{-13} g cm^{-3}	youngest stars 10^{3}–10^{4} years	55.16–57.25	[736]
Hydrogen burning	pp chain below about 18 million K, CNO above	a few million to more than 10^{12} years	62.45–74.02	[745]
Helium burning, giant	about 10^{8} K, the 7.65 MeV state	about 10^{9} years for one solar mass	67.73	[788][751]
White dwarf (below about 8 M☉)	over 97% of stars	cooling to 7,140 K in 1.5 billion years	68.10	[753]
Core collapse (above about 8 M☉)	99% of the energy in neutrinos	SN 1987A: 25 events in about 13 s	35.49	[761]
Merger of compact stars	neutron stars of 1.17–1.60 M☉	kilonova ejecta 0.078 M☉	—	[782][794]

The stage boundaries lie at masses of 0.08, about 8 and about 2.2 to 2.35 M☉, and at temperatures of about 18 million K and 10^{8} K (chapter 27). All the stages are seen at once in the Galaxy.

The net's own texts read a star as a body in which the central stretch reaches closure for the heaviest knots present, and lighter knots follow [26]. They take this order from Larson (1984): heaviest elements first, then lighter with rising central temperature [26].

What this part of the history shows

The elements were made in steps, and each step uses the product of the one before. Hydrogen burns to helium with 26.73 MeV per chain, and helium to carbon with 7.274 MeV [787][788]. Iron from the explosions is the seed of the s-process, which builds up to lead and bismuth; read on the net, the residue becomes the alphabet [791].

The triple-alpha process reads as what closes, stays. Two helium nuclei form beryllium-8, which lasts 8.19×10^{-17} s, at position −0.56 [788]. Three form carbon, which stays.

The neutron captures read as loading, holding and discharge. In the s-process captures come one every 10 to 100 years, over thousands of years (50.97 to 55.16) [791][793]. In the r-process they come up to 100 per second (28.96), and GW170817 threw out about 0.078 M☉ at 0.14 to 0.27 c [793][794].

"Matter is formed in nature, continuously, in amounts beyond any human scale." [33] The strontium of one merger alone weighed at least 2×10^{25} kg, 3.3 Earth masses [33]. In the Milky Way a core-collapse supernova adds its elements about every 61 years [758].

The first metals read as a depth opened once and filled many times. The iron of SMSS J0313−6708, less than $10^{-7.1}$ of the Sun's, fits a single supernova of about 60 M☉ [722]. By 300 million years after the Big Bang a galaxy held 0.05 to 0.2 of the Sun's metals, and in the thick disk the metallicity rose tenfold in 5 to 6 billion years [721][726].

The mixture of the elements reads as form and carrier. The Sun's photosphere and the meteorites agree to 0.00 ± 0.05 dex across 45 elements [799]. Two analyses twelve years apart agree within 0.006 in hydrogen and 0.0005 in the heavier elements [798] [799].

The net's own texts read a star as a body whose heaviest knots reach closure first [26]. The order is taken from Larson (1984), with lighter elements following as the central temperature rises [26].

The Sun’s magnetic cycle recurs in other stars. Of 111 dwarf stars in the Mount Wilson core sample, 60% cycle [806]. Half of 65 solar-type stars show cycles of 7 to 18 years (50.64 to 51.50), on two branches of cycle length against spin [806][807].

29. The Sun

The Sun is the one star seen from close by. Its oldest companions, grains preserved in meteorites, date its birth to 4,567.30 ± 0.16 million years ago [265]. That age sits at position 69.12 on the ladder of time, just below the age of the universe at 70.12.

Everything else in this chapter is measured from a distance of one astronomical unit. That distance, 149,597,870,700 m, sits at size position 38.81 [133]. Light crosses it in 499.0 s, which sits at time position 38.81 as well, because the ladder's unit of size is its unit of time times the speed of light (chapter 24).

The history runs in this order.

First the birth and the slow brightening over 4.6 billion years.

Then the body as it stands now, from the core outward to the edge of its wind at about 120 AU. Then the record of its activity: ten thousand years in tree rings and ice, 270 years of counted sunspots, and the storms of the last 170 years. The chapter ends with the Sun's orbit in the Galaxy and the path ahead.

Birth and age

Stars form in cold molecular clouds. A typical giant cloud has 100 particles per cm^3 and an interior temperature of 10 K [736]. Only about 2% of a cloud's mass ends in stars, and the clouds are dispersed after about 10 million years (position 63.54) [735].

The collapse of a cloud core runs through measured stages. The dust warms to 60–100 K, a first hydrostatic core forms at a density of about 10^{-13} g cm^{-3}, and hydrogen molecules begin to split when the core reaches about 2,000 K [736].

The stellar core proper appears once the infalling gas reaches about 10^{-8} g cm^{-3} [736]. The youngest stars seen today are about 1,000 years old (MWC 349, position 55.16) and possibly under 10,000 years (VLA 1623, 57.25) [736].

The Sun's own birth is dated by the first solids that condensed around it. Calcium–aluminium-rich inclusions (CAIs) give a uranium-corrected lead–lead age of 4,567.30 ± 0.16 million years [265]. Chondrules, the next grains, range from 4,567.32 ± 0.42 to 4,564.71 ± 0.30 million years, so their formation lasted about 3 million years (position 62.45) [265].

The Sun itself is dated by models of stellar evolution at about 4.6 billion years [133]. The birth of the disk and its planets is the subject of chapter 30.

The steady star: mass, light and brightening

The International Astronomical Union fixes the Sun by five nominal numbers [810]. They are a radius of 6.957×10^8 m, an irradiance at 1 AU of 1,361 W m^{-2} and a luminosity of 3.828×10^{26} W. The other two are an effective temperature of 5,772 K and a mass parameter GM of 1.3271244×10^{20} m^3 s^{-2}.

They are conversion constants, chosen as standards [810].

The best measured values sit within 0.02% of them. The photospheric radius is 695,658 ± 140 km, the luminosity $(3.8275 \pm 0.0014) \times 10^{26}$ W and the effective temperature 5,772.0 ± 0.8 K [810]. The radius sits at size position 33.92.

The NASA fact sheet gives the mass as 1.9884×10^{30} kg, 332,900 Earth masses [733]. The mean radius is 695,700 km, 109.2 Earth radii, and the mean density 1,408 kg m^{-3} [733]. Surface gravity is 274.0 m s^{-2}, 28.0 times the Earth's, and the escape speed 617.6 km s^{-1} [733].

The Sun is a star of spectral type G2 V, absolute magnitude +4.83, apparent magnitude

−26.74 [733]. Its surface emits 6.294 × 10^{7} W per square metre [733]. Each kilogram of the Sun releases on average 1.925 × 10^{-4} W [733].

The light carries mass away. The fact sheet gives a mass conversion rate of 4.26 × 10^{9} kg s^{-1} [733]. The check is L/c^2 = 3.828 × 10^{26} / (2.998 × 10^{8})^2 = 4.26 × 10^{9} kg s^{-1}.

That loss comes from fusion. About 9.2 × 10^{37} proton–proton reactions take place each second, and about 6 × 10^{11} kg of hydrogen is fused per second [133]. The two rates give the share of fused mass that leaves as energy: 4.26 × 10^{9} / 6 × 10^{11} = 0.0071, or 0.71%.

At the present rate the whole mass would last 1.9884 × 10^{30} / 4.26 × 10^{9} = 4.67 × 10^{20} s, or 1.48 × 10^{13} years (position 76.47). Over its age of 4.567 billion years the Sun has lost, at the present rate, 4.26 × 10^{9} × 1.441 × 10^{17} s = 6.1 × 10^{26} kg. That is 0.031% of its mass.

The Sun keeps its form while matter flows through it. As a reading, this is the form of metabolism from chapter 24: the content flows through while the form holds.

The hydrogen burns by the proton–proton chain. One whole chain yields 26.73 MeV per helium nucleus, and 2.2% (0.59 MeV) of it leaves as neutrinos [787]. In the Sun the branch pp-I makes 83.3% of the helium, pp-II 16.68% and pp-III 0.02%; about 99% of the energy comes from these chains [787].

The chain is slow. The average proton in the core waits 9 × 10^{9} years before it fuses with another (position 69.73) [787]. The proton–proton chain and the carbon–nitrogen–oxygen (CNO) cycle are equally efficient at a core temperature of 18 MK, the core of a star of about 1.5 solar masses [745].

The Sun’s time on the main sequence is about 10^{10} years (position 69.83), of which about 4.5 billion years (69.10) have passed [745]. The same source gives about 12 billion years of hydrogen burning in all (70.00) [745].

The composition has changed with time. The photosphere holds 74.9% hydrogen and 23.8% helium by mass; the Sun began with 71.1% hydrogen, 27.4% helium and 1.5% heavier elements [133]. In the core the helium share has risen from about 24% to about 60% [133].

By number the photosphere is 90.965% hydrogen and 8.889% helium [733]. The heavier elements follow in parts per million: oxygen 774, carbon 330, neon 112, nitrogen 102, iron 43, magnesium 35, silicon 32, sulphur 15 [733]. The solar model S starts from a hydrogen mass fraction X_0 = 0.709 [811], and helioseismology gives the helium mass fraction of the outer envelope as Y = 0.2485 ± 0.0034 [800].

The Sun has brightened as its core filled with helium. Over the last 420 million years (position 66.94) the irradiance at the Earth rose by about 50 W m^{-2}, a forcing of about +9 W m^{-2} [399].

The irradiance today is measured from orbit. The SORCE/TIM radiometer gave 1,360.8 ± 0.5 W m^{-2} at the solar minimum of 2008 [812]. Earlier, higher readings are attributed mainly to scattered light in older instruments [812].

In the net’s texts a star differs from a planet in kind, not in mesh size. In a star the central stretch reaches closure for the heaviest knots present; a planet only passes what its meshes let through [26][845]. Jupiter, the largest planet, sends out 7.485 W m^{-2} from within, which over its area of 4π × (69,911 km)^2 is 4.60 × 10^{17} W [846].

The Sun sends out 3.828 × 10^{26} W, 8.3 × 10^{8} times more than Jupiter’s inner heat.

The older value of about 1,368 W m^{-2} is still quoted [133]; it is 7.2 W m^{-2}, or 0.53%, above the TIM value.

The irradiance varies on every timescale measured [813]. Over minutes to hours it changes by about 0.01%, from convection and oscillations. Over the 11-year cycle it rises about 0.1% from minimum to maximum, about 1.4 W m^{-2}.

The largest short-term drop on record came with a sunspot passage in late October 2003: 0.34%, or 4.6 W m^{-2} [813]. The X17 flare of 28 October 2003 raised the irradiance by 0.028%, 0.38 W m^{-2}, for a short time [813]. Reconstructions place the Maunder Minimum 0.5–1 W m^{-2} (0.04–0.08%) below today’s mean; Judge and

colleagues give 3 W m^{-2} (0.2%) [813].

The core and its neutrinos

The core reaches from the centre to about 20–25% of the solar radius [133]. At 0.25 R☉ that is 1.74 × 10^{8} m, position 32.66. Ninety-nine per cent of the power is made inside the innermost 24% of the radius [133].

The model values for the centre are a temperature of 1.571 × 10^{7} K, a density of 1.622 × 10^{5} kg m^{-3} and a pressure of 2.477 × 10^{11} bar [733]. Another source gives close to 15.7 million K and a density of up to 150 g cm^{-3} [133]. The peak power density is about 276.5 W m^{-3} [133].

Energy leaves the core by two carriers at very different speeds. A neutrino leaves the Sun in 2.3 s (position 33.91) [133]. A photon’s energy takes between 10,000 and 170,000 years to reach the surface (positions 57.25–59.83), and the overall energy transport time is about 3 × 10^{7} years (64.54) [133].

The two escape times differ by a factor of 10^{4} × 3.156 × 10^{7} / 2.3 = 1.4 × 10^{11} to 1.7 × 10^{5} × 3.156 × 10^{7} / 2.3 = 2.3 × 10^{12}. The neutrinos show the core as it is now; the sunlight carries energy made thousands of years ago. As a reading, this is the form of form and carrier: the form lasts, and its carriers pass through and are replaced.

The neutrinos were measured in a sequence of experiments over half a century. The first was a tank of chlorine in the Homestake mine. Its reaction, $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$, ran from 1970 over 108 extractions and gave 2.56 ± 0.16 (stat) ± 0.16 (syst) solar neutrino units (SNU) [128].

That rate was around a third of the number the standard solar model predicted [120]. The gap became known as the solar neutrino problem.

Gallium came next. The SAGE experiment measured 65.4 (+3.1/−3.0 stat, +2.6/−2.8 syst) SNU above 233 keV in 168 extractions through December 2007 [129]. Combined with GALLEX/GNO it gave 66.1 ± 3.1 SNU and a proton–proton neutrino flux at the Earth of (6.0 ± 0.8) × 10^{10} cm^{-2} s^{-1} [129].

The Sudbury Neutrino Observatory, filled with heavy water, separated the flavours in 2002 [118]. For the ^{8}B neutrinos above 5 MeV it measured an electron-type flux of 1.76 ± 0.05 ± 0.09 × 10^{6} cm^{-2} s^{-1}. The other flavours added 3.41 ± 0.45 (+0.48/−0.45) × 10^{6}, and the total was 5.09 (+0.44/−0.43)(+0.46/−0.43) × 10^{6} cm^{-2} s^{-1} [118].

The total matched the solar models, and the non-electron share stood 5.3 standard deviations above zero [118]. The electron-type share is 1.76 / 5.09 = 34.6%, about one third, the same fraction Homestake had seen. Nobel Prizes followed in 2002 for Davis and Koshiba and in 2015 for Kajita and McDonald [120].

Borexino at Gran Sasso, under 3,800 m water equivalent with 278 t of liquid scintillator, took data from May 2007 until October 2021 [120]. It resolved the branches one by one. In Phase II, over 1,291.51 days between 0.19 and 2.93 MeV, it counted 134 ± 10 (+6/−10) proton–proton events per day per 100 t [131].

The same phase gave 48.3 ± 1.1 (+0.4/−0.7) ^{7}Be events, measured to 2.7%, and 2.43 ± 0.36 (+0.15/−0.22) pep events, per day per 100 t [131]. The CNO rate stayed below 8.1 per day per 100 t at 95% confidence [131]. Borexino’s proton–proton flux of (6.6 ± 0.7) × 10^{10} cm^{-2} s^{-1} compares with a model prediction of (5.98 ± 0.04) × 10^{10} [787].

Phase III, from July 2016 to February 2020, ran 1,072 days on a fiducial mass of 71.3 t [132]. It detected CNO neutrinos at a rate of 7.2 (+3.0/−1.7) per day per 100 t, with 5.1σ significance [132]. The flux at the Earth is 7.0 (+3.0/−2.0) × 10^{8} cm^{-2} s^{-1}.

The CNO cycle supplies “of the order of 1%” of the Sun’s energy [132]. Another source gives 0.8% [133]. The proton–proton flux exceeds the ^{8}B flux by 6.0 × 10^{10} / 5.09 × 10^{6} = 1.2 × 10^{4}.

The interior heard: rotation and oscillation

The record of the Sun’s rotation begins in 1630. Christoph Scheiner then measured the equator turning faster than the higher latitudes [814]. Carrington’s numbered rotations start on 9 November 1853, with a sidereal period of 25.38 days and a synodic period of 27.2753 days; Bartels’ rotations of exactly 27 days count from 8 February 1832 [814].

The fact sheet gives a sidereal rotation of 609.12 h, or 25.38 days, at latitude 16° (position 46.44) [733]. The Sun’s axis is tilted 7.25° to the ecliptic [733]. The synodic Carrington period of 27.2753 days sits at 46.51.

Doppler measurements give the surface rate as $\Omega/2\pi = 451.5 - 65.3\cos^2\theta - 66.7\cos^4\theta$ nHz, with θ the colatitude [811]. At the equator that is 451.5 nHz, a period of 25.63 days (46.45). At the pole it is $451.5 - 132.0 = 319.5$ nHz, a period of 36.2 days (46.77), so the poles turn 1.41 times slower than the equator.

Other sources give 25.6 days at the equator and 33.5 days (46.70) at the poles [133]. Another gives an equatorial sidereal 24.47 days (46.41) and a polar synodic period of almost 38 days (46.81) [814]. A review gives “around 25 d at the equator to more than 30 d near the poles” [811].

The interior was opened by sound. In 1962 Leighton and colleagues found oscillations of the surface with periods around 300 s (position 38.34), lasting at most a few periods [811]. Ulrich (1970) and Leibacher and Stein (1971) proposed standing acoustic waves; Deubner (1975) found the predicted ridges, and Claverie and colleagues (1979) confirmed the global modes [811].

The modes have frequencies above 500 μHz [811]. Of order 10^7 of them ring at once; each moves the surface by at most about 10 cm s^{-1}, and together they move it by about 500 m s^{-1} [811]. The highest degrees observed exceed $l = 1{,}000$ [811].

The catalogues of the GONG and MDI programmes hold about 3,000 modes, with degrees up to about 200 and frequencies of about 1–4.5 mHz [800]. Those periods, 1,000 s to 222 s, sit at positions 39.44 to 38.07. The BiSON and GONG networks have run for decades; SOHO has given high-quality data since 1996 and SDO since 2010 [814].

From the frequencies the inner structure follows. The convection zone begins at $r = 0.7133 \pm 0.0005$ R☉ (GONG data); an earlier analysis gave 0.713 ± 0.001 R☉ [800]. That base lies 4.962×10^8 m from the centre (position 33.61), and the zone above it is 0.2867 R☉ deep, 1.995×10^8 m (32.78).

The uncertainty, 0.0005 R☉, is 348 km, position 27.00. The solar model S mixes its envelope fully down to $r = 0.711$ R [811]. The second ionisation zone of helium shows at $r \approx 0.98$ R☉, and the sound speed is known to better than 0.01% through most of the interior [800].

Below the convection zone lies the radiative zone, from about 0.25 to about 0.7 R☉ [133]. Across it the temperature falls from about 7 million to 2 million K and the density from 20,000 to 200 kg m^{-3} [133].

Between the two zones lies the tachocline. Its centre is at $r = 0.693 \pm 0.002$ R☉ (4.82×10^8 m, position 33.59) and its equatorial thickness is 0.039 ± 0.013 R☉ (2.71×10^7 m, 30.97) [815]. It is prolate: about 0.024 R☉ shallower at latitude 60° than at the equator, and a spherical tachocline is rejected at 99% confidence [815].

A later review places the centroid of the shear just below the base of the convection zone, with a thickness around 0.05 R☉ [816]. Another source gives at most 0.70 R☉ for its position and about 0.04 R☉ for its thickness; the name was coined by Spiegel and Zahn in 1992 [814].

The rotation inside is measured in the same way. The radiative interior turns approximately as a solid body; between 0.2 and 0.6 R☉ the rate “barely varied with radius” [816]. The differential rotation of the surface reaches down through the convection zone and ends at the tachocline [816].

A second shear zone lies near the surface. It runs from the fastest-rotating level at about 0.95 R☉ (33.87) to the surface and is resolved to about 15 Mm (30.43) [816]. Bands of flow a few m s^{-1} faster or slower than their surroundings, under 0.5% of the

rotation and a few nHz, march with the 11-year cycle [816].

The Sun is nearly round: its flattening is about 8.2×10^{-6} [133].

As a reading, the tachocline has the form of the edge from chapter 24. Inside, the radiative interior turns as one body; outside, every latitude turns at its own rate. The shear of the whole Sun is gathered into a shell 0.039 R☉ thick between them.

The surface, the corona and the wind

The visible surface, the photosphere, is about 500 km thick (position 27.33) [733]. Its temperature runs from 6,600 K at the bottom to 4,400 K at the top, and its gas pressure from 125 mb to 0.868 mb [733]. The effective temperature is 5,772 K; a blackbody value of 5,777 K is also quoted [733][133].

The magnetic field at the poles is 1–2 G, the field in sunspots 3,000 G, in prominences 10–100 G and in chromospheric plages 200 G [733]. The bright chromospheric network holds 25 G and the small ephemeral active regions 20 G [733].

Above the photosphere the chromosphere is about 2,500 km thick (28.80), and its top reaches about 30,000 K [733]. Then the temperature jumps. Across a transition region about 100 km thick (25.87) it rises from about 20,000 K to over 1 million K [817].

The corona above is typically 1–2 million K [817]. Active regions average 2–4 million K and reach up to 20 million K [817]. The corona is 1×10^6 / 5,772 = 173 to 2×10^6 / 5,772 = 346 times hotter than the photosphere.

At its base the corona holds about 10^{15} particles per cubic metre [817]. Just above the limb it is about 10^{-6} as bright as the photosphere [817].

Its light was first read in 1869, when a green line at 5,303 Å was seen [817]. The line was ascribed to an unknown element, “coronium”. After Grotrian’s work of 1939, Edlén identified it in 1940 as iron that has lost 13 electrons, Fe XIV [817].

Keeping the corona hot needs a steady supply of energy. The requirement is about 300 W m^{-2} in the quiet Sun and about 10^4 W m^{-2} in active regions [818]. Another source gives about 1 kW m^{-2}, about 1/40,000 of the escaping light [817].

Against the surface emission of 6.294×10^7 W m^{-2}, 300 W m^{-2} is 0.00048% and 10^4 W m^{-2} is 0.016%. The transition region radiates more than half of the energy deposited in the corona [818]. The hot loops seen by Yohkoh exceed 2 million K; the warm loops are near 1 million K [818].

Two families of heating were proposed.

Schatzman (1949) proposed waves, and the first observed magneto-acoustic waves carried about 10% of the energy needed [817]. Parker proposed small explosive releases, nanoflares, dated 1988 in one source and 1952 in another [818][817]. The canonical nanoflare releases 10^{24} erg, 10^{17} J [818].

As a reading, the surface of the Sun has the form of the edge as well. Inside, the temperature falls outward from 15.7 million K at the centre to 5,772 K at the surface. At the edge, over the 100 km of the transition region, it rises by a factor of 50.

From the corona the solar wind flows out. Parker predicted it in 1958, Luna 1 measured it directly in January 1959 (Gringauz), and Mariner 2 found in 1962 that it comes in slow and fast streams (Neugebauer) [819].

The slow wind runs at 300–500 km s^{-1} near the Earth, at about 100,000 K, about twice as dense as the fast wind, with a composition like the corona [819]. The fast wind runs at about 750 km s^{-1} and about 800,000 K, with a composition close to the photosphere [819].

At 1 AU the wind moves at 250–750 km s^{-1} and holds 3–10 particles per cm^3 at 10^4–10^6 K, with a pressure of 1–6 nPa [819]. The Sun loses about 1.3×10^{36} particles per second, 1.3–1.9 $\times 10^9$ kg s^{-1}, or (2–3) $\times 10^{-14}$ solar masses a year [819].

The wind thus carries off 1.3/4.26 = 0.31 to 1.9/4.26 = 0.45 of the mass the light carries

off. Over 4.567 billion years at today's rate it would have removed $1.3 \times 10^{9} \times 1.441 \times 10^{17} / 1.9884 \times 10^{30} = 0.0094\%$ to 0.014% of the Sun. The source gives about 0.01% over the lifetime [819].

Near the Sun the wind is still held by the magnetic field. It breaks free at the Alfvén surface, where its speed exceeds the magnetic signal speed. Earlier estimates put that surface at 10–20 solar radii (36.02–36.65); one source gives 16–20 [819][133].

The Parker Solar Probe crossed it on 28 April 2021 at 18.8 R☉, 1.31×10^{10} m from the centre (position 36.59) [819]. The same craft first observed switchbacks in the wind in 2018 [819].

On 24 December 2024 at 6:53 a.m. ET the probe made its closest approach [820]. It passed 3.8 million miles above the surface at 430,000 miles per hour, the fastest human-made object recorded; its survival was confirmed by a beacon tone late on 26 December [820].

In metric units the height is 6.12×10^{6} km above the surface (35.90). Adding the radius of 695,700 km, the craft was 6.81×10^{6} km from the centre, 9.8 R☉ (position 36.00) and 1/22 of an AU. Its speed was 192 km s^{-1}, 0.064% of the speed of light and 31% of the escape speed at the solar surface.

The edge of the heliosphere

The wind blows a bubble into the gas between the stars, the heliosphere. Two spacecraft have crossed its boundaries on two different tracks.

Voyager 1 crossed the termination shock in December 2004 at 94 AU (position 42.94) [821]. Voyager 2 crossed it in August 2007 at 84 AU (42.84) [821]. The two crossings lie 10 AU apart.

At Voyager 1 the outward speed of the wind fell to zero on 13 December 2010, about 17.4×10^{9} km from the Earth [819]. That is 116 AU (43.13). The stagnation region is placed at about 113 AU (43.11) [822].

Voyager 1 entered interstellar space on 25 August 2012, at about 122 AU [821]; another source gives 121 AU [822]. Both values sit at position 43.17–43.18.

Voyager 2 crossed the heliopause on 5 November 2018 [823]. Its plasma instrument "observed a steep decline in the speed of the solar wind particles on Nov. 5" [823].

Its cosmic-ray instrument saw the particles of the heliosphere fall away and the galactic cosmic rays rise [823].

Radio signals from Voyager 2 then took about 16.5 hours to reach the Earth [823]. That light time, 59,400 s, sits at time position 43.16, and the distance it implies, 119.0 AU, sits at size position 43.16. The distance is also given directly as 119 AU [822].

The two heliopause crossings, 121–122 AU and 119 AU, lie only 2–3 AU apart. The heliosheath between shock and heliopause is $121 - 94 = 27$ AU thick along the Voyager 1 track (41.81) and $119 - 84 = 35$ AU along Voyager 2's (42.04).

At the heliopause Voyager 1 measured a forty-fold rise in plasma density [822]. The inner edge of the heliosheath is about 80–100 AU out (42.80–43.00); the tail of the heliosphere reaches several thousand AU and shows four lobes in the IBEX maps [822]. A bow shock once expected near 230 AU (43.76) is probably absent, from IBEX data of 2012 [822].

The wind leaves the Sun at about 400 km s^{-1}; the speed of sound in the interstellar gas is about 100 km s^{-1} [822]. The gas outside is the Local Interstellar Cloud, about 9.2 pc across (51.97), at about 7,000 K and 0.3 atoms per cm^{3} [824]. The Solar System entered it within the past 10,000 years (57.25) and will leave it within at most 1,900 years (55.74) [824].

The heliopause is the edge of the Sun's flow. The net's texts place a second, wider edge: the distance where the Sun's own pull falls to the stretch of the surrounding Galaxy. In their words, "The solar knot ends where its own stretch thins to the stretch around it"

[701].

The surrounding stretch follows from the Sun’s orbit. The circular speed at the Sun is 229.0 ± 0.2 km s^{-1} [825], and the distance to the Galactic Centre is 8,178 pc, 2.5235×10^{20} m [784]. The centripetal acceleration is $(2.29 \times 10^5)^2 / 2.5235 \times 10^{20} = 2.08 \times 10^{-10}$ m s^{-2}.

Across 153 galaxies the observed accelerations follow one relation with one scale, $g\dagger = 1.20 \pm 0.02$ (random) ± 0.24 (systematic) $\times 10^{-10}$ m s^{-2} [826]. The Sun’s orbit runs at 2.08 / 1.20 = 1.73 times that scale.

The edge lies where $GM_\odot / r^2$ equals the surrounding stretch, so $r = \sqrt{(GM_\odot / g)}$. The net’s text takes $g = 2.07 \times 10^{-10}$ m s^{-2} (from R = 8.2 kpc): $\sqrt{(1.327 \times 10^{20} / 2.07 \times 10^{-10})} = 8.01 \times 10^{14}$ m = 5,350 AU, position 46.62 [701].

With the scale 1.2×10^{-10} m s^{-2} in place of the background, the same formula gives 7,030 AU (46.87) [827]. With $cH_0/2\pi = 1.08 \times 10^{-10}$ m s^{-2} it gives 7,400 AU (46.92) [27]. The three values come from three inputs to one formula.

The flow edge stands at position 43.17, the winding edge at 46.62 to 46.92. Between them lie three to four positions, a factor of about 44 to 61 in distance. Chapter 32 follows the comets that orbit in that band and beyond.

Ten thousand years of activity

The Sun’s activity before the telescope is read from isotopes: ^{14}C in tree rings and ^{10}Be in the ice of Greenland and Antarctica [828].

A reconstruction over nine millennia combines six ^{10}Be series from Greenland and Antarctica with the global ^{14}C production [828]. It shows a slow variation of about 6,000 years, with low activity near 5500 BC and near AD 1500 [828]. The two lows lie about 7,000 years apart (position 56.93).

In the same record the grand minima stand out as a separate component [828]. The grand maxima do not separate from the main component in a statistically significant way [828].

A grand minimum is defined as a period when the smoothed sunspot number stays below 15 for at least two consecutive decades [829]. A grand maximum is a period above 50 for at least two decades [829].

Since 9500 BC the record holds 27 grand minima and 19 grand maxima [829]. The Sun spends about 17% of its time in a grand minimum, and about 9% or 22% in a grand maximum, depending on the series used [829].

The minima come in two lengths: “short (30–90 years) minima of Maunder type” and “long (>110 years) minima of Spörer type” [829]. The durations of the grand maxima follow an exponential distribution [829]. The waiting times between minima do not, so the minima cluster [829].

The 27 minima, with the centre year and duration of each [829]:

Centre	Duration (years)	Position of the duration	Name
9165 BC	150	53.43	
8215 BC	110	53.15	
7515 BC	150	53.43	
7305 BC	30	51.97	
7035 BC	50	52.43	
6400 BC	80	52.86	
6215 BC	30	51.97	
5985 BC	30	51.97	
5710 BC	20	51.60	
5620 BC	40	52.23	
5460 BC	60	52.60	

5260 BC	140	53.37	
4325 BC	50	52.43	
4225 BC	30	51.97	
3940 BC	60	52.60	
3625 BC	50	52.43	
3500 BC	40	52.23	
3335 BC	70	52.74	
2860 BC	60	52.60	
1390 BC	40	52.23	
765 BC	90	52.97	
360 BC	60	52.60	
AD 685	70	52.74	
AD 1040	60	52.60	
AD 1305	70	52.74	Wolf
AD 1470	160	53.49	Spörer
AD 1680	80	52.86	Maunder

The durations add up to 1,880 years out of 11,500 (9500 BC to AD 2000), or 16.3%, which matches the stated 17%. They range from 20 to 160 years, with a mean of 69.6 years (52.73) and a median of 60 (52.60). Five minima last 110 years or more: 9165, 8215, 7515 and 5260 BC, and AD 1470.

The centres are not spread evenly. The gaps between successive minima range from 90 years (5710 to 5620 BC) to 1,470 years (2860 to 1390 BC). Six minima fall within 990 years, from 4325 to 3335 BC, and seven within 1,140 years, from 6400 to 5260 BC.

The named minima of the last millennium are dated in two ways. The historical dates are about the fourteenth century for the Wolf minimum, about 1450–1550 for the Spörer, 1645–1715 for the Maunder and about 1790–1820 for the Dalton [446]. The isotope table gives the Maunder 80 years centred on 1680 and the Spörer 160 years centred on 1470 [829].

The Maunder Minimum lasted 70 years by the historical dates, position 52.74. Every duration in the table sits between 51.60 (20 years) and 53.49 (160 years). Closure depth 53, at 93.4 years, lies inside that band, near its upper end, where the long Spörer-type minima stand.

North Atlantic drift-ice records of the Holocene vary together with the production of ^{14}C and ^{10}Be [830].

Single years stand out as well. Tree rings record sudden rises of ^{14}C, called Miyake events [831]. Six are listed: 12,350–12,349 BCE, 7176 BCE, 5259 BCE, about 664–663 BCE, AD 774–775 and AD 993–994 [831].

The oldest, found in trees of the French Alps, shows a ^{14}C rise nearly double that of AD 774, while the event behind it is inferred to be only about 18% stronger [831]. It lies about 14,400 years ago, position 57.58. The spike of 5259 BCE falls inside the long minimum centred on 5260 BC.

The sunspot record, 1755 to 2024

The Schwabe cycle lasts about 11 years, with “a variable length of 9–14 years for individual cycles” [446]. The fact sheet gives 11.4 years (51.09) [733]. The 11-year period sits at position 51.05.

The cycles are numbered from 1755. The revised International Sunspot Number (version 2.0, kept by SILSO) gives each minimum and maximum as a month and a smoothed sunspot number [832]:

Cycle	Minimum	SN at minimum	Maximum	SN at maximum	Length (yr-mo)	Rise (yr)
1	1755 Feb	14.0	1761 Jun	144	11-4	6.3

2	1766 Jun	18.6	1769 Sep	193	9-0	3.2
3	1775 Jun	12.0	1778 May	264	9-3	2.9
4	1784 Sep	15.9	1788 Feb	235	13-7	3.4
5	1798 Apr	5.3	1805 Feb	82	12-3	6.8
6	1810 Jul	0.0	1816 May	81	12-10	5.8
7	1823 May	0.1	1829 Nov	119	10-6	6.5
8	1833 Nov	12.2	1837 Mar	245	9-8	3.3
9	1843 Jul	17.6	1848 Feb	220	12-5	4.6
10	1855 Dec	6.0	1860 Feb	186	11-3	4.2
11	1867 Mar	9.9	1870 Aug	234	11-9	3.4
12	1878 Dec	3.7	1883 Dec	124	11-3	5.0
13	1890 Mar	8.3	1894 Jan	147	11-10	3.8
14	1902 Jan	4.5	1906 Feb	107	11-6	4.1
15	1913 Jul	2.5	1917 Aug	176	10-1	4.1
16	1923 Aug	9.3	1928 Apr	130	10-1	4.7
17	1933 Sep	5.8	1937 Apr	199	10-5	3.6
18	1944 Feb	12.9	1947 May	219	10-2	3.2
19	1954 Apr	5.1	1958 Mar	285	10-6	3.9
20	1964 Oct	14.3	1968 Nov	157	11-5	4.1
21	1976 Mar	17.8	1979 Dec	233	10-6	3.8
22	1986 Sep	13.5	1989 Nov	213	9-11	3.2
23	1996 Aug	11.2	2001 Nov	180	12-4	5.2
24	2008 Dec	2.2	2014 Apr	116	11-0	5.3
25	2019 Dec	1.8	2024 Oct	161	running	4.8

The rise is the time from minimum to maximum, computed from the months in the table. The source gives a median length of 11 years 3 months, a median minimum of 9.3 and a median maximum of 180 [832].

The 24 completed cycles span 264.83 years, from February 1755 to December 2019. Their mean length is 264.83 / 24 = 11.03 years (position 51.06), with a standard deviation of 1.16 years. The shortest is cycle 2 at 9.0 years (50.87), the longest cycle 4 at 13.58 years (51.24).

The maxima range from 81 (cycle 6) to 285 (cycle 19), a factor of 3.5, with a mean of 178. Twenty-one of the 24 completed cycles rise faster than they fall; cycles 1, 5 and 7 rise more slowly. The rise takes 2.9–6.8 years, 4.4 on average (50.22); the fall takes 6.7 years on average (50.60).

The shape of a cycle tracks its strength. Across the 25 cycles the rise time and the maximum correlate at r = −0.75: strong cycles rise fast. Across 24 pairs a long cycle is followed by a weak one, r = −0.70; the length of a cycle and its own maximum correlate only at r = −0.32.

The two weakest maxima, cycles 5 and 6 with 82 and 81, fall in 1805 and 1816, in the Dalton interval. The longest spells without spots between maxima lasted 1,028 days (1870–1883), 1,023 days (1906–1917), 817 days (2001–2014) and 849 days (2014–2024) [832]. The shortest spell, 227 days, fell between 1958 and 1968 [832].

Cycle 24 peaked at 116, the weakest in a century. Cycle 25 reached its maximum smoothed monthly number, 161, in October 2024; September gave 159 and November 157 [833]. The daily smoothed peak was 159 on 20 October 2024, and the predictions of 2019 were “significantly lower than reality” [833].

Other stars run cycles of the same kind. The Mount Wilson programme, begun by Olin Wilson in 1966, followed about 2,000 stars [806]. Of a core sample of 111 dwarfs, 60% show cyclic or apparently cyclic activity, 25% vary irregularly and 15% stay flat [806].

Among 65 solar-type stars and cooler dwarfs followed for decades, about half show cycles of 7–18 years (50.64–51.50) [807]. Cool dwarfs that turn faster than once in 5 days show brightness cycles of up to 80 years (52.86) [807]. Cycle length and rotation

period group the stars into an active and an inactive branch [806].

The Kepler mission measured rotation periods for 34,030 of 133,030 main-sequence targets, between 0.2 and 70 days (42.03–47.37) [804]. The Sun's 25–36 days sit inside that range. Spin slows with age, and ages from rotation and colour, calibrated on the Sun, reach a precision of about 15% [805].

The cycle reads as loading, holding and discharge, which the net's texts find on every timescale of the solar knot. The activity rises to its maximum in 4.4 years and decays over 6.7, and the stronger the loading, the faster the rise. The grand minima are the long rests of the same rhythm, one sixth of the time.

The longer periods

Behind the 11-year cycle stand longer ones, seen in sunspots, magnetograms and isotopes [446]. They are listed here from the shortest.

The Hale cycle of 22 years (position 51.68) is the magnetic polarity cycle: "The background for the 11-year Schwabe cycle is the 22-year Hale magnetic polarity cycle" [446]. The field returns to its starting polarity only after two Schwabe cycles.

As a reading, this has the form of a closure that is never loaded twice: it cannot load twice in succession without first discharging. Between two cycles of one polarity stands a cycle of the other.

The Gleissberg cycle has a "mean period of about 90 years" with "a varying timescale of 60–120 years" [446]. Ninety years sits at position 52.97, the range at 52.60–53.23.

Here the history reaches closure depth 53.

At that depth the ladder of three and the ladder of two nearly meet: $3^{53} \approx 2^{84}$, with a remainder of 1.00209. The time of the depth is $3^{53} \times 1.520655 \times 10^{-16}$ s = 2.948×10^{9} s, or 93.4 years.

The Gleissberg cycle stands there, 0.03 below the depth. The net's table of depths names the long solar cycle of 80–100 years in that row [29].

The de Vries or Suess cycle has "a period of 205–210 years" (53.72–53.74) [446]. Eddy-type variations have "a characteristic time of 600–700 years or 1000–1200 years" and come and go (54.69–54.83 or 55.16–55.32) [446]. The Hallstatt cycle of 2,000–2,400 years shows in radiocarbon (55.79–55.95) [446].

The slowest is the trend of about 6,000 years (56.79) in the nine-millennia reconstruction [828]. Together the seven periods fill positions 51.05 to 56.79, a band of less than six positions in time.

The torsional oscillation inside the Sun follows the 11-year cycle (above) [816]. The same period thus shows in the flows of the convection zone and in the spots at the surface.

Storms and flares, 1859 to 2024

Flares are graded by their soft X-ray flux at 0.1–0.8 nm [834]. Class A lies below 10^{-7} W m^{-2}, B at 10^{-7}–10^{-6}, C at 10^{-6}–10^{-5}, M at 10^{-5}–10^{-4} and X above 10^{-4} W m^{-2} [834].

At solar maximum several flares occur per day, at minimum less than one a week [834]. An average cycle brings about eight X10 flares and about 2,000 M1 flares [834]. Compact flares release 10^{22}–10^{23} J, long-duration flares up to about 10^{25} J, and a flare lasts about 15 minutes on average (position 39.34) [817].

Coronal mass ejections carry on average at least 1.6×10^{12} kg into space [835]. Their plane-of-sky speeds run from 20 to 3,200 km s^{-1}, with a mean of 489 km s^{-1} [835]. Their rate rises from about 0.2 a day at minimum to 3.5 a day at maximum, a factor of 17.5; they reach the Earth in 1–5 days (43.50–44.96) [835].

The first coronal mass ejection was seen in images on 14 December 1971 by OSO-7

[835]. The first flare was seen by eye more than a century earlier.

On 1 September 1859 Carrington and Hodgson watched a flare in white light [836]. The Greenwich magnetometer recorded a crochet beginning at 11:18 UT. The mass ejection crossed to the Earth in 17.5 hours (43.21), a mean speed of 2,356 km s⁻¹ [836].

The storm that followed reached a Dst index of about −900 nT (+50/−150) [836]. A single reading at Colaba gave −1,600 nT, and Tsurutani and colleagues gave −1,760 nT [836]. Aurorae reached down to about 18° geomagnetic latitude [836].

The flare is placed at class X45 (±5) [836]. It radiated about 5×10^{25} J; with the kinetic energy of the ejection the total was about 2×10^{26} J [836]. The best estimate of the proton fluence above 30 MeV is 1.1×10^{10} cm⁻², about twice the largest modern events at 5–7 × 10^{9} [836].

The storm of May 1921 came close, with Dst −825 to −900 nT and aurora at Samoa, 15.3° S geomagnetic [836]. Its sunspot group covered 1,709 millionths of the solar hemisphere against 2,300 in 1859 [836]. The storm of March 1989 reached −589 nT [836].

The largest flare measured by instruments came on 4 November 2003 [834]. It saturated the GOES detectors; it was first rated X28 by extrapolation and later X45 from its effects on the ionosphere [834]. Cliver and Dietrich give X35 (±5) [836].

The storm of 10–13 May 2024 reached a minimum Dst of −412 nT, with some readings at −518 nT [837]. It was rated G5 with Kp 9, and its Ap of 271 was the second highest after 13 November 1960 [837]. Its source was region 13664, whose largest flare of the episode was an X8.7 on 14 May [837].

Storms of that magnitude “occur approximately once every 12.5 years” (position 51.17), but one of that length was “expected only once every 41 years” (52.25) [833]. The strongest flare of cycle 25 so far was an X9.0 on 3 October 2024 [838].

Flare classes span at least five decades of X-ray flux, from below 10^{-7} to beyond 10^{-3} W m⁻². The storms at the Earth range from about −900 nT (1859, 1921) through −589 nT (1989) to −412 nT (2024).

As a reading, a flare has the form of discharge: the energy held in an active region is released in about 15 minutes on average. The coronal mass ejections follow the cycle, seventeen times more frequent at maximum than at minimum.

The Sun in the Galaxy

The Sun circles the centre of the Milky Way. The distance to the central black hole is R_0 = 8,178 ± 13 (stat) ± 22 (syst) pc, measured from the orbit of the star S2 with the GRAVITY instrument [784]. S2 orbits in about 16 years (position 51.39) and passed its pericentre in May 2018 [784].

That distance is 2.523×10^{20} m, or 26,670 light-years, position 58.15. Other sources give 24,000–28,000 light-years [133].

The centre’s apparent motion across the sky measures the Sun’s speed. Sagittarius A* moves −6.411 ± 0.008 mas yr⁻¹ along the Galactic plane and −0.219 ± 0.007 mas yr⁻¹ toward the north Galactic pole [839]. At R_0 = 8.178 kpc this gives 4.74047 × 6.411 × 8.178 = 248.5 km s⁻¹ for the Sun’s total speed along the plane.

The Sun moves relative to the local standard of rest at (U, V, W) = (11.1 ± 0.74, 12.24 ± 0.47, 7.25 ± 0.37) km s⁻¹ [840]. Subtracting V gives a circular speed of 248.5 − 12.2 = 236 km s⁻¹. The vertical motion from the proper motion, 4.74047 × 0.219 × 8.178 = 8.5 km s⁻¹, compares with W = 7.25 km s⁻¹.

The peculiar speed is $\sqrt{(11.1^2 + 12.24^2 + 7.25^2)}$ = 18.0 km s⁻¹. The fact sheet gives 19.4 km s⁻¹ relative to the nearby stars [733]. The Sun’s motion relative to the cosmic background light is about 370 km s⁻¹, toward a point near Vega [133].

The Sun sits 20.8 ± 0.3 pc above the Galactic midplane, by Gaia star counts [841]. That height is 6.42×10^{17} m, 67.8 light-years, position 52.71. In one orbit model the Sun

swings about 99 pc (54.13) from the plane with a period of about 83 million years (65.47) [133].

Closure depth 53, 93.4 light-years or 28.6 pc, lies between the Sun's present height (52.71) and its greatest distance from the plane (54.13). The same Gaia counts show the disc itself rippling: deficits of stars near 0.4, 0.9 and 1.5 kpc above the plane, excesses near 0.2, 0.7 and 1.1 kpc [841].

One circuit at 248.5 km s^{-1} takes $2\pi \times 2.523 \times 10^{20}$ m / 2.485×10^{5} m s^{-1} = 6.38×10^{15} s, or 202 million years (66.28). At 230 km s^{-1} it takes 218 million years (66.35). The quoted galactic year is 225–250 million years (66.38–66.47), with an orbital speed of about 251 km s^{-1} [133].

Since its birth the Sun has made 4,567 / 202 = 22.6 circuits, or 4,567 / 218 = 20.9. The source gives 20–25 orbits over its lifetime [133].

The Sun ahead

The main sequence holds the Sun for about 10^{10} years in all [745]. It leaves the main sequence in about 5 billion years (position 69.20) [751]. It then grows into a red giant of about 256 solar radii, about 1.2 AU, and loses 38% of its mass [751].

That radius, $256 \times 6.957 \times 10^{8}$ m = 1.78×10^{11} m, sits at size position 38.97, just beyond 1 AU at 38.81. The red-giant phase of a star of one solar mass lasts about 1 billion years (67.73) [751].

Stars of this kind end as white dwarfs. More than 97% of the stars of the Milky Way end so, and the observed masses of white dwarfs cluster strongly at 0.6 solar masses [842].

The Galaxy moves on meanwhile. In the next 15 million years (63.91), 694 stars will pass within 5 pc (51.41) of the Sun, 26 within 1.0 pc (49.95) and 7 within 0.5 pc [843]. The closest, Gliese 710, will pass at 0.167 ± 0.012 light-years (47.24) in about 1.29–1.30 million years (61.68) [843].

The Andromeda galaxy approaches. A forecast from Hubble data gives a first pericentre in 3.87 (+0.42/−0.32) billion years (68.97) and a merger in 5.86 (+1.61/−0.72) billion years (69.34) [844]. The Sun will most likely (85%) end at a larger radius in the merged galaxy, possibly beyond 50 kpc (10%) [844].

What this part of the history shows

As a reading, the Sun has the form of metabolism. It sends 4.26×10^{9} kg s^{-1} away as light and fuses about 6×10^{11} kg of hydrogen each second. Yet in 4.567 billion years it has lost only 0.031% of its mass to light.

The two carriers of its energy read as form and carrier. A neutrino leaves the core in 2.3 s; the energy carried by light needs 10,000 to 170,000 years to reach the surface. The core seen in neutrinos and the surface seen in light differ by a factor of 10^{11} to 10^{12} in travel time.

As a reading, the edge of chapter 24 shows at three places. The tachocline, 0.039 R☉ thick, gathers the shear between an interior turning as one body and an envelope turning by latitude. The transition region, about 100 km thick, raises the temperature by a factor of 50, and at the heliopause, 121–122 AU out, Voyager 1 saw the plasma density rise forty-fold.

No knot stands alone in the net's reading. The Sun's orbit runs at an acceleration of 2.08×10^{-10} m s^{-2}, 1.73 times the scale 1.20×10^{-10} m s^{-2} measured across 153 galaxies. Against that surrounding stretch the Sun's own pull ends near 5,350 AU (46.62), against the bare scale near 7,030–7,400 AU (46.87–46.92), beyond the flow edge at 43.17.

The activity reads as loading, holding and discharge. Cycles rise in 4.4 years on average and fall in 6.7, and the strongest rise fastest ($r = -0.75$). A flare releases its energy in about 15 minutes, the ejections grow seventeen-fold from minimum to maximum, and

the 27 grand minima since 9500 BC take about one sixth of the time.

The magnetic cycle reads as a closure never loaded twice. The polarity does not repeat from one Schwabe cycle to the next; the Hale cycle of 22 years returns it after two.

Closure depth 53 stands among the Sun’s longer rhythms. The Gleissberg cycle of about 90 years sits at 52.97, 0.03 below the depth at 93.4 years, and the 27 grand minima fill positions 51.60 to 53.49. In size, the depth at 93.4 light-years lies between the Sun’s height above the Galactic plane, 52.71, and its greatest excursion, 54.13.

In the net’s texts a star differs from a planet in kind: in a star the central stretch reaches closure for the heaviest knots present [26][845]. Jupiter sends out 4.60×10^{17} W from within; the Sun sends out 3.828×10^{26} W, 8.3×10^{8} times more [846].

The cycle is not the Sun’s alone. Of 111 dwarf stars followed since 1966, 60% cycle, and about half of 65 solar-type stars and cooler dwarfs show cycles of 7–18 years [806][807]. The Sun’s 11 years sits inside that range, and the same period runs in the flows below its surface and in the spots on it.

30. The Birth of Planets

The planets formed in the disk of gas and dust that circled the young Sun. Within a few million years the gas was gone, and the bodies left behind had taken up their orbits. This chapter follows that birth from the first grains to the scattering of the outer belts.

The Sun kept almost everything. Its mass is 1.9884×10^{30} kg [733], and the eight planets together hold 2.667×10^{27} kg [847]. The Sun thus holds 99.866% of the system's mass and the planets 0.134%.

Among the planets one dominates. Jupiter, at 1.898×10^{27} kg, holds 71% of the planetary mass, 2.47 times all the other planets together [847]. The four giants hold 99.56%; the four rocky planets share 1.18×10^{25} kg.

The history is read from two archives. Meteorites date the first solids and the growth of bodies, to within fractions of a million years. Disks around young stars show the same stages now, elsewhere in the Galaxy; numerical models connect the two and are reported here as models.

A disk around a young star

A star forms when a core of a molecular cloud collapses (chapter 29) [736]. The Milky Way's disk holds 8,107 catalogued molecular clouds with 1.2×10^{9} solar masses of molecular hydrogen [734]. The most probable cloud radius is about 30 pc, position 53.04 [734].

That radius stands near closure depth 53, which in size is 93.4 light-years, or 28.6 pc. Inside the clouds the scales fall: clumps average 1 pc (49.95), cores are a factor 10 smaller, and dense cores along filaments are spaced 0.15 pc apart (48.22) [735].

Most prestellar cores lie within 0.1 pc (47.85) of dense filaments [736]. A cluster forms dozens to tens of thousands of stars at nearly the same time [736].

The sharpest picture of the disk around a young star was taken in 2014.

During its Long Baseline Campaign, the ALMA array imaged the disk of the young star HL Tau at wavelengths of 2.9, 1.3 and 0.87 mm [848]. The angular resolution reached 0.075″ to 0.025″, "about 10 to 3.5 AU" (positions 40.90 to 39.95) [848]. The disk showed bright and dark rings at all three wavelengths.

The rings are ellipses on the sky. Fitted to the clearest rings, they give an inclination of $46.72 \pm 0.05°$ and a position angle of $+138.02 \pm 0.07°$ [848]. The ring offsets increase with radius, and many orbital resonances are present among the rings [848].

The spectral index at 1.0 mm is about 2.0 in the optically thick central peak and in the two brightest rings [848]. In the dark rings it is 2.3–3.0. The grain emissivity index is 0.8 in the innermost dark ring and lower in the later ones, which the authors read as grain growth [848].

The gas moves as the planets move. Lines of HCO^{+} (1–0), at a resolution of 35 AU (42.04), show velocities of 2–12 km s^{-1} "consistent with Keplerian motion around a ~1.3 solar mass star" [848].

As a reading, the rings of HL Tau have the form of what fits, stays. Many orbital resonances are present among the rings, and the dark rings hold other grains than the bright ones.

The first solids

The clock of planet formation starts with the oldest grains in meteorites. These are the calcium–aluminium-rich inclusions, CAIs, preserved in chondritic meteorites [265].

Uranium-corrected lead–lead dating of single CAIs gives 4,567.30 ± 0.16 million years [265]. One CAI from the meteorite Northwest Africa 2364 gives 4,568.2 million years, making the Solar System “0.34–1.91 million years older than previously thought” [266]. The two ages stand 0.9 million years apart (position 61.35); both sit at time position 69.12.

The chondrules formed next. Their ages run from 4,567.32 ± 0.42 to 4,564.71 ± 0.30 million years [265]. From the first CAI to the youngest dated chondrule is 2.59 million years (62.31); the whole process lasted about 3 million years (62.45) [265].

All later events in this chapter are counted in millions of years after the CAIs. The meteorites that carry them still fall. About 86% of observed falls are chondrites, 8% achondrites, 5% irons and 1% stony-irons [849].

From dust to planetesimals

Between the grains and the planets lies a gap in size. Simulations frame the problem as the step “from metre-sized boulders to kilometre-scale planetesimals” [850]. One metre sits at size position 15.39, one kilometre at 21.67.

Boulders of a metre spiral into the young star “in a few hundred orbits” [850]. At 1 AU an orbit lasts one year, so the drift takes a few hundred years (300 years: position 54.06). At Jupiter’s distance an orbit lasts 4,332.589 days, 11.86 years [847], and 300 orbits last about 3,600 years (56.31).

In the simulations the solids gather faster than they drift. Turbulence concentrates them, and a streaming instability augments the concentration “a further order of magnitude” [850]. Gravitationally bound clusters then form “with masses comparable to dwarf planets”, and the collapse “happens much faster than radial drift” [850].

Linear theory gives the condition. The streaming instability grows fastest when the density of solids and gas are of the same order, and it grows faster than the radial drift [851]. These are results of theory and simulation.

The measured record shows bodies of about 100 km early on (position 25.87) [273]. From them grew planetary embryos with diameters of about 1,000–5,000 km (27.96–29.43) [273].

The asteroid belt holds survivors of this stage. Its mass, from the motions of planets and spacecraft, is $(4.008 \pm 0.029) \times 10^{-4}$ Earth masses [852]. That is $4.008 \times 10^{-4} \times 5.9724 \times 10^{24} = 2.394 \times 10^{21}$ kg, 3.3% of the Moon’s mass.

Between 700,000 and 1.7 million belt asteroids are 1 km or larger, and over 200 exceed 100 km [853]. Ceres, Vesta, Pallas and Hygiea hold about 62% of the belt’s mass, Ceres alone 39% [853].

Ceres has a mean diameter of 939.4 km (27.90) and a density of 2.16 g cm^{-3} [854]. Vesta has a mean diameter of 525.4 ± 0.2 km (27.38), a density of 3.456 ± 0.035 g cm^{-3} and a core 90–220 km across [855]. One meteorite in sixteen comes from Vesta, and over 1,200 of its HED meteorites are known [855].

Vesta grew early. Its mean accretion time by the hafnium–tungsten clock is $\bar{t} = 0.8 \pm 0.8$ million years after the CAIs (61.24), or 2.6 million years in a two-stage model [268].

The sizes climb the ladder step by step. Boulders of a metre sit at 15.39, planetesimals of a kilometre at 21.67 and of 100 km at 25.87. Embryos of 1,000–5,000 km sit at 27.96–29.43, and the Earth’s diameter of 12,756 km at 30.28 [847].

As a reading, this sequence has the form of the residue that becomes the alphabet. Each closed body becomes a letter of the next closure: grains build planetesimals, planetesimals build embryos, embryos build planets.

Jupiter first

The iron meteorites record the next step. Their molybdenum and tungsten isotopes fall

into two genetic groups, a non-carbonaceous reservoir (NC) and a carbonaceous reservoir (CC) [856]. The two reservoirs coexisted and stayed apart from about 1 million years to 3–4 million years after the CAIs [856].

Something held them apart for that time. The authors name a gap opened by Jupiter as “the most plausible mechanism for this efficient separation” [856]. On that reading Jupiter’s core reached about 20 Earth masses in less than 1 million years (position 61.45), then grew more slowly to about 50 Earth masses by at least 3–4 million years (62.45–62.71) [856].

Twenty Earth masses are $20 \times 5.9722 \times 10^{24} = 1.19 \times 10^{26}$ kg, and fifty are 2.99×10^{26} kg. Jupiter today has $1{,}898.13 \times 10^{24}$ kg, 317.8 Earth masses [847]. The early core was 6.3% of the planet of today.

That makes Jupiter the oldest planet of the Solar System [856]. Its core stood before the youngest dated chondrule (2.59 million years) and before half the disks around young stars have dispersed (1.7 million years, next section).

As a reading, the two reservoirs have the form of the edge of chapter 24. On either side the material keeps its own isotopic signature; at the edge the two do not mix, for two to three million years.

The disk clears

Disks around young stars are counted in clusters of known age. The surveys measure an excess of light in the L band at 3.5 µm, the mark of a disk [857].

A survey of the clusters NGC 2264, NGC 2362 and NGC 1960 found disk fractions of 52 ± 10%, 12 ± 4% and 3 ± 3% [857]. With other clusters the sample spans ages of 0.3 to 30 million years (60.35 to 64.54). The initial disk fraction is “> 80%” [857].

Half the stars in a cluster lose their disks in less than about 3 million years (62.45) [857]. The overall disk lifetime is about 6 million years (63.08): “This is the timescale for essentially all the stars in a cluster to lose their disks” [857].

A wider compilation fits the decline with an exponential [858]. The fraction of young stars with optically thick disks or signs of accretion falls with a characteristic time of about 2.5 million years (62.28), a half-life of 1.7 million years (61.93) [858]. The check is $1.7 / \ln 2 = 2.45$ million years.

With that time, $e^{(-6/2.5)} = 9\%$ of the disks remain after 6 million years, and $e^{(-10/2.5)} = 1.8\%$ after 10 million years. The clusters themselves scatter about the curve: samples of the same age, 2–5 million years, differ from cluster to cluster [858].

The time depends on the star. It ranges from about 1 million years for stars above 1.3 solar masses to about 3 million years for brown dwarfs below 0.08 solar masses [858]. HL Tau’s star, at about 1.3 solar masses, stands at the border of the short-lived class.

As a reading, the form of context shows here: the same rule takes other values in other surroundings. The same dispersal runs around every young star, and its time takes another value with another central mass, from 1 to 3 million years.

The giant planets had to gather their gas within this window. Jupiter’s core of 20 Earth masses within 1 million years stands inside the first half-life. Among the 6,445 planets now confirmed around other stars, one was found through the kinematics of its disk [859].

Embryos and the rocky planets

The hafnium–tungsten clock dates the growth of the rocky bodies. ^{182}Hf decays to ^{182}W with a half-life of 9 million years (63.45) [268]. It dates the growth of bodies and the formation of their cores [268][274].

The clock orders the bodies by size [268]. Vesta accreted with a mean time of 0.8 ± 0.8 million years after the CAIs. The source rock of the Martian shergottites gives 2 (+3/−2)

million years, and the Earth 11 ± 1 million years (63.63), with core formation complete at 29.5 million years in a two-stage model (64.53).

Mars was about half its present size within “two million years or less” (62.08) [273]. It is counted as a planetary embryo [273]. The cores of Vesta, Mars and the Earth formed “during the first ~30 million years” (64.54) [274].

The Earth/Mars mass ratio is 5.9722 / 0.64169 = 9.31 [847]. A numerical model, the Grand Tack, gives a ratio consistent with it [860]. In that model Jupiter migrates inward through the gas disk “to 1.5 au” (39.18) and then outward again [860].

Jupiter’s turn leaves the disk of planetesimals “truncated at 1 au” (38.81), and from it the rocky planets form over 30–50 million years (64.54–65.01) [860]. Scattering by Jupiter “initially empties but then repopulates the asteroid belt”, with inner-belt bodies coming from 1–3 AU [860].

The four rocky planets differ in size and in density [847]. Mercury is 4,879 km across at 5,429 kg m^{-3}, Venus 12,104 km at 5,243 and the Earth 12,756 km at 5,514. Mars is 6,792 km across at 3,934 kg m^{-3}.

The densest planet is the Earth, and the smallest, Mercury, is nearly as dense. Mars, the embryo, is the lightest of the four in density.

The giants rearrange

In the models the giants moved after they formed. A numerical model, the Nice model, derives their present orbits from an earlier arrangement [861].

The model reproduces the present eccentricities of Jupiter, Saturn and Uranus, given there as about 6, 9 and 8 per cent, and orbital planes within about 2° of Jupiter’s [861]. The fact sheets give the present eccentricities as 0.0487, 0.0520 and 0.0469 [847]. The result holds “provided that Jupiter and Saturn crossed their 1:2 orbital resonance” [861].

Today Saturn’s period of 10,747 days stands 2.48 times Jupiter’s 4,331 days [847]. The pair lies beyond the 1:2 ratio the model has them cross.

A companion model places a spike of impacts late. “A cataclysmic spike in the cratering rate occurred ~700 million years after the planets formed” (67.41), from a sudden delivery of planetesimals to the inner Solar System [337]. Counted from 4,567 million years ago, that places the spike near 3,870 million years ago (68.97).

On the Earth the oldest impact spherule bed, S1 at Warrawoona, dates to about 3,472 million years ago (68.87) [862].

Beyond Neptune lie the outer belts. The Kuiper belt reaches from Neptune’s orbit at 30 AU to about 50 AU (41.90–42.37) [863]. More than 100,000 bodies larger than 100 km are thought to orbit there, and over 2,000 had been found by 2018 [863].

The Kuiper belt holds (1.97 ± 0.030) × 10^{-2} Earth masses, 1.18 × 10^{23} kg, about 49 times the asteroid belt [852]. Its dynamically hot population carries about 1% of an Earth mass, the cold population about 0.03% [863].

Neptune’s resonances mark the belt. About 200 known bodies, Pluto among them, orbit in the 2:3 resonance with Neptune [863]. The classical belt lies between the 2:3 and the 1:2 resonances, at about 42–48 AU (42.21–42.33), and “The 1:2 resonance at 47.8 AU appears to be an edge” [863].

Pluto’s period of 90,560 days is 1.514 times Neptune’s 59,800 days, 0.9% from 3:2 [847]. Its orbit, inclined 17.16°, reaches at perihelion 4,436.8 × 10^{6} km from the Sun, inside Neptune’s aphelion at 4,558.9 × 10^{6} km [847][847].

The belt holds bodies that New Horizons has visited. Arrokoth, passed on 1 January 2019, is 34.5 km along its longest axis (24.90), two lobes of 20.1 km and 15.0 km joined [864]. It orbits at 44.2 AU (42.26) in 294 years [864].

Farther out lies the Oort cloud, known from the orbits of long-period comets and from

models. It spans about 2,000 to 200,000 AU (45.73–49.92) [865]. In all, 50–100 Earth masses of material are estimated to have been thrown out; the outer cloud holds about 5 Earth masses, with an older estimate of up to 380 [865].

Jupiter's resonances mark the inner belt in the same way. Kepler's third law gives the semimajor axes where an asteroid's period is a simple fraction of Jupiter's 4,332.589 days [847]. The 4:1 ratio falls at 2.064 AU, 3:1 at 2.500 AU, 5:2 at 2.824 AU, 7:3 at 2.957 AU and 2:1 at 3.277 AU (positions 39.47 to 39.89).

The belt's inner boundary is the 4:1 Kirkwood gap at 2.06 AU, and its dense core lies between the 4:1 and 2:1 gaps at 2.06 and 3.27 AU [853]. Few asteroids orbit beyond 4.2 AU (40.11) until Jupiter's orbit [853].

In the net's reading, Kepler's third law is the closure condition of an orbit in a field that thins as $1/r^2$ [827]. The Kirkwood gaps are orbits that did not return in phase and were unwound [827].

In the texts' words: "What fits, stays." [827]

Between Saturn at 9.57 AU (40.86) and Uranus at 19.17 AU (41.50) lies closure depth 41. It sits at $3^{41} \times 4.558816 \times 10^{-8}$ m = 1.66×10^{12} m, or 11.1 AU, where the ladder of three and the ladder of two nearly meet (chapter 24). The giant planets straddle it; chapter 31 follows what stands there.

What the birth left

The orbits that came out of the disk are listed in the fact sheets [847]. The semimajor axes in AU follow from the mean distances with 1 AU = 149.598×10^6 km.

Body	Distance (AU)	Size position	Period (days)	Time position	Mass (10^{24} kg)	Density (kg m^{-3})	Inclination (°)	Eccentricity
Mercury	0.387	37.94	88.0	47.57	0.330	5,429	7.0	0.206
Venus	0.723	38.51	224.7	48.43	4.87	5,243	3.4	0.007
Earth	1.000	38.81	365.2	48.87	5.97	5,514	0.0	0.017
Mars	1.524	39.19	687.0	49.45	0.642	3,934	1.8	0.094
Jupiter	5.204	40.31	4,331	51.12	1,898	1,326	1.3	0.049
Saturn	9.572	40.86	10,747	51.95	568	687	2.5	0.052
Uranus	19.165	41.50	30,589	52.90	86.8	1,270	0.8	0.047
Neptune	30.181	41.91	59,800	53.51	102	1,638	1.8	0.010
Pluto	39.482	42.15	90,560	53.89	0.0130	1,850	17.2	0.244

Two groups stand apart. The four inner planets have densities of 3,934–5,514 kg m^{-3} and diameters of 4,879–12,756 km [847]. The four giants have densities of 687–1,638 kg m^{-3} and diameters of 49,528–142,984 km (positions 31.51–32.48) [847].

The asteroid belt lies between the two groups, from 2.06 to about 4.2 AU. In size position the inner planets fill 37.94–39.19, the belt 39.47–40.11 and the giants 40.31–41.91.

The ratios of successive periods are 2.553 (Venus/Mercury), 1.625 (Earth/Venus), 1.881 (Mars/Earth) and 6.304 (Jupiter/Mars). Beyond Jupiter they are 2.481 (Saturn/Jupiter), 2.846 (Uranus/Saturn), 1.955 (Neptune/Uranus) and 1.514 (Pluto/Neptune). The largest step, 6.304, spans the belt.

Two closure depths frame the giants' orbits. In size, depth 41 at 11.1 AU lies between Saturn and Uranus. In time, depth 53 at 93.4 years lies between the periods of Uranus, 83.7 years (52.90), and Neptune, 163.7 years (53.51).

The orbits share one direction. All eight planetary orbits are inclined between 0.0° and 7.0° to the ecliptic, so all run around the Sun in the same sense [847]. The Sun's own equator is tilted 7.25° to the ecliptic, so it too turns in the same sense [733].

Most spins follow. Mercury, the Earth, Mars, Jupiter, Saturn and Neptune have obliquities between 0.034° and 28.3° [847]. Venus, at 177.4°, turns backward, once in

243.0 days; Uranus turns on its side at 97.8°, and Pluto at 119.5° [847][847].

Among the large moons one orbits against the rest. Triton “has a retrograde orbit, indicating that it was captured rather than forming in place” [866].

As a reading, the planets carry the form of one direction. The rule is symmetric; the system keeps one sense, shared by the Sun’s spin and by the orbits. The net’s texts read the ecliptic as the plane in which the solar winding closed [701].

The same birth around other stars

Around other stars 6,445 planets are confirmed [859]. Among them, 1,070 systems hold two or more planets [867]. Their orbits show the same forms as the Sun’s system, and chapter 33 gives them in full.

One system has eight known planets, like the Sun’s: KOI-351, or Kepler-90 [867]. Its periods run from 7.008151 days (position 45.27) to 331.60296 days (48.78), all inside the Earth’s year. The ratios of neighbouring periods are 1.244, 1.657, 4.134, 1.539, 1.359, 1.687 and 1.574.

Some systems keep their resonances whole. TRAPPIST-1 has “at least seven planets similar to Earth in radius and in mass”, in “a complex chain, with three-body resonances linking every member” [868]. Its periods run from 1.510826 days (43.88) to 18.772866 days (46.17) [867].

The neighbour ratios of TRAPPIST-1 are 1.6031 (near 8:5), 1.6719 (5:3), 1.5067 and 1.5092 (3:2), 1.3416 (4:3) and 1.5198 (3:2). Its masses are known to 3–5%, and the system is “stable on 10 Myr timescales” [869].

Kepler-223 holds “a resonant chain of four transiting, sub-Neptune planets” [870]. Its period ratios are 1.3333, 1.5021 and 1.3338, a chain of 3:4:6:8 [867]. In TOI-178, “All planets but the innermost one form a 2:4:6:9:12 chain of Laplace resonances” [871]; the neighbour ratios from the archive periods are 1.692, 2.025, 1.519, 1.529 and 1.360.

Not every planet stays bound to a star. Microlensing towards the Galactic bulge finds 21 (+23/−13) free-floating or very-wide-orbit planets of 0.33–6,660 Earth masses per star, with a total mass of 80 (+73/−47) Earth masses per star [872]. Planets of Jupiter’s mass are rare among them: at most 0.25 per main-sequence star [873].

The Sun’s system threw out a comparable mass. The material estimated to have been ejected in the making of the Oort cloud amounts to 50–100 Earth masses [865].

The bodies born from clouds and disks divide by mass. Half of a body’s initial deuterium burns at about (13.0 ± 0.8) Jupiter masses for most conditions [747]. Brown dwarfs run from about 13 to 80 Jupiter masses; above about 80 Jupiter masses, 0.080 ± 0.008 solar masses, hydrogen fuses and the body is a star [746].

Jupiter has 1/1,047.6 of the Sun’s mass [847][733]. Eighty Jupiter masses are thus 0.076 solar masses. In the field, brown dwarfs between 0.01 and 0.08 solar masses make up 37% of the objects and 4.3% of the mass [742].

In the net’s texts planet and star differ in kind: a planet reads, a star opens. In a star the central stretch reaches closure for the heaviest knots present; a planet passes what its meshes let through [26][845].

What this part of the history shows

As a reading, the birth of planets has the form of the residue that becomes the alphabet. Boulders of a metre (position 15.39) gather into planetesimals of a kilometre (21.67) and of 100 km (25.87). Planetesimals build embryos of 1,000–5,000 km (27.96–29.43), and embryos build planets: the Earth at 30.28, Jupiter at 32.48.

The hafnium–tungsten clock orders the bodies by size. Vesta accreted within about a million years, Mars reached half its size within two million years, and the Earth took 11 million years on average and about 30 million for its core.

The two isotopic reservoirs read as the edge. Non-carbonaceous and carbonaceous material stayed apart from about 1 to 3–4 million years after the first solids. On the authors' reading, Jupiter's core of 20 Earth masses, grown within the first million years, stood at that edge.

The disk's dispersal reads as the form of context. Half the disks are gone within 1.7 million years, nearly all within 6. The same dispersal takes about 1 million years around stars above 1.3 solar masses and about 3 million around brown dwarfs.

The orbits show what fits, stays. Kepler's law places the resonances with Jupiter at 2.06, 2.50, 2.82, 2.96 and 3.28 AU, and the belt's inner edge and dense core stand at the 4:1 and 2:1 ratios, 2.06 and 3.27 AU. Pluto runs 1.514 times Neptune's period, 0.9% from 3:2, and the Kuiper belt ends at the 1:2 resonance at 47.8 AU.

Other systems show the same form whole. TRAPPIST-1 links seven planets in neighbour ratios of 8:5, 5:3, 3:2, 3:2, 4:3 and 3:2; Kepler-223 runs a 3:4:6:8 chain, and TOI-178 a 2:4:6:9:12 chain. The rings of HL Tau show many resonances among themselves.

The system keeps one direction. Eight orbits lie within 7.0° of the ecliptic and the Sun's equator within 7.25°. The exceptions, Venus, Uranus, Pluto and the captured Triton, stand out against that common sense.

In the models the giants' rearrangement reads as loading, holding and discharge. A long hold of about 700 million years ends in a sudden delivery of planetesimals to the inner planets. The Earth's oldest spherule bed, at 3,472 million years, comes about 1,100 million years after the first solids.

Closure depth 53 stands at the start of the history: the most probable radius of a molecular cloud, about 30 pc, sits at 53.04, against 53.00 for the depth. In time the same depth lies between the periods of Uranus and Neptune. In size closure depth 41, at 11.1 AU, lies between Saturn and Uranus.

Star and planets came from one disk and parted in kind. The Sun kept 99.866% of the mass; the planets hold 0.134%. In the net's texts a planet reads and a star opens: in a star the central stretch reaches closure for the heaviest knots present [26][845].

31. The Planets and Their Moons

Chapter 30 left the Sun with a disk that was gone within a few million years. What remained were eight planets, a dwarf planet called Pluto, several hundred moons, and the rings of four giants. This chapter describes that family as it stands now, measured by telescopes and spacecraft.

On the ladder of chapter 24 the planets fill a narrow band. Their diameters run from 4,879 km (position 29.40) to 142,984 km (32.48). Their distances from the Sun run from 0.387 AU (37.94) to 30.18 AU (41.91), and their years from 88.0 days (47.57) to 164 years (53.51).

Inside that band lies one closure depth of the net: depth 41, at 11.1 AU and 92.4 minutes. It falls in the empty stretch between Saturn and Uranus. The section on depth 41 gives what stands there.

The family as it stands

The NASA planetary fact sheets give one table for all the planets [847][847]. One astronomical unit (AU) is 1.495978707 × 10^{11} m, at position 38.81. The table below gives each planet’s mean distance, diameter and orbital period, with their positions.

Body	Distance (10^6 km)	AU	pos	Diameter (km)	pos	Period (days)	pos	[n]
Mercury	57.9	0.387	37.94	4,879	29.40	88.0	47.57	[847]
Venus	108.2	0.723	38.51	12,104	30.23	224.7	48.43	[847]
Earth	149.6	1.000	38.81	12,756	30.28	365.256	48.87	[847] [847]
Mars	228.0	1.524	39.19	6,792	29.71	687.0	49.45	[847]
Jupiter	778.5	5.204	40.31	142,984	32.48	4,332.589	51.12	[847] [847]
Saturn	1,432.0	9.572	40.86	120,536	32.32	10,747	51.95	[847]
Uranus	2,867.0	19.165	41.50	51,118	31.54	30,589	52.90	[847]
Neptune	4,515.0	30.181	41.91	49,528	31.51	59,800	53.51	[847]
Pluto	5,906.4	39.482	42.15	2,376	28.75	90,560	53.89	[847]

Two groups stand apart in it [847]. The four inner planets have densities of 3,934–5,514 kg/m³ and diameters of 4,879–12,756 km (positions 29.40–30.28). The four giants have densities of 687–1,638 kg/m³ and diameters of 49,528–142,984 km (31.51–32.48).

The masses differ by far more than the sizes [847][847]. Jupiter holds 1,898.13 × 10^{24} kg, which is 1,898.13 / 5.9722 = 317.8 Earth masses.

The other seven together hold 0.330 + 4.87 + 5.97 + 0.642 + 568 + 86.8 + 102 = 768.6 × 10^{24} kg. Jupiter alone has 2.47 times the mass of all the rest.

The orbits are nearly flat and nearly round [847][847]. Inclinations to the Earth’s orbit run from 0.0° to 7.0° (Mercury), and only Pluto lies at 17.2°. Eccentricities run from 0.007 (Venus) to 0.206 (Mercury), with Pluto at 0.244.

All orbital inclinations lie far below 90°, so all the planets go round the Sun in one sense. One of the net’s texts reads the ecliptic as the plane in which the Sun’s winding closed, and the zodiac as the human record of that ring [701]. As a reading, the form is one direction: the net keeps the direction of what was laid down first, here the turn of the disk.

The rotations are less orderly than the orbits [847][847]. Giants turn in 9.9 to 17.2 hours (positions 42.70–43.20); Venus turns backward once in 243.0 days (48.50); Mercury turns three times in two orbits. Obliquities run from 0.034° (Mercury) through 23.44° (Earth) and 97.77° (Uranus) to 177.36° (Venus).

Mercury, Venus, Earth and Mars

Mercury. The innermost planet has a mass of 0.33010 × 10²⁴ kg, a density of 5,429 kg/m³ and a surface gravity of 3.70 m/s² [847]. It orbits at 57.909 × 10⁶ km (37.94), between a perihelion of 46.0 × 10⁶ km (37.73) and an aphelion of 69.8 × 10⁶ km (38.11). Its eccentricity, 0.2056, is the largest of the eight planets, and its inclination is 7.004°.

Mercury turns once in 1,407.6 hours (47.21) and goes round the Sun in 88.0 days, which is 2,112 hours [847][847]. The ratio is 1,407.6 / 2,112 = 0.667, two thirds: three turns in two orbits. One solar day on Mercury lasts 4,222.6 hours (48.21), and 4,222.6 / 2,112 = 2.00 orbits.

The surface averages 440 K (167 °C) and reaches 590–725 K on the sunward side [847]. The pressure of its gas is below about 5 × 10⁻¹⁵ bar. Its Bond albedo is 0.068, its black-body temperature 439.6 K, and its moment of inertia factor 0.35.

Venus. Venus has 4.8673 × 10²⁴ kg, a density of 5,243 kg/m³ and a gravity of 8.87 m/s² [847]. It turns backward once in 5,832.6 hours, 243.0 days (48.50); the comparison table prints 5,832.5 hours [847]. Its year lasts 224.7 days (48.43), so its sidereal day is 1.082 times its year, and one solar day lasts 2,802.0 hours, 116.75 days (47.83).

The rotation of Venus sits at position 48.50, between two layers of the ladder. The net's climate text reads a small group of cycles as lying on half-layers: the day (43.50), the rotation of Venus, the lunar beat and the Saros [29]. The half layer is a reading of that text, which gives the half step as measured.

The atmosphere of Venus weighs about 4.8 × 10²⁰ kg, 9.9 × 10⁻⁵ of the planet [847]. It is 96.5 % carbon dioxide and 3.5 % nitrogen, with 150 ppm sulphur dioxide, 70 ppm argon and 20 ppm water. At the ground the pressure is 92 bar and the gas density about 65 kg/m³, 6.5 % of the density of liquid water.

The surface averages 737 K (464 °C), with almost no difference between day and night [847]. The black-body temperature is 226.6 K, so the surface stands 737 − 226.6 = 510 K above it. Venus is 108.2 / 57.9 = 1.87 times farther from the Sun than Mercury, yet its surface is 297 K hotter than Mercury's average.

Surface winds blow at 0.3–1.0 m/s, and the scale height of the air is 15.9 km (24.19) [847]. The Bond albedo of Venus is 0.77, the highest of the planets on the sheets. Mercury has 0.068, Earth 0.294, Mars 0.250, Jupiter 0.343, Saturn 0.342, Uranus 0.300, Neptune 0.290 and Pluto 0.72.

Earth. The Earth has 5.9722 × 10²⁴ kg, an equatorial radius of 6,378.1 km (29.65) and a polar radius of 6,356.8 km [847]. Its density is 5,513 kg/m³ on the planet sheet and 5,514 kg/m³ in the comparison table, the highest of all the planets [847][847]. It turns in 23.9345 hours (43.50) and orbits in 365.256 days (48.87) at an eccentricity of 0.0167 and an obliquity of 23.44°.

Its Moon has 0.073 × 10²⁴ kg, a diameter of 3,475 km (29.10) and a density of 3,340 kg/m³ [847]. It orbits at 0.384 × 10⁶ km (33.38) in 27.3 days (46.51). It turns once in 655.7 hours, 27.32 days, the same as its orbit: one face always looks at the Earth.

Mars. Mars has 0.64169 × 10²⁴ kg, an equatorial radius of 3,396.2 km (29.07) and a density of 3,934 kg/m³ [847]. It turns in 24.6229 hours (43.52) and its solar day lasts 24.6597 hours (43.52). Its obliquity, 25.19°, is close to the Earth's, and its eccentricity is 0.0935.

The Earth has 5.9722 / 0.64169 = 9.31 times the mass of Mars [847]. The air of Mars weighs about 2.5 × 10¹⁶ kg and is 95.1 % carbon dioxide, 2.59 % nitrogen, 1.94 % argon, 0.16 % oxygen and 210 ppm water. At mean radius the pressure is 6.36 mbar, ranging from 4.0 to 8.7 mbar with the seasons.

The air averages about 214 K (−59 °C) on the planet sheet; the comparison table gives −65 °C [847][847]. At the Viking 1 lander the day ran from 184 K to 242 K. The Bond albedo is 0.250 and the black-body temperature 209.8 K.

The history of water on Mars is told in layers of depth and time. About 4.5 Ga ago (position 69.10) Mars held enough water to cover the planet at least 137 m deep (19.86)

[890]. That figure comes from the ratio of deuterium to hydrogen in its water vapour today, about 7 times that of the Earth’s ocean, and at least 8 times in the polar ice.

Large volumes of liquid water existed on the surface more than 3 billion years ago (68.73) [891]. Geomorphic evidence allows past surface water as deep as 500 m (21.04) [900]. Estimates of the area of an ancient ocean differ: 36 % of the planet (a 2010 study) and 19 % (a 2015 deuterium study) [900].

The water has not all left. The polar caps hold water ice equal to a global layer 30 m deep (18.48), a volume similar to the Greenland ice sheet [900]. Seismic velocities and gravity near the InSight lander are best fitted by fractured igneous rock saturated with liquid water at 11.5 to 20 km depth (23.90–24.40) [891].

A 2025 study placed a water layer at 5.4 to 8 km depth (23.21–23.57), equal to an ocean 520 to 780 m deep (21.08–21.45) [900]. The present air holds 210 ppm water vapour [847]. In order of size: 30 m of polar ice now, at least 137 m early on, up to 500 m from landforms, and 520–780 m in the crust.

Olympus Mons, the great volcano of Mars, rises 21.287 km (24.46) above the Martian datum on a base about 600 km wide (27.50) [899]. Its height is 1/28 of its width and 0.63 % of the radius of Mars.

The local relief to the summit approaches 26 km (24.64) [899]. The caldera measures 60 × 80 km (25.40–25.66) and is up to 3.2 km deep (22.73); a basal cliff rises up to 8 km (23.57). The mean flank slope is only 5 %, and the magma chamber lies about 32 km (24.83) below the caldera floor.

Crater counts date the youngest lava flows on the north-west flank to between 115 million years (65.76) and 2 million years (62.08) [899]. The volcano was active within the last few million years of the planet’s 4.5-billion-year history.

The two moons of Mars are small [847]. Phobos has radii of 13.0, 11.4 and 9.1 km (longest axis 26 km, 24.64), a mass of 10.6×10^{15} kg and a density of 1,900 kg/m³. Deimos has radii of 7.8, 6.0 and 5.1 km (longest axis 15.6 km, 24.17), 2.4×10^{15} kg and 1,750 kg/m³.

Phobos orbits at 9,378 km (30.00), only 2.76 Mars radii from the centre, in 0.31891 days, which is 7.654 hours (42.46) [847]. That is shorter than the 24.6229-hour turn of Mars: Phobos goes round 24.6229 / 7.654 = 3.2 times while Mars turns once. Deimos orbits at 23,459 km (30.83) in 1.26244 days, 30.30 hours (43.71).

Jupiter and Saturn

Jupiter. Jupiter has $1{,}898.13 \times 10^{24}$ kg in a volume of $143{,}128 \times 10^{10}$ km³ [847]. Its equatorial radius at the 1-bar level is 71,492 km (31.85) and its polar radius 66,854 km (31.79). The flattening is (71,492 − 66,854) / 71,492 = 0.065.

Its density is 1,326 kg/m³, its escape velocity 59.5 km/s [847]. Surface gravity is 25.92 m/s² on the planet sheet (mean, 1 bar) and 23.1 m/s² in the comparison table [847][847]. Its moment of inertia factor is 0.254 and its gravity harmonic J_2 is $14{,}736 \times 10^{-6}$.

Jupiter turns in 9.9250 hours (42.70), the shortest day of the planets [847]. It orbits at 778.479×10^{6} km, 5.2038 AU (40.31), in 4,332.589 days, 11.862 years (51.12). Its eccentricity is 0.0487, its inclination 1.304° and its obliquity 3.13°.

These two numbers carry Kepler’s third law. In AU and years, $5.2038^3 / 11.862^2 = 140.92 / 140.71 = 1.0015$, against exactly 1 for the Earth. One of the net’s texts reads that law as the closure condition of a winding in the stretch around one knot, and an ellipse as the shape of a closed winding there [827].

The 1-bar level stands at 165 K (−108 °C) [847]. The gas is 89.8 % hydrogen and 10.2 % helium by volume, each ± 2.0 %. Winds blow up to 150 m/s within 30° of the equator and up to 40 m/s beyond.

Jupiter’s core reached about 20 Earth masses (1.19×10^{26} kg) within 1 million years of the first solids, and grew to about 50 Earth masses by 3–4 million years [856]. Chapter

30 tells that early history. The planet now holds 317.8 Earth masses.

Saturn. Saturn has 568.32 × 10^{24} kg, an equatorial radius of 60,268 km (31.69) and a polar radius of 54,364 km (31.60) [847]. Its flattening, (60,268 − 54,364) / 60,268 = 0.098, is the largest of the planets. Its density, 687 kg/m^3, is below the 1,000 kg/m^3 of water.

Gravity is 11.19 m/s^2 on the sheet and 9.0 m/s^2 in the table; escape velocity is 35.5 km/s [847][847]. The moment of inertia factor is 0.210, the Bond albedo 0.342 and the black-body temperature 81.0 K. The 1-bar level stands at 134 K (−139 °C).

Saturn's gas is 96.3 % hydrogen and 3.25 % helium (± 2.4 %), with 4,500 ppm methane, 125 ppm ammonia, 110 ppm HD and 7 ppm ethane [847]. Jupiter holds 10.2 % helium. Winds reach 400 m/s within 30° of the equator and 150 m/s beyond.

Saturn's rotation has two measured values. The radio period, System III, is 10.656 hours (42.76) [847]. Ring seismology gives 10 h 33 min 38 s, which is 10.5606 hours (42.75), 5.7 minutes (38.46) shorter [894].

Saturn orbits at 1,432.041 × 10^6 km, 9.573 AU (40.86), with an eccentricity of 0.0520, an inclination of 2.486° and an obliquity of 26.73° [847]. Its year lasts 10,747 days, 29.42 years (51.95) [847]. Its perihelion lies at 1,357.6 × 10^6 km (40.82) and its aphelion at 1,506.5 × 10^6 km, 10.07 AU (40.91).

The two giants run in a fixed ratio. Saturn's period over Jupiter's is 10,747 / 4,331 = 2.481 [847]. They meet in the sky once every 1 / (1/11.862 − 1/29.423) = 19.87 years (51.59); the net's text gives 19.86 years from slightly different periods [701].

A model of the young Solar System, the Nice model, gives the present orbits of the giants provided Jupiter and Saturn crossed their 1:2 resonance [861]. The present ratio, 2.481, lies beyond 2. The crossing belongs to the history of chapter 30.

Over Saturn's north pole stands a hexagonal cloud pattern roughly 30,000 km wide (31.06), with a tight polar vortex at its centre [702]. It has turned with the planet since the Voyager era. As a reading, the net's text on Saturn sees in the hexagon six cells in a regular hexagon around the centre cell [702].

Depth 41: between Saturn and Uranus

The net has closure depths where the ladder of three and the ladder of two nearly meet (chapter 24). Depth 41 is one of them: 3^{41} lies close to 2^{65}. The remainder is $3^{41} / 2^{65}$ = 0.98860; seen from the doubling side, $2^{65} / 3^{41}$ = 1.0115, an overshoot of 1.15 %.

As a length, depth 41 is 3^{41} × 4.558816 × 10^{-8} m = 1.6627 × 10^{12} m. Divided by 1.495978707 × 10^{11} m, that is 11.11 AU. The net's climate text prints 11.12 AU, from the rounded unit 45.6 nm [29].

As a time, depth 41 is 3^{41} × 1.520655 × 10^{-16} s = 5,546 s, which is 92.4 minutes. The two are one: the unit of length is the unit of time times the speed of light (4.558816 × 10^{-8} / 1.520655 × 10^{-16} = 2.998 × 10^8 m/s). Sunlight takes 92.4 minutes to reach 11.1 AU.

Depth 41 falls in the gap between two orbits. Saturn's mean orbit lies at 40.86 and its farthest point, 10.07 AU, at 40.91, 1.04 AU inside the depth. Uranus's nearest point, 2,732.7 × 10^6 km or 18.27 AU, lies at 41.45, 7.16 AU beyond it [847].

One small body crosses that gap. Chiron, about 180 km across (26.40), orbits the Sun with a semimajor axis of 13.637 AU (41.19) and a period of 50.7 years (52.44) [905]. Its perihelion at 8.46 AU (40.75) lies inside Saturn's orbit, and its aphelion at 2 × 13.637 − 8.46 = 18.81 AU (41.48) lies near Uranus's [905][906].

Chiron is listed both as an asteroid and as comet 95P [905][906]. Twice in every 50.7-year orbit it passes through 11.1 AU. Chapter 32 places it among the small bodies.

Sunlight at depth 41 is 92.4 minutes old. At Saturn it is 9.573 × 499.0 s = 79.6 minutes old (40.86), at Uranus 159.4 minutes (41.50). The net's climate text names the orbit of Saturn in its row 41 [29].

The next closure depth, 53, falls among the planets in time rather than size: 93.4 years lies between the years of Uranus, 83.75 (52.90), and Neptune, 163.7 (53.51).

Here the form is where three meets two: no closure is exact, and at 41 the remainder is 1.15 %. At this position the Solar System holds the gap between the sixth and seventh orbits, crossed by bodies that pass through it.

Uranus, Neptune and Pluto

Uranus. Uranus has 86.811 × 10²⁴ kg, an equatorial radius of 25,559 km (30.91) and a polar radius of 24,973 km (30.89) [847]. Its density is 1,270 kg/m³, its gravity 9.01 m/s², its Bond albedo 0.300 and its black-body temperature 58.1 K. It orbits at 19.165 AU (41.50) in 30,589 days, 83.75 years (52.90), with an eccentricity of 0.0469 and an inclination of 0.770°.

Uranus lies on its side. Its obliquity is 97.77°, and it turns backward once in 17.24 hours (43.20), a period measured in magnetic coordinates by the Voyager 2 radio experiment [847].

The 1-bar level stands at 76 K (−197 °C); the lowest temperature recorded in its tropopause is 49 K [847][895]. The gas is 82.5 % hydrogen, 15.2 % helium (± 3.3 %), 2.3 % methane and 148 ppm HD. Winds blow at 0–250 m/s.

Neptune. Neptune has 102.409 × 10²⁴ kg, an equatorial radius of 24,764 km (30.88) and a polar radius of 24,341 km (30.87) [847]. It is smaller than Uranus but 102.409 / 86.811 = 1.18 times heavier, and denser: 1,638 against 1,270 kg/m³. Its gravity is 11.27 m/s², its Bond albedo 0.290, its black-body temperature 46.6 K.

It orbits at 30.181 AU (41.91) in 59,800 days, 163.7 years (53.51), on the roundest of the planetary orbits after Venus, eccentricity 0.0097 [847][847]. It turns in 16.11 hours (43.14) and leans 28.32°. Its 1-bar level stands at 72 K (−201 °C), the coldest of the four giants.

The gas is 80.0 % hydrogen, 19.0 % helium (± 3.2 %) and 1.5 % methane [847]. Neptune’s winds reach 580 m/s, about 2,100 km/h, the fastest of the planets [847][896]. In 1989 Voyager 2 saw a Great Dark Spot of 13,000 × 6,600 km (30.30 × 29.68) [896].

Neptune was first seen by telescope on 23 September 1846, 180 years ago (53.60) [896]. Since then it has gone 180 / 163.7 = 1.10 times round the Sun.

Pluto. Pluto has 0.01303 × 10²⁴ kg, a mean radius of 1,188 km (28.12) and a diameter of 2,376 km (28.75) [847][847]. Its density is 1,854 kg/m³ on its sheet and 1,850 kg/m³ in the table. Its gravity is 0.62 m/s², its escape velocity 1.21 km/s, its Bond albedo 0.72 and its geometric albedo 0.52.

Pluto turns backward once in 153.2928 hours, 6.387 days (45.19), at an obliquity of 119.51° [847]. Its largest moon, Charon, orbits in 6.3872 days, also 153.29 hours. Pluto and Charon turn the same face to each other.

Its orbit is long and tilted [847][847]. The table gives a mean distance of 5,906.4 × 10⁶ km, 39.48 AU (42.15); the sheet gives 5,869.656 × 10⁶ km. The eccentricity is 0.2444 (J2000 elements 0.2488) and the inclination 17.16° (17.14°).

At perihelion Pluto comes to 4,436.8 × 10⁶ km, 29.66 AU (41.89) [847]. Neptune’s aphelion lies at 4,558.9 × 10⁶ km, 30.47 AU (41.92). For part of each orbit Pluto is nearer the Sun than Neptune, by up to 122 × 10⁶ km (38.62).

Pluto’s year lasts 90,560 days, 247.9 years (53.89) [847]. Its surface stands at 24–38 K under a gas pressure of about 13 microbar on its sheet and 10 microbar in the table [847][847].

Fields and inner heat

Six of the planets carry a global magnetic field: Mercury, Earth, Jupiter, Saturn, Uranus and Neptune [847]. Venus, Mars and the Moon have no global field. The fact sheets give

each field as an equatorial dipole strength times the planet's radius cubed [847][847].

The dipole moment follows as $m = (4\pi/\mu_0)\, B_0 R^3 = 10^7 \times B_0 \times R^3$, with B_0 in tesla and R in metres. For Jupiter, $10^7 \times 4.30 \times 10^{-4}$ T $\times (7.1492 \times 10^7\ \text{m})^3 = 1.57 \times 10^{27}$ A m². The table gives all six.

Planet	B_0 (gauss)	R (km)	pos (R)	Dipole moment (A m²)	/ Earth	Tilt	Offset	[n]
Mercury	0.002	2,439.5	28.77	2.9×10^{19}	3.7×10^{-4}	0.0°	0.17 R	[847]
Earth	0.306	6,378	29.65	7.94×10^{22}	1	—	0.076 R	[847]
Jupiter	4.30	71,492	31.85	1.57×10^{27}	19,800	9.4°	0.119 R	[847]
Saturn	0.215	60,268	31.69	4.71×10^{25}	593	0.0°	—	[847]
Uranus	0.228	25,559	30.91	3.81×10^{24}	48	58.6°	0.352 R	[847]
Neptune	0.142	24,764	30.88	2.16×10^{24}	27	46.9°	0.485 R	[847]

The moments span eight orders of magnitude, from Mercury to Jupiter [847][847]. Jupiter's surface field is 4.0–13.0 gauss, Saturn's 0.18–0.84, Uranus's 0.1–1.0, Neptune's 0.1–0.9, Mercury's 0.0025–0.007, the Earth's 0.24–0.66. Saturn's equatorial field, about 0.2 gauss, is roughly one twentieth of Jupiter's [894].

Saturn's dipole lies on its spin axis, at 0.0° [847]. The dipoles of Uranus and Neptune lean 58.6° and 46.9° and sit 0.352 and 0.485 radii off the centre. On Uranus the surface field runs from 0.1 gauss in the south to 1.1 gauss in the north, with an average of 0.23 gauss [895].

One moon carries a field of its own. Galileo found that Ganymede has an equatorial surface field of about 750 nT, with its dipole tilted about 10° [882]. That is 750 / 30,600 = 0.025 of the Earth's equatorial dipole field.

The giants send out more heat than the Sun gives them. Cassini measured Jupiter's Bond albedo at 0.503 ± 0.012, higher than the 0.343 of the fact sheet [846][847]. Jupiter absorbs 6.613 ± 0.160 W m⁻², emits 14.098 ± 0.031 W m⁻², and has an internal heat flux of 7.485 ± 0.160 W m⁻².

The ratio of emitted to absorbed power is 2.132 ± 0.051 [846]. Over the whole planet, with a mean radius of 69,911 km (31.83), the internal flux gives $7.485 \times 4\pi \times (6.9911 \times 10^7\ \text{m})^2 = 4.60 \times 10^{17}$ W.

Neptune radiates about 2.61 times what it receives from the Sun [896]. Uranus emits 1.06 ± 0.08 times what it absorbs, with an internal flux of 0.042 ± 0.047 W m⁻² [895]. That is below the Earth's own internal heat flux of about 0.075 W m⁻².

Saturn's air holds 3.25 % helium by volume against Jupiter's 10.2 % [847]. One proposal (de Pater and Lissauer 2010) gives droplets of helium raining out inside Saturn as a source of its heat [894].

The 1-bar levels stand above the black-body temperatures: Jupiter 165 against 109.9 K, Saturn 134 against 81.0 K, Uranus 76 against 58.1 K, Neptune 72 against 46.6 K [847]. The differences are 55, 53, 18 and 25 K. Uranus, closest to balance, shows the smallest.

In the net's texts a planet is a body in which no knot reaches the stretch at which it opens; it passes what its meshes let through and no more [26]. A star is where the central stretch opens its heaviest knots. Jupiter, at 317.8 Earth masses, gives out twice what it receives and still stays on the planet side of that line.

Orbits that keep time together

Around Jupiter, three large moons run in step. NASA states it in counts: each time Ganymede goes round Jupiter once, Europa goes round twice and Io four times [879].

The mean orbits fitted by JPL give the periods and distances below [877].

Moon	Distance (km)	pos	Period (days)	pos	Ratio to inner neighbour	[n]
Io	421,800	33.46	1.762732	44.02	—	[877]
Europa	671,100	33.89	3.525463	44.65	2.0000	[877]
Ganymede	1,070,400	34.31	7.155588	45.29	2.0297	[877]
Callisto	1,882,700	34.83	16.690440	46.06	2.3325	[877]

Europa’s period is 3.525463 / 1.762732 = 2.0000 times Io’s. Ganymede’s is 7.155588 / 3.525463 = 2.030 times Europa’s in these fitted mean elements, and 4.059 times Io’s [877]. Callisto, outside the chain, runs at 2.333 times Ganymede’s period.

Saturn’s moons keep two such pairs [877][880]. Enceladus goes round twice for each turn of Dione: 2.736916 / 1.370218 = 1.997. Tethys and Mimas run at 1.887802 / 0.942422 = 2.003.

Moon	Distance (km)	pos	Period (days)	pos	Eccentricity	[n]
Mimas	186,000	32.72	0.942422	43.45	0.020	[877]
Enceladus	238,400	32.94	1.370218	43.79	0.005	[877]
Tethys	295,000	33.14	1.887802	44.08	0.001	[877]
Dione	377,700	33.36	2.736916	44.42	0.002	[877]
Titan	1,221,900	34.43	15.945448	46.02	0.029	[877]
Hyperion	1,481,500	34.61	21.276658	46.28	0.105	[877]

Enceladus orbits at about 238,000 km in 32.9 hours (43.79), which is the 1.370218 days of the table [877][880]. Farther out, Hyperion runs at 21.276658 / 15.945448 = 1.334 times Titan’s period, close to 4:3. Hyperion’s orbit has the largest eccentricity of the six, 0.105.

Pluto’s small moons are spaced by Charon’s period [847]. Charon orbits the system’s centre at 19,596 km (30.67) in 6.3872 days (45.19). Styx, Nix, Kerberos and Hydra follow at 3.16, 3.89, 5.04 and 5.98 Charon periods, close to 3, 4, 5 and 6.

Moon	Distance (km)	pos	Period (days)	pos	Periods of Charon	[n]
Charon	19,596	30.67	6.3872	45.19	1	[847]
Styx	42,413	31.37	20.16	46.23	3.16	[847]
Nix	48,690	31.50	24.85	46.42	3.89	[847]
Kerberos	57,750	31.65	32.17	46.66	5.04	[847]
Hydra	64,721	31.76	38.20	46.82	5.98	[847]

Among the planets, Neptune and Pluto keep the clearest step [847]. Pluto’s period over Neptune’s is 90,560 / 59,800 = 1.514, close to 3:2. Pluto crosses inside Neptune’s orbit while keeping that step.

The successive period ratios of the planets are less regular [847]. They are 2.553 (Venus/Mercury), 1.625 (Earth/Venus), 1.881 (Mars/Earth), 6.304 (Jupiter/Mars), 2.481 (Saturn/Jupiter), 2.846 (Uranus/Saturn), 1.955 (Neptune/Uranus) and 1.514 (Pluto/Neptune). The largest gap lies between Mars and Jupiter, where chapter 32 finds the asteroid belt.

The net’s text on the Solar System reads these steps in one sentence: “Only windings that return in phase with themselves persist; all others unwind.” [827] Here the form is what closes, stays. The orbits that return together in whole numbers of turns, 1:2:4 at Jupiter, 1:2 twice at Saturn, 3:2 at Neptune, are the ones measured now.

As a reading, the moon systems repeat the planetary system at a smaller size. Io, Europa and Ganymede lie at positions 33.46 to 34.31, the planets at 37.94 to 41.91, and both carry whole-number steps. The form is the same winding at every depth, with the moons inside the planets’ addresses as shorter addresses inside longer ones.

The moons

The number of known moons grows by the year. The NASA fact sheet of 18 March 2025 lists 2 for Mars, 95 for Jupiter, 274 for Saturn, 28 for Uranus, 16 for Neptune and 5 for Pluto [847]. The JPL list of discovery circumstances, read in October 2026, gives 115 for Jupiter and 293 for Saturn, and 460 planetary satellites in all, Pluto's included and the Earth's left out [875].

The newest entries in that list are S/2024 J1 at Jupiter and the Saturnian moons S/2023 S1 to S/2023 S54, announced in 2026 [875]. Of Jupiter's 115, 73 have permanent designations and 57 have names; of Saturn's 293, 67 are designated and 63 named [893]. Uranus has 29 known moons, 19 regular and 10 irregular; Neptune has 16, Pluto 5 and Mars 2 [878][893][895].

The counts add up. 2 + 115 + 293 + 29 + 16 = 455 moons circle the planets beyond the Earth; with Pluto's 5 that is 460, the JPL total [875]. With the Earth's Moon, 461.

Seven moons are larger than 2,700 km across. The JPL physical parameters give their radii and densities; masses follow from GM / G with G = 6.6743 × 10⁻¹¹ m³ kg⁻¹ s⁻² [876].

Moon (planet)	Diameter (km)	pos	Mass (kg)	/ Moon	Density (g/cm³)	[n]
Ganymede (J)	5,262.4	29.47	1.481 × 10²³	2.02	1.9416	[876]
Titan (S)	5,149.5	29.45	1.345 × 10²³	1.83	1.8814	[876]
Callisto (J)	4,820.6	29.39	1.076 × 10²³	1.46	1.8340	[876]
Io (J)	3,643.0	29.14	8.93 × 10²²	1.22	3.5276	[876]
Moon (E)	3,474.8	29.10	7.346 × 10²²	1	3.344	[876]
Europa (J)	3,121.6	29.00	4.799 × 10²²	0.653	3.0130	[876]
Triton (N)	2,705.2	28.87	2.14 × 10²²	0.291	2.0649	[876]
Titania (U)	1,577.8	28.38	3.40 × 10²¹	0.046	1.653	[876]
Rhea (S)	1,527.0	28.35	2.31 × 10²¹	0.031	1.2372	[876]
Oberon (U)	1,522.8	28.34	3.08 × 10²¹	0.042	1.664	[876]
Iapetus (S)	1,468.6	28.31	1.81 × 10²¹	0.025	1.0887	[876]
Charon (P)	1,212.0	28.14	1.59 × 10²¹	0.022	1.853	[876]
Umbriel (U)	1,169.4	28.10	1.28 × 10²¹	0.017	1.523	[876]
Ariel (U)	1,157.8	28.10	1.25 × 10²¹	0.017	1.539	[876]
Dione (S)	1,122.8	28.07	1.10 × 10²¹	0.015	1.4781	[876]
Tethys (S)	1,062.2	28.02	6.18 × 10²⁰	0.008	0.9840	[876]
Enceladus (S)	504.2	27.34	1.08 × 10²⁰	0.0015	1.6097	[876]
Miranda (U)	471.6	27.28	6.4 × 10¹⁹	0.0009	1.178	[876]
Mimas (S)	396.4	27.12	3.75 × 10¹⁹	0.0005	1.1501	[876]

Ganymede and Titan are wider than the planet Mercury, 4,879 km, yet hold only 0.449 and 0.408 of its mass [847][876]. The large moons fall into two sets by density. Io, the Moon and Europa lie at 3.0–3.5 g/cm³; Ganymede, Titan, Callisto and Triton at 1.8–2.1 g/cm³.

Io, at 3.5276 g/cm³, is the densest of the large moons; Tethys, at 0.9840 g/cm³, the least dense in the list [876]. Charon's density is 1.853 g/cm³ in the JPL list; the Pluto sheet's radius of 606 km and mass of 1.586 × 10²¹ kg give 1.700 g/cm³ [847][876]. Charon has 1.586 × 10²¹ / 1.303 × 10²² = 0.122 of Pluto's mass.

Triton, Neptune's largest moon, goes round its planet backward [896]. Its retrograde orbit is read as the sign that it was captured rather than formed in place.

Under the ice of several moons lie oceans. Europa, 3,100 km across in NASA's figure, has an ice shell 15 to 25 km thick (24.14–24.60) over an ocean 60 to 150 km deep (25.40–26.23) [879]. That ocean may hold twice as much water as all of the Earth's.

Ganymede's ocean is about 100 km thick (25.87), under a crust of mostly ice about 150

km thick (26.23) [881]. It may hold more water than all the water on the Earth’s surface. Hubble found it in 2015 from the aurorae: their rocking was reduced to 2° instead of the 6° expected if no ocean were present.

Ganymede’s ocean may lie as a layer between shells of ice, and Callisto counts among the best-established water worlds [901]. Titan’s interior ocean is thought to hold water with ammonia [901]. The Huygens probe landed on Titan on 14 January 2005 [894].

Enceladus is only about 500 km across (27.33) [880]. In 2005 Cassini found plumes of water at its south pole, fed by a global ocean inside the moon. There its ice shell is only 1 to 5 km thick (21.67–23.14), against a global average of about 20 to 25 km (24.40–24.60).

Silica grains in the plumes need water warmer than about 90 °C [880]. The jets supply Saturn’s E ring. Enceladus is the most reflective body in the Solar System.

The rings of Saturn

Four planets have rings: Jupiter, Saturn, Uranus and Neptune [847]. Mercury, Venus, Earth, Mars and Pluto have none. Saturn’s are by far the largest, and the NASA ring fact sheet gives their radii from the planet’s centre [874].

Feature	Inner radius (km)	pos	Outer radius (km)	pos	Optical depth	Thickness (m)	[n]
D ring	66,900	31.79	74,510	31.89	10^{-5}	—	[874]
C ring	74,658	31.89	91,975	32.08	0.05–0.35	5	[874]
B ring	91,975	32.08	117,507	32.30	0.4–2.5	5–10	[874]
Cassini division	117,507	32.30	122,340	32.34	0–0.1	20	[874]
A ring	122,340	32.34	136,780	32.44	0.4–1.0	10–30	[874]
F ring	139,826	32.46	—	—	0.1	—	[874]
G ring	166,000	32.61	173,000	32.65	10^{-6}	10^{5}	[874]
E ring	180,000	32.69	480,000	33.58	10^{-6}	10^{7}	[874]

Within the main rings lie narrow features [874]. The Titan ringlet sits at 77,871 km and the Maxwell gap at 87,491 km, each with a surface density of 17 g/cm². The Encke gap opens at 133,410 km (32.42) and the Keeler gap at 136,487 km (32.44).

The widths follow from the radii. The D ring is 7,610 km wide (29.81), the C ring 17,317 km (30.56), the B ring 25,532 km (30.91), the Cassini division 4,833 km (29.40) and the A ring 14,440 km (30.39). The thin E ring spreads over 300,000 km (33.15).

In units of Saturn’s radius, 60,268 km, the C ring begins at 1.239, the B ring ends at 1.950 and the A ring at 2.270 [847][874]. The E ring reaches 7.96 radii.

The main rings are thin beyond any common measure. The B ring, 25,532 km wide, is 5–10 m thick (16.85–17.48) [874]. Its width is 2.6 to 5.1 million times its thickness.

Surface densities rise inward from the A ring to the B ring [874]. The C ring holds 1.4–7 g/cm², the Cassini division 18–20, the A ring 20–40, and the inner B ring 20–100 g/cm². Albedos run from 0.12–0.30 in the C ring to 0.4–0.6 in the A and B rings, and 0.6 in the F ring.

The rings are 99.9 % water ice [897]. Their local thickness is as little as 10 m (17.48) and as much as 1 km (21.67). The dense main rings reach from 7,000 km to 80,000 km above Saturn’s equator.

Cassini weighed them by gravity in the orbits of its Grand Finale. The ring mass is $(1.54 \pm 0.49) \times 10^{19}$ kg, which is 0.41 ± 0.13 of the mass of the moon Mimas [897]. That is $1.54 \times 10^{19} / 5.6832 \times 10^{26} = 2.7 \times 10^{-8}$ of Saturn.

The age of the rings is in dispute, and both sides are measured. From the ring mass and their darkening, the rings may be between 10 and 100 million years old (63.54–65.64) [897]. The C ring would be about 100 million years old if it came from a broken body,

and closer to a billion years (67.73) if its material came mostly from micrometeoroids.

Cassini’s dust analyser measured the infall of micrometeoroids directly [883]. It found a mass flux of 6.9 × 10^{-17} to 2.7 × 10^{-16} kg m^{-2} s^{-1}. With the rings polluted by 0.1–2 % non-icy material by volume, that gives an exposure time of about 100 to 400 million years (65.64–66.90).

Impact simulations answer from the other side [884][885]. Only about 1 % or less of the impacting material sticks to the ring particles; a conference report gives 1–3 %. With that retention the ages run from about 100 million years to several billion years (65.64 to 68.73 for three billion).

A review of 2025 gives an exposure age of a few hundred million years [886]. It names self-cleaning of the particles as a caveat. The young ages run from 10 to 400 million years; if the rings resist pollution, they may be several billion years old.

The rings also lose mass to the planet. Keck observations give a ring rain of 432–2,870 kg/s [897]. Cassini measured an equatorial inflow of 4,800–44,000 kg/s in September 2017.

Ring rain alone would remove the rings in about 292 (+818/−124) million years (66.61) [897]. With the Cassini inflow they could be gone in under 100 million years. The present mass divided by the Cassini inflow gives 1.54 × 10^{19} kg / 44,000 kg/s = 11 million years (63.63), and with 4,800 kg/s, 102 million years (65.66).

As a reading, the form is form and carrier. The ring holds its shape while its material flows through it. Ice rains onto Saturn at thousands of kilograms per second, dust falls in, and Enceladus feeds the E ring from its jets [880][883][897].

Storms that last

Jupiter’s Great Red Spot has been watched for nearly two centuries. Cassini saw a “Permanent Spot” from 1665 to 1713, 48 years (52.39), which probably does not correspond to the present one [888][898]. The present spot has been observed frequently since 5 September 1831, 195 years (53.67).

The spot lies about 22° south of the equator, its cloud tops about 8 km (23.57) above their surroundings [898]. Its winds reach up to 432–496 km/h. In 2008 it turned once in about 4.5 days (44.87).

It has been shrinking for as long as it has been measured [889][898].

Year	Long axis (km)	pos	/ Earth’s diameter	[n]
late 1800s	41,000	31.34	3.21	[889]
1979 (Voyager)	23,300	30.83	1.83	[889]
1995 (Hubble)	20,950	30.73	1.64	[889]
2009 (Hubble)	17,910	30.59	1.40	[889]
2014 (Hubble)	16,500	30.51	1.29	[889]
3 April 2017 (Juno)	16,350	30.51	1.28	[898]

From the late 1800s (taken as 1880) to 2014 the mean shrinking rate is (41,000 − 16,500) / 134 = 183 km per year. From 1979 to 2014 it is 194 km per year, from 1995 to 2009 217 km per year, from 2009 to 2014 282 km per year. Amateur observations since 2012 show 930 km per year [889].

A study of 150 years of observations finds the length shrinking by about 0.194° of longitude per year and the width by 0.048° of latitude per year [887]. At 22° latitude on a planet of 71,492 km radius, 0.194° per year is 2π × 71,492 × cos 22° / 360 × 0.194 = 224 km per year. The spot’s westward drift rose from about 0.26° per day in the 1980s to about 0.36° per day, and since 2014 its colour has changed.

Simulations favour a birth from a disturbance in the flow between two opposing jets [888]. The spot has turned faster as it has shrunk.

As a reading, the spot shows form and carrier once more. A storm of 1.3 Earth

diameters has kept its form for 195 years while its size, speed and colour changed.

Saturn’s polar hexagon, 30,000 km across, has turned with the planet since the Voyager era [702]. Neptune’s Great Dark Spot, 13,000 × 6,600 km, was seen in 1989 [896].

The visits

Most of the numbers in this chapter were measured up close, by spacecraft sent out since 1977.

Voyager 1 was launched on 5 September 1977 [902]. It passed Jupiter on 5 March 1979 at about 349,000 km (33.29) and Saturn on 12 November 1980 at 124,000 km (32.35). Its Titan flyby came within 6,490 km (29.66); another part of the record gives 6,400 km.

Voyager 2 was launched on 20 August 1977 [903]. It passed Jupiter on 9 July 1979 within 570,000 km (33.74) and Saturn on 26 August 1981 at 101,000 km (32.16). It remains the only craft to have passed Uranus, on 24 January 1986 within 81,500 km of the cloud tops (31.97), and Neptune, on 25 August 1989 about 4,950 km above the north pole (29.42).

Another page gives Voyager 2’s Neptune pass as within 4,400 km of the atmosphere (29.31) [896]. The journey from launch to Neptune took 12.0 years (51.13). Voyager 2 now moves at 15.341 km/s and stood 143.05 AU from the Earth in February 2026 (43.33) [903].

Voyager 1 crossed the solar wind’s termination shock at 94 AU in December 2004 (42.94) and the heliopause at 121 AU on 25 August 2012 (43.17) [902]. Voyager 2 crossed the heliopause on 5 November 2018 at 119.7 AU (43.16) [903]. Chapter 29 tells what was found at those boundaries.

In August 2026 Voyager 1 stood 171.19 AU from the Sun (43.49), moving at about 61,000 km/h [902]. From 121 AU in 2012 to 171.19 AU in 2026 it covered 50.2 AU in 14 years, 3.58 AU per year or 17.0 km/s.

On 18 November 2026 Voyager 1 will be 25.902×10^{9} km from the Earth, one light-day [892]. That is 299,792.458 km/s × 86,400 s = 2.5903×10^{10} km, which is 173.15 AU. On the ladder it lies at 43.50, the same position as the day itself, because the unit of length is the unit of time carried at the speed of light.

Cassini went into orbit around Saturn on 1 July 2004 [894]. Its Huygens probe landed on Titan on 14 January 2005, and the Grand Finale ended the mission on 15 September 2017. In those last orbits it weighed the rings.

New Horizons was launched on 19 January 2006 at about 16.26 km/s [904]. It passed Jupiter on 28 February 2007 at 2.3 million km (35.01) and Pluto on 14 July 2015 at 11:49 UTC, 12,500 km above the surface (30.26). The flight to Pluto took 9.48 years (50.92).

New Horizons went on into the Kuiper belt; chapter 32 follows it there [904]. In April 2026 it stood 64.45 AU from the Sun (42.60).

Other craft gave single numbers to this chapter. MESSENGER gave Mercury’s field model of 2010, Galileo found Ganymede’s field in 1996, Juno measured the Red Spot in 2017, and InSight’s seismic data placed water in the Martian crust [847][882][891][898].

What this part of the history shows

The planets fill a narrow band of the ladder: orbits from 37.94 (Mercury) to 41.91 (Neptune), diameters from 29.40 to 32.48, years from 47.57 to 53.51. Inside that band they fall into two groups, four small dense planets of 3,934–5,514 kg/m³ and four giants of 687–1,638 kg/m³. Jupiter alone holds 2.47 times the mass of all the rest.

All orbits turn one way and lie within 7° of the Earth’s plane, Pluto’s at 17°. As a reading, this is the form of one direction: the turn of the disk, laid down first, is kept by

the planets that formed in it. The spins are freer: Venus turns backward in 243.0 days (48.50), Uranus lies at 97.77°, and Triton orbits Neptune backward.

Whole-number steps hold the moon systems together. Ganymede, Europa and Io keep 1:2:4; Enceladus–Dione and Mimas–Tethys keep 1:2; Hyperion and Titan run near 4:3; Pluto's small moons sit near 3, 4, 5 and 6 Charon periods. Among the planets, Neptune and Pluto keep 3:2 though their paths cross.

These steps show the form of what closes, stays. What returns in phase is what remains in the record. In the net's reading, Kepler's third law, $5.2038^3 / 11.862^2 = 1.0015$ for Jupiter, is the closure condition of such a winding in the stretch around the Sun.

As a reading, the same form returns at a smaller size. The Galilean moons lie at positions 33.46–34.31 and keep the steps the planets keep at 37.94–41.91. Moons sit inside planets as planets sit inside the Sun's system: addresses nested inside longer addresses.

Depth 41 lies at 11.1 AU and 92.4 minutes, between Saturn's farthest point (10.07 AU, 40.91) and Uranus's nearest (18.27 AU, 41.45). There the ladder of three and the ladder of two nearly meet, with a remainder of 1.15 %. Chiron, 180 km across, crosses the gap at the depth twice in each 50.7-year orbit, and sunlight arrives there 92.4 minutes after it leaves the Sun.

As a reading, the rings and the Red Spot show form and carrier. Saturn's rings, 1.54×10^{19} kg of ice 5–30 m thick, lose 432–44,000 kg/s to the planet and gather dust from outside, while their shape holds. The Red Spot has kept its form for 195 years while it shrank from 41,000 to 16,350 km.

The giants stay planets. Jupiter emits 2.132 times what it absorbs and holds 317.8 Earth masses, yet in the net's texts it remains a body that passes what its meshes let through, without opening a knot. Chapter 30 gives the mass limits between planets, brown dwarfs and stars.

Two measured positions coincide with the day. The rotation of the Earth sits at 43.50, and so does one light-day, the distance Voyager 1 reaches on 18 November 2026. Venus's rotation lies at 48.50, in the group of cycles that the net's climate text reads on half-layers.

32. The Small Bodies

Not all the solids of the young disk went into planets. Millions of bodies were left over: rocks and metal between Mars and Jupiter, ice beyond Neptune, and a far cloud of comets around the whole system. This chapter gives their history, from the first solids 4,567 million years ago to the dust that falls on the Earth today.

On the ladder of chapter 24 the small bodies spread far wider than the planets. In size they run from dust of 200 µm (position 7.63) to Ceres, 939.4 km across (27.90). In distance they reach from the inner asteroid belt at 2.06 AU (39.47) to the outer comet cloud at up to 200,000 AU (49.92).

Two catalogues keep the count, and both grow every month. The Minor Planet Center lists 1,578,500 objects; NASA’s Small-Body Database lists 1,554,070 asteroids and 4,080 comets [907][908]. Chiron, the small body that crosses closure depth 41 (chapter 31), is one of them.

The oldest pieces

The small bodies hold the oldest dated solids of the Solar System. The first solids, the inclusions called CAIs in chondritic meteorites, give a uranium-corrected lead–lead age of 4,567.30 ± 0.16 million years (69.12) [265]. One inclusion from the meteorite Northwest Africa 2364 gives 4,568.2 million years (69.12), 0.9 million years older [266].

Chondrules formed from 4,567.32 ± 0.42 to 4,564.71 ± 0.30 million years ago [265]. The span from the first inclusion to the youngest dated chondrule is 4,567.30 − 4,564.71 = 2.59 million years (62.31). Chondrule formation lasted about 3 million years from the time of the inclusions (62.45).

The meteorites also carry carbon chemistry. The Murchison meteorite holds amino acids with an excess of the left-handed form of 7.0 % and 9.1 % [935]. For the amino acid isovaline the excess is 18.5 ± 2.6 % in Murchison and 15.2 ± 4.0 % in Orgueil.

This is a reading: the leftover bodies have the form of the residue that becomes the alphabet of the next depth. They keep the material and the dates of the first solids. Chapter 30 told the formation.

The census

The Minor Planet Center lists 895,910 numbered and 677,946 unnumbered minor planets, 4,644 comets and 558,660,555 observations [907]. NASA’s Small-Body Database, queried on 15 October 2026, gives 1,554,070 asteroids, 895,910 of them numbered, and 4,080 comets [908]. The two catalogues differ by date and by definition.

The Minor Planet Center sorts the bodies by orbit [907].

Class	Count	[n]
Atens	3,540	[907]
Apollos	22,011	[907]
Amors	17,201	[907]
Hungarias	32,907	[907]
Mars-crossers	30,513	[907]
Main-belt asteroids	1,446,102	[907]
Hildas	7,410	[907]
Jupiter Trojans	16,724	[907]
Distant objects	8,349	[907]
Dwarf planets	5	[907]

The main belt holds 1,446,102 of the 1,578,500 objects, 91.6 %. Jupiter’s Trojans, which

share its orbit, number 16,724, and the Hildas, between the belt and Jupiter, 7,410. The Small-Body Database counts 7,300 trans-Neptunian objects; the Minor Planet Center lists 8,349 distant objects [907][908].

The main belt

The main belt lies between the 4:1 and 2:1 gaps at 2.06 and 3.27 AU (39.47–39.89), with few asteroids beyond 4.2 AU (40.11) until Jupiter's orbit [910]. Between 700,000 and 1.7 million of its asteroids are 1 km across or more (21.67). Over 200 are larger than 100 km (25.87), and their mean separation is about 965,600 km (34.22).

The whole belt is light. Ephemeris fits to planetary and spacecraft ranging give its mass as $(4.008 \pm 0.029) \times 10^{-4}$ Earth masses [852]. With the Earth at 5.9724×10^{24} kg, that is 2.394×10^{21} kg, and divided by the Moon's 7.346×10^{22} kg it is 3.3 % of the Moon [852][278].

Four bodies hold most of that mass [910][911]. Ceres alone holds 39 %, and Ceres, Vesta, Pallas and Hygiea together about 62 %. The belt's table gives Vesta 10.8 %, Pallas 8.52 % and Hygiea 3.63 %.

Ceres. Giuseppe Piazzi found Ceres at Palermo on 1 January 1801 [911]. Dawn went into orbit around it on 6 March 2015. Its mass is $(9.38392 \pm 0.00005) \times 10^{20}$ kg and its mean diameter 939.4 km (27.90), with a density of 2.16 g/cm³.

Ceres carries $9.38392 \times 10^{20} / 2.394 \times 10^{21} = 0.392$ of the belt's mass [852][911].

It turns in 9 hours 4 minutes [911]; the fact sheet gives 9.074 hours (42.61) [905]. It orbits at 2.768 AU (39.73) in 4.60 years (50.26), with an eccentricity of 0.0758 and an inclination of 10.59° [905]. Its geometric albedo is 0.090, its surface 110–235 K with a mean of 172.5 K [911].

Its surface shows water and brine [911]. The crater Occator, 80 km across (25.66), holds bright deposits; Ahuna Mons is an ice volcano no older than 240 million years (66.43). Water ice was found at the crater Oxo in 2016 and a deep brine reservoir in 2020.

Vesta. Vesta has $(2.590271 \pm 0.000058) \times 10^{20}$ kg in a body of 572.6 × 557.2 × 446.4 km, mean diameter 525.4 km (27.38) [912]. Its density is 3.456 g/cm³. It holds $2.590 \times 10^{20} / 2.394 \times 10^{21} = 10.8$ % of the belt; an older estimate gives 9 % [852][912].

Its south pole carries the basin Rheasilvia, 500 km wide (27.33), with a central peak about 23 km (24.53) above the lowest floor; another figure gives about 22 km [912]. Rheasilvia formed about 1 billion years ago (67.73), on top of an older basin, Veneneia. Vesta's core is 90–220 km across (25.77–26.58), and Dawn's gravity data point to about 220 km.

Vesta has sent pieces to the Earth. About 1 in 16 meteorites came from Vesta, and over 1,200 HED meteorites are known [912]. Dawn orbited it from 16 July 2011 to 4 September 2012; another date given is 5 September.

The measured asteroids. NASA's asteroid fact sheet gives sizes, masses and orbits; most masses and many sizes are rough estimates [905]. It lists Chiron at 180 km (26.40).

Asteroid	Size (km)	pos (longest)	Mass (10^{15} kg)	Rotation (h)	pos	a (AU)	pos	[n]
Ceres	965 × 961 × 891	27.93	939,300	9.074	42.61	2.768	39.73	[905]
Pallas	582 × 556 × 500	27.47	205,000	7.813	42.48	2.772	39.74	[905]
Vesta	569 × 555 × 453	27.45	259,000	5.342	42.13	2.362	39.59	[905]
Juno	234	26.64	20,000	—	—	—	—	[905]

Lutetia	124 × 101 × 80	26.06	1,700	—	—	—	—	[905]
Mathilde	66 × 48 × 46	25.49	103.3	417.7	46.10	—	—	[905]
Ida	58 × 23	25.37	—	—	—	—	—	[905]
Eros	33 × 13 × 13	24.86	6.69	—	—	1.458	39.15	[905]
Toutatis	4.6 × 2.4 × 1.9	23.06	—	130	45.04	—	—	[905]
Itokawa	0.5 × 0.3 × 0.2	21.04	0.000035	12.13	42.88	—	—	[905]
Bennu	0.49	21.02	0.000073	4.276	41.93	1.126	38.92	[905]

Pallas orbits at nearly the same distance as Ceres but tilted 34.84° to the planets' plane [905]. Mathilde turns once in 417.7 hours, more than 17 days. Itokawa, 0.5 km long, has a mass of 3.5 × 10¹⁰ kg; Bennu, 0.49 km across, 7.3 × 10¹⁰ kg.

The gaps. Kepler's third law places the orbits that would run in step with Jupiter. With Jupiter's period of 4,332.589 days, an asteroid on a 3:1 orbit has a period of 1,444.2 days and, from a = (P / 365.256 d)^(2/3), a semimajor axis of 2.500 AU [847].

Step with Jupiter	Period (days)	a (AU)	pos	[n]
4:1	1,083.1	2.064	39.47	[847]
3:1	1,444.2	2.500	39.64	[847]
5:2	1,733.0	2.824	39.75	[847]
7:3	1,856.8	2.957	39.79	[847]
2:1	2,166.3	3.277	39.89	[847]

The belt's inner boundary is the 4:1 gap at 2.06 AU and its dense core ends at the 2:1 gap at 3.27 AU [910].

The net's text on the Solar System places the gaps near 2.50, 2.82, 2.95 and 3.27 AU [827]. It reads them as windings that did not close in phase and were unwound. This is a reading of the form in which only what fits stays.

Families. About one third of the belt's asteroids belong to families [910]. The Veritas family formed about 8.3 million years ago (63.37) and the Karin family about 5.7 million years ago (63.03), from a parent 33 km in radius. The Datura cluster is about 530,000 years old (60.87), and the Flora family less than 1 billion years (67.73).

The dated families run from Flora, under 1 billion years, to Veritas at 8.3 million and Datura at 530,000 years. Against the 4,567 million years of the first solids, the last three are recent.

Near the Earth

Some asteroids leave the belt and cross the inner planets. The Minor Planet Center counts 42,752 near-Earth asteroids; the Small-Body Database counts 42,590 [907][908]. Of these, 873 (MPC) or 875 (SBDB, absolute magnitude H ≤ 17.75) are about 1 km across or larger (21.67).

The Small-Body Database counts 11,756 near-Earth asteroids with H ≤ 22, the class of roughly 140 m and larger (19.88) [908][909]. Potentially hazardous asteroids number 2,542 in one catalogue and 2,550 in the other. The database also lists 209 near-Earth comets.

Two near-Earth asteroids stand in the fact sheet [905]. Eros, 33 × 13 × 13 km (24.86), orbits at 1.458 AU (39.15) with a mass of 6.69 × 10¹⁵ kg. Bennu, 0.49 km across (21.02), orbits at 1.126 AU (38.92) and turns in 4.276 hours (41.93).

Impacts on the Earth

A model of the giant planets' migration places a spike in the cratering rate about 700

million years after the planets formed (67.41) [337]. Counted from the first solids, that is 4,567 − 700 = 3,867 million years ago (68.97). Chapter 30 tells that model.

The Earth Impact Database lists 190 confirmed impact structures [921]. Its systematic search began in 1955 at the Dominion Observatory in Ottawa. A secondary list gives 194 or more confirmed structures as of 2024 [922].

The oldest impact record is a bed of spherules, S1-Warrawoona, about 3,472 million years old (68.87) [922]. The oldest confirmed crater is Yarrabubba in Australia, 30 km across (24.77), 2,229 million years old (68.46). It and the largest structures are listed below in order of age.

Structure	Country	Diameter (km)	pos	Age (Ma)	pos	[n]
Yarrabubba	Australia	30	24.77	2,229	68.46	[922]
Vredefort	South Africa	160	26.29	2,023 ± 4	68.37	[922]
Sudbury	Canada	130	26.10	1,849	68.29	[922]
Acraman	Australia	90	25.77	580	67.24	[922]
Siljan	Sweden	65–75	25.47–25.60	380.9 ± 4.6	66.85	[922]
Manicouagan	Canada	100	25.87	215.56 ± 0.05	66.34	[922]
Morokweng	South Africa	70	25.54	146.06 ± 0.16	65.98	[922]
Chicxulub	Mexico	150	26.23	66.051 ± 0.031	65.26	[922]
Popigai	Russia	100	25.87	35.7 ± 0.2	64.70	[922]

Vesta was struck as well. Its Rheasilvia basin, 500 km wide, formed about 1 billion years ago (67.73) [912].

Chicxulub. The crater lies buried about 1 km deep (21.67) under the Yucatán peninsula, its centre near 21°24′N 89°30′W [917]. It is about 200 km across (26.50), or about 300 km (26.87) if the 180 km ring is taken as an inner wall. The list of structures gives 150 km [922].

Its peak ring is about 80 km across (25.66) and was cored in 2016 by expedition 364 of the International Ocean Discovery Program, in hole M0077A [917]. The impactor was about 10 km across (23.77), a carbon-rich body like a carbonaceous chondrite. Its energy was 10^{23}–10^{25} J.

One assessment gives the impactor a kinetic energy of 1.3×10^{24} to 5.8×10^{25} J [918]. Its mass would be 1.0×10^{15} to 4.6×10^{17} kg and its diameter 10.6 to 80.9 km (23.82–25.67).

At 4.185×10^{15} J per megaton of TNT, the energy is 3.1×10^{8} to 1.4×10^{10} megatons.

Argon dating of tektites from Haiti and ash beds in Montana gives an age of 66.043 ± 0.011 million years (65.26), ± 0.043 million years with systematic error [917]. Spherules from Gorgonilla give 66.051 ± 0.031 million years. The extinction boundary has also been dated to 65.5 million years (65.25) [919].

Life returned to the crater within years of the impact [920]. A high-productivity ecosystem stood there within 30,000 years (58.25).

The Hoba meteorite. The largest known meteorite, Hoba in Namibia, fell less than 80,000 years ago (59.15) [934]. It weighs more than 60 t and measures 2.7 × 2.7 × 0.9 m (16.29). It is about 84 % iron and 16 % nickel, an ataxite of group IVB, and was found in 1920.

Tunguska. On 30 June 1908, at about 07:14 local time, a body burst in the air at 60°54′N 101°54′E [915]. Its energy is given as 3–50 megatons of TNT (1.26×10^{16} to 2.09×10^{17} J); other studies give 3–30, 3–5, 10–30 and 20–30 megatons. It was a stony body 50–60 m across (18.95–19.11), or 50–80 m (19.38) in a 2013 model, and burst at 5–14 km height (23.14–24.08).

It flattened 2,150 km² of forest, a square of √2,150 = 46.4 km on a side (25.17) [915].

The often-quoted figure of over 80 million trees rests on an area four times too large.

Chelyabinsk. On 15 February 2013, at about 09:20 local time, an asteroid about 19 m across (18.07; 17–20 m) burst over Chelyabinsk in Russia [913][914]. Its energy was about 500 ± 100 kilotons of TNT, which at 4.185 × 10¹² J per kiloton is 2.09 × 10¹⁵ J. It weighed about 10,000 t and entered at about 19.2 km/s at an angle of 18°.

It burst near 30 km height (24.77) [914]. 1,491 people sought medical attention. The largest fragment, 654 kg, was raised from Lake Chebarkul on 16 October 2013; the stones are LL5 ordinary chondrites, shock stage S4.

The global record of airbursts of 1 kiloton and more suggests that impactors tens of metres across may be ten times more frequent than other estimates [913]. A population of 10–50 m bodies out of balance with the larger ones has been proposed.

The rate. Satellite records of bolides over 8.5 years show that the Earth is hit about once a year by an object of about 5 kilotons [916]. Tunguska-like events, taken as 10 megatons, occur about once every 1,000 years (55.16).

From Chelyabinsk (0.5 megaton) to Tunguska (10 megatons) the energy rises 20 times [913][916]. From Tunguska (4.2 × 10¹⁶ J) to Chicxulub (at least 1.3 × 10²⁴ J) it rises at least 3 × 10⁷ times [918].

The larger the strike, the rarer it is: yearly at 5 kilotons, once in 1,000 years at 10 megatons. Five of the structures listed above reach 100 km or more.

This is a reading: the strikes have the form of loading, holding and discharge. Small releases come often and large ones rarely, over energies from 2.09 × 10¹⁵ to at least 1.3 × 10²⁴ J.

Comets

The comets have catalogues of their own. The Minor Planet Center lists 4,644 comets and the Small-Body Database 4,080 [907][908]. NASA’s comet fact sheet gives the measured orbits of the best known [906].

Comet	Period (years)	pos	Perihelion q (AU)	pos	Semimajor axis (AU)	pos	Eccentricity	Inclination	[n]
2P/Encke	3.30	49.96	0.340	37.83	—	—	—	—	[906]
9P/Tempel 1	5.51	50.42	—	—	—	—	—	—	[906]
81P/Wild 2	6.39	50.56	—	—	—	—	—	—	[906]
67P/Churyumov–Gerasimenko	6.57	50.58	1.292	39.04	3.51	39.95	—	—	[906]
55P/Tempel–Tuttle	32.92	52.05	—	—	—	—	—	—	[906]
95P/Chiron	50.7	52.44	8.46	40.75	13.637	41.19	—	—	[905] [906]
1P/Halley	76.1	52.81	0.587	38.32	17.94	41.44	0.967	162.2°	[906]
Hale–Bopp	about 4,000	56.42	—	—	250	43.83	0.995	89.4°	[906]
Hyakutake	about 40,000	58.52	—	—	about 1,165	45.23	0.9998	—	[906]

The periods run from 3.30 years to about 40,000 years, from position 49.96 to 58.52. Encke’s nucleus has a radar radius of 0.4–4.0 km (20.84–22.94), measured from Arecibo in 1980 [906]. Comet 73P/Schwassmann–Wachmann 3 split into three large pieces in 1995.

Chiron’s orbit crosses closure depth 41. It runs from 8.46 AU (40.75) to 2 × 13.637 − 8.46 = 18.81 AU (41.48), and passes 11.1 AU twice in each 50.7-year orbit [905][906]. Chapter 31 describes that position between Saturn and Uranus.

Halley. Halley’s Comet has the longest written record. Its first certain record dates from 240 BC, 2,265 years ago (55.90), and its period has varied between 74 and 80 years since then, 74.7 years in the summary value (52.80) [923]. The fact sheet gives

76.1 years [906].

Its last perihelion fell on 9 February 1986 at 0.587 AU (38.32); another page gives 8 February [906][923]. Its aphelion lies at about 35 AU, 35.14 AU in the precise value (42.05). The next perihelion is due on 28 July 2061, 35 years from now (52.11).

The nucleus measures about 15 × 8 × 8 km (24.14), with a mean effective diameter of 11 km (23.86) [923]. Its mass is $(2.2 \pm 0.9) \times 10^{14}$ kg, its density about 0.55 g/cm³, its albedo about 0.04. Halley orbits backward, at an inclination of 162.2° [906].

Halley sheds the dust of two meteor showers, the Eta Aquariids in May and the Orionids in October [923]. This is a reading: the streams have the form of form and carrier. The comet's orbit holds while its grains spread along it.

The Kuiper belt

Beyond Neptune lies a second belt. It reaches from Neptune's orbit at 30 AU to about 50 AU (41.90–42.37), with outlying regions to about 55 AU (42.46) [925]. More than 100,000 of its bodies are thought to be larger than 100 km (25.87); over 2,000 had been found by 2018.

The Kuiper belt is far heavier than the main belt. The same ephemeris fits give $(1.97 \pm 0.030) \times 10^{-2}$ Earth masses, including the 31 largest trans-Neptunian objects; another page prints the error as ± 0.30 [852][925]. That is $1.97 \times 10^{-2} \times 5.9724 \times 10^{24} = 1.177 \times 10^{23}$ kg, about 49 times the main belt.

The 31 largest objects hold about 40 % of that mass [852]. The dynamically hot population holds about 1 % of an Earth mass and the cold population about 0.03 % [925].

Neptune's steps show in the belt. About 200 known objects, Pluto among them, orbit in the 2:3 resonance with Neptune [925]. The classical belt lies between the 2:3 and 1:2 resonances, at about 42–48 AU (42.21–42.33).

The 1:2 resonance at 47.8 AU (42.33) appears to be an edge [925]. Beyond 50 AU the number of bodies of 100 km and more falls off.

This is again a reading of the form in which only what fits stays. The bodies that keep a whole-number step with Neptune gather in the 2:3 orbit, as Pluto does with its period ratio of 1.514 against 3:2 (chapter 31).

Pluto, 2,370 km across (28.75), is the best known of these bodies [925]. Eris is 27 % more massive. The Minor Planet Center counts five dwarf planets [907].

Many small bodies have moons of their own. As of November 2025, 471 asteroid moons and 149 trans-Neptunian moons were known [938]. Among the dwarf planets Haumea has 2 moons and Orcus, Quaoar, Makemake, Gonggong and Eris 1 each.

This is a reading: the moons have the form of community as shared prefix. Moons sit inside small bodies inside the belts inside the Sun's system, addresses inside longer addresses.

Arrokoth. New Horizons passed the Kuiper belt object Arrokoth on 1 January 2019 at 05:33 UTC, at a distance of 3,538 km (29.11) [926]. The craft's own record gives about 3,500 km, at 43.4 AU from the Sun (42.24) [904]. Arrokoth orbits at 44.2 AU (42.26) in 294 years (54.04) and turns in 15.938 hours (43.13).

It is 34.5 km long (24.90) and about 13.8 km thick (24.06) [926]. It is made of two lobes, Wenu, 20.1 km (24.41), and Weeyo, 15.0 km (24.14). The lowest estimate of its density is 0.29 g/cm³.

Its surface holds methanol and complex organic molecules [926]. Its red colour comes from tholins.

This is a reading: Arrokoth has the form of the pair, two closures together. Two lobes touch and turn as one body.

The Oort cloud and the edge of the Sun’s reach

Long-period comets come from much farther out. Oort proposed a distant cloud of comets in 1950, 76 years ago (52.81) [924]. Its size and mass come from the orbits of long-period comets and from models.

The cloud spans 2,000 to 200,000 AU (45.73–49.92), 0.03 to 3.2 light-years [924]. Its inner edge is given as 2,000–5,000 AU (45.73–46.56). Its outer edge is given as 50,000 AU (48.66), or 100,000–200,000 AU (49.29–49.92) where the galaxy’s tides cut it off.

One model divides it in two: a torus-shaped inner cloud of 2,000–20,000 AU (45.73–47.82) and a spherical outer cloud of 20,000–50,000 AU (47.82–48.66) [924]. The outer cloud may hold trillions of bodies larger than 1 km. Its mass is about 5 Earth masses; an older estimate gave up to 380.

In all, 50–100 Earth masses of material are thought to have been thrown out of the planetary region [924]. Up to 90 % of the comets that come in from the cloud are sent by the galaxy’s tide.

The cloud’s comets have the longest periods measured. C/1999 F1 has a period of about 4.3 million years (62.77) [924]. Hale–Bopp, about 4,000 years (56.42), and Hyakutake, about 40,000 years (58.52), come from nearer in [906].

Between the Kuiper belt and the cloud lies Sedna, whose closest approach to the Sun is 76 AU (42.75) [924]. The net’s climate text gives its farthest point as about 940 AU (45.04) [29].

The net’s texts compute where the Sun’s own stretch meets the stretch of the galaxy around it. Set the Sun’s pull, $GM_\odot / r^2$, equal to the background acceleration a and solve: $r = \sqrt{(GM_\odot / a)}$, with $GM_\odot = 1.327 \times 10^{20}$ m³ s⁻² [827][701][27].

Background acceleration a (m/s²)	GM☉ / a (m²)	r (m)	r (AU)	pos	[n]
1.2×10^{-10} (threshold from galaxy rotation)	1.106×10^{30}	1.052×10^{15}	7,030	46.87	[827]
1.08×10^{-10} ($cH_0/2\pi$)	1.229×10^{30}	1.108×10^{15}	7,410 (text: 7,400)	46.92	[27]
2.07×10^{-10} (the galaxy’s pull at the Sun)	6.41×10^{29}	8.01×10^{14}	5,350	46.62	[701]

The third value uses the stretch in which the Sun already sits [701]. The Sun orbits the galaxy’s centre at R = 8.2 kpc, 2.531×10^{20} m, at about 229 km/s. That gives $(2.29 \times 10^5)^2 / 2.531 \times 10^{20} = 2.07 \times 10^{-10}$ m/s², 1.7 times the threshold.

All three edges, 5,350 to 7,410 AU (46.62–46.92), fall inside the inner Oort cloud of 2,000–20,000 AU. The text names what lies there: “Comets are the knots of the transition layer: bound, but barely.” [701]

Here the form is the edge of a knot. In the text’s words, the solar knot ends where its own stretch thins to the stretch around it.

The heliopause, the outer boundary of the solar wind, lies much nearer, at about 120 AU (43.17) (chapter 29). The comet cloud lies 17 to 1,700 times farther out.

The edge is crossed from outside as well. Among the stars near the Sun, 694 will come within 5 pc in the next 15 million years, 26 within 1.0 pc and 7 within 0.5 pc [939]. The closest, Gliese 710, will pass at 0.167 light-years, 10,560 AU (47.24), in about 1.29–1.30 million years (61.68): through the inner Oort cloud.

Visitors from other stars

Three bodies from outside the Solar System have been seen passing through it. Each moved too fast to be bound to the Sun: their orbits are open, with eccentricities above

1.

1I/‘Oumuamua. Robert Weryk found the first with the Pan-STARRS telescope on Haleakalā on 19 October 2017 [927]. It had passed perihelion on 9 September 2017 at 0.255 AU (37.56), and its speed far from the Sun was 26.33 km/s. Its eccentricity was 1.20.

Its light curve gives an average radius of 55 m, a diameter of about 110 m (19.66) [928]. Its axis ratio was about 6:1, extreme for small bodies of the Solar System. Its length is given as 100–1,000 m (19.58–21.67) and its width as 35–167 m, for an assumed albedo of 10 % [927].

The light curve shows a two-peaked period of about 8.26 hours (42.53) [928]. Other studies give 8.10 hours (42.51) and 7.3 hours (42.42), and it tumbled [927]. Its colours were B−V = 0.70 ± 0.06 and V−R = 0.45 ± 0.05 [928].

On 27 June 2018 a non-gravitational acceleration was reported, a change of speed of about 17 m/s [927].

2I/Borisov. Gennadiy Borisov found the second at his MARGO observatory in Crimea on 29–30 August 2019 [929]. Its speed far from the Sun was 32.3 km/s and its eccentricity 3.3565. It passed perihelion on 8 December 2019 at 2.00652 AU (39.44).

Early estimates of its nucleus ran from 1.4 to 16 km (21.98–24.20); later limits gave less than 0.4 km (20.84) and less than 0.5 km (21.04) [929]. Its gas held 35–105 % as much carbon monoxide as water. Comets of the Solar System hold about 4 %.

3I/ATLAS. The ATLAS survey found the third at Río Hurtado in Chile on 1 July 2025 [931]. Its eccentricity is about 6.1, its speed far from the Sun about 58 km/s, and its perihelion about 1.36 AU [930]. Its light varied little over about 4 days (44.76).

Later orbits give an eccentricity of 6.14135 ± 0.00002 and a perihelion of 1.35645 AU (39.09) on 29 October 2025, at a peak speed of about 68 km/s [931]. It passed Mars on 3 October 2025 at 0.193664 AU (37.31). Hubble limits its diameter to below 5.6 km, within a range of 0.32–5.6 km (20.64–23.24).

Its age is estimated at 7.6–14 billion years (69.58–70.14) if it comes from the galaxy’s thick disk, or at 3–11 billion years (68.73–69.92) [931]. Either range reaches beyond the Sun’s 4.6 billion years.

The James Webb Space Telescope measured its gas in August 2025 [931]. The ratio of carbon dioxide to water was 8.0 ± 1.0, about 129 kg/s of carbon dioxide against 6.6 kg/s of water. The VLT found nickel at 4.6 ± 0.7 g/s by 21 August 2025, with no iron.

The three arrived in 2017, 2019 and 2025, at intervals of 2 years (49.50) and 6 years (50.50). Their speeds far from the Sun rose from 26.33 to 32.3 to 58 km/s; 58 / 26.33 = 2.2. Their eccentricities rose from 1.20 to 3.36 to 6.14.

This is a reading: the visitors have the form of context. Bodies of the same kind, from other surroundings, hold other mixtures. Borisov held carbon monoxide at 35–105 % of water against 4 % at home; 3I/ATLAS held carbon dioxide at eight times water.

Dust and falling stones

The small bodies still reach the Earth every day. Craters on the Long Duration Exposure Facility give a mass accretion of cosmic dust of (40 ± 20) × 10^{6} kg per year [936]. That is 40 × 10^{6} / 365.25 = 110 t per day, or 1.27 kg per second.

The dust particles weigh 10^{-9} to 10^{-4} g, and the mass peaks near 1.5 × 10^{-5} g, a diameter of about 200 µm (7.63) [936]. This dust brings in as much mass as all bodies from 1 cm to 10 km (11.19–23.77) do on average, or more.

The dust that scatters the zodiacal light has particles of 10–300 µm (4.91–8.00), with masses from about 1 ng to tens of µg [937]. Over 85 % of it comes from the break-up of nearly dormant Jupiter-family comets. Juno’s record shows dust from the Earth’s orbit out to the 4:1 resonance at 2.06 AU (39.47).

This is a reading: the zodiacal cloud has the form of form and carrier. The cloud is the form; its grains, fed from comets, are the carriers.

Larger stones fall as meteorites. The Meteoritical Bulletin Database listed 72,271 valid meteorite names at its update of 3 September 2023 [932]. A secondary count gives 85,860 meteorites as of April 2026, provisional names included [933].

Of these, 1,180 were confirmed falls as of January 2019 [933]. More than 30,000 finds lie in collections, and more than 23,000 classified specimens have been recovered from Antarctica since 1974, over 52 years (52.47).

Usually five to ten falls a year are seen and then recovered [933]. About 8–9 falls of more than 1 kg strike each million square kilometres per year. Among falls, about 86 % are chondrites, 8 % achondrites, 5 % irons and 1 % stony-irons; irons are 0.4 % of the Antarctic finds.

What this part of the history shows

The small bodies are the residue of planet building, and they keep its record. The first solids date to 4,567.30 ± 0.16 and 4,568.2 million years (69.12); chondrules formed over the next 2.59 million years. Read as the residue that becomes the alphabet of the next depth, these grains and stones carry the dates of the first solids.

The belts read as the form in which only what fits stays. The main belt ends at the 4:1 and 2:1 steps with Jupiter, at 2.06 and 3.27 AU (39.47–39.89), and the steps at 2.50, 2.82 and 2.96 AU lie within it. In the Kuiper belt about 200 bodies keep the 2:3 step with Neptune, and the 1:2 step at 47.8 AU (42.33) marks an edge.

The masses are small beside the planets. The main belt weighs 2.394×10^{21} kg, 3.3 % of the Moon, and Ceres holds 39 % of it. The Kuiper belt weighs 1.177×10^{23} kg, 49 times the main belt; the outer Oort cloud is estimated at about 5 Earth masses.

Impacts on the Earth read as loading, holding and discharge. A 5-kiloton strike comes about yearly, a 10-megaton strike about once in 1,000 years (55.16), and a strike of at least 1.3×10^{24} J at Chicxulub 66.043 million years ago (65.26). The database holds 190 confirmed structures; the largest listed run from Yarrabubba at 2,229 million years to Popigai at 35.7 million years.

The Sun’s reach has an edge. The net’s texts place it at 5,350, 7,030 and 7,400 AU (46.62–46.92), where the Sun’s pull falls to the stretch of the galaxy around it. That edge lies inside the inner Oort cloud, 2,000–20,000 AU, where the comets are bound but barely.

Nested systems appear among the smallest bodies: 471 asteroid moons and 149 trans-Neptunian moons are known. Arrokoth is two lobes, 20.1 and 15.0 km, joined into one body of 34.5 km. Both read as forms of the net: addresses inside addresses, and the pair.

The visitors from other stars read as context. Three objects, in 2017, 2019 and 2025, came in at 26.33, 32.3 and 58 km/s. Their gas held other mixtures: carbon monoxide at 35–105 % of water, carbon dioxide at eight times water, nickel without iron.

The flow has not stopped. About 40×10^{6} kg of dust falls on the Earth every year, at 1.27 kg per second, and five to ten meteorite falls are recovered each year. Over 85 % of the zodiacal dust comes from comets, and Halley feeds two meteor showers; read as form and carrier, the cloud and the streams hold while their grains change.

33. Worlds Around Other Stars

The Solar System is one planetary system among thousands now measured. The first planets outside it were confirmed in 1992. By 15 October 2026 the NASA Exoplanet Archive listed 6,445 confirmed planets in 4,834 systems [859][867].

This chapter tells that history in the order it was found. It begins with three small planets around a dead star and one giant planet around a Sun-like star. It ends with resonant chains of seven planets, the nearest worlds at 1.30 pc, and air read on planets hundreds of light-years away.

On the ladder of chapter 24 the measured orbits of other worlds run from periods under one day (43.50) to thousands of days. Most of the known planets, 83.4 %, have years shorter than 100 days. The nearest of them lie at positions 50.19 to 51.05, between 4.2 and 11 light-years away.

The first worlds

The first planets confirmed outside the Solar System circle a pulsar. In 1992 Wolszczan and Frail found two planets around the millisecond pulsar PSR B1257+12; a third followed in 1994 [940][959]. The pulsar spins once in 6.21853194840048 ms (28.53) and lies 2,300 ± 100 light-years away, 710 ± 40 pc (55.92) [940].

Planet	Mass (M⊕)	Period (days)	pos	Semimajor axis (AU)	pos	[n]
Draugr (b, A)	0.020 ± 0.002	25.262 ± 0.003	46.44	0.19	37.30	[940]
Poltergeist (c, B)	4.3 ± 0.2	66.5419 ± 0.0001	47.32	0.36	37.88	[940]
Phobetor (d, C)	3.9 ± 0.2	98.2114 ± 0.0002	47.67	0.46	38.10	[940]

The three orbits lie within 0.46 AU [940], close to the 0.387 AU of Mercury’s orbit around the Sun [847]. The period of Phobetor is 98.2114 / 66.5419 = 1.476 times that of Poltergeist, near 3:2. Poltergeist’s period is 2.634 times Draugr’s.

The first planet around a Sun-like star on the main sequence came three years later. On 6 October 1995 Michel Mayor and Didier Queloz of the University of Geneva announced 51 Pegasi b, found by the wobble of its star’s radial velocity [941]. The discovery shared the Nobel Prize in Physics of 2019.

51 Pegasi b has a minimum mass of about half that of Jupiter [941]. It orbits in 4.2307966 ± 0.0000027 days (44.81) at 0.052344942 AU (36.12), about 50 light-years (15 pc) from the Earth. For a Bond albedo of 0.1 its equilibrium temperature is 1,265 K.

That is a giant planet nearer its star than Mercury is to the Sun, by a factor of 0.387 / 0.0523 = 7.4 [941][847].

The first brown dwarfs were confirmed in the same years [956]. Teide 1 was found in 1994 and confirmed in 1995 by its lithium; Gliese 229B, confirmed in 1995, was the first of the coolest class, T, with methane in its air.

The archive’s year table carries this beginning: 2 planets in 1992, 1 in 1994 and 1 in 1995 [867]. The 1992 pair and the 1994 planet are those of PSR B1257+12, and the planet of 1995 is 51 Pegasi b.

The census grows

For the next fifteen years the planets came in tens per year; from 2011 they came in hundreds [867]. Two years stand out: 872 planets in 2014 and 1,504 in 2016.

Year	Planets	Year	Planets	Year	Planets

1992	2	2004	27	2016	1,504
1994	1	2005	36	2017	152
1995	1	2006	32	2018	308
1996	6	2007	52	2019	194
1997	1	2008	62	2020	234
1998	6	2009	87	2021	564
1999	13	2010	93	2022	367
2000	16	2011	141	2023	323
2001	12	2012	144	2024	260
2002	29	2013	128	2025	246
2003	22	2014	872	2026 (to 15 Oct)	361
		2015	155		

The yearly counts as returned sum to 6,451; the total of the same table is 6,445 [859] [867]. The years 2014 and 2016 together hold 872 + 1,504 = 2,376 planets, 36.9 % of all. From the first discovery in 1992 to now is 34 years (52.08).

Most planets were found by their transits across their stars. The archive counts the methods as follows [859][867].

Method	Planets	Share	[n]
Transit	4,781	74.2 %	[859]
Radial velocity	1,203	18.7 %	[859]
Microlensing	292	4.5 %	[859]
Imaging	97	1.5 %	[859]
Transit-timing variations	29	0.4 %	[859]
Eclipse-timing variations	17	0.3 %	[859]
Orbital brightness modulation	9	0.1 %	[859]
Pulsar timing	8	0.1 %	[859]
Astrometry	6	0.1 %	[859]
Pulsation-timing variations	2	—	[859]
Disk kinematics	1	—	[859]

Of all confirmed planets, 4,811 transit their stars [859]. Three space missions found most of them. Kepler confirmed 2,787 planets of 4,717 candidates, with 1,977 still unconfirmed; K2 confirmed 550 with 975 candidates left; TESS confirmed 1,008 of 8,148 candidates, with 4,823 unconfirmed.

Kepler, K2 and TESS together account for 2,787 + 550 + 1,008 = 4,345 planets, 67.4 % of the confirmed total [859].

What the census holds

Periods. Of the 6,097 planets with a measured period, 164 orbit in less than one day (43.50) [867]. 2,773 orbit in 1–10 days (43.50–45.60), 2,149 in 10–100 days (45.60–47.69) and 1,011 in 100 days (47.69) or more. These are 2.7 %, 45.5 %, 35.2 % and 16.6 %.

The Earth’s year lies at 48.87. Of the discovered planets, (164 + 2,773 + 2,149) / 6,097 = 83.4 % have periods shorter than 100 days, near or below Mercury’s 88-day year at 47.57 [847]. These are counts of found planets, with the detection biases of transit and radial-velocity surveys.

Sizes. Of 4,381 planets smaller than 8 Earth radii (31.54), the archive gives the counts in steps of half an Earth radius [867]. One Earth radius is 6,378.1 km (29.65) [847].

Radius (R⊕)	pos	Planets	[n]
< 0.5	< 29.02	8	[867]
0.5–1	29.02–29.65	223	[867]
1–1.5	29.65–30.02	782	[867]

1.5–2	30.02–30.28	782	[867]
2–2.5	30.28–30.48	850	[867]
2.5–3	30.48–30.65	714	[867]
3–3.5	30.65–30.79	363	[867]
3.5–4	30.79–30.91	197	[867]
4–4.5	30.91–31.02	124	[867]
4.5–5	31.02–31.11	82	[867]
5–5.5	31.11–31.20	67	[867]
5.5–6	31.20–31.28	45	[867]
6–6.5	31.28–31.35	44	[867]
6.5–7	31.35–31.42	41	[867]
7–7.5	31.42–31.48	32	[867]
7.5–8	31.48–31.54	27	[867]

Between 1 and 2 Earth radii lie 1,564 planets (35.7 %), and between 2 and 4 Earth radii 2,124 (48.5 %). Only 231 (5.3 %) are smaller than the Earth.

The most common size in the catalogue, 2–2.5 Earth radii, lies between the Earth and Neptune. Neptune has 24,764 / 6,378.1 = 3.88 Earth radii [847].

The radius gap. Precise stellar radii sharpen the picture. In a Kepler sample of 2,025 planets, close-in small planets with periods under 100 days show a deficit of at least a factor of 2 at 1.5–2.0 Earth radii (30.02–30.28) [942]. The gap separates a population below 1.5 Earth radii from one at 2.0–3.0 Earth radii (30.28–30.65).

How common. Counts of found planets differ from the rate at which stars carry them. Radial-velocity surveys of nearby Sun-like stars find hot Jupiters around 1.2 ± 0.38 % of them [943]. That is more than double the rate an earlier study reported for Kepler stars.

In the catalogue, 709 planets of more than 0.3 Jupiter masses have periods under 10 days, 11.0 % of all; the methods over-represent them.

Kepler found 1,235 planets within 0.25 AU (37.55), with periods under 50 days (47.06), around 156,000 target stars [944]. Their occurrence varies by more than three orders of magnitude across sizes and periods. Planets of 2–4 Earth radii are seven times more common around the coolest stars of the sample than around the hottest, over stellar temperatures of 3,600 to 7,100 K.

This is a reading: the rates have the form of context. The same kinds of planet occur at different rates around different stars.

Earths in the warm zone. Kepler’s final data, with Gaia distances, give the number of rocky planets of 0.5–1.5 Earth radii in the habitable zones of stars of 4,800–6,300 K [945]. In the conservative zone there are between 0.37 (+0.48/−0.21) and 0.60 (+0.90/−0.36) such planets per star. In the optimistic zone there are 0.58 to 0.88.

The nearest such planet around a G or K dwarf would lie about 6 pc away (51.58), at 95 % confidence [945]. Within 10 pc (52.04) there would be about 4.

An earlier study of 42,000 Kepler stars found 603 planets, 10 of them 1–2 Earth radii across [946]. It gave 11 ± 4 % of Sun-like stars an Earth-size planet receiving 1–4 times the Earth’s sunlight. For orbits of 200–400 days (48.32–48.95) it gave 5.7 (+1.7/−2.2) %.

The two studies differ in size range, zone and sample. The central value of the later one is 0.37 / 0.057 = 6.5 times the earlier.

Across the Milky Way, a 2013 Kepler analysis gives 17 billion Earth-size planets [963]. Other estimates give up to 40 billion Earth-size planets in habitable zones, 11 billion of them around Sun-like stars, and a 2020 estimate more than 300 million habitable planets. The galaxy holds 100–400 billion stars, with at least as many planets.

Systems of many planets

The archive counts the known planets by the number in their system [867]. From these the number of systems follows: a system of n planets is counted n times.

Planets in system	Planets	Systems	[n]
1	3,764	3,764	[867]
2	1,438	719	[867]
3	672	224	[867]
4	332	83	[867]
5	145	29	[867]
6	72	12	[867]
7	14	2	[867]
8	8	1	[867]

That gives 4,834 systems. Of these, 1,070 (22.1 %) hold two or more known planets, and they contain 2,681 planets, 41.6 % of the total. Twelve systems have six planets, two have seven, and one has eight.

Planets of one system share one star. This is a reading: a system has the form of community as shared prefix, its planets carrying their star’s address as the first part of their own.

Kepler-90. The one known system of eight planets is KOI-351, Kepler-90 [867]. Its periods are 7.008151, 8.719375, 14.44912, 59.73667, 91.93913, 124.9144, 210.73514 and 331.60296 days (45.27 to 48.78). The ratios between neighbours are 1.244, 1.657, 4.134, 1.539, 1.359, 1.687 and 1.574.

All eight orbits of Kepler-90 fit within 331.6 days, shorter than the Earth’s year (48.87). The Solar System’s eight run from 88.0 days to 59,800 days, 164 years [847].

TRAPPIST-1. Around the small star TRAPPIST-1 circle at least seven planets similar to the Earth in radius and mass [868]. They form a complex chain, with three-body resonances linking every member. The outermost, h, has a period of 18.77 days and an equilibrium temperature of 173 K; the star turns in 3.3 days (44.59).

Planet	Period (days)	pos	Mass (M⊕)	Radius (R⊕)	pos	Ratio to inner neighbour	[n]
b	1.510826	43.88	1.374	1.116	29.75	—	[867]
c	2.421937	44.30	1.308	1.097	29.73	1.6031 (8:5)	[867]
d	4.049219	44.77	0.388	0.788	29.43	1.6719 (5:3)	[867]
e	6.101013	45.15	0.692	0.920	29.57	1.5067 (3:2)	[867]
f	9.20754	45.52	1.039	1.045	29.69	1.5092 (3:2)	[867]
g	12.352446	45.79	1.321	1.129	29.76	1.3416 (4:3)	[867]
h	18.772866	46.17	0.326	0.755	29.39	1.5198 (3:2)	[867]

In units of the period of b the seven periods are 1, 1.603, 2.680, 4.038, 6.094, 8.176 and 12.426. The archive gives h a radius of 0.755 Earth radii; the discovery paper gives 0.727 [867][868].

Spitzer timed the transits over four years (50.13), and the variations in those times give the masses to 3–5 % [947]. That precision equals a radial-velocity precision of 2.5 cm/s. The system is stable over 10 million years (63.54), and a uniform fit gives the planets 21 % iron by weight against 32 % for the Earth.

Kepler-223. Four sub-Neptune planets around Kepler-223 form a resonant chain of small whole-number ratios [870].

Planet	Period (days)	pos	Mass (M⊕)	Radius (R⊕)	pos	[n]
b	7.38449	45.32	7.4	2.99	30.65	[867]

c	9.84564	45.58	5.1	3.44	30.77	[867]
d	14.78869	45.95	8.0	5.24	31.16	[867]
e	19.72567	46.21	4.8	4.60	31.04	[867]

The neighbour ratios are 1.3333 (4:3), 1.5021 (3:2) and 1.3338 (4:3). In units of one third of b’s period, the periods are 3, 4, 6.008 and 8.014: the chain 3:4:6:8.

TOI-178. Six transiting planets circle TOI-178 with periods of 1.91, 3.24, 6.56, 9.96, 15.23 and 20.71 days (44.09 to 46.26) [871]. All but the innermost form a chain of Laplace resonances written 2:4:6:9:12. In units of half of c’s period, the precise periods give 1.18, 2, 4.05, 6.15, 9.41 and 12.79 [867].

The neighbour ratios are 1.692, 2.025 (2:1), 1.519 (3:2), 1.529 (3:2) and 1.360 (4:3) [867][871]. The radii run from 1.152 to 2.87 Earth radii (29.78–30.61), and the masses from 0.96 to 5.63 Earth masses [867]. The density drops from 1.02 to 0.177 times the Earth’s between planets c and d.

This is a reading: the chains have the form in which only what fits stays. Their orbits return together in whole-number steps, 8:5, 5:3, 3:2 and 4:3, as the moons of Jupiter and Saturn do (chapter 31).

It reads as the same winding at two depths. Io, Europa and Ganymede keep 1:2:4 at periods of 1.76 to 7.16 days (44.02–45.29) [877]; the planets of TRAPPIST-1 keep 3:2 and 4:3 at 1.51 to 18.77 days (43.88–46.17). A system of moons and a system of planets carry whole-number steps in one band of the ladder.

The nearest worlds

The nearest star, Proxima Centauri, lies 1.295 pc away (50.18), 4.2465 light-years [948] [962]. It is a red dwarf of about 12 % of the Sun’s mass, 0.14 solar radii (32.13), about 3,050 K and 0.1 % of the Sun’s light, turning in about 83 days (47.52) [948]. It circles Alpha Centauri AB at 12,947 ± 260 AU (47.43) in about 547,000 years (60.90) [962].

On 24 August 2016 the Pale Red Dot campaign announced a planet around it from HARPS and UVES radial velocities [948][949]. Proxima b orbits in about 11.2 days with a minimum mass of 1.3 Earth masses at about 0.05 AU. Later data give a period of 11.18465 ± 0.00053 days (45.70), a semimajor axis of 0.04848 AU (36.05) and a minimum mass of 1.055 ± 0.055 Earth masses.

Its star’s wobble has an amplitude of 1.226 ± 0.062 m/s [949]. Its equilibrium temperature is 234 K.

The archive lists twelve planets around five stars within 3.5 pc [867].

Planet	Found	Period (days)	pos	Minimum mass (M⊕)	Distance (pc)	pos	[n]
Proxima Cen b	2016	11.18465	45.70	1.055	1.30119	50.19	[867]
Proxima Cen d	2025	5.12338	44.99	0.26	1.30119	50.19	[867]
Barnard b	2024	3.1542	44.55	0.299	1.82655	50.49	[867]
Barnard c	2025	4.1244	44.79	0.335	1.82655	50.49	[867]
Barnard d	2025	2.3402	44.27	0.263	1.82655	50.49	[867]
Barnard e	2025	6.7392	45.24	0.193	1.82655	50.49	[867]
eps Eri b	2000	2,680	50.68	317.83	3.2026	51.01	[867]
GJ 887 b	2020	9.2619	45.53	3.9	3.28679	51.03	[867]
GJ 887 c	2020	21.784	46.30	6.5	3.28679	51.03	[867]
GJ 887 d	2026	50.77	47.07	6.1	3.28679	51.03	[867]
GJ 887 e	2026	4.4249	44.85	1.46	3.28679	51.03	[867]
Ross 128 b	2017	9.8658	45.58	1.40	3.37454	51.05	[867]

Barnard’s Star, 1.827 pc away, has four known planets of 0.19 to 0.34 Earth masses, all found in 2024–2025 [867]. Barnard e orbits at 0.0381 AU (35.83). Epsilon Eridani b, a

planet of one Jupiter mass, orbits at 3.53 AU (39.96) in 2,680 days (50.68), 7.3 years.

Of the twelve, eleven orbit in less than 51 days, shorter than Mercury’s 88-day year. Seven were found in 2024–2026.

The neighbourhood around these stars is crowded with small stars. Within 10 pc (52.04) a catalogue lists 540 stars, brown dwarfs and exoplanets in 339 systems [960]. About 28 % of the systems are multiple, and about 61 % of the stars and brown dwarfs are M dwarfs.

Within 20 light-years (51.60) lie 133 known objects in 95 systems: 103 main-sequence stars (78 of them red dwarfs), 6 white dwarfs, 20 brown dwarfs and 4 sub-brown dwarfs [939]. Only 22 of them can be seen without a telescope. Within 20 pc (52.67) a census counts about 3,600 stars and brown dwarfs, with a mean mass of 0.41 solar masses [961].

The nearest systems lie, in order, at 4.2465 light-years (Alpha Centauri with Proxima, 50.19), 5.9629 (Barnard’s Star, 50.50) and 6.5102 (Luhman 16, 50.58) [939]. Then follow WISE 0855−0714 at 7.430 (50.70), Wolf 359 at 7.856 (50.75), Lalande 21185 at 8.3044 (50.80) and Sirius at 8.7094 light-years (50.84).

Air on other worlds

The James Webb Space Telescope began to read the air of exoplanets in 2022. Its NIRSpec spectrum of the hot giant WASP-39b, from 3.0 to 5.5 µm (3.81–4.36), showed a prominent carbon dioxide absorption at 4.3 µm (4.14), at 26σ significance [950]. It was the first identification of carbon dioxide in an exoplanet’s atmosphere.

The spectrum matches models at 10 times the Sun’s metallicity [950]. A small feature near 4.0 µm (4.07) remained unexplained.

K2-18b. K2-18b has a mass of 8.63 ± 1.35 Earth masses and a radius of 2.610 ± 0.087 Earth radii (30.52) [951]. It orbits in 32.940045 days (46.68) at 38.025 pc, 124 light-years (53.26). Its bulk density is 8.63 / 2.61³ = 0.485 times the Earth’s.

Without a greenhouse its temperature would be 250–300 K, 265 ± 5 K in the summary value [951]. Water vapour was reported in 2019.

JWST spectra from 0.9 to 5.2 µm (2.72–4.31) showed methane at 5σ and carbon dioxide at 3σ, each about 1 % by volume, with potential signs of dimethyl sulphide [952]. In 2025 MIRI spectra at about 6–12 µm (4.44–5.07) were inconsistent with a flat spectrum at 3.4σ and gave evidence for dimethyl sulphide and/or dimethyl disulphide at 3σ, at 10 ppmv or more [953].

Two analyses of the same year disagree. A joint analysis of all three instruments, 0.6–12 µm (2.35–5.07), finds insufficient evidence for either molecule [954]. About 25 more MIRI transits would be needed to reject a flat line at 3σ.

A second study finds that the claims of biosignatures vanish when the space of models is widened, with many alternatives fitting as well or better [955]. The significance of a detection depends on which models are compared.

Further reanalyses give a tentative detection (2024), a signature that might be other molecules or a flat line (2025), and low significance (2024) [951]. Routes that make dimethyl sulphide without life have been described in 2025.

Worlds without a star

Some planets circle no star. Gravitational microlensing of the galactic bulge over nine years, by MOA-II, finds free-floating planets down to about one Earth mass [872]. The shortest event lasted 0.057 ± 0.016 days (40.89), with an Einstein angle of 0.90 ± 0.14 µas.

The survey gives about 21 (+23/−13) free-floating or very wide-orbit planets of 0.33 to 6,660 Earth masses per star [872]. Their total mass is about 80 (+73/−47) Earth masses

per star. They are 19 (+23/−13) times as numerous as planets in wide orbits.

The mass function rises toward small planets, as (M / 8 M⊕) to the power −0.96 (+0.47/−0.27) below 0.02 solar masses [872]. For the Roman telescope the survey expects 988 (+1,848/−566) free-floating planets down to the mass of Mars, 575 of them of 0.1–1 Earth masses.

Jupiter-mass planets without a star are rare. OGLE events of 2010–2015 set a 95 % upper limit of 0.25 such planets per main-sequence star [873].

The OGLE events show no excess of events lasting 1–2 days (43.50–44.13). A few events shorter than 0.5 day (42.87) may come from free-floating planets of Earth to super-Earth mass.

Where planets end

The line between a planet and a star is drawn by what burns inside. A body of about 13 Jupiter masses burns deuterium: 50 % of its deuterium burns at (13.0 ± 0.8) Jupiter masses for most conditions [747]. The limit runs from about 11.0 Jupiter masses at three times the Sun’s metallicity to about 16.3 at zero metallicity.

In Earth masses, 13 Jupiter masses are 13 × 317.83 = 4,132 Earth masses [867]. The free-floating mass range of MOA-II reaches 6,660 Earth masses, 21 Jupiter masses, above that limit [872].

Brown dwarfs lie between about 13 and 80 Jupiter masses [956]. Hydrogen burning begins near 80 Jupiter masses, 0.080 ± 0.008 solar masses [956][958]. Below about 65 Jupiter masses a brown dwarf never burns its lithium.

The working definition of the IAU calls a body above 13 Jupiter masses a brown dwarf wherever it formed, and a body below 13 Jupiter masses orbiting a star a planet [956]. The definition is disputed. Brown dwarfs come in spectral classes M at 2,100–3,500 K, L at 1,300–2,100 K, T at 600–1,300 K and Y below 600 K.

Over 1,800 brown dwarfs have been identified, and 25 to 100 billion are estimated in the Milky Way [956]. The nearest, the pair Luhman 16 AB, lies about 6.5 light-years away (50.57). In the field, brown dwarfs of 0.01–0.08 solar masses are 37 % of all objects but 4.3 % of the mass [957]; within 20 pc stars outnumber brown dwarfs four to one [961].

The lightest star measured directly is EBLM J0555-57Ab, at the hydrogen-burning limit [744]. Its mass is 85 ± 4 Jupiter masses, 0.081 solar masses, and its radius 0.84 Jupiter radii, 0.084 solar radii. That is 0.84 × 71,492 km = 60,053 km (31.69), the size of Saturn, whose equatorial radius is 60,268 km (31.69).

The net’s texts state the line in three words: “Planets read; stars open.” [26] In their terms a planet passes what its meshes let through and no more; in a star the central stretch reaches closure for the heaviest knots present. On the ladder, the texts add, the difference is not in mesh size.

This is a reading of EBLM J0555-57Ab and Saturn: a star and a planet at one position, 31.69, on two sides of the line.

What this part of the history shows

The history of other worlds is short. It began with three planets of 0.020–4.3 Earth masses around a pulsar in 1992–1994 and one giant at 0.052 AU around 51 Pegasi in 1995. Thirty-four years later (52.08) the archive holds 6,445 planets in 4,834 systems.

The census shows a band. Of the planets with a period, 83.4 % orbit in less than 100 days (47.69), and the most common size is 2–2.5 Earth radii (30.28–30.48), between the Earth and Neptune. Small close-in planets split at a gap of 1.5–2.0 Earth radii (30.02–30.28).

The rate depends on the star. Hot Jupiters orbit 1.2 % of Sun-like stars; planets of 2–4

Earth radii are seven times more common around the coolest stars than around the hottest. Read as context, the same kinds of planet take other rates in other surroundings.

Planets of one system share their star. 1,070 systems hold two to eight known planets, 2,681 planets in all; read as shared prefix, each planet’s address begins with its star’s.

The resonant chains read as the form in which only what fits stays. TRAPPIST-1 runs 8:5, 5:3, 3:2, 3:2, 4:3, 3:2; Kepler-223 runs 3:4:6:8; TOI-178 runs 2:4:6:9:12. The planets of TRAPPIST-1, at 43.88–46.17 in period, keep steps of the same kind as the moons of Jupiter at 44.02–45.29, read as the same winding at two depths.

The nearest worlds lie at 50.19–51.05. Twelve planets circle five stars within 3.5 pc, eleven of them with years shorter than Mercury’s; seven were found in 2024–2026. Within 10 pc there are 540 stars, brown dwarfs and planets.

Air has been read on other worlds. Carbon dioxide stands at 26σ in WASP-39b; on K2-18b methane stands at 5σ and carbon dioxide at 3σ, while dimethyl sulphide at 3σ is disputed by two analyses.

Planets also travel alone. About 21 free-floating or wide-orbit planets per star are inferred, with 80 Earth masses per star; Jupiter-mass ones number fewer than 0.25 per star.

The line between planet and star runs through burning, not size. Deuterium burns from about 13 Jupiter masses, hydrogen from about 80; the lightest star, 85 Jupiter masses, has the radius of Saturn (31.69). In the net’s words, planets read and stars open, and the difference does not lie in mesh size on the ladder.

34. The Milky Way and the Sun’s Neighbourhood

The Sun formed 4.567 Gyr ago (chapter 29) inside a galaxy that was already old. Its first disc of stars had begun 13 Gyr ago, 0.8 Gyr after the Big Bang. A large merger had shaped its inner halo about 10 Gyr ago, and its thin disc had been forming for about 3.4 Gyr (8 − 4.567) before the Sun appeared.

This chapter tells the history of that galaxy, the Milky Way, and of the region around the Sun within a few hundred parsecs. It runs from the first disc to the gas cloud the Sun crosses now and the stars it will meet next.

Sizes run from the nearest star at 1.30 pc (position 50.19) to the farthest listed satellite galaxy at 459 kpc (61.81). Times run from a 16-year orbit around the central black hole (51.39) to the 14.46 Gyr age of the star HD 140283 (70.17).

One closure depth of the ladder lies in this chapter. Depth 53 is 3^{53} natural units: 93.4 light-years in length and 93.4 years in time. It is a radius around the Sun, and the chapter names what stands inside it and at its rim.

On the ladder of chapter 24, every size has a position, log base 3 of the size over 4.558816×10^{-8} m. A parsec is 3.0857×10^{16} m and a light-year 9.4607×10^{15} m; one solar mass ($M_\odot$) is 1.9884×10^{30} kg. Ages before now are placed as durations.

The first disc and the great merger: 13 to 8 Gyr ago

The oldest dated part of the Galaxy is its thick disc. Ages of subgiant stars from LAMOST spectra and Gaia EDR3 parallaxes show that its star formation “started 13 Gyr ago”, only 0.8 Gyr after the Big Bang [726]. Thirteen Gyr sits at time position 70.07; 0.8 Gyr at 67.53.

Most thick-disc stars formed 11 Gyr ago (69.92) [726]. The stars’ ages and metallicities split into two almost disjoint groups, separated at 8 Gyr. Over the following 5–6 Gyr the metal content of new stars rose by a factor of 10 [726].

The oldest globular clusters are as old as 12.7 Gyr (70.05) [966]. The oldest stars of the Galaxy are “nearly as old as the universe itself” [967]. One of them passes through the Sun’s neighbourhood: HD 140283, a metal-poor subgiant with [Fe/H] = −2.40, has an age of 14.46 ± 0.31 Gyr (statistical), ± 0.8 Gyr with all uncertainties [679].

Its parallax is 17.15 ± 0.14 mas, a distance of 1/0.01715 = 58.3 pc (position 53.65) [679]. Its age, 14.46 Gyr at 70.17, overlaps within its error the 13.77 ± 0.06 Gyr age of the universe used for comparison [679].

About 10 Gyr ago (69.83) a single dwarf galaxy fell in. It is called Gaia–Enceladus, or the Gaia Sausage. At infall it was “slightly more massive than the Small Magellanic Cloud”, and the mass ratio with the young Milky Way was about 4:1 [964].

Its debris now dominates the inner stellar halo. The merger heated the precursor of the thick disc. Thirteen globular clusters and hundreds of RR Lyrae stars came with it [964].

A second study used seven-dimensional data on main-sequence stars within about 10 kpc. Halo stars with [Fe/H] > −1.7 move on strongly radial orbits, with anisotropy $\beta \approx 0.9$; more metal-poor stars have $0.2 < \beta < 0.4$ [965]. The accreted satellite had a virial mass above 10^{10} $M_\odot$, and it arrived between 8 and 11 Gyr ago [965].

Twelve members of Gaia–Enceladus lie within 100 pc of the Sun (100 pc at position 54.14) [992]. The halo of the neighbourhood thus holds the debris of an event 10 Gyr old.

The thin disc followed. The cooling of its white dwarfs dates it at about 8 Gyr (69.63) [842]. This is the age at which the old and young sequences of stars separate [726].

Event	Time before now	Position	Source
Thick-disc star formation begins	13 Gyr	70.07	[726]
Oldest globular clusters	12.7 Gyr	70.05	[966]
Most thick-disc stars formed	11 Gyr	69.92	[726]
Gaia–Enceladus merger	≈ 10 Gyr (8–11 Gyr)	69.83	[964][965]
Thin disc (white-dwarf clock); split of old and young sequences	≈ 8 Gyr	69.63	[842][726]
The Sun forms	4.567 Gyr	69.12	chapter 29

The shape of the Galaxy

The Milky Way is “a luminous barred spiral with a central box/peanut bulge, a dominant disk, and a diffuse halo” [970]. In the colour–magnitude diagram of galaxies it lies in the “green valley” [970].

Its size depends on the method. The isophotal diameter at 25 mag arcsec^{-2}, the D25, is 26.8 ± 1.1 kpc, or 87,400 ± 3,600 ly (8.27×10^{20} m, position 59.23) [967]. Comparable galaxies have a mean isophotal size of 28.3 kpc [967].

Single disc stars reach farther. LAMOST and APOGEE spectra find disc stars beyond 26 kpc from the centre at 99.7% confidence and beyond 31 kpc at 95.4% [968]. A radius of 31 kpc (59.36) gives a stellar disc at least 62 kpc across, about 200,000 ly (59.99), more than twice the isophotal diameter [968].

The Triangulum–Andromeda ring was proposed in 2015 as part of the disc, which would make it at least 50 kpc across; a 2018 paper “somewhat ruled out” this [967]. The dark halo reaches farther still. Its splashback edge lies at 292 ± 61 kpc (61.40), a diameter of 584 ± 122 kpc (62.03); simulations suggest about 613 kpc [967].

The disc is thin. The thin disc is 220–450 pc thick (54.86–55.51); the thick disc 2.6 ± 0.5 kpc (57.10) [967]. The Sun sits 8.18 kpc from the centre, about 61% of the D25 radius of 13.4 kpc (58.60) and 26% of the 31 kpc stellar radius.

In the centre lies a bar. Its red-clump giants were mapped in the VVV, UKIDSS and 2MASS surveys over $|b| < 9°$ and $|l| < 40°$ [969].

They give a half-length of 5.0 ± 0.2 kpc (57.70) for a two-component bar, and 4.6 ± 0.3 kpc for the thin bar alone [969]. The bar lies at 28–33° to the line from the Sun to the centre. It reaches $l \approx 25°$ at $|b| \approx 5°$ and $l \approx 30°$ nearer the plane [969].

The bar has two components. A thin bar of about 180 pc scale height (54.67) resembles the old thin disc; a second, super-thin bar component has a scale height of about 45 pc (53.41) [969]. Older studies give half-lengths of 1–5 kpc and orientations of 10–50° [967].

The spiral pattern differs by tracer. Gas and young stars trace four arms: the Near 3 kpc/Perseus, Norma/Outer, Far 3 kpc/Scutum–Centaurus and Carina–Sagittarius arms [967]. Old stars trace two major arms, Perseus and Scutum–Centaurus; the pitch angle lies between about 7° and 25° [967].

Between the major arms run smaller arms and spurs. One of them, the Orion–Cygnus Arm, holds the Sun [967]. A gas structure called the Radcliffe Wave occupies about 20% of that arm’s width [990].

Structure	Value	Position	Source
D25 diameter	26.8 ± 1.1 kpc	59.23	[967]
Disc stars beyond	26 kpc (99.7%); 31 kpc (95.4%)	59.20; 59.36	[968]
Halo edge (splashback radius)	292 ± 61 kpc	61.40	[967]
Thin disc thickness	220–450 pc	54.86–55.51	[967]

Thick disc thickness	2.6 ± 0.5 kpc	57.10	[967]
Bar half-length	5.0 ± 0.2 kpc	57.70	[969]
Bar scale heights	≈ 180 pc; ≈ 45 pc	54.67; 53.41	[969]
Bar angle to Sun–centre line	28–33°	—	[969]
Arms	4 in gas; 2 major in old stars; pitch 7–25°	—	[967]

Rotation and mass

The disc turns. At the Sun the circular speed is v_c = 229.0 ± 0.2 km s⁻¹, with systematic uncertainty of 2–5% [825]. This value comes from the Jeans equation applied to six-dimensional data for more than 23,000 red giants from APOGEE, Gaia DR2, WISE and 2MASS [825].

From 5 to 25 kpc the curve declines gently, by −1.7 ± 0.1 km s⁻¹ per kpc; the inner 5 kpc are left out because of the bar [825]. A mass model gives v_0 = 232.8 ± 3.0 km s⁻¹, or 226.8 ± 4.2 km s⁻¹ with a looser prior on the Sun's distance [971].

Beyond 19 kpc the curve falls faster. Gaia DR3 data show a Keplerian decline from about 19 to 26.5 kpc (58.91 to 59.22) [972].

The speed drops by about 30 km s⁻¹ between 19.5 and 26.5 kpc, and a flat curve is rejected at 3σ [972]. The total mass from this curve is 2.06 (+0.24/−0.13) × 10^{11} M☉, or 4.10 × 10^{41} kg, with an upper limit of 5.4 × 10^{11} M☉ [972].

A second Gaia DR3 study follows 120,309 stars to about 30 kpc. It fits the dark halo with a cored Einasto profile of slope parameter 0.91 (+0.04/−0.05) and finds a halo virial mass of only 1.81 (+0.06/−0.05) × 10^{11} M☉ [973]. The 2023 Gaia mass is about a tenth of earlier values [967].

Other methods give more. Thirty-four halo globular clusters with Gaia DR2 proper motions give M(< 21.1 kpc) = 0.21 (+0.04/−0.03) × 10^{12} M☉ and a circular speed of 206 (+19/−16) km s⁻¹ at 21.1 kpc (59.01) [974]. With 46 clusters out to 39.5 kpc (59.58): M(< 39.5 kpc) = 0.42 (+0.07/−0.06) × 10^{12} M☉ and a virial mass of 1.54 (+0.75/−0.44) × 10^{12} M☉ [974].

That virial mass is 3.06 × 10^{42} kg. It is 1.54 × 10^{12} / 2.06 × 10^{11} = 7.5 times the Gaia DR3 rotation-curve mass. Earlier estimates ran "from below 10^{12} M☉ to above 2 × 10^{12} M☉" [974].

The mass model of McMillan gives a virial mass of 1.30 ± 0.30 × 10^{12} M☉ [971]. Eilers and co-workers give a dark-halo virial mass of 7.25 ± 0.26 × 10^{11} M☉ [825].

Further published values are 1.15 × 10^{12} M☉, 8.8 × 10^{11} M☉ within 200 kpc, and 5.8 × 10^{11}, 8.5 × 10^{11} and 1.29 × 10^{12} M☉ [967]. Dark-matter masses range from 8 × 10^{11} to 4.5 × 10^{12} M☉ [967].

Near the Sun the dark-matter density is 0.38 ± 0.04 GeV cm⁻³ in one model [971] and 0.30 ± 0.03 GeV cm⁻³ in the other [825]. The stars are the best-weighed part. Their mass is 6.08 ± 1.14 × 10^{10} M☉ in a Bayesian combination of published values [739], and 54.3 ± 5.7 × 10^{9} M☉ in the McMillan model [971].

At the Sun's distance the escape velocity is 550 km s⁻¹ [967]. The orbital speed is often given as about 220 km s⁻¹, 0.073% of the speed of light [967].

Quantity	Value	Source
v_c at the Sun	229.0 ± 0.2 km s⁻¹	[825]
v_0 (mass model)	232.8 ± 3.0 km s⁻¹	[971]
Slope 5–25 kpc	−1.7 ± 0.1 km s⁻¹ kpc⁻¹	[825]
Drop 19.5–26.5 kpc	≈ 30 km s⁻¹	[972]
Mass from Gaia DR3 curve	2.06 × 10^{11} M☉	[972]
Halo virial mass (Einasto)	1.81 × 10^{11} M☉	[973]
Halo virial mass	7.25 ± 0.26 × 10^{11} M☉	[825]

Virial mass (model)	1.30 ± 0.30 × 10^{12} M☉	[971]
Virial mass (globular clusters)	1.54 (+0.75/−0.44) × 10^{12} M☉	[974]
Stellar mass	6.08 ± 1.14 × 10^{10}; 5.43 ± 0.57 × 10^{10} M☉	[739]; [971]
Local dark-matter density	0.30–0.38 GeV cm^{-3}	[825]; [971]
Escape velocity at the Sun	550 km s^{-1}	[967]

Stars, gas and the rate of renewal

The Galaxy holds 100–400 billion stars [967]. A Local Group table gives (2.5 ± 1.5) × 10^{11} [980]. Dividing the stellar mass, 6.08 × 10^{10} M☉, by the mean mass of 0.41 M☉ per object found within 20 pc gives about 1.5 × 10^{11} objects, if the local mix holds everywhere [739][961].

The Gaia satellite has measured a large share of them. Its third data release, built on 34 months of data, gives astrophysical parameters for about 470 million and 1,500 million sources in two sets [975]. It holds more than 33 million radial velocities, about 220 million low-resolution spectra, about 10 million variable stars in 24 classes and some 800,000 binaries [975].

The same release holds more than 150,000 objects of the Solar System [975]. The stars carry at least as many planets [967]. A 2013 Kepler analysis gives 17 billion Earth-size planets in the Galaxy; another gives up to 40 billion Earth-size planets in habitable zones, 11 billion of them around Sun-like stars [967].

Brown dwarfs, between about 13 and 80 Jupiter masses, number an estimated 25–100 billion [746]. Neutron stars number about one billion; about 3,200 are known in the Milky Way and the Magellanic Clouds [998]. More than 97% of the Galaxy's stars end as white dwarfs [842].

Gas becomes stars in molecular clouds. A catalogue of 8,107 clouds over the whole disc holds 1.2 × 10^{9} M☉ of molecular hydrogen, about 2.4 × 10^{39} kg; the most probable cloud radius is about 30 pc (53.04) [734]. The molecular ring lies 3.5–7.5 kpc from the centre (57.37–58.07) [997].

Interstellar gas makes up 10–15% of the stellar mass [967]. The Galaxy turns 1.65 ± 0.19 M☉ of gas into stars per year [739]; a harmonised value from earlier estimates of 1–10 M☉ per year is 1.9 ± 0.4 M☉ per year [740]. The first rate is 3.28 × 10^{30} kg per year, or 1.04 × 10^{23} kg each second.

At that rate the present stellar mass would take 6.08 × 10^{10} / 1.65 = 3.7 × 10^{10} years to build. The Galaxy is 13 Gyr old, so the rate was higher in the past, as the thick-disc record shows [726].

Massive stars end as core-collapse supernovae. The Milky Way rate is 1.63 ± 0.46 per century, a mean interval of 61 (+24/−14) years [758]. That interval sits at time position 52.61; its range of 47–85 years spans 52.37 to 52.91.

The last supernova seen in the Galaxy was Kepler's, in 1604 [996]. From 1604 to 2026 are 422 years (54.37), about seven mean intervals.

Quantity	Value	Source
Stars	100–400 × 10^{9}	[967]
Gaia DR3 sources with parameters	≈ 1.5 × 10^{9}	[975]
Gaia DR3 radial velocities	> 33 × 10^{6}	[975]
Gaia DR3 binaries	≈ 800,000	[975]
Brown dwarfs (estimate)	25–100 × 10^{9}	[746]
Neutron stars (estimate; known)	≈ 10^{9}; ≈ 3,200	[998]
Molecular clouds catalogued	8,107; 1.2 × 10^{9} M☉ H_2	[734]
Star-formation rate	1.65 ± 0.19; 1.9 ± 0.4 M☉ yr^{-1}	[739]; [740]
Core-collapse supernova interval	61 (+24/−14) yr	[758]
Last Galactic supernova seen	1604	[996]

The centre

At the centre lies the black hole Sagittarius A*. Its mass, from the orbits of the stars S2, S29, S38, S55 and thirteen more, is 4.30×10^{6} M☉ to about ±0.25%, or 8.55×10^{36} kg [783]. Any extended mass inside the farthest point of S2's orbit is at most 3,000 M☉, below 0.1% of the black hole [783].

S2 circles the black hole in 16 years (time position 51.39). After 27 years of tracking, the GRAVITY instrument measured the gravitational redshift of its light at 20σ, with f = 1.04 ± 0.05 [784]. The same orbit fixes the distance from the Sun to the centre: R_0 = 8,178 ± 13 (stat.) ± 22 (sys.) pc, or 26,670 ly, 2.52×10^{20} m, at size position 58.15 [784].

A mass model gives R_0 = 8.20 ± 0.09 kpc, or 7.97 ± 0.15 kpc with a looser prior [971]. Older values are 8.3 kpc and 7.86 kpc [967].

The Event Horizon Telescope imaged the black hole at a wavelength of 1.3 mm in 2017. It shows "a bright, thick ring with a diameter of 51.8 ± 2.3 μas" [785]. At 8,178 pc that angle is 51.8×10^{-6} / 206,265 × 2.52×10^{20} m = 6.34×10^{10} m, or 0.42 AU (size position 38.03).

The Schwarzschild radius of 4.30×10^{6} M☉ is $2GM/c^2 = 1.27 \times 10^{10}$ m (36.56). Very-long-baseline radio observations had measured a diameter of 44 million km for the source (37.69), 3.5 Schwarzschild radii [976]. An X-ray flare 400 times brighter than usual was reported in January 2015 [976].

The young massive stars near the centre formed in one event a few million years ago; another passage of the same page gives about 1 Myr [976]. Starbursts of this kind recur about every 500 Myr (67.10), and the next is expected in about 200 Myr (66.27) [976].

Above and below the centre stand two pairs of bubbles. The Fermi Large Area Telescope found two gamma-ray bubbles "extending 50 degrees above and below the Galactic center", about 40° wide in longitude, with a hard spectrum $dN/dE \sim E^{-2}$ [977]. Their edges match X-ray features at 1.5–2 keV seen by ROSAT, and the candidate origins are a nuclear starburst in the last 10 Myr or activity of the black hole [977].

Seen from 8.178 kpc, a structure reaching 50° above the centre extends 8.178 × tan 50° = 9.7 kpc (58.30). One encyclopaedia page gives each bubble a diameter of about 25,000 ly (7.7 kpc); another gives the bubbles a reach of about 25,000 ly above and below the centre [967][976].

The eROSITA X-ray telescope found larger bubbles. They "extend approximately 14 kiloparsecs above and below the Galactic centre" (58.64), and their energy is about 10^{56} erg, or 10^{49} J [978]. Their reach exceeds the 13.4 kpc radius of the disc's isophote.

Quantity	Value	Position	Source
Mass of Sgr A*	4.30×10^{6} M☉ ± 0.25%	—	[783]
Extended mass inside S2 orbit	≤ 3,000 M☉	—	[783]
S2 period	16 yr	51.39 (time)	[784]
R_0	8,178 ± 13 ± 22 pc	58.15	[784]
EHT ring	51.8 ± 2.3 μas = 0.42 AU	38.03	[785]
Schwarzschild radius	1.27×10^{10} m	36.56	computed
Radio diameter	44×10^{6} km	37.69	[976]
Starburst recurrence	≈ 500 Myr	67.10 (time)	[976]
Fermi bubbles	±50° latitude, 40° wide	58.30 (9.7 kpc)	[977]
eROSITA bubbles	≈ 14 kpc above and below; ≈ 10^{49} J	58.64	[978]

Satellites and globular clusters

Small galaxies orbit the Milky Way. Sixty-one are confirmed within 420 kpc (61.73) [979]. The list on the same page includes later finds up to 2024, and its most distant entries, Leo K at 434 kpc and Leo M at 459 kpc (61.81), lie beyond that radius [979].

The nearest is the Sagittarius dwarf at 20 kpc (58.96). It is being absorbed, and it passes through the disc within about 100 Myr [979]. The Large Magellanic Cloud lies at 48.5 kpc (59.77) and the Small Magellanic Cloud at 61 kpc (59.98) [979].

Their masses are 1×10^{10} M☉ (1.99×10^{40} kg) and 7×10^{9} M☉ [980]. Gaia–Enceladus, at infall, was slightly heavier than the Small Cloud [964].

Globular clusters are the oldest bound groups of stars. Over 150 were known; 158 by the end of 2010; later finds brought the total to 160, with more expected hidden in the bulge [966]. Gaia EDR3 gives mean parallaxes and proper motions for 170, velocity-dispersion profiles for more than 100 and rotation in more than 20 [981].

The Gaia DR3 census of star clusters recovers 134 globular clusters among its literature matches [982]. About 40% of the Galaxy's globular clusters move on retrograde orbits [967]. Thirteen of them came with Gaia–Enceladus [964], 13/170 = 7.6% of the clusters with Gaia motions.

Most globular clusters have half-light radii below 10 pc (52.04). They hold tens of thousands to many millions of stars [966]. 47 Tucanae has about one million stars, and Omega Centauri weighs several million M☉ [966].

Other galaxies have more. Andromeda has about 460 [999] to up to 500 globular clusters [966], about three times the Milky Way's 160. M87 has up to about 13,000, about 80 times as many [966].

Quantity	Value	Position	Source
Satellites within 420 kpc	61	61.73	[979]
Sagittarius dwarf	20 kpc; through the disc within ≈ 100 Myr	58.96	[979]
LMC; SMC	48.5 kpc; 61 kpc	59.77; 59.98	[979]
LMC; SMC mass	1×10^{10}; 7×10^{9} M☉	—	[980]
Globular clusters known	> 150; 158 (2010); 160	—	[966]
With Gaia EDR3 motions	170	—	[981]
Recovered in Gaia DR3 census	134	—	[982]
Retrograde share	≈ 40%	—	[967]
From Gaia–Enceladus	13	—	[964]
Andromeda; M87	≈ 460–500; ≈ 13,000	—	[999][966]

The Sun's orbit

The Sun lies 8,178 pc from the centre [784] and 20.8 ± 0.3 pc above the midplane of the disc (6.42×10^{17} m, position 52.71) [841]. Gaia DR2 star counts show the disc itself rippling vertically, with deficits near 0.4, 0.9 and 1.5 kpc and peaks near 0.2, 0.7 and 1.1 kpc from the plane [841]. Within a few hundred parsecs the mean vertical velocity of stars is constant to better than 1 km s^{-1} [841].

Seen from the Sun, Sagittarius A* moves across the sky at -6.411 ± 0.008 mas yr^{-1} along the Galactic plane and -0.219 ± 0.007 mas yr^{-1} toward the North Galactic Pole [839]. Converted to a speed, this apparent motion is the Sun's own orbit around the centre.

At 8.178 kpc the motion along the plane is $4.74047 \times 6.411 \times 8.178 = 248.5$ km s^{-1}. This is the circular speed plus the Sun's own forward motion. The vertical part is $4.74047 \times 0.219 \times 8.178 = 8.5$ km s^{-1}.

Relative to the mean motion of its neighbours, the local standard of rest, the Sun moves at (U, V, W) = (11.1 ± 0.74, 12.24 ± 0.47, 7.25 ± 0.37) km s^{-1} [840]. The total is $\sqrt{(11.1^2 + 12.24^2 + 7.25^2)} = 18.0$ km s^{-1}; a fact sheet gives 19.4 km s^{-1} relative to nearby stars [733]. Subtracting V = 12.24 from 248.5 leaves a circular speed of 236 km s^{-1} at the Sun.

One orbit is the galactic year. With R_0 = 8,178 pc and 248.5 km s^{-1}, $2\pi R_0 / v$ = 202 Myr (66.28); with 229 km s^{-1} it is 219 Myr (66.35). Quoted values are 212 Myr (66.32) and

about 240 Myr (66.43) [967], and 225–250 Myr [133].

Over 4.567 Gyr the Sun has made 4.567/0.219 = 20.9 orbits at 219 Myr, and 22.6 at 202 Myr. A quoted figure is 20–25 orbits [133].

The Sun also moves up and down through the disc. From the motions of the Radcliffe Wave and the mass density of the midplane, 0.085 $M_\odot$ pc^{-3}, its vertical period is 95 (+12/−10) Myr (65.59) [983]. It crosses the plane every 48 (+6/−5) Myr (64.97) [983].

Visible matter alone gives a period of 95.3 Myr; visible matter with a spherical dark halo gives 88.2 Myr (65.52) [983]. One orbit model gives a vertical reach of about 99 pc and a period of about 83 Myr (65.47) [133].

The Sun moves at 369.82 ± 0.11 km s^{-1} relative to the cosmic background light [25]. That motion adds the Sun's orbit to the motion of the Galaxy itself, which belongs to the next chapter.

The Sun's orbit gives the pull of the Galaxy at its place. The centripetal acceleration is $v^2/R_0 = (2.29 \times 10^5)^2 / 2.52 \times 10^{20} = 2.08 \times 10^{-10}$ m s^{-2}. This is 1.7 times the acceleration scale of 1.20×10^{-10} m s^{-2} that galaxy rotation curves share (chapter 35) [826].

Quantity	Value	Position	Source
Height above midplane	20.8 ± 0.3 pc	52.71	[841]
Sgr A* proper motion	−6.411 ± 0.008 mas yr^{-1}	—	[839]
Speed along the orbit	248.5 km s^{-1}	—	computed
(U, V, W)	11.1, 12.24, 7.25 km s^{-1}	—	[840]
Peculiar speed	18.0 km s^{-1}; 19.4 km s^{-1}	—	computed; [733]
Galactic year	202–219 Myr (computed); 212, 225–250 Myr (quoted)	66.28–66.43	[967][133]
Orbits since birth	≈ 21–23	—	computed
Vertical period	95 (+12/−10) Myr	65.59	[983]
Plane crossing	every 48 Myr	64.97	[983]
Speed relative to the background light	369.82 ± 0.11 km s^{-1}	—	[25]
Galactic acceleration at the Sun	2.08×10^{-10} m s^{-2}	—	computed

Clusters and gas of the last 700 million years

Around the Sun the record of the last 700 Myr is held in star clusters and gas.

The Gaia DR3 all-sky census, built from 729 million sources to magnitude G ≈ 20, recovers 7,167 clusters, 2,387 of them candidate new objects [982]. A stricter cut keeps 4,105 highly reliable clusters, 739 of them new; up to a few thousand may be unbound moving groups [982]. The census matches 4,782 clusters of the literature [982].

The Hyades

The Hyades are the nearest rich open cluster. Hipparcos parallaxes put the centre of mass at 46.34 ± 0.27 pc, or 151 ly (1.43×10^{18} m, size position 53.44) [801]. Gaia DR2 puts the centre at 47.03 ± 0.20 pc, 153 ly (53.45) [984].

Isochrone fits give an age of 625 ± 50 Myr (time position 67.31) [801]; Gaia DR2 gives 640 (+67/−49) Myr (67.33) [984]. The helium abundance is Y = 0.26 ± 0.02, and the internal velocity dispersion about 0.3 km s^{-1} [801].

The cluster is coming apart. Over a 70° radius of sky Gaia DR2 finds 1,764 candidate objects; within 30 pc of the centre 710; inside the 10 pc tidal radius 385; inside the core radius 85 [984]. Eight candidate brown dwarfs belong to it, and its mass function runs from 0.04 to 2.5 $M_\odot$ [984].

So 385/1,764 = 22% of the candidates lie inside the tidal radius. The core radius is 2.7 pc, or 8.8 ly (50.85); the tidal radius 10 pc, or 33 ly (52.04) [985]. The infobox of the same page gives a core of 10 ly [985].

The present mass is 400 M☉; the original mass was 800–1,600 M☉ [985]. About 200 members have high probability [985]. The metallicity is +0.14, and the cluster moves through the Galaxy at (U, V, W) = (−41.92 ± 0.16, −19.35 ± 0.13, −1.11 ± 0.11) km s⁻¹ [985].

The Pleiades

The Pleiades are younger and farther. Very-long-baseline radio parallaxes give 136.2 ± 1.2 pc, 444 ly (54.42), “the most accurate and precise yet presented” in 2014 [986]. Hipparcos had given 120.2 ± 1.5 pc (54.31), and other techniques 133.5 ± 1.2 pc [986].

The VLBI result moved the cluster 136.2/120.2 − 1 = 13% farther than Hipparcos. The full record runs: Hipparcos 1999, 118.3 pc; HST guidance sensors 2004, 134.6 ± 3.1 pc; revised Hipparcos 2009, 120.2 ± 1.9 pc; near-infrared colour–magnitude fit 2011, 138 ± 6 pc [987]. Gaia DR1 gives 134 ± 6 pc, DR2 136.2 ± 5.0 pc and DR3 135.74 ± 0.10 pc [987].

The age is 75–150 Myr from fits of the colour–magnitude diagram and about 115 Myr (65.76) from the lithium depletion boundary [987]. About 100 Myr (65.64) is generally accepted; the infobox gives 124.53 (+3.34/−2.70) Myr [987].

More than 1,000 members are confirmed, with a total mass of about 800 M☉ [987]. The core radius is about 8 ly (50.76) and the tidal radius about 43 ly (52.29) [987]. The cluster has about 250 Myr left before it disperses (66.47) [987].

The two clusters differ in age by a factor 625/115 = 5.4 and in distance by 136.2/46.34 = 2.9.

Gould’s Belt and the Radcliffe Wave

For about 150 years the bright young stars near the Sun were described as a ring, Gould’s Belt, tilted about 20° to the plane [989]. John Herschel and Benjamin Gould reported it in the 19th century [988]. The ring is tilted 16–20°, holds many O and B stars and formed 30–50 Myr ago (64.54–65.01) [988].

In 2020 a three-dimensional map of dust, with Gaia DR2 distances, replaced the ring with a wave. The Radcliffe Wave is “a narrow and coherent 2.7 kpc arrangement of dense gas” (8.33 × 10¹⁹ m, 57.14), with an aspect ratio of about 1:20 [989]. It holds about 3 million M☉ of gas (5.97 × 10³⁶ kg) [989].

Its shape is a damped sinusoid. The average period along its length is about 2 kpc (56.87) and the maximum amplitude about 160 pc (54.57) [989]. Many clouds once assigned to Gould’s Belt belong to it, and the Belt’s circular look comes mostly from projection [988][989].

Its nearest part, the Taurus Molecular Cloud, is about 400 ly away (54.32); its farthest, Cygnus X, about 5,000 ly (56.62); its length is 8,800 ly [990]. It was published on 7 January 2020 [990].

In 2024 the wave was found to move. The Sun lies within 300 pc of it [983]. Its maximum vertical velocity is about 14 km s⁻¹, and the fitted maximum amplitude is 219.88 pc, about 220 pc (54.86) [983].

The wavelength is about 2 kpc. Its local value ranges from about 400 pc near Cygnus X to 4,000 pc near CMa OB1 [983].

The phase velocity ranges from about 5 km s⁻¹ near Cygnus X to about 40 km s⁻¹ near CMa OB1 [983]. The whole wave drifts away from the Solar System at 4.9 km s⁻¹, and at 1.0 km s⁻¹ along its length [983].

The Local Bubble

The Sun lies inside a cavity of thin gas, the Local Bubble. Its present radius is 165 ± 6

pc, or 538 ly (5.09 × 10^{18} m, size position 54.59) [808]. Its age is 14.4 (+0.7/−0.8) Myr (time position 63.87) [808].

The bubble was blown by 15 (+11/−7) supernovae [808]. At the assumed 10^{51} erg each, that is 1.5 × 10^{52} erg, or 1.5 × 10^{45} J. Its swept-up shell holds 1.4 (+0.65/−0.62) × 10^{6} M☉, or 2.8 × 10^{36} kg [808].

The shell still expands, at 6.7 (+0.5/−0.4) km s^{-1} [808]. The mean speed over its life is 165 pc / 14.4 Myr = 5.09 × 10^{18} m / 4.54 × 10^{14} s = 11.2 km s^{-1}.

Stars form on the shell. Every well-known molecular cloud within about 200 pc lies on its surface, except the Perseus cloud, and star formation on the shell began 14 Myr ago (63.85) [808]. The study traced back the three-dimensional positions and motions of young clusters within 400 pc [808].

Other values for the same structure are a size of at least 1,000 ly and a radius of 500 ly [991]. Fourteen to twenty supernovae from the Lower Centaurus–Crux and Upper Centaurus–Lupus groups formed it in the past 10–20 Myr [991].

Inside, neutral hydrogen has a density of about 0.05 cm^{-3}, against an average of 0.5 cm^{-3} for the interstellar medium of the Galaxy [991]. The Sun entered the bubble about 4.5 Myr ago (62.81); another passage of the same page gives “the last five to ten million years” [991].

The supernovae left iron on Earth. Iron-60 and manganese-53 peak 1.7–3.2 Myr ago (61.93–62.50), and a second iron-60 peak lies 6.5–8.7 Myr ago (63.15–63.41) [991]. Iron-60 is found in deep-sea sediments, Antarctic snow and lunar soil [991].

The runaway star ζ Ophiuchi and the pulsar PSR B1706−16 come from one supernova 1.78 ± 0.21 Myr ago (61.97) [991].

The Local Interstellar Cloud

Within the bubble the Sun moves through a small warm cloud, the Local Interstellar Cloud. It is about 30 ly, 9.2 pc, across (51.97) [824]. Its temperature is about 7,000 K and its density 0.3 atoms cm^{-3}, six times the 0.05 cm^{-3} of the bubble [824].

That density is 3 × 10^{5} atoms m^{-3}. The magnetic field is 370–550 pT; earlier estimates gave 180–250 pT [824]. The cloud borders the G-Cloud [824].

The Solar System entered the cloud within the past 10,000 years (57.25) [824]. It will leave it within 1,900 years (55.74) [824].

The same page reports interstellar iron-60 in Antarctic snow (Koll et al. 2019) [824].

Structure	Size	Position	Age or time	Position	Source
Hyades	46.34 ± 0.27 pc; 47.03 ± 0.20 pc	53.44; 53.45	625 ± 50; 640 Myr	67.31; 67.33	[801][984]
Hyades tidal radius	10 pc	52.04	—	—	[985]
Pleiades	136.2 ± 1.2 pc	54.42	≈ 100–125 Myr	65.64–65.84	[986][987]
Gould’s Belt	tilt 16–20°	—	30–50 Myr	64.54–65.01	[988]
Radcliffe Wave	2.7 kpc; amplitude 160–220 pc	57.14; 54.57–54.86	—	—	[989][983]
Local Bubble	radius 165 ± 6 pc	54.59	14.4 Myr	63.87	[808]
^{60}Fe peaks	—	—	1.7–3.2; 6.5–8.7 Myr	61.93–63.41	[991]
Local Interstellar Cloud	9.2 pc	51.97	entered < 10,000 yr ago; exit ≤ 1,900 yr	57.25; 55.74	[824]

The neighbourhood star by star

The nearest stars

The nearest star is Proxima Centauri. Its Gaia DR3 parallax is 768.0665 ± 0.0499 mas, so its distance is 1/0.7680665 = 1.30197 pc, or 4.2465 ly (4.02×10^{16} m, size position 50.19) [993]. Robert Innes found it in 1915 [993].

Proxima is a red dwarf of type M5.5Ve. It has about 12.2–12.5% of the Sun's mass, about 14% of its diameter and 0.16% of its luminosity [993].

Its surface is at about 3,000 K (2,992 K), and its age is about 4.85 Gyr (69.17) [993]. It orbits the pair α Centauri A and B at 12,947 ± 260 AU (47.43), between 4,300 and 13,000 AU, once in about 547,000 years (60.90) [993].

It flares. On 6 May 2019 a flare released 2×10^{30} erg in the far ultraviolet, and a superflare in 2016 brightened the star 68 times [993]. Two planets are known: Proxima b, of at least 1.06 Earth masses with an 11.2-day orbit, and Proxima d, of at least 0.26 Earth masses with a 5.1-day orbit [993].

Proxima b was found in 2016 from radial velocities. Its first minimum mass was 1.3 Earth masses at a star distance of 1.295 pc [948]; later work gives 1.055 ± 0.055 Earth masses and a period of 11.18465 ± 0.00053 d [867].

The nearest systems, in order, are α Centauri with Proxima (4.2465 ly), Barnard's Star (5.9629 ly), Luhman 16 (6.5102 ly) and WISE 0855−0714 (7.430 ly) [843]. Next come Wolf 359 (7.856 ly), Lalande 21185 (8.3044 ly) and Sirius (8.7094 ly) [843]. Their positions run from 50.19 to 50.84.

Luhman 16 is the nearest brown dwarf pair, at about 2.0 pc [746]. Sirius holds a white dwarf, Sirius B, of 1.018 ± 0.011 M☉ in a radius of 5,634 ± 34 km [756][995].

It orbits Sirius A (2.063 ± 0.023 M☉) every 50.13 years (52.43), and its cooling age is about 126 Myr [756]. Alvan Graham Clark first saw it on 31 January 1862 [995].

Twelve planets around five stars are known within 3.5 pc (51.09) [867]. Proxima has two, and Barnard's Star at 1.82655 pc has four, found in 2024–2025 [867].

ε Eridani at 3.2026 pc has one, a giant of 317.83 Earth masses at 3.53 AU [867]. GJ 887 at 3.28679 pc has four and Ross 128 at 3.37454 pc has one [867].

Farther out, 51 Pegasi b, the first planet found around a Sun-like main-sequence star, lies about 50 ly, 15 pc, away (52.41) [994]. Kepler counts give about four rocky planets in the habitable zones of G and K dwarfs within 10 pc, the nearest about 6 pc away (51.58) [945].

System	Distance	Position	Source
α Centauri (Proxima)	4.2465 ly = 1.302 pc	50.19	[993][843]
Barnard's Star	5.9629 ly = 1.828 pc	50.50	[843]
Luhman 16	6.5102 ly = 1.996 pc	50.58	[843]
WISE 0855−0714	7.430 ly = 2.278 pc	50.70	[843]
Wolf 359	7.856 ly = 2.409 pc	50.75	[843]
Lalande 21185	8.3044 ly = 2.546 pc	50.80	[843]
Sirius	8.7094 ly = 2.670 pc	50.84	[843]
ε Eridani	3.2026 pc	51.01	[867]
GJ 887	3.28679 pc	51.03	[867]
Ross 128	3.37454 pc	51.05	[867]
51 Pegasi	≈ 15 pc	52.41	[994]

Counts within 20 ly, 10 pc, 20 pc and 100 pc

Within 20 ly, 6.13 pc (51.60), 133 objects are known in 95 systems [843]. They are 103 main-sequence stars (78 red dwarfs and 25 others), 6 white dwarfs, 20 brown dwarfs and 4 sub-brown dwarfs; only 22 are bright enough to be seen without a telescope [843]. Red dwarfs make up 78/133 = 59% and brown and sub-brown dwarfs 24/133 = 18%.

Within 10 pc (52.04) a catalogue of the Gaia era holds 540 stars, brown dwarfs and exoplanets in 339 systems [960]. The multiplicity frequency is about 28%, about 61% of the stars and brown dwarfs are M stars, and more than half of these lie between types M3.0 V and M5.0 V [960].

The sphere of 10 pc has a volume of 4,189 pc³. So the density is 540/4,189 = 0.129 objects and 339/4,189 = 0.081 systems per pc³, and the mean spacing between systems is (1/0.081)^(1/3) = 2.3 pc (50.70). Gaia gave the first direct parallaxes for five objects in multiple systems within 10 pc [992].

Within 20 pc (52.67) a full-sky census counts about 3,600 individual stars and brown dwarfs [961]. Stars outnumber brown dwarfs 4 to 1, and the mean mass per object is 0.41 M☉ [961]. The density is 3,600/33,510 = 0.107 per pc³.

The same census gives the slopes of the initial mass function [961]. They are α = 2.3 from 0.55 to 8.00 M☉ and 1.3 from 0.22 to 0.55 M☉ [961]. Below that, α = 0.25 from 0.05 to 0.22 M☉ and 0.6 from 0.01 to 0.05 M☉ [961].

Within 100 pc (54.14) the Gaia Catalogue of Nearby Stars holds 331,312 objects [992]. It contains at least 92% of the stars of type M9 within that distance, and about 9% of its entries probably lie beyond it [992]. Its density, 331,312/4.189 × 10^6 = 0.079 per pc³, is lower because faint objects drop out at that distance.

White dwarfs number eight among the 100 nearest star systems [842].

Radius	Position	Count	Density (per pc³)	Source
20 ly (6.13 pc)	51.60	133 objects, 95 systems	0.138	[843]
10 pc	52.04	540 objects, 339 systems	0.129; 0.081 systems	[960]
20 pc	52.67	≈ 3,600 stars and brown dwarfs	0.107	[961]
100 pc	54.14	331,312 objects	0.079	[992]

Depth 53: a radius of 93.4 light-years

At 3^{53} natural units the ladder reaches a closure depth. 3^{53} = 1.938 × 10^{25}, and 1.938 × 10^{25} × 4.558816 × 10^{-8} m = 8.836 × 10^{17} m. That is 93.40 ly, or 28.64 pc, at size position 53.00.

In time the same depth is 1.938 × 10^{25} × 1.520655 × 10^{-16} s = 93.40 years. Light crosses the radius in exactly that time, because the natural unit of length is the unit of time times the speed of light.

Depth 53 is a closure depth because 3^{53} comes close to a power of two: $3^{53}/2^{84}$ = 1.00209 (chapter 24). Three and two meet there with a remainder of 0.21%.

A sphere of 28.64 pc around the Sun has a volume of 4/3 π × 28.64^3 = 98,400 pc³. At the 20-pc density of 0.107 objects per pc³ it holds about 10,500 stars and brown dwarfs. At the 100-pc density of 0.079 it holds about 7,800, and at the 10-pc density of 0.129, which includes exoplanets, about 12,700.

The radius is 2.9 times the 10-pc catalogue radius, so the volume is 2.9^3 = 23.5 times larger. Every star named above stands inside it: α Centauri and Proxima, Barnard’s Star, Luhman 16, Wolf 359, Sirius, ε Eridani, GJ 887, Ross 128 and 51 Pegasi.

The Local Interstellar Cloud, 9.2 pc across, lies well inside. The Sun stands 20.8 pc above the midplane, so the sphere reaches 28.64 − 20.8 = 7.84 pc below the plane.

Just outside the rim stands the nearest star cluster. The centre of the Hyades lies at 46.34–47.03 pc, at positions 53.44–53.45, just beyond depth 53. Its tidal sphere of 10 pc reaches inward to 46.34 − 10 = 36.34 pc, 7.7 pc outside the rim.

The net’s own ladder table names the Hyades, at 153 ly, as the occupant of row 53, a nearest-layer reading [29].

Just beyond also lie the old halo star HD 140283 at 58.3 pc (53.65) and the Pleiades at 136 pc (54.42). The Local Bubble, radius 165 pc, has its wall at 54.59.

In time, depth 53 lies near two rhythms of this chapter: the mean interval between Galactic supernovae, 61 years (52.61), and the orbit of Sirius B, 50.13 years (52.43). The Sun moves at a peculiar speed of 18.0 km s^{-1}. It crosses 28.64 pc in 8.836×10^{17} m / 1.8×10^{4} m s^{-1} = 4.91×10^{13} s = 1.56 Myr (61.85).

Depth 53	Value	Position
Length	8.836×10^{17} m = 93.40 ly = 28.64 pc	53.00 (size)
Time	93.40 yr	53.00 (time)
Residue $3^{53}/2^{84}$	1.00209	—
Volume of the sphere	98,400 pc^3	—
Objects inside (scaled from 20 pc; 100 pc; 10 pc)	≈ 10,500; 7,800; 12,700	—
Hyades centre	46.34–47.03 pc	53.44–53.45
Sun above midplane	20.8 pc	52.71

What comes next

The Sun will leave the Local Interstellar Cloud within 1,900 years (55.74) [824]. Its path then runs on through the Local Bubble, whose shell still expands at 6.7 km s^{-1} [808].

Stars will pass close. In the next 15 Myr (63.91), 694 stars will come within 5 pc of the Sun (51.41), 26 within 1.0 pc (49.95) and 7 within 0.5 pc (49.32) [843]. The closest is Gliese 710, at 0.167 ± 0.012 ly, or 10,560 AU (47.24), in about 1.29–1.30 Myr (61.68) [843].

That passage lies inside the 12,947 AU at which Proxima circles α Centauri. It falls inside the Oort cloud, which spans 2,000 to 200,000 AU around the Sun (chapter 32) [865].

The Sagittarius dwarf will pass through the disc within about 100 Myr (65.64) [979]. The next starburst at the Galactic centre is expected in about 200 Myr (66.27) [976]. The Pleiades have about 250 Myr left before they disperse (66.47) [987].

The Sun’s plane crossings come every 48 Myr, and one galactic year takes 202–240 Myr [983][967]. The largest event ahead, the approach of Andromeda, belongs to the next chapter.

What this part of the history shows

The Galaxy shows one form at several depths. “The Milky Way is a knot; stars and solar systems are its sub-knots” [827]. The star S2 circles the central black hole in 16 years, the Sun circles the same centre in 202–240 Myr, and the planets circle the Sun, read as the same winding at every depth.

The nesting continues in the gas. The Sun sits in the Local Interstellar Cloud, 9.2 pc across (51.97), inside the Local Bubble of radius 165 pc (54.59). Beyond lie the 2.7 kpc Radcliffe Wave (57.14), a disc 26.8 kpc across (59.23) and a dark halo out to 292 kpc (61.40).

This is a reading: the disc has the form of what closes, stays, its content flowing through while the form holds. Its stars have formed for 13 Gyr. Each year 1.65–1.9 $M_\odot$ of gas becomes stars, and every 61 years a massive star ends as a supernova.

Read as an edge, the Local Bubble has rest inside and tension at its wall. Inside it the gas rests at about 0.05 atoms cm^{-3}, a tenth of the Galactic average. At its wall lies every well-known molecular cloud within 200 pc but one, and there new stars have formed for 14 Myr.

Its history reads as loading and discharge. Fifteen supernovae, about 1.5×10^{45} J, opened the bubble in 14.4 Myr; their iron reached the Earth in two pulses, 6.5–8.7 and 1.7–3.2 Myr ago. At the centre the same reading holds at a larger depth: starbursts every 500 Myr, and X-ray bubbles reaching 14 kpc with about 10^{49} J.

Read as a depth opened once and then filled, the disc shows the order of its record. Star formation in the thick disc began 13 Gyr ago, and most of its stars formed 11 Gyr ago. Over the following 5–6 Gyr the metal content of new stars rose tenfold, and the thin disc has kept filling for 8 Gyr, now with 7,167 clusters in the Gaia census.

This is a reading: shared motion has the form of community as shared prefix. The stars of Gaia–Enceladus keep the radial orbits of the galaxy they came from, β ≈ 0.9, and twelve of them pass within 100 pc of the Sun 10 Gyr after the merger. The Hyades share one velocity, (−41.92, −19.35, −1.11) km s⁻¹, even as 1,764 candidates spread over 70° of sky and only 385 stay inside the tidal radius.

The Sun stands in a stretched part of the Galaxy. Its acceleration, 2.08×10^{-10} m s^{-2}, is 1.7 times the scale of 1.20×10^{-10} m s^{-2}; in the net's text it lives in weave already stretched, just above the threshold. The rotation, near 229 km s⁻¹ from 5 to 25 kpc and 30 km s⁻¹ lower beyond 19 kpc, reads as context.

Depth 53 stands at 93.40 ly, where three and two meet with a remainder of 1.00209. Its sphere holds about 10,500 stars and brown dwarfs, every named neighbour of the Sun among them, and reaches 7.8 pc below the midplane. Just outside its rim, at 53.44–53.45, stand the Hyades, the nearest star cluster.

35. Galaxies and the Cosmic Web

The Milky Way of chapter 34 is one galaxy among about two trillion. Chapter 26 told how the first of them lit up within a few hundred million years of the beginning. This chapter tells what they became: how many there are, how their shapes changed, how they turn, and how they gather into groups, clusters, superclusters, walls and voids.

The chapter runs outward in size. It starts with single galaxies, near 26.8 kpc across (size position 59.23), and ends at the edge of the observable universe, 46.5 Gly away (71.23). In time it runs from the Bullet Cluster's crossing 150 Myr ago (66.01) to the age of the universe, 13.797 Gyr (70.12).

On the ladder of chapter 24, every size has a position, log base 3 of the size over 4.558816×10^{-8} m; every time, log base 3 of the time over 1.520655×10^{-16} s. A megaparsec (Mpc) is 3.0857×10^{22} m; one solar mass ($M\odot$) is 1.9884×10^{30} kg. Sizes given in h^{-1} Mpc are converted with $h = 0.7$.

How many galaxies

Counting galaxies means counting faint ones. Integrating the measured stellar-mass functions out to redshift $z \approx 8$, and extending them to low masses, gives the number of galaxies heavier than 10^6 $M\odot$ [1000]. It is $2.0\ (+0.7/-0.6) \times 10^{12}$, "two trillion", almost ten times what an all-sky survey at the depth of the Hubble Ultra Deep Field would see [1000].

The number density of galaxies, φ_T, falls with cosmic time as t^{-1} [1000]. Galaxies were more numerous per unit volume in the past than now.

A second measure comes from the dark of the outer Solar System. New Horizons, at 42–45 AU from the Sun, measured the optical background light of the universe between 0.4 and 0.9 µm: 15.9 ± 4.2 or 18.7 ± 3.8 nW m^{-2} sr^{-1} in two analyses [1001].

Known galaxies supply part of it. A residual of 8.8 ± 4.9 or 11.9 ± 4.6 nW m^{-2} sr^{-1} remains [1001]. If faint galaxies supply that residual, counts must steepen above magnitude V = 24, and "existing surveys are missing half the galaxies with V < 30" [1001].

Other estimates of the total run in the hundreds of billions rather than trillions [1002]. The observable universe holds about 10^{24} stars and about 1.5×10^{53} kg of ordinary matter [1002].

Shared over two trillion galaxies, that is $1.5 \times 10^{53} / 2 \times 10^{12} = 7.5 \times 10^{40}$ kg, or 3.8×10^{10} $M\odot$ of ordinary matter per galaxy. The stars give $10^{24} / 2 \times 10^{12} = 5 \times 10^{11}$ per galaxy, of the order of the Milky Way's 10^{11}.

Quantity	Value	Source
Galaxies above 10^6 $M\odot$, $z < 8$	$2.0\ (+0.7/-0.6) \times 10^{12}$	[1000]
Other estimates	hundreds of billions	[1002]
Optical background (New Horizons)	15.9 ± 4.2; 18.7 ± 3.8 nW m^{-2} sr^{-1}	[1001]
Residual beyond known galaxies	8.8 ± 4.9; 11.9 ± 4.6 nW m^{-2} sr^{-1}	[1001]
Stars in the observable universe	$\approx 10^{24}$	[1002]
Ordinary matter	$\approx 1.5 \times 10^{53}$ kg	[1002]
Ordinary matter per galaxy	3.8×10^{10} $M\odot$	computed

Shapes, then and now

Hubble's scheme of 1926 sorted galaxies into three broad classes; the de Vaucouleurs system followed in 1959 [1005]. The shares of the classes changed over the last half of cosmic history.

The same classification was applied to galaxies of comparable mass in the local universe (from the Sloan Digital Sky Survey) and 6 Gyr ago (from the GOODS fields) [1003]. Six Gyr sits at time position 69.36. The local sample holds 116 galaxies and the distant one 143 [1003].

Today the local universe “is dominated by spirals galaxies that represent 72% of the population” [1003]. Lenticulars (S0) make up 15 ± 4%, ellipticals 3 ± 1% and peculiar galaxies 10 ± 3%, of which irregulars 4 ± 2% [1003].

Six Gyr ago the shares were different. Spirals made up 31 ± 7%, S0 13 ± 2%, ellipticals 4 ± 1% and peculiar galaxies 52 ± 9%, of which irregulars 26 ± 7% [1003].

So spirals were 72/31 = 2.3 times less abundant in the past, and peculiar galaxies have since decreased by a factor of 5 [1003]. Ellipticals and lenticulars kept nearly the same shares.

Many spirals carry a bar.

In a volume-limited sample of 13,665 disc galaxies at $0.01 < z < 0.06$, brighter than $M_r = -19.38$, 29.4 ± 0.5% have a bar in Galaxy Zoo images [1004]. Another account gives roughly half of all spirals [1005]. The Milky Way is one of the barred ones (chapter 34).

Class	Today (n = 116)	6 Gyr ago (n = 143)	Source
Spiral	72 ± 8%	31 ± 7%	[1003]
Lenticular (S0)	15 ± 4%	13 ± 2%	[1003]
Elliptical	3 ± 1%	4 ± 1%	[1003]
Peculiar	10 ± 3%	52 ± 9%	[1003]
of which irregular	4 ± 2%	26 ± 7%	[1003]
Barred discs (Galaxy Zoo 2)	29.4 ± 0.5%	—	[1004]

Black holes at the centres

Two galaxy centres have been imaged. The black hole in the Milky Way, Sagittarius A*, weighs 4.30×10^6 M☉ to about ±0.25% [783]. The one in M87, a member of the Virgo Cluster [1018], weighs $(6.5 \pm 0.7) \times 10^9$ M☉ [786].

The Event Horizon Telescope imaged both at 1.3 mm. M87* shows a ring 42 ± 3 μas across, with a brightness ratio of about 10:1 between ring and central depression [786]. The two masses differ by a factor of $6.5 \times 10^9 / 4.30 \times 10^6 = 1{,}500$, yet their rings, 42 and 52 μas, are of similar angular size (chapter 27).

M87 also has up to about 13,000 globular clusters, against 160 in the Milky Way [966].

How galaxies turn: one acceleration

In 1977 Tully and Fisher found that a galaxy’s luminosity follows the width of its rotational line, and turned the relation into a method for distances [1006]. The relation is tighter in the near-infrared K band than in visible light, tighter still with stellar mass, and tightest with the total mass of ordinary matter [1006]. That baryonic mass goes as the rotation speed to a power of about 3.5–4 [1006].

In 2000 the baryonic form was set out over five decades of stellar mass, for rotation speeds $30 < V_c < 300$ km s⁻¹ [1007]. Galaxies slower than 90 km s⁻¹ fall below the luminosity relation, and adding their gas puts them back on it [1007]. The relation takes the form “Md = A Vc^4” [1007].

The SPARC sample of 118 disc galaxies with Spitzer photometry at 3.6 μm sharpened it. The scatter is smallest for stellar mass-to-light ratios above 0.5, the slope is close to 4, and “the intrinsic scatter is ~0.1 dex, below general LCDM expectations” [1008]. A scatter of 0.1 dex is a factor of 10^0.1 = 1.26.

In 2016 the same relation was traced point by point. The SPARC catalogue holds 175 disc galaxies; ten with inclinations below 30° and twelve with asymmetric curves were

set aside, leaving 2,693 of 3,149 points [826]. Stellar discs were given a mass-to-light ratio of 0.50 M☉/L☉ at 3.6 µm, and bulges 0.7 [826].

“The same relation is followed by 2693 points in 153 galaxies” of very different shapes [826]. It links the observed acceleration g_obs to the acceleration g_bar expected from the ordinary matter alone, with one fitted scale: “g† = 1.20 ± 0.02 (random) ±0.24 (systematic) ×10−10 m s−2” [826].

The residuals form a Gaussian of width 0.11 dex, with an rms of 0.13 dex [826]. The errors alone give 0.12 dex: 0.08 dex from distances, 0.05 dex from inclinations and 0.06 dex from variation in mass-to-light ratio [826].

So the scatter is what the errors allow. In the authors’ words, “the dark matter contribution is fully specified by that of the baryons”, and “The correlation persists even when dark matter dominates” [826].

The scale had been found before. In 1983 Milgrom presented a modified law of motion in three papers in the Astrophysical Journal [1009]. Fits of that law to rotation curves found $a_0 \approx 1.2 \times 10^{-10}$ m s^{-2} optimal (Begeman and co-workers, 1991), and the value has not changed since [1009].

The RAR scale g† = 1.20×10^{-10} m s^{-2} equals that a_0 to the quoted digits [826][1009]. The same law leaves galaxy clusters with a mass discrepancy about a fifth of the Newtonian one [1009].

a_0 lies within an order of magnitude of cH_0, the speed of light times the expansion rate [1009]. With $H_0 = 67.4$ km s^{-1} Mpc^{-1} (2.18×10^{-18} s^{-1}) [238], $cH_0 = 6.55 \times 10^{-10}$ m s^{-2} and $cH_0/2\pi = 1.04 \times 10^{-10}$ m s^{-2}. With $H_0 = 70$ km s^{-1} Mpc^{-1} (2.27×10^{-18} s^{-1}), $cH_0 = 6.80 \times 10^{-10}$ and $cH_0/2\pi = 1.08 \times 10^{-10}$ m s^{-2}.

The net’s texts set a_0 beside $cH_0/2\pi$ and record the pair as a correspondence: one full turn, 2π, between the expansion and the galactic threshold [26]. The measured scale is 1.20/1.08 = 1.11 times the value with $H_0 = 70$.

Near the Sun the Galaxy’s pull is 2.08×10^{-10} m s^{-2}, 1.7 times g† (chapter 34). At accelerations near and below g† orbit wide pairs of stars, thousands of AU apart.

Wide binaries in Gaia DR3 divide the analysts. One study selects 2,463 statistically pure binaries [1010]. For accelerations below about 10^{-10} m s^{-2} it finds γ_g = g_obs/g_pred = 1.49 (+0.21/−0.19), matching 1.49 ± 0.07 in a larger sample, at a significance of about 5.0σ [1010].

In that study the binaries are Newtonian below separations of about 2,000 AU (45.73). Above about 5,000 AU (46.56) their velocities exceed the Newtonian value by a factor γ_vp = 1.20 ± 0.06 (stat.) ± 0.05 (sys.) [1010].

Another study takes 8,611 wide binaries within 250 pc (54.97), at separations of 2,000–30,000 AU (45.73–48.19) [1011]. It prefers Newtonian dynamics at 19σ and excludes the modified law at 16σ [1011].

Its gravity parameter is α_grav = −0.021 (+0.065/−0.045), where 0 is Newton and 1 the modified law, which predicts a velocity excess of about 20% [1011]. A 2023 study of 26,615 wide binaries within 200 pc reported deviations below accelerations of 1 nm s^{-2}; its results are disputed [1009].

Relation	Value	Source
Tully–Fisher (1977)	luminosity ∝ line width	[1006]
Baryonic Tully–Fisher	$M_b = A V_c^4$; 30–300 km s^{-1}	[1007]
BTFR intrinsic scatter	≈ 0.1 dex (118 galaxies)	[1008]
RAR sample	2,693 points, 153 galaxies	[826]
RAR scale g†	$1.20 \pm 0.02 \pm 0.24 \times 10^{-10}$ m s^{-2}	[826]
RAR rms scatter	0.13 dex (0.12 from errors)	[826]
a_0 (rotation-curve fits)	$\approx 1.2 \times 10^{-10}$ m s^{-2}	[1009]
$cH_0/2\pi$ (H_0 = 67.4; 70)	1.04; 1.08×10^{-10} m s^{-2}	computed
Wide binaries, pure sample	γ_g = 1.49 (+0.21/−0.19); ≈ 5.0σ	[1010]
Wide binaries, 8,611 pairs	Newton preferred at 19σ	[1011]

Two clusters through each other

In the merging cluster 1E 0657−558, the Bullet Cluster, at redshift z = 0.296, two clusters of galaxies have passed through one another [1012]. Its comoving distance is 1.141 Gpc, or 3.72 Gly (size position 68.93) [1013].

The smaller cluster crossed the centre of the larger 150 Myr ago (time position 66.01), at about 4,500 km s^{-1}; a later Sunyaev–Zeldovich analysis gives about 3,950 km s^{-1} [1013]. After the collision the collisionless stars and the X-ray-emitting gas were separated [1012].

The shocked gas has a temperature of 17.4 ± 2.5 keV, which is 17.4×10^3 / $8.617 \times 10^{-5} = 2.0 \times 10^8$ K [1013]. The gas of the sub-cluster is at 70 MK and that of the main cluster at 100 MK [1013].

Weak gravitational lensing maps the total mass. It follows the galaxies, not the hot gas that holds most of the ordinary matter: “An 8-sigma significance spatial offset of the center of the total mass” from the centre of the baryonic mass [1012].

About 40 galaxies of the cluster are listed [1013]. A 2010 claim that the collision speed was too high for the standard cosmological model was later traced to a wrong in-fall velocity [1013].

Two other measures of dark matter belong to single galaxies. Near the Sun its density is 0.30–0.38 GeV cm^{-3} [971][825]. In rotating galaxies the required dark component follows the ordinary matter point by point to within 0.13 dex [826].

Quantity	Value	Position	Source
Redshift	0.296	—	[1012]
Comoving distance	1.141 Gpc = 3.72 Gly	68.93	[1013]
Lensing–baryon offset	8σ	—	[1012]
Collision speed	≈ 4,500; ≈ 3,950 km s^{-1}	—	[1013]
Time since core passage	150 Myr	66.01 (time)	[1013]
Gas temperature	17.4 ± 2.5 keV = 2.0×10^8 K	—	[1013]

The Local Group

The Milky Way belongs to a small group of galaxies. More than 100 galaxies have distances that place them within 3 Mpc of the Sun (size position 63.52) [1014]. Within 1 Mpc of the group’s centre (62.52), 134 members are known, most of them dwarfs; the Milky Way hides others behind its disc [980].

The group is 5.11 Mpc across along its major axis (64.01) [980]. Its two lobes lie about 800 kpc apart (62.32) [980]. Its barycentre lies 447 ± 26 kpc from the Sun (61.79), toward Andromeda [980].

The galaxies move within it with a velocity dispersion of 49 km s^{-1} [980]. Gas between them is at (2–3) × 10^6 K [980].

Its mass is of the order of 2×10^{12} M☉ [980]. Published values are a binding mass of (2.47 ± 0.15) × 10^{12} M☉, (2.3 ± 0.7) × 10^{12} M☉ (Peñarrubia and co-workers, 2014) and (1.29 ± 0.14) × 10^{12} M☉ (Karachentsev and Kashibadze, 2006) [980].

The motion of Andromeda gives another. The timing argument, built on Andromeda’s velocity vector, gives “M_LG = M_MW(vir) + M_M31(vir) = (3.17 +/- 0.57) x 10^12 solar masses” [1015]. That is 6.30×10^{42} kg.

Two galaxies dominate. Andromeda has a mass of (1.5 ± 0.5) × 10^{12} M☉, about 10^{12} stars and a D25 diameter of 152,000 ly (59.73) [980]. The Milky Way has (1.54 ± 0.1) × 10^{12} M☉, (2.5 ± 1.5) × 10^{11} stars and 87,400 ly (59.23) [980].

The third is M33: 5×10^{10} M☉, 4×10^{10} stars and 61,100 ly (58.90) [980]. The two large galaxies weigh nearly the same, 1.5/1.54 = 0.97.

Andromeda

Andromeda lies about 765 kpc, 2.5 Mly, away (62.28) [999]. Other mass estimates from 2018–2019 run from 0.8 to 1.1 × 10^{12} M☉; the infobox gives (1.5 ± 0.2) × 10^{12} M☉ [999]. It has more than 20 dwarf satellites [999].

Seen from the Sun it approaches at −301 ± 1 km s^{-1} [999]. Corrected for the Sun's own orbit, the Hubble Space Telescope measurements of 2012 give a Galactocentric radial velocity of −109.3 ± 4.4 km s^{-1} [1015].

Its sideways motion decided the forecast. The heliocentric transverse velocity is (v_W, v_N) = (−125.2 ± 30.8, −73.8 ± 28.4) km s^{-1} [1015]. The Galactocentric tangential velocity is V_tan = 17.0 km s^{-1}, below 34.3 km s^{-1} at 1σ: a nearly radial orbit [1015].

M33 is bound to Andromeda at 95% confidence [1015]. Gaia DR2 proper motions of Andromeda are (65 ± 18, −57 ± 15) µas yr^{-1}, plus 16 µas yr^{-1} of systematic error per component [1016].

Combined with HST, they give a tangential velocity of 57 (+35/−31) km s^{-1} [1016]. The same data detect the rotation of Andromeda's disc, V_rot = −206 ± 86 km s^{-1} [1016].

The collision forecast

At a constant 109.3 km s^{-1}, Andromeda would cover its 765 kpc, 2.36 × 10^{22} m, in 2.16 × 10^{17} s = 6.8 Gyr (time position 69.48). Gravity speeds the fall.

The 2012 forecast from HST velocities puts the first close passage at 3.87 (+0.42/−0.32) Gyr from now (68.97) and the merger at 5.86 (+1.61/−0.72) Gyr (69.34) [844]. The probability of a direct hit, a pericentre below 25 kpc, is 41% [844].

The same study gives M33 a 9% chance of hitting the Milky Way first and a 7% chance of being thrown out of the Local Group [844]. The Sun will most likely (85%) end farther from the centre of the merged galaxy than now, with a 10% chance beyond 50 kpc [844]. There is a 20% chance that the Sun passes within 10 kpc of M33's centre in the next 10 Gyr [844].

In 2025 a new analysis combined Gaia and HST data and added M33 and the Large Magellanic Cloud [1017]. A merger had been predicted "in around five billion years" [1017]. The new result gives "a probability of close to 50% that there is no Milky Way - Andromeda merger" in the next 10 Gyr (69.83) [1017].

The group in motion

The whole group moves. Relative to the cosmic background light the Sun moves at 369.82 ± 0.11 km s^{-1}, and the Local Group at 620 ± 15 km s^{-1} [25]. The motion appears as a dipole of 3.3621 ± 0.0010 mK in the background temperature [25].

Quantity	Value	Position	Source
Galaxies within 3 Mpc	> 100	63.52	[1014]
Members within 1 Mpc	134	62.52	[980]
Diameter (major axis)	5.11 Mpc	64.01	[980]
Barycentre distance	447 ± 26 kpc	61.79	[980]
Mass (timing)	(3.17 ± 0.57) × 10^{12} M☉	—	[1015]
Mass (other)	1.29–2.47 × 10^{12} M☉	—	[980]
Andromeda distance	≈ 765 kpc	62.28	[999]
Andromeda radial velocity (Galactocentric)	−109.3 ± 4.4 km s^{-1}	—	[1015]
Andromeda tangential velocity	17.0 km s^{-1} (HST); 57 (+35/−31) km s^{-1} (Gaia DR2 + HST)	—	[1015][1016]
First pericentre (2012)	3.87 Gyr ahead	68.97	[844]
Merger (2012)	5.86 Gyr ahead	69.34	[844]
Direct hit (2012)	41%	—	[844]
No merger within 10	≈ 50%	69.83	[1017]

Gyr (2025)			
Local Group speed relative to the background light	620 ± 15 km s⁻¹	—	[25]

The Virgo Cluster and Laniakea

The nearest large cluster of galaxies is the Virgo Cluster, 16.5 ± 0.1 Mpc, or 53.8 ± 0.3 Mly, away (size position 65.07) [1018]. It has about 1,300 member galaxies, possibly up to 2,000; its infobox gives about 1,500 [1018].

Within 8° of its centre, a radius of about 2.2 Mpc (63.24), it holds 1.2 × 10¹⁵ M☉, or 2.39 × 10⁴⁵ kg; the infobox gives a binding mass of 10¹⁵ M☉ [1018]. It spans about 8° of sky, and its galaxies move with peculiar velocities of up to 1,600 km s⁻¹ [1018].

M87 and M49 move at 1,204 km s⁻¹ relative to the background light [1018]. The cluster's mass slows the Local Group's recession from it by about 10% [1018]. Virgo weighs 1.2 × 10¹⁵ / 3.17 × 10¹² = 380 Local Groups.

In 2014 the supercluster that holds Virgo was given a boundary. Peculiar velocities came from the Cosmicflows-2 distances, and the boundary was drawn where the flows of galaxies diverge [1019]. The result is "a supercluster 160 megaparsecs across and containing 10¹⁷ solar masses" (67.14) [1019].

It was named Laniakea and defined in September 2014 [1020]. A 2023 value gives it "roughly 120 Mpc (400 million ly)" (66.88); the infobox gives a major axis of 124 Mpc [1020].

Laniakea holds about 100,000 galaxies; the infobox gives 100,000–150,000 [1020]. Its mass of 10¹⁷ M☉ is 2.0 × 10⁴⁷ kg, 10¹⁷ / 1.2 × 10¹⁵ = 83 Virgo clusters.

Within it lies the Great Attractor, about 77 Mpc, 250 Mly, away near Norma (66.48) [1020]. Laniakea's parts include the Virgo, Hydra–Centaurus, Southern, Ophiuchus and Pavo–Indus superclusters and the Norma Wall [1020].

Structure	Value	Position	Source
Virgo Cluster distance	16.5 ± 0.1 Mpc	65.07	[1018]
Virgo members	≈ 1,300 (up to 2,000)	—	[1018]
Virgo mass within 2.2 Mpc	1.2 × 10¹⁵ M☉	63.24	[1018]
Peculiar velocities	up to 1,600 km s⁻¹	—	[1018]
Laniakea (2014)	160 Mpc; 10¹⁷ M☉	67.14	[1019]
Laniakea (2023)	≈ 120 Mpc	66.88	[1020]
Laniakea galaxies	≈ 100,000	—	[1020]
Great Attractor	≈ 77 Mpc	66.48	[1020]

Voids, filaments and walls

On larger scales the galaxies trace a web. Filaments of galaxies commonly reach 50 to 80 Mpc (66.08–66.51) [1023]. In simulations classified into nodes, filaments, walls and voids, filaments extend beyond 100 h⁻¹ Mpc, 143 Mpc (67.04) [1024].

Between them lie voids, typically 10–100 Mpc across (64.62–66.71) [1022]. Their mean density is less than a tenth of the cosmic average, yet even the emptiest parts hold more than about 15% of the mean matter density [1022]. The Milky Way lies in the KBC Void [1022].

The Boötes Void was found in 1981, in a paper titled "A million cubic megaparsec void in Bootes" [1021]. Its radius is 62 Mpc, nearly 200 Mly (66.28), and its centre is about 700 Mly away (67.41) [1021].

It contains 60 galaxies where about 2,000 would be expected for its volume, 60/2,000 = 3% [1021]. A sphere of radius 62 Mpc has a volume of 4/3 π × 62³ = 1.0 × 10⁶ Mpc³. The 1981 diameter is given elsewhere as nearly 50 h⁻¹ Mpc, later 34 h⁻¹ Mpc [1022].

The largest structures are walls and rings. The CfA2 Great Wall (1989) is 251 Mpc long (67.55), and the Sloan Great Wall (2003) 433 Mpc (68.05) [1023]. The Huge Large Quasar Group (2013) has a longest dimension of 1.24 Gpc (69.01) and a characteristic size of 500 Mpc; Quipu (2025) is 400 Mpc [1023].

The Giant Arc, traced by magnesium absorption in quasar spectra at z ≈ 0.8, "spans ~1 Gpc (proper size, present epoch)" (68.81) [1026]. Its significance is about 4.5σ, 3.0σ or 4.8σ by three methods, and its overdensity δρ/ρ ≈ 1.3 ± 0.3 [1026]. It is about twice the size of the Sloan Great Wall [1026].

About 12° from it on the sky, at the same z ≈ 0.8, lies the Big Ring: diameter about 400 Mpc (67.98), at a significance of up to 5.2σ [1027].

The Hercules–Corona Borealis Great Wall is a cluster of gamma-ray bursts at 1.6 < z < 2.1 "with an estimated angular size of 2000-3000 Mpc" (69.44–69.81) [1025]. It is described as more than 10 billion ly across and still unconfirmed [1023].

Structure	Size	Position	Source
Filaments	50–80 Mpc	66.08–66.51	[1023]
Voids	10–100 Mpc	64.62–66.71	[1022]
Boötes Void radius	62 Mpc; 60 of ≈ 2,000 galaxies	66.28	[1021]
CfA2 Great Wall	251 Mpc	67.55	[1023]
Sloan Great Wall	433 Mpc	68.05	[1023]
Big Ring	≈ 400 Mpc	67.98	[1027]
Quipu	400 Mpc	67.98	[1023]
Giant Arc	≈ 1 Gpc	68.81	[1026]
Huge-LQG	1.24 Gpc	69.01	[1023]
Hercules–Corona Borealis Great Wall	2,000–3,000 Mpc	69.44–69.81	[1025]

Mapping the web

The web is mapped by redshift surveys. The first detection of the acoustic peak, in 2005, used 46,748 luminous red galaxies of the Sloan survey over 3,816 square degrees [710] [1030]. It fixed the ratio of distances to z = 0.35 and to z = 1089 "to 4% fractional accuracy" [710].

The Dark Energy Spectroscopic Instrument, with 5,000 robotic fibres on the Mayall 4 m telescope at Kitt Peak, began its survey on 14 May 2021 [1031]. Its first data release measured more than 6 million extragalactic objects at 0.1 < z < 4.2 [124]. The public release of 19 March 2025 holds 18.7 million objects: about 4 million stars, 13.1 million galaxies and 1.6 million quasars [1031].

The second release used more than 14 million galaxies and quasars [125]. Bright galaxies trace z = 0.1–0.4, luminous red galaxies 0.4–1.1, emission-line galaxies 0.8–1.6 and quasars 0.8–3.5; the hydrogen forest in quasar spectra reaches z_eff = 2.33, measured to 0.64% [125].

The survey aims at more than 47 million galaxies and quasars by 2026, and the five-year survey was completed by April 2026 [1031]. Its preferred separation is the acoustic ruler: about 150 Mpc, "≈490 million light years in today's universe" [1030].

Where the web becomes smooth

On the largest scales the web evens out. The WiggleZ survey mapped more than 200,000 blue galaxies in a volume of about 1 $(\mathrm{Gpc}/h)^3$ out to z = 1 [1028]. It counted galaxies in spheres of growing radius and asked where the counts grow as r^3 to within 1% [1028].

That happens at 71 ± 8 h^{-1} Mpc at z ≈ 0.2, 70 ± 5 at z ≈ 0.4, 81 ± 5 at z ≈ 0.6 and 75 ± 4 at z ≈ 0.8 [1028]. With h = 0.7 these are 100–116 Mpc (66.71–66.85).

The fractal dimension D_2 lies within 1% of 3 from about 80 h^{-1} Mpc up to about 300 h^{-1} Mpc, 114–429 Mpc (66.84–68.04) [1028]. Values $D_2 < 2.97$ are excluded on these scales at 99.99% [1028].

A study of the fractal dimension in the standard cosmological model sets an upper limit on the scale of homogeneity “close to 260 Mpc/h”, 371 Mpc (67.91) [1029]. The Big Ring, Quipu, the Giant Arc, the Huge-LQG and the Hercules–Corona Borealis Great Wall are each larger than this scale.

The web carries one standard length. Sound waves in the young universe left a preferred separation between galaxies (chapter 25). It was first found in 2005 as a peak at 100 h^{-1} Mpc, 143 Mpc, in those galaxies at $0.16 < z < 0.47$ [710].

The DESI survey takes the sound horizon at the drag epoch as r_d = 147.05 Mpc (67.06) [125]. In the background light the same length appears as r^* = 144.43 ± 0.26 Mpc (67.05) [25].

So the standard ruler stands at position 67.06, beside Laniakea at 67.14. The scale of homogeneity, 100–116 Mpc, lies just below them at 66.71–66.85.

The edge of the observable universe

The universe is 13.797 ± 0.023 Gyr old in the PDG table (time position 70.12) [25]; the Planck fit of chapter 24 gives 13.787 ± 0.020 Gyr. Light from its most distant sources was emitted by matter that is now 14.26 Gpc, 46.5 Gly or 4.40×10^{26} m, away: the comoving radius of the observable universe (size position 71.23) [1002].

The diameter is about 28.5 Gpc, 93 Gly or 8.8×10^{26} m (71.86) [1002]. The radius is 46.5/13.797 = 3.4 times the light-travel age in light-years. The cosmic event horizon now lies about 16 Gly away (70.26) [1002].

The Hubble radius c/H_0 is $2.998 \times 10^8 / 2.18 \times 10^{-18} = 1.37 \times 10^{26}$ m, 14.5 Gly, for H_0 = 67.4 km s^{-1} Mpc^{-1} [238]. It stands at size position 70.17, and the Hubble time $1/H_0$ = 14.5 Gyr at time position 70.17: the two coincide because the unit of length is the unit of time times c.

The net’s texts place the observable universe on the ladder at depth 71 [29]. Its radius stands at 71.23 and its diameter at 71.86, the largest size in this book.

Quantity	Value	Position	Source
Homogeneity (WiggleZ)	70–81 h^{-1} Mpc = 100–116 Mpc	66.71–66.85	[1028]
$D_2 \approx 3$	80–300 h^{-1} Mpc	66.84–68.04	[1028]
Upper limit (ΛCDM)	≈ 260 h^{-1} Mpc = 371 Mpc	67.91	[1029]
BAO first peak (2005)	100 h^{-1} Mpc	67.04	[710]
Sound horizon r_d	147.05 Mpc	67.06	[125]
Sound horizon r^*	144.43 ± 0.26 Mpc	67.05	[25]
Age of the universe	13.797 ± 0.023 Gyr	70.12 (time)	[25]
Hubble radius (H_0 = 67.4)	1.37×10^{26} m	70.17	computed
Cosmic event horizon	≈ 16 Gly	70.26	[1002]
Comoving radius	14.26 Gpc = 46.5 Gly	71.23	[1002]
Diameter	28.5 Gpc = 93 Gly	71.86	[1002]

What this part of the history shows

The web reads as knots joined by strands. “Galaxies lie on filaments; the filaments meet in knots” [694]. Filaments run 50–80 Mpc, clusters such as Virgo hold 1,300–2,000 galaxies, and the voids, 10–100 Mpc across, hold as few as 60 galaxies where 2,000 would be expected.

This is a reading: the voids have the form of rest inside an edge. Inside them the matter stands at less than a tenth of the mean density, and above about 15% even in the emptiest parts.

One acceleration runs through all disc galaxies. In 2,693 points across 153 galaxies of very different shapes, the observed pull follows the pull of the ordinary matter. One scale, $g\dagger = 1.20 \times 10^{-10}$ m s^{-2}, fits them all, with a scatter of 0.13 dex that the errors alone account for.

This reads as the same winding at every depth: one scale holds in small galaxies and large, and the Sun’s own orbit sits at 1.7 times it.

The scale reads as a state of the surroundings. It lies beside $cH_0/2\pi$, 1.04–1.08 $\times 10^{-10}$ m s^{-2}, where the expansion of the universe and one full turn meet. Wide binaries at 2,000–30,000 AU stand at that threshold, where two studies read two different laws.

Read as a shared prefix, membership places the Milky Way in the Local Group, 134 galaxies within 1 Mpc. The net’s text calls Laniakea, 160 Mpc and 10^{17} M$\odot$ with Virgo inside it, the highest winding in which the Milky Way demonstrably turns [694]. Its boundary is drawn where the flows of its galaxies diverge.

The nesting climbs the ladder in steps. The Local Group spans 5.11 Mpc (64.01), Virgo lies at 16.5 Mpc (65.07), Laniakea spans 160 Mpc (67.14), the great walls reach 251 Mpc to 3 Gpc (67.55–69.81) and the observable universe 46.5 Gly (71.23). This reads as turning within turning.

The spiral disc reads as a form opened once and then filled many times. Six Gyr ago 31% of comparable galaxies were spirals and 52% peculiar; today the shares are 72% and 10%. Ellipticals and lenticulars stayed near 3–4% and 13–15%.

Encounters read as loading and discharge. Two clusters passed through each other in the Bullet Cluster 150 Myr ago at about 3,950–4,500 km s^{-1}, and their gas stands at 2.0 $\times 10^{8}$ K. Andromeda closes on the Milky Way at 109.3 km s^{-1}, with a first passage forecast in 3.87 Gyr and an even chance of no merger within 10 Gyr.

Part IV — The Ladder

36. The Ladder from Particle to Cosmos

Every length and every time in this book has a position on one ladder. The position of a length is log base 3 of the length over 4.558816×10^{-8} m. The position of a time is log base 3 of the time over 1.520655×10^{-16} s.

An age is placed as the time from then to now. This chapter sets the lengths, durations and ages in three tables, 2,407 positions in all.

A row that holds several values in one cell stays in the catalogue. Each row names the case, its value, the chapter where it is told, and its source.

Lengths

901 positions.

Position	What	Value	Chapter	Source
-59.77	Stoney length (Stoney units)	1.380678e-36 m	8	[1; 214]
-57.53	Planck length (reference) (vacuum)	1.616255e-35 m	6	[1]
-57.53	Planck length (Planck units)	1.616255e-35 m	8	[1]
-34.60	Equivalent disc radius of cross section (antineutrino)	1.4e-24 m	4	[109]
-30.72	Electron radius limit, Penning trap (Dehmelt 1988)	<1e-22 m	2	[17]
-29.27	Wavelength of 2.5 PeV photon	4.96e-22 m	1	[24]
-28.74	Wavelength of 1.4 PeV photon	8.86e-22 m	1	[22]
-22.54	Vacuum value length hbar c / v (Higgs field)	8.01e-19 m	6	[152]
-22.34	Electron radius limit, energy uncertainty	<1e-18 m	2	[17]
-22.22	Top reduced Compton wavelength (top quark)	1.144e-18 m	6	[113]
-21.93	Higgs reduced Compton wavelength (Higgs boson)	1.576e-18 m	6	[113]
-21.64	Z reduced Compton wavelength (Z boson)	2.164e-18 m	5	[113]
-21.52	W reduced Compton wavelength (W boson)	2.455e-18 m	5	[113]
-17.47	Proton reduced Compton length	2.103e-16 m	3	[13]
-17.47	Neutron reduced Compton length	2.100e-16 m	3	[13]
-16.22	Bezginov 2019 proton radius	0.833(10) fm	2	[48]
-16.22	PRad 2019 proton radius	0.831 ± 0.007 ± 0.012 fm	2	[53]
-16.22	Proton charge radius, H Lamb shift (Bezginov), 2019	0.833 fm	3	[72]
-16.22	Proton charge radius, PRad, 2019	0.831 fm	3	[53]
-16.21	Maisenbacher 2026 proton radius	0.8406(15) fm	2	[50]

-16.21	Pohl 2010 muonic hydrogen proton radius	0.84184(67) fm	2	[51]
-16.21	Antognini 2013 r_E (proton)	0.84087(39) fm	2	[52]
-16.21	CODATA 2022 muonic-only proton radius	0.84060(66) fm	2	[2]
-16.21	PDG proton radius	0.8409(4) fm	2	[54]
-16.21	Proton charge radius, muonic H (Pohl), 2010	0.84184 fm	3	[51]
-16.21	Proton charge radius, muonic H (Antognini), 2013	0.84087 fm	3	[52]
-16.21	Proton charge radius, CODATA 2022, 2022	0.84075 fm	3	[1]
-16.21	Proton charge radius, CODATA muonic Lamb shifts, 2022	0.8406 fm	3	[107]
-16.21	Proton charge radius, PDG electronic, 2024	0.8409 fm	3	[69]
-16.21	Proton radius, muonic Lamb shifts	0.84060(66) fm	8	[2]
-16.20	CODATA 2022 electronic-only proton radius	0.8529(13) fm	2	[2]
-16.20	Proton charge radius, CODATA electronic H+D only, 2022	0.8529 fm	3	[107]
-16.20	Magnetic radius PDG (proton)	0.851 ± 0.026 fm	3	[69]
-16.20	Proton radius, H and D only	0.8529(13) fm	8	[2]
-16.18	Antognini 2013 magnetic radius (proton)	0.87(6) fm	2	[52]
-16.18	Magnetic radius 2013 (proton)	0.87(6) fm	3	[52]
-16.17	Proton radius before 2010 (CODATA as quoted 2010)	0.8768(69) fm	2	[51]
-16.17	Proton radius e-p scattering (Sick and Trautmann 2014)	0.8775(5) fm	2	[54]
-16.17	Proton charge radius, H spectroscopy, before 2010	0.8768 fm	3	[72]
-16.17	Proton charge radius, e-p scattering, before 2010	0.8775 fm	3	[72]
-16.17	Proton charge radius, consensus, pre-2010	0.877 fm	3	[72]
-15.98	Antognini 2013 Zemach radius (proton)	1.082(37) fm	2	[52]
-15.98	Zemach radius 2013 (proton)	1.082(37) fm	3	[52]
-15.85	Nuclear radius constant r0 (nuclei)	1.25 ± 0.2 fm	3	[85]
-15.64	Radius r0 A^(1/3), A=2 (deuteron)	1.57 fm	3	[85]
-15.57	Hydrogen nucleus diameter (proton)	1.70 fm	3	[85]
-15.43	Radius r0 A^(1/3), A=4 (helium-4)	1.98 fm	3	[85]
-15.01	Radius r0 A^(1/3),	3.15 fm	3	[85]

	A=16 (oxygen-16)			
-14.63	Radius r0 A^(1/3), A=56 (iron-56)	4.78 fm	3	[85]
-14.60	Radius r0 A^(1/3), A=62 (nickel-62)	4.95 fm	3	[85]
-14.23	Radius r0 A^(1/3), A=208 (lead-208)	7.41 fm	3	[85]
-14.19	Radius r0 A^(1/3), A=238 (uranium-238)	7.75 fm	3	[85]
-14.12	Radius r0 A^(1/3), A=294 (oganesson-294)	8.31 fm	3	[85]
-13.81	Uranium nucleus diameter	11.7 fm	3	[85]
-11.01	Muon orbit radius a0/206.77 (computed) (muonic hydrogen)	2.56e-13 m	2	[51]
-10.63	Reduced Compton wavelength (CODATA 2022)	3.8615926744e-13 m	8	[1]
-10.20	2 MeV geoneutrino wavelength	0.62 pm	4	[30]
-9.59	Pair threshold photon wavelength	1.2132e-12 m	1	[16]
-9.59	Pair threshold photon wavelength (electron-positron pair)	1.2132 pm	7	[201]
-8.96	Electron Compton wavelength	2.42631023538e-12 m	1	[1]
-8.33	Maximum Compton shift at 180 degrees (photon)	4.85e-12 m	1	[1]
-7.67	Spectrum band edge: Gamma (photon energy 124 keV)	1e-11 m	1	[10]
-5.86	Wavelength of 17 keV X-ray (computed) (photon)	7.29e-11 m	1	[1]
-5.57	Spectrum band edge: Hard X-ray (photon energy 12.4 keV)	1e-10 m	1	[10]
-1.38	Spectrum band edge: Soft X-ray (photon energy 124 eV)	1e-08 m	1	[10]
-1.38	Pb nanocluster size in a 4.4 Gyr Hadean zircon (Hadean crust)	about 10 nm	13	[297]
-1.38–0.08	Pb nanocluster spacing in a 4.4 Gyr Hadean zircon (Hadean crust)	10–50 nm	13	[297]
-1.38	Nanocluster size (Hadean zircon)	about 10 nm	21	[297]
-1.38 to 0.08	Nanocluster spacing (Hadean zircon)	10-50 nm	21	[297]
0.00	Unit S0 = 1/(2R_H) (net)	4.5588e-8 m	1	[26]
-0.00	Unit S0 with R_inf (net)	4.55634e-8 m	1	[26]
0.00	S0 = 1/(2R_H) (ladder unit)	45.5882 nm	8	[26]
0.00	Ladder length unit	4.558816e-8 m	24	[681]
0.63	Lyman limit 1/R_H (hydrogen)	9.118e-8 m	1	[1]
0.63	Lyman limit 1/R_H = 2	91.176 nm	8	[26]

	S0 (hydrogen)			
0.72	Mohideen-Roy 1998 range lower (Casimir)	0.1 um	9	[228]
0.89	Spectrum band edge: Extreme UV (photon energy 10.2 eV)	1.21e-07 m	1	[10]
0.89	1S-2S wavelength (computed) (hydrogen)	1.21567e-7 m	2	[49]
1.07	Th-229m wavelength	148.3821828827(15) nm	8	[221]
1.52	1S-2S single excitation photon wavelength (hydrogen)	2.4313e-7 m	2	[49]
1.98	Spectrum band edge: Near UV (photon energy 3.1 eV)	4e-07 m	1	[10]
2.00	H-delta = 9 S0 (identity) (hydrogen)	4.102935e-7 m	1	[29]
2.00	2S-6P wavelength (computed) = H-delta (hydrogen)	4.10287e-7 m	2	[50]
2.00	Identity H-delta = 9 S0 (hydrogen)	410.2935 nm	8	[29]
2.07	Growth per year (Naica gypsum)	442 nm	21	[623]
2.18	Bressi 2002 range lower (Casimir)	0.5 um	9	[229]
2.35	Lamoreaux 1997 range lower (Casimir)	0.6 um	9	[227]
2.49	Spectrum band edge: Visible red end (photon energy 1.77 eV)	7e-07 m	1	[10]
2.72	Mohideen-Roy 1998 range upper (Casimir)	0.9 um	9	[228]
2.81	Spectrum band edge: Near IR (photon energy 1.24 eV)	1e-06 m	1	[10]
3.81	Bressi 2002 range upper (Casimir)	3.0 um	9	[229]
4.14	WASP-39b CO2 at 4.3 µm	4.3 µm	33	[950]
4.44	Lamoreaux 1997 range upper (Casimir)	6 um	9	[227]
4.91	Spectrum band edge: Mid IR (photon energy 124 meV)	1e-05 m	1	[10]
4.91	Dobson unit (ozone)	0.01 mm	15	[411]
4.91–8.00	Zodiacal dust sizes	10–300 µm	32	[937]
6.88	Tau c tau	87.03e-6 m	2	[35]
7.00	Spectrum band edge: Far IR (photon energy 12.4 meV)	0.0001 m	1	[10]
7.62	Mohideen-Roy 1998 sphere diameter (Casimir)	196 um	9	[228]
7.63	Dust size peak (cosmic dust)	200 µm	32	[936]
9.10	Spectrum band edge: Far IR lower edge (photon energy 1.24 meV)	0.001 m	1	[10]
9.10 to 11.19	BIF band thickness (banded iron formation)	a few mm to a few cm	22	[346]

9.15	CMB Wien peak wavelength (computed) (CMB photons)	1.063e-3 m	1	[25]
9.15	Peak of the background spectrum (net ladder text) (background light)	1.06 mm	25	[29]
9.19	APOLLO range accuracy (lunar laser ranging)	1.1 mm	12	[313]
10.91	Relic wavelength at 1.7e-4 eV (relic neutrinos)	7.3 mm	4	[114]
11.19	Spectrum band edge: Microwave EHF (photon energy 124 μeV)	0.01 m	1	[10]
11.48	Greenland sea level since 1972 (Greenland ice sheet)	13.7 mm	19	[549]
11.87	Ice-sheet sea-level contribution 1992–2020 (ice sheets)	21.0 ± 1.9 mm	19	[584]
12.66	Toba ash over India	5 cm	18	[500]
13.27	Sea-level rise since 1993 (sea level)	97.8 mm	14	[368]
13.29	Spectrum band edge: Microwave SHF (photon energy 12.4 μeV)	0.1 m	1	[10]
13.29	Tōhoku axis shift (Earth rotation)	10–25 cm	18	[523]
13.66	Crawford Lake section thickness (Anthropocene GSSP proposal)	15 cm	23	[675]
13.92	Sea-level rise 1901–2018 (sea level)	0.20 (0.15–0.25) m	14	[383]
13.92	Sea-level rise 1901–2018 (sea level)	0.20 m	19	[563]
13.97	21-cm line (net ladder text) (hydrogen)	0.21 m	25	[29]
14.35	Glacier sea-level equivalent (glaciers)	0.32 ± 0.08 m	19	[586]
14.83	Open-ocean lunar amplitude (tides)	about 54 cm	12	[310]
14.83	Open-ocean tidal amplitude (tide)	54 cm	14	[374]
15.39	Spectrum band edge: Microwave UHF (photon energy 1.24 μeV)	1 m	1	[10]
15.39	Open-ocean tidal range (tides)	<1 m	12	[311]
15.39	tsunami deep-ocean height	1 m	18	[525]
15.39	Boulder-to-planetesimal step (disk solids)	1 m to 1 km	30	[850]
16.02	Hunga tsunami Peru and Chile (Hunga Tonga)	2 m	18	[511]
16.02	H4 sea-level rise (Heinrich event 4)	2 ± 1 m	19	[579]
16.18	Tōhoku coast shift (Tōhoku 2011)	2.4 m	18	[523]

16.29	Hoba size	2.7 m	32	[934]
16.39	Modern groundwater depth equivalent	~3 m	20	[601]
16.47	WAIS collapse (West Antarctic ice sheet)	3.3 m	19	[548]
16.63	Lake mean depth (lakes)	3.9 m	20	[602]
16.71	WAIS full melt (West Antarctic ice sheet)	4.3 m	19	[548]
16.76	MWP-1A Fennoscandian/Barents share (meltwater pulse 1A)	4.5–7.9 m	19	[564]
16.85–17.48	B ring thickness (Saturn rings)	5–10 m	31	[874]
17.21	Greenland sea-level equivalent (Greenland ice sheet)	~7.4 m	19	[581]
17.39	Chandler amplitude (Chandler wobble)	9 m	16	[459]
17.48	Spectrum band edge: Radio VHF (photon energy 124 neV)	10 m	1	[10]
17.48	Coastal tidal range (tides)	>10 m	12	[311]
17.54	Hilo tsunami 1960 (Valdivia)	10.7 m	18	[520]
17.57	Detector distance from reactor (Cowan–Reines detector)	11 m	4	[109]
17.57	Valdivia average slip	11 m	18	[520]
17.60	Largest gypsum crystal length (Naica gypsum)	11.40 m	21	[622]
17.65	Detector depth (Cowan–Reines detector)	12 m	4	[109]
17.79	MWP-1A rise (meltwater pulse 1A)	14–18 (12–22) m	19	[367]
17.85	Sumatra slip (Sumatra 2004)	15 m	18	[522]
17.93	Bay of Fundy maximum range (tides)	16.3 m	12	[310]
17.93	Bay of Fundy max range (tide)	16.3 m	14	[374]
18.07	Chelyabinsk size	19 m	32	[913]
18.11	Pole drift since 1900 (polar motion)	20 m	16	[460]
18.11	Hunga tsunami Tonga (Hunga Tonga)	20 m	18	[511]
18.11	Tōhoku slip, early (Tōhoku 2011)	20–40 m	18	[523]
18.28	Tōhoku seabed shift (Tōhoku 2011)	24 m	18	[523]
18.32	Valdivia offshore slip	25–30 m	18	[520]
18.32	Valdivia local tsunami	25 m	18	[520]
18.48	Mars polar ice WEG	30 m	31	[900]
18.72	Tōhoku run-up Aneyoshi (Tōhoku 2011)	38.9 m	18	[523]
18.74	Fall into glacial state (sea level)	40 m in <2000 yr	14	[366]
18.74	Fast fall amount (LGM sea level)	~40 m	19	[366]

18.76	Tōhoku run-up Miyako (Tōhoku 2011)	40.5 m	18	[523]
18.85	Hunga run-up Tofua (Hunga Tonga)	45 m	18	[511]
18.95–19.38	Tunguska body	50–80 m	32	[915]
18.97	Sumatra tsunami run-up (Sumatra 2004)	51 m	18	[522]
19.01	EAIS sea-level equivalent (East Antarctic ice sheet)	53.3 m	19	[548]
19.08	Antarctic sea-level equivalent (Antarctic ice sheet)	58 m	19	[582]
19.11	Temagami BIF thickness (Temagami, Canada)	up to 60 m	22	[346]
19.19	Two ice sheets sea level	65.4 m	19	[581]
19.25	EOT sea-level fall (Eocene–Oligocene transition)	~70 m	19	[546]
19.28	Bedmap2 bed lower than Bedmap1	72 m	19	[582]
19.58	Spectrum band edge: Radio HF (photon energy 12.4 neV)	100 m	1	[10]
19.58	Cretaceous sea-level peak (sea level)	100 ± 50 m	14	[363]
19.66	Rise 14,000–6,500 yr ago (sea level)	110 m	14	[365]
19.66	Rise 14,000–6,500 years ago (deglaciation)	110 m	19	[365]
19.66	Naica cave length (Cave of the Crystals)	109 m	21	[622]
19.66	ʻOumuamua diameter (1I/ʻOumuamua)	110 m	32	[928]
19.78	Paleozoic maximum eustatic amplitude (sea level)	125 m	14	[364]
19.78	LGM low stand (Fairbanks; Yokoyama) (LGM sea level)	−125 m	19	[560]
19.82	LGM sea level (secondary)	-130 m	14	[365]
19.83	Sea-level equivalent of excess ice (computed) (sea level)	132 m	14	[311]
19.84	LGM sea level	-134 m	14	[366]
19.84	LGM low stand (LGM sea level)	−134 m	19	[366]
19.86	Mars early water layer ~4.5 Ga	137 m GEL	31	[890]
20.21	Mean sea level last 100 Myr	200 m	14	[365]
20.41	Fossil water in wells deeper than (groundwater)	250 m	20	[607]
20.58	Namib dune height	300 m	20	[593]
20.58	Naica cave depth (Cave of the Crystals)	300 m	21	[622]
20.84	ocean crust sediments	0.4 km	17	[472]
20.84–22.94	Encke radar radius	0.4–4.0 km	32	[906]

	(2P/Encke)			
20.84	Borisov nucleus limit (2I/Borisov)	0.4 km	32	[929]
21.02	Bennu longest axis	0.49 km	32	[905]
21.04	ocean crust unit 2A	0.5 km	17	[472]
21.04	Mars geomorphic water depth	500 m	31	[900]
21.04	Itokawa longest axis	0.5 km	32	[905]
21.08–21.45	Mars 2025 ocean equivalent	520–780 m	31	[900]
21.09	Lituya Bay run-up (tsunami)	524 m	18	[525]
21.58	Hamersley BIF thickness (Hamersley, Western Australia)	>900 m	22	[346]
21.67	Spectrum band edge: Radio MF (photon energy 1.24 neV)	1000 m	1	[10]
21.67	rift valley relief (ridges)	1000 (up to) m	17	[468]
21.67	CCD deepening (equatorial Pacific)	>1 km	19	[547]
21.67	BedMachine bed corrections (Antarctic margins)	up to 1 km	19	[583]
21.67–23.14	Enceladus south-polar shell	1–5 km	31	[880]
22.04	ocean crust unit 2B	1.5 km	17	[472]
22.11	One mile tube length (light)	1609 m	1	[6]
22.14	Greenland mean thickness (Greenland ice sheet)	1,673 m	19	[549]
22.30	Sporadic E thickness (ionosphere)	2 km	16	[447]
22.30	ridge height above basin floor (ridges)	2000 m	17	[468]
22.30	Deccan thickness (Deccan Traps)	2 (more than) km	18	[487]
22.30	Chimborazo beyond Everest, metadata	2000 m	18	[493]
22.30	Meltwater lid thickness (Snowball exit)	up to 2 km	19	[480]
22.30	Lysocline rise (PETM)	~2 km	19	[543]
22.34	Chimborazo beyond Everest from centre	2072 m	18	[493]
22.35	Chimborazo beyond Everest, other account	2100 m	18	[494]
22.39	Antarctic mean thickness (Antarctic ice sheet)	2.2 km	19	[548]
22.47	Deep fracture fluid depth (Timmins, Ontario)	2.4 km	20	[592]
22.51	WAIS bed below sea level (West Antarctic ice sheet)	>2,500 m	19	[548]
22.51	Deepest sea-floor life (oceanic crust)	about 2.5 km	22	[651]
22.54	ridge crest depth (ridges)	2600 m	17	[468]
22.63	Tambora summit after	2851 m	18	[505]

22.67	PREM ocean floor depth (Earth shells)	3 km	11	[279]
22.68	Dome Fuji second hole	3,035 m	19	[558]
22.68	GRIP bedrock	3,029 m	19	[558]
22.69	GISP2 bedrock	3,053 m	19	[558]
22.70	NGRIP depth	3,085 m	19	[558]
22.73	Laurentide height near Keewatin Dome (Laurentide ice sheet)	3.2 km	19	[560]
22.73	Olympus caldera depth (Mars)	3.2 km	31	[899]
22.75	EPICA bedrock depth (EPICA Dome C)	3,260 m	19	[558]
22.76	Vostok depth at 420 kyr (Vostok ice core)	3,310 m	19	[558]
22.81	Greenland maximum thickness (Greenland ice sheet)	3,488 m	19	[549]
22.82	Mean depth of measured cells (ocean floor)	3504.49 m	14	[360]
22.86	Ocean mean depth (Charette & Smith)	3682.22 m	14	[360]
22.86	Mean depth of altimetry cells (ocean floor)	3699.73 m	14	[360]
22.86	Ocean volume and mean depth (NOAA)	3688 m	14	[311]
22.86	mean ocean depth	3682.22 m	18	[360]
22.86	Vostok 5 depth 2007 (Vostok ice core)	3,661 m	19	[558]
22.86	Ocean mean depth	3,688 m	20	[311]
22.86	Water beside the ground in the Climate text (climate shell)	mean ocean depth 3.7 km	20	[29]
22.87	Mean depth Menard & Smith 1966 (ocean)	3729 m	14	[360]
22.87	Mean depth Baumgartner & Reichel 1975 (ocean)	3733 m	14	[360]
22.87	Mean depth Shiklomanov & Sokolov 1983 (ocean)	3703 m	14	[360]
22.88	Vostok deepest core (Vostok ice core)	3,769 m	19	[558]
22.89	Borexino depth	3800 m w.e.	4	[120]
22.89	Mean depth Murray 1888 (ocean)	3797 m	14	[360]
22.89	Mean depth Kossinna 1921 (ocean)	3814 m	14	[360]
22.94	ocean crust at very slow ridges	4–5 km	17	[472]
22.94	Colombia 2026 offset from San José del Palmar	4 km	18	[516]
23.00	net ladder mountain	4.3 km	18	[29]
23.00	Tambora summit before	4300 m	18	[505]
23.04	Modern CCD (Pacific)	~4,500 m	19	[547]
23.06	Toutatis longest axis	4.6 km	32	[905]
23.12	Antarctic maximum thickness (Antarctic ice sheet)	~4.9 km	19	[581]

23.14–25.54	Crust thickness range	5–70 km	11	[281]
23.14–23.77	Oceanic crust thickness	5–10 km	11	[281]
23.14	Jet thickness (jet stream)	<5 km	15	[416]
23.14	ocean crust unit 3	5 km	17	[472]
23.14	Moho below ocean floor	5–10 km	17	[452]
23.14	Deepest continental life (continental crust)	about 5 km	22	[651]
23.21–23.57	Mars 2025 water layer	5.4–8 km	31	[900]
23.24	Half-mass height (air)	5.6 km	15	[397]
23.24	3I/ATLAS diameter limit	5.6 km	32	[931]
23.27	Scale height (secondary) (air)	5.5–6 km	15	[397]
23.30	Troposphere top poles	6 km	15	[410]
23.30	oceanic lithosphere at ridges	6 km	17	[354]
23.45	ocean crust thickness	7 ± 1 km	17	[472]
23.45	syntaxis uplift per Myr (Himalaya)	7 km	18	[469]
23.57	Polar tropopause (circulation)	8 km	15	[415]
23.57	Olympus escarpment (Mars)	8 km	31	[899]
23.57	GRS cloud tops (Jupiter)	8 km	31	[898]
23.59	Challenger Deep HMS Challenger 1875	8184 m	14	[362]
23.62	Scale height (air)	8.5 km	15	[277]
23.64	Fizeau 1849 baseline Suresnes-Montmartre (light)	8633 m	1	[5]
23.64	Phanerozoic total lowering at mean rate (continents)	8,672 m	21	[626]
23.66	Everest height, 2020	8848.86 m	18	[492]
23.66	Everest height, 1856	8840 m	18	[492]
23.66	Everest height, 1952–54	8847.73 m	18	[492]
23.66	Everest height, 1975	8848.13 m	18	[492]
23.66	Everest height, 1999	8850 m	18	[492]
23.66	Everest height, 2005	8844.43 ± 0.21 m	18	[492]
23.66	Everest height, 2010	8848 m	18	[492]
23.67	Troposphere top 50°	9 km	15	[410]
23.68	Polar jet height (jet stream)	9.1 km	15	[416]
23.77	Spectrum band edge: Radio LF (photon energy 124 peV)	10000 m	1	[10]
23.77 (10 km)	Theia blob size	tens of km	12	[307]
23.77	rift valley width, slow ridges	10–20 km	17	[468]
23.77	2026 Venezuela M7.5 depth (earthquakes 2026)	10 km	18	[516]
23.77	NS radius order (neutron stars)	10 km	27	[767]
23.77	Chicxulub impactor	10 km	32	[917]

23.79	Mauna Kea base to peak	10210 (more than)	18	[493]
23.82–25.67	Chicxulub impactor diameter range	10.6–80.9 km	32	[918]
23.84	Challenger Deep PMEL 2015	10854.7 ± 8.9 m	14	[362]
23.85	Challenger Deep 2021	10935 ± 6 m	14	[362]
23.85	Challenger Deep Trieste 1960	10911 ± 7 m	14	[362]
23.85	Challenger Deep Limiting Factor 2019	10925 ± 4 m	14	[362]
23.85	Challenger Deep western basin 2020	10923 ± 4 m	14	[362]
23.86	Challenger Deep sonar 2010	10994 ± 40 m	14	[362]
23.86	Challenger Deep Gardner 2014	10984 ± 25 m	14	[362]
23.86	Halley nucleus (1P/Halley)	11 km	32	[923]
23.90	Mars mid-crust water top	11.5 km	31	[891]
23.94	Troposphere mean top (secondary)	12 km	15	[397]
23.96	Kola Superdeep borehole (crust)	12260 m	16	[452]
23.97	Radius of 1.4 M_sun NS (neutron stars)	12.45 ± 0.65 km	27	[766]
23.98	2026 Panama M7.7 depth (earthquakes 2026)	12.6 km	18	[516]
23.99	PSR J0030+0451 radius	12.71 (+1.14/−1.19) km	27	[765]
24.06	PSR J0740+6620 radius	13.7 (+2.6/−1.5) km	27	[766]
24.06	Arrokoth thickness	13.8 km	32	[926]
24.14	PREM upper/lower crust boundary (Earth shells)	15 km	11	[279]
24.14	depth Unimak 1946-04-01 (earthquakes M≥8.5)	15 km	18	[516]
24.14	depth Assam–Tibet 1950-08-15 (earthquakes M≥8.5)	15 km	18	[516]
24.14–24.60	Europa ice shell	15–25 km	31	[879]
24.14	Arrokoth lobe Weeyo	15.0 km	32	[926]
24.17	Deimos longest axis (Mars)	15.6 km	31	[847]
24.19	Venus scale height	15.9 km	31	[847]
24.20	Ninety-percent height (air)	16 km	15	[397]
24.20	Fastest pulsar radius limit (PSR J1748−2446ad)	<16 km	27	[769]
24.35	Troposphere top equator	18–20 km	15	[410]
24.40	ocean crust under Iceland	20 km	17	[472]
24.40	Moho below continents	20–90 km	17	[452]
24.40	Yellowstone magma body width	20 km	18	[499]
24.40	depth Ecuador–Colombia 1906-01-31	20 km	18	[516]

	(earthquakes M≥8.5)			
24.40	depth Wharton Basin 2012-04-11 (earthquakes M≥8.5)	20 km	18	[516]
24.40	Magnetar diameter (magnetars)	20 km	27	[772]
24.40	Mars mid-crust water bottom	20 km	31	[891]
24.40–24.60	Enceladus mean shell	20–25 km	31	[880]
24.41	Arrokoth lobes	20.1 and 15.0 km	30	[864]
24.41	Arrokoth lobe Wenu	20.1 km	32	[926]
24.46	Equatorial minus polar radius (computed) (Earth)	21.385 km	11	[277]
24.46	Olympus Mons height (Mars)	21.287 km	31	[899]
24.47	depth Kamchatka 1952 1952-11-04 (earthquakes M≥8.5)	21.6 km	18	[516]
24.52	depth Maule 2010-02-27 (earthquakes M≥8.5)	22.9 km	18	[516]
24.53	Rheasilvia peak (Vesta)	23 km	32	[912]
24.57	Polar-night jet height (jet stream)	24 km	15	[416]
24.58	PREM Moho depth (Earth shells)	24.4 km	11	[279; 280]
24.58	PREM lid top (crust)	24.4 km	16	[280]
24.60–25.66	Continental crust thickness	25–70 (locally 50–80) km	11	[281]
24.60	Mid-Atlantic opening per Myr (ridge)	25 km	17	[467]
24.60	depth Valdivia 1960-05-22 (earthquakes M≥8.5)	25 km	18	[516]
24.60	depth Prince William Sound 1964-03-28 (earthquakes M≥8.5)	25 km	18	[516]
24.60	depth Atka 1957-03-09 (earthquakes M≥8.5)	25 km	18	[516]
24.60	depth Banda Sea 1938-02-01 (earthquakes M≥8.5)	25 km	18	[516]
24.60	LFE depth Vancouver Island (slow slip)	25–37 km	18	[528]
24.64	Olympus Mons relief (Mars)	26 km	31	[899]
24.64	Phobos longest axis (Mars)	26 km	31	[847]
24.71	LFE depth southern Cascadia (slow slip)	28–47 km	18	[528]
24.74	depth Tōhoku 2011-03-11 (earthquakes M≥8.5)	29 km	18	[516]
24.77	Pinatubo evacuation radius	30 km	18	[506]
24.77	depth Sumatra–Andaman 2004-12-26 (earthquakes M≥8.5)	30 km	18	[516]
24.77	depth Singkil 2005-03-28 (earthquakes M≥8.5)	30 km	18	[516]
24.77	Yarrabubba diameter	30 km	32	[922]

24.77	Chelyabinsk burst height	30 km	32	[914]
24.78	depth Rat Islands 1965-02-04 (earthquakes M≥8.5)	30.3 km	18	[516]
24.83	Ozone peak height	32 km	15	[397]
24.83	Olympus magma chamber depth (Mars)	32 km	31	[899]
24.86	Mean continental thickness (computed) (continental crust)	33 km	13	[350]
24.86	Eros longest axis	33 km	32	[905]
24.88	Pinatubo ash cloud, other section	34 km	18	[506]
24.90	Arrokoth length	34.5 km	30	[864]
24.91	Moho below continents, mean	35 km	17	[452]
24.91	depth Kamchatka 2025 2025-07-29 (earthquakes M≥8.5)	35 km	18	[516]
24.91	depth Kuril Islands 1963-10-13 (earthquakes M≥8.5)	35 km	18	[516]
25.03	Pinatubo ash cloud	40 km	18	[506]
25.10	Tambora plume height	43 km	18	[504]
25.23	Stratosphere top	50 km	15	[410]
25.30	Mohorovičić depth 1909	54 km	16	[452]
25.30	Moho depth, Zagreb 1909	54 km	17	[452]
25.35	Hunga plume (Hunga Tonga)	57 km	18	[510]
25.35	2026 Philippines M7.8 depth (earthquakes 2026)	57 km	18	[516]
25.37	Hunga plume, other account (Hunga Tonga)	58 km	18	[511]
25.37	Ida longest axis	58 km	32	[905]
25.40–25.66	Olympus caldera (Mars)	60 × 80 km	31	[899]
25.40–26.23	Europa ocean depth	60–150 km	31	[879]
25.47–25.60	Siljan diameter	65–75 km	32	[922]
25.49	Mathilde longest axis	66 km	32	[905]
25.54	depth Vallenar 1922-11-11 (earthquakes M≥8.5)	70 km	18	[516]
25.54	shallow earthquakes depth (earthquake depth)	0–70 km	18	[524]
25.54	Morokweng diameter	70 km	32	[922]
25.66	Yellowstone magma body length	80 km	18	[499]
25.66	Occator crater (Ceres)	80 km	32	[911]
25.66	Chicxulub peak ring	80 km	32	[917]
25.72	Mesosphere top	85 km	15	[410]
25.77–26.58	Vesta core	90–220 km	32	[912]
25.77	Acraman diameter	90 km	32	[922]
25.87	Spectrum band edge: Radio VLF (photon energy 12.4 peV)	100000 m	1	[10]
25.87	Planetesimals still forming	about 100 km	11	[273]

25.87–28.46	LMO initial depth range (Moon)	100 to Moon radius km	12	[300]
25.87	Kármán line (air)	100 km	15	[397]
25.87	oceanic lithosphere at subduction zones	100 (over) km	17	[354]
25.87	Transition region thickness (Sun)	100 km	29	[817]
25.87	Early planetesimals (disk solids)	100 km	30	[273]
25.87	Ganymede ocean	100 km	31	[881]
25.87	Manicouagan diameter	100 km	32	[922]
25.87	Popigai diameter	100 km	32	[922]
25.94	Colombia 2026 PAGER depth	108.2 km	18	[516]
25.95	Colombia 2026 depth (essay)	110 km	18	[524]
26.00	Colombia 2026 depth	116.13 km	18	[516]
26.04	2026 Vanuatu M7.3 depth (earthquakes 2026)	121 km	18	[516]
26.06	Lutetia longest axis	124 km	32	[905]
26.10	Sudbury diameter	130 km	32	[922]
26.23	Ganymede ice crust	150 km	31	[881]
26.23	Chicxulub diameter	150 km	32	[922]
26.24	Himalaya width east	151 km	18	[469]
26.29	Vredefort diameter	160 km	32	[922]
26.35	F1 layer (ionosphere)	160–180 km	16	[447]
26.40	Chiron diameter	180 km	31	[905]
26.50	Inner belt over SAA (radiation belts)	200 km	16	[439]
26.50	D'' thickness (D'' layer)	200 km	16	[449]
26.50	continental lithosphere	200 km	17	[354]
26.50	Tōhoku rupture width (Tōhoku 2011)	200 km	18	[523]
26.50	tsunami wavelength	200 (up to) km	18	[525]
26.50	Chicxulub crater (crater page)	200 km	32	[917]
26.58	PREM 220 km discontinuity (Earth shells)	220 km	11	[279]
26.58	PREM jump 220 km (mantle)	220 km	17	[279]
26.64	2026 Tonga M7.5 depth (earthquakes 2026)	234 km	18	[516]
26.64	Juno longest axis	234 km	32	[905]
26.70	continental crust subducted to (slabs)	250 km	17	[462]
26.87	Acasta distance north of Yellowknife	about 300 km	13	[341]
26.87	F2 layer peak (ionosphere)	300 km	16	[447]
27.01	Himalaya width west	350 km	18	[469]
27.12	Mimas diameter	396.4 km	31	[876]
27.13	PREM transition zone top (Earth shells)	400 km	11	[279]
27.13	PREM jump 400 km (mantle)	400 km	17	[279]
27.13	brittle failure	400 km	18	[524]

	suppressed below (earthquake depth)			
27.13	PREM transition zone top (mantle)	400 km, 13.4 GPa	21	[279]
27.15	Upper mantle base	410 km	11	[282]
27.15 to 27.58	Transition zone (mantle)	410-660 km	21	[282]
27.28	Miranda diameter	471.6 km	31	[876]
27.33	Tōhoku rupture length (Tōhoku 2011)	500 km	18	[523]
27.33	Photosphere thickness (Sun)	500 km	29	[733]
27.33	Enceladus diameter (NASA)	500 km	31	[880]
27.33	Rheasilvia width (Vesta)	500 km	32	[912]
27.34	Enceladus diameter	504.2 km	31	[876]
27.38	Vesta diameter	525.4 ± 0.2 km	30	[855]
27.38	Vesta diameter	525.4 km	32	[912]
27.42	abrupt change near (earthquake depth)	550 km	18	[524]
27.45	Vesta longest axis	569 km	32	[905]
27.47	Pallas longest axis	582 km	32	[905]
27.50	Thermosphere top	600 km	15	[410]
27.50	Pole distance from Resolute Bay 2001 (magnetic poles)	600 km	16	[425]
27.50	deepest slab earthquakes (slabs)	600–700 km	17	[462]
27.50 to 27.64	Deepest earthquakes in slabs (subducting slabs)	about 600-700 km	21	[628]
27.50	Olympus Mons width (Mars)	600 km	31	[899]
27.54	Bolivia 1994 depth (earthquake depth)	630 km	18	[524]
27.54	2026 Kota Belud M7.1 depth (earthquakes 2026)	629 km	18	[516]
27.58	Transition zone base (mantle)	660 km	11	[282]
27.60	PREM lower mantle top (Earth shells)	670 km	11	[279]
27.60	PREM jump 670 km (mantle)	670 km	17	[279]
27.60	PREM step (mantle)	670 km	18	[279]
27.60	Bridgmanite stability, top (lower mantle)	about 670 km	21	[620]
27.61	deep earthquakes lower end (earthquake depth)	680 km	18	[524]
27.64	Thermosphere top (secondary)	700 km	15	[397]
27.76	Jack Hills distance north of Perth	about 800 km	13	[327]
27.76	plateau depth under Siberia (Hawaii hotspot)	800 km	18	[471]
27.76	Valdivia rupture	800 km	18	[520]
27.90	Ceres diameter	939.4 km	30	[854]
27.96–29.43	Planetary embryo diameters (planetary	1000–5000 km	11	[273]

	embryos)			
27.96	LLSVP height (Earth mantle)	about 1000 km	12	[305]
27.96	LMO initial depth (typical model) (Moon)	1000 km	12	[300]
27.96	LLSVP height (LLSVPs)	1000 km	16	[305]
27.96	basal mantle structures height	1000 km	18	[305]
28.02	Tethys diameter	1062.2 km	31	[876]
28.07	Dione diameter	1122.8 km	31	[876]
28.10	Umbriel diameter	1169.4 km	31	[876]
28.10	Ariel diameter	1157.8 km	31	[876]
28.12	Pluto mean radius	1188 km	31	[847]
28.13	Sumatra rupture (Sumatra 2004)	1200–1300 km	18	[522]
28.14	PREM inner-core radius (Earth core)	1221.5 km	11	[280]
28.14	Inner core radius (Ahrens 1995)	1220 ± 10 km	11	[284]
28.14	Inner core radius	about 1221 km	11	[285]
28.14	Inner-core radius (PREM) (inner core)	1221.5 km	16	[280]
28.14	Charon diameter	1212.0 km	31	[876]
28.27	Inner core discovery radius (Lehmann 1936)	1400 km	11	[285]
28.27	Lehmann’s inner-core radius 1936 (inner core)	1400 km	16	[448]
28.31	Iapetus diameter	1468.6 km	31	[876]
28.34	Oberon diameter	1522.8 km	31	[876]
28.35	Rhea diameter	1527.0 km	31	[876]
28.38	Titania diameter	1577.8 km	31	[876]
28.39	Sumatra slip length (Sumatra 2004)	1600 km	18	[522]
28.46	Moon mean radius	1737.4 km	12	[278]
28.46	Moon equatorial / polar radius	1738.1 / 1736.0 km	12	[278]
28.50	D’ thickness (lower mantle)	1800 km	16	[449]
28.61	Bridgmanite depth span (lower mantle)	2,030 km	21	[620]
28.70	Outer core thickness	about 2260 km	11	[284]
28.75	Pluto diameter	2376 km	31	[847]
28.75	Pluto diameter	2370 km	32	[925]
28.76	Himalaya length	2400 km	18	[469]
28.80	Chromosphere thickness (Sun)	2500 km	29	[733]
28.87	Bridgmanite stability, bottom (lower mantle)	about 2,700 km	21	[620]
28.87	Triton diameter	2705.2 km	31	[876]
28.93	PREM core–mantle boundary depth (Earth shells)	2891 km	11	[279]
28.93	Mantle thickness	about 2900 km	11	[282]
28.93	Core–mantle boundary depth	2891 km	16	[280]
28.93	deepest slabs (core–mantle boundary)	2890 km	17	[462]
28.93	PREM core-mantle boundary	2,891 km, 135.8 GPa	21	[279]

28.96	Pacific LLSVP width (Earth mantle)	3000 km	12	[306]
28.96	Pacific basal structure width (mantle)	3000 km	18	[306]
29.00	Europa diameter	3121.6 km	31	[876]
29.10	PREM outer-core radius (Earth core)	3480.0 km	11	[280]
29.10	Core radius (NSSDC) (Earth core)	3485 km	11	[277]
29.10	Outer core radius (Ahrens 1995)	3483 ± 5 km	11	[284]
29.10	Outer-core radius (PREM)	3480.0 km	16	[280]
29.10	Moon diameter	3474.8 km	31	[876]
29.11	Arrokoth flyby distance	3538 km	32	[926]
29.14	Io diameter	3643.0 km	31	[876]
29.39	Callisto diameter	4820.6 km	31	[876]
29.39	TRAPPIST-1 h radius	0.755 R⊕	33	[867]
29.40	Mercury diameter	4879 km	31	[847]
29.40	Cassini division width (Saturn rings)	4833 km	31	[874]
29.42	Voyager 2 Neptune (spacecraft)	4950 km	31	[903]
29.43	Atlantic width at 25 mm/yr over 200 Myr	5000 km	17	[467]
29.43	TRAPPIST-1 d radius	0.788 R⊕	33	[867]
29.45	PREM inner-core boundary depth (Earth shells)	5149.5 km	11	[279]
29.45	Titan diameter	5149.5 km	31	[876]
29.47	Ganymede diameter	5262.4 km	31	[876]
29.52	White dwarf radius min (white dwarfs)	0.8% R_sun	27	[753]
29.54	Sirius B radius	5634 ± 34 km	27	[757]
29.57	TRAPPIST-1 e radius	0.92 R⊕	33	[867]
29.62	Hawaiian–Emperor chain length (Hawaii hotspot)	6200 km	18	[470]
29.65	Earth mean radius	6371.000 km	11	[277]
29.65	Earth equatorial radius	6378.137 km	11	[277]
29.65	Earth polar radius	6356.752 km	11	[277]
29.66	Voyager 1 Titan flyby (spacecraft)	6490 km	31	[902]
29.69	TRAPPIST-1 f radius	1.045 R⊕	33	[867]
29.71	Mars diameter	6792 km	31	[847]
29.73	G ring width (Saturn rings)	7000 km	31	[874]
29.73	TRAPPIST-1 c radius	1.097 R⊕	33	[867]
29.75	TRAPPIST-1 b radius	1.116 R⊕	33	[867]
29.76	TRAPPIST-1 g radius	1.129 R⊕	33	[867]
29.81	D ring width (Saturn rings)	7610 km	31	[874]
30.00	Phobos orbit (Mars)	9378 km	31	[847]
30.02–30.28	Radius gap (small planets)	1.5–2.0 R⊕	33	[942]
30.06	Exosphere top	10000 km	15	[410]
30.22	Inner belt (radiation belts)	0.2–2 Earth radii	16	[442]

30.23	Venus diameter	12104 km	31	[847]
30.26	New Horizons Pluto (spacecraft)	12500 km	31	[904]
30.28	Earth diameter	12742 km	11	[277]
30.28	Earth diameter	12756 km	31	[847]
30.29	Columbia north–south extent	12900 km	17	[477]
30.30–29.68	Neptune Great Dark Spot	13,000 × 6,600 km	31	[896]
30.36	White dwarf radius max (white dwarfs)	2% R_sun	27	[753]
30.39	A ring width (Saturn rings)	14440 km	31	[874]
30.51	Great Red Spot long axis 2014 (Jupiter)	16500 km	31	[889]
30.51	Great Red Spot long axis 2017 (Jupiter)	16350 km	31	[898]
30.52	Tachocline prolateness (Sun)	0.024 R_sun	29	[815]
30.52	K2-18b radius	2.61 R⊕	33	[951]
30.56	C ring width (Saturn rings)	17317 km	31	[874]
30.59	Great Red Spot long axis 2009 (Jupiter)	17910 km	31	[889]
30.65	Magnetopause during reversals (magnetosphere)	3 Earth radii	16	[431]
30.65	Kepler-223 b radius	2.99 R⊕	33	[867]
30.67	Charon orbit	19596 km	31	[847]
30.73	Great Red Spot long axis 1995 (Jupiter)	20950 km	31	[889]
30.77	Kepler-223 c radius	3.44 R⊕	33	[867]
30.83	Deimos orbit (Mars)	23459 km	31	[847]
30.83	Great Red Spot long axis 1979 (Jupiter)	23300 km	31	[889]
30.88	Neptune equatorial radius	24764 km	31	[847]
30.91	Uranus equatorial radius	25559 km	31	[847]
30.91	B ring width (Saturn rings)	25532 km	31	[874]
30.97	Tachocline thickness (Sun)	0.039 ± 0.013 R_sun	29	[815]
31.04	Kepler-223 e radius	4.6 R⊕	33	[867]
31.06	Saturn hexagon (net reading: six cells around a centre cell)	30000 km	31	[702]
31.11	Paleoarchean magnetopause (magnetosphere)	<=5 Earth radii	16	[430]
31.11	Magnetopause May 2024 (magnetosphere)	5 Earth radii	16	[441]
31.16	Kepler-223 d radius	5.24 R⊕	33	[867]
31.32	Earth’s circumference	40075 km	15	[277]
31.34	Great Red Spot long axis late 1800s (Jupiter)	41000 km	31	[889]
31.37	Styx orbit	42413 km	31	[847]
31.50	Nix orbit	48690 km	31	[847]
31.51	Neptune diameter	49528 km	31	[847]
31.52	mid-ocean ridge length	50000 km	17	[354]

	(50,000 km-long system) (ridges)			
31.54	Uranus diameter	51118 km	31	[847]
31.60	Saturn polar radius	54364 km	31	[847]
31.61	subduction margins length (trenches)	55000 km	17	[462]
31.65	Kerberos orbit	57750 km	31	[847]
31.69	mid-ocean ridge length (60,000 km) (ridges)	60000 km	17	[462]
31.69	Saturn equatorial radius	60268 km	31	[847]
31.69	EBLM J0555-57Ab radius (Saturn size)	60053 km	33	[744]
31.74	Magnetopause day side (magnetosphere)	10 Earth radii	16	[425]
31.76	mid-ocean ridge length (continuous mountain range) (ridges)	65000 km	17	[468]
31.76	Hydra orbit	64721 km	31	[847]
31.79	Magnetopause range (magnetosphere)	6–15 Earth radii	16	[440]
31.79	Jupiter polar radius	66854 km	31	[847]
31.79	D ring inner radius (Saturn rings)	66900 km	31	[874]
31.85	Jupiter equatorial radius	71492 km	31	[847]
31.89	D ring outer radius (Saturn rings)	74510 km	31	[874]
31.89	C ring inner radius (Saturn rings)	74658 km	31	[874]
31.95	mid-ocean ridge length (total oceanic ridge system) (ridges)	80000 km	17	[468]
31.97	Voyager 2 Uranus (spacecraft)	81500 km	31	[903]
32.08	C ring outer radius (Saturn rings)	91975 km	31	[874]
32.08	B ring inner radius (Saturn rings)	91975 km	31	[874]
32.13	Proxima star radius (Proxima Centauri)	0.14 R☉	33	[948]
32.16	Voyager 2 Saturn (spacecraft)	101000 km	31	[903]
32.30	B ring outer radius (Saturn rings)	117507 km	31	[874]
32.30	Cassini division inner radius (Saturn rings)	117507 km	31	[874]
32.32	Saturn diameter	120536 km	31	[847]
32.34	Cassini division outer radius (Saturn rings)	122340 km	31	[874]
32.34	A ring inner radius (Saturn rings)	122340 km	31	[874]
32.35	Voyager 1 Saturn closest approach (spacecraft)	124000 km	31	[902]
32.42	Encke gap (Saturn rings)	133410 km	31	[874]
32.44	A ring outer radius (Saturn rings)	136780 km	31	[874]
32.44	Keeler gap (Saturn rings)	136487 km	31	[874]
32.46	F ring radius (Saturn rings)	139826 km	31	[874]

32.48	Jupiter diameter	142984 km	31	[847]
32.61	G ring inner radius (Saturn rings)	166000 km	31	[874]
32.64	Present rate over 4.5 Gyr (computed) (Earth–Moon)	1.7×10^{5} km	12	[310]
32.65	G ring outer radius (Saturn rings)	173000 km	31	[874]
32.66	Core outer edge (Sun core)	0.20–0.25 R_sun	29	[133]
32.69	E ring inner radius (Saturn rings)	180000 km	31	[874]
32.72	Mimas orbit	186000 km	31	[877]
32.78	Convection-zone depth (computed) (Sun)	0.2867 R_sun	29	[800]
32.94	Enceladus orbit	238400 km	31	[877]
33.14	Tethys orbit	295000 km	31	[877]
33.15	E ring width (Saturn rings)	300000 km	31	[874]
33.27	1.4 Ga Earth–Moon distance	340,900 ± 2,600 km	12	[324]
33.27	Earth–Moon distance 1.4 Ga (1.4 Ga rhythmites)	340,900 ± 2,600 km	19	[324]
33.29	Voyager 1 Jupiter closest approach (spacecraft)	349000 km	31	[902]
33.33	Moon perigee (Earth–Moon)	363,300 km	12	[278]
33.36	Dione orbit	377700 km	31	[877]
33.38	Moon semimajor axis (Earth–Moon)	384,400 km	12	[278]
33.38	Moon orbit	384400 km	31	[847]
33.43	Moon apogee (Earth–Moon)	405,500 km	12	[278]
33.46	Io orbit	421800 km	31	[877]
33.58	E ring outer radius (Saturn rings)	480000 km	31	[874]
33.59	Radiative zone (Sun)	0.25–0.7 R_sun	29	[133]
33.59	Tachocline centre (Sun)	0.693 ± 0.002 R_sun	29	[815]
33.61	Convection-zone base (Sun)	0.7133 ± 0.0005 R_sun	29	[800]
33.61	Model S mixed envelope (Sun)	0.711 R_sun	29	[811]
33.74	Voyager 2 Jupiter (spacecraft)	570000 km	31	[903]
33.87	Near-surface shear layer start (Sun)	0.95 R_sun	29	[816]
33.89	Europa orbit	671100 km	31	[877]
33.90	He II ionisation zone (Sun)	0.98 R_sun	29	[800]
33.92	Solar radius (Sun)	695700 km	27	[733]
33.92	Nominal solar radius (Sun)	6.957e8 m	29	[810]
33.92	Photospheric radius (Sun)	695658 ± 140 km	29	[810]
33.92	Volumetric mean radius (Sun)	695700 km	29	[733]
34.22	Mean separation (main belt)	965600 km	32	[910]

34.31	Ganymede orbit	1070400 km	31	[877]
34.43	Titan orbit	1221900 km	31	[877]
34.47	Magnetotail (magnetosphere)	>200 Earth radii	16	[425]
34.61	Hyperion orbit	1481500 km	31	[877]
34.83	Callisto orbit	1882700 km	31	[877]
35.01	New Horizons Jupiter (spacecraft)	2300000.0 km	31	[904]
36.00	PSP perihelion distance from centre (computed) (Parker Solar Probe)	9.8 R_sun	29	[820]
36.05	Lake shoreline (lakes)	7.2 × 10^6 km	20	[602]
36.05	Proxima b semimajor axis (Proxima Centauri)	0.04848 AU	33	[949]
36.12	51 Peg b semimajor axis (51 Pegasi)	0.052344942 AU	33	[941]
36.56	Schwarzschild radius (computed) (Sagittarius A*)	1.27e10 m	34	[783]
36.59	Alfven surface crossing (PSP) (solar wind)	18.8 R_sun	29	[819]
37.30	Draugr semimajor axis (PSR B1257+12)	0.19 AU	33	[940]
37.31	3I/ATLAS Mars pass	0.193664 AU	32	[931]
37.34	R136a1 radius	42.7 R_sun	27	[749]
37.56	‘Oumuamua perihelion (1I/‘Oumuamua)	0.255 AU	32	[927]
37.69	Radio diameter (Sagittarius A*)	44e6 km	34	[976]
37.83	2P/Encke perihelion	0.34 AU	32	[906]
37.88	Poltergeist semimajor axis (PSR B1257+12)	0.36 AU	33	[940]
37.94	Mercury semimajor axis (Solar System)	0.387 AU	30	[847]
37.94	Mercury mean distance from Sun	57.9 10^6 km	31	[847]
38.03	EHT ring physical (computed) (Sagittarius A*)	6.34e10 m	34	[785]
38.10	Phobetor semimajor axis (PSR B1257+12)	0.46 AU	33	[940]
38.32	1P/Halley perihelion	0.587 AU	32	[906]
38.51	Venus semimajor axis (Solar System)	0.723 AU	30	[847]
38.51	Venus mean distance from Sun	108.2 10^6 km	31	[847]
38.62	Pluto perihelion inside Neptune aphelion (Pluto, Neptune)	122 10^6 km	31	[847]
38.74	RGB radius (red giants)	200 R_sun	27	[751]
38.81	Astronomical unit (Earth orbit)	149597870700 m	29	[133]
38.81	Grand Tack disk truncation (inner disk (model))	1 AU	30	[860]
38.81	Earth semimajor axis (Solar System)	1.0 AU	30	[847]
38.81	Earth mean distance from Sun	149.6 10^6 km	31	[847]

38.92	Bennu semimajor axis	1.126 AU	32	[905]
38.97	Sun as red giant radius	256 R_sun (1.19 AU)	27	[751]
38.97	Red-giant radius (Sun)	256 R_sun	29	[751]
39.04	67P/Churyumov–Gerasimenko perihelion	1.292 AU	32	[906]
39.06	Photon reduced Compton wavelength from PDG bound	>1.97e11 m	5	[7; 8]
39.09	3I/ATLAS perihelion	1.35645 AU	32	[931]
39.15	Eros semimajor axis	1.458 AU	32	[905]
39.18	Grand Tack inner turnaround (Jupiter (model))	1.5 AU	30	[860]
39.19	Mars semimajor axis (Solar System)	1.524 AU	30	[847]
39.19	Mars mean distance from Sun	228.0 10^6 km	31	[847]
39.44	Borisov perihelion (2I/Borisov)	2.00652 AU	32	[929]
39.47	Jupiter 4:1 resonance semimajor axis (computed) (asteroid belt)	2.064 AU	30	[847]
39.47	Belt core between Kirkwood gaps (asteroid belt)	2.06–3.27 AU	30	[853]
39.47	Main belt inner gap 4:1	2.06 AU	32	[910]
39.59	Vesta semimajor axis	2.362 AU	32	[905]
39.64	Jupiter 3:1 resonance semimajor axis (computed) (asteroid belt)	2.5 AU	30	[847]
39.73	Ceres orbit	2.768 AU	32	[905]
39.74	Pallas semimajor axis	2.772 AU	32	[905]
39.75	Jupiter 5:2 resonance semimajor axis (computed) (asteroid belt)	2.824 AU	30	[847]
39.79	Jupiter 7:3 resonance semimajor axis (computed) (asteroid belt)	2.957 AU	30	[847]
39.89	Jupiter 2:1 resonance semimajor axis (computed) (asteroid belt)	3.277 AU	30	[847]
39.89	Main belt 2:1 gap	3.27 AU	32	[910]
39.95	HL Tau finest resolution (HL Tau disk)	3.5 AU	30	[848]
39.95	67P/Churyumov–Gerasimenko semimajor axis	3.51 AU	32	[906]
40.11	Few asteroids beyond (asteroid belt)	4.2 AU	30	[853]
40.31	Jupiter semimajor axis (Solar System)	5.204 AU	30	[847]
40.31	Jupiter mean distance from Sun	778.5 10^6 km	31	[847]
40.75	Chiron perihelion	8.46 AU	31	[906]
40.75	95P/Chiron perihelion	8.46 AU	32	[906]
40.86	Saturn semimajor axis (Solar System)	9.572 AU	30	[847]

40.86	Saturn mean distance from Sun	1432.0 10^6 km	31	[847]
40.91	Saturn aphelion	1506.5 10^6 km	31	[847]
41.00	Depth 41 as length (closure depth 41)	11.11 AU	31	[29]
41.19	Chiron semimajor axis at depth 41	13.637 AU	31	[905]
41.19	95P/Chiron semimajor axis	13.637 AU	32	[905]
41.44	1P/Halley semimajor axis	17.94 AU	32	[906]
41.45	Uranus perihelion	18.27 AU	31	[847]
41.48	Chiron aphelion	18.81 AU	31	[905]
41.50	Uranus semimajor axis (Solar System)	19.165 AU	30	[847]
41.50	Uranus mean distance from Sun	2867.0 10^6 km	31	[847]
41.81	Heliosheath thickness V1 (computed) (heliosphere)	27 AU	29	[822]
41.90	Kuiper belt inner	30 AU	32	[925]
41.91	Neptune semimajor axis (Solar System)	30.181 AU	30	[847]
41.91	Neptune mean distance from Sun	4515.0 10^6 km	31	[847]
42.04	Heliosheath thickness V2 (computed) (heliosphere)	35 AU	29	[822]
42.04	HCO+ resolution (HL Tau disk)	35 AU	30	[848]
42.05	Halley aphelion (1P/Halley)	35.14 AU	32	[923]
42.15	Pluto semimajor axis (Solar System)	39.482 AU	30	[847]
42.15	Pluto mean distance from Sun	5906.4 10^6 km	31	[847]
42.21	Classical belt (Kuiper belt)	42–48 AU	30	[863]
42.21–42.33	Classical belt (Kuiper belt)	42–48 AU	32	[925]
42.24	Arrokoth distance at flyby	43.4 AU	32	[904]
42.26	Arrokoth semimajor axis	44.2 AU	30	[864]
42.33	1:2 resonance edge (Kuiper belt)	47.8 AU	30	[863]
42.33	1:2 edge (Kuiper belt)	47.8 AU	32	[925]
42.37	Kuiper belt outer	50 AU	32	[925]
42.60	New Horizons April 2026 (spacecraft)	64.45 AU	31	[904]
42.75	Sedna perihelion	76 AU	32	[924]
42.84	Voyager 2 termination shock (heliosphere)	84 AU	29	[821]
42.94	Voyager 1 termination shock (heliosphere)	94 AU	29	[821]
43.11	Stagnation region (heliosphere)	113 AU	29	[822]
43.13	Wind speed zero at Voyager 1 (heliosphere)	116 AU	29	[819]
43.16	Voyager 2 heliopause (heliosphere)	119 AU	29	[822]

43.16	Voyager 2 heliopause (spacecraft)	119.7 AU	31	[903]
43.17	Voyager 1 heliopause (alt.) (heliosphere)	121 AU	29	[822]
43.18	Voyager 1 heliopause (heliosphere)	122 AU	29	[821]
43.33	Voyager 2 February 2026 (spacecraft)	143.05 AU	31	[903]
43.49	Voyager 1 August 2026 (spacecraft)	171.19 AU	31	[902]
43.50	Voyager 1 one light-day (18 Nov 2026) (spacecraft)	25902000000.0 km	31	[892]
43.83	Hale–Bopp semimajor axis	250 AU	32	[906]
45.04	Sedna aphelion (text)	940 AU	32	[29]
45.23	Hyakutake semimajor axis	1165 AU	32	[906]
45.67	S2 apocentre (computed)	2.8e14 (1,880 AU) m	27	[783]
45.73	Oort cloud extent	2000–200,000 AU	30	[865]
45.73	Oort cloud inner	2000 AU	32	[924]
45.73	Newtonian below (wide binaries)	2000 AU	35	[1010]
45.73-48.19	Banik separations (wide binaries)	2000-30000 AU	35	[1011]
46.56	Oort inner edge (alt) (Oort cloud)	5000 AU	32	[924]
46.62	Winding edge, embedded (solar knot)	5350 AU	29	[701]
46.87	Winding edge, a0 = 1.2e-10 (solar knot)	7030 AU	29	[827]
46.92	Winding edge, a0 = 1.08e-10 (solar knot)	7400 AU	29	[27]
46.92	Winding edge a0=1.08e-10 (solar knot)	7410 AU	32	[27]
47.24	Gliese 710 closest approach	0.167 ± 0.012 ly	29	[843]
47.24	Gliese 710 closest approach	10560 AU	32	[939]
47.24	Gliese 710 closest approach	0.167 ± 0.012 ly = 10560 AU	34	[843]
47.43	Proxima orbit around α Cen AB (Proxima Centauri)	12947 AU	33	[962]
47.43	Proxima orbit around alpha Cen (Proxima Centauri)	12947 ± 260 AU	34	[993]
47.82	Oort inner/outer division (Oort cloud)	20000 AU	32	[924]
47.85	Core size (molecular clouds)	0.1 pc	27	[735]
47.85	Prestellar cores near filaments	0.1 pc	27	[736]
48.22	Filament core spacing (filaments)	0.15 pc	27	[735]
48.66	Oort outer edge (Oort cloud)	50000 AU	32	[924]
48.87	Bok globule size (Bok globules)	1 ly	27	[736]
49.29	Oort outer edge (tidal) low (Oort cloud)	100000 AU	32	[924]

49.92	Oort outer edge (tidal) high (Oort cloud)	200000 AU	32	[924]
49.95	Clump size (molecular clouds)	1 pc	27	[735]
50.18	Proxima distance (Proxima Centauri)	1.295 pc	33	[948]
50.19	Proxima Cen d distance	1.30119 pc	33	[867]
50.19	Proxima distance (Proxima Centauri)	1.30197 pc	34	[993]
50.49	Barnard b distance	1.82655 pc	33	[867]
50.49	Barnard c distance	1.82655 pc	33	[867]
50.49	Barnard d distance	1.82655 pc	33	[867]
50.49	Barnard e distance	1.82655 pc	33	[867]
50.50	Barnard’s Star distance	5.9629 ly	33	[939]
50.50	Barnard’s Star	5.9629 ly	34	[843]
50.57	Nearest brown dwarf distance (Luhman 16 AB)	6.5 ly	27	[746]
50.57	Luhman 16 distance (brown dwarfs)	6.5 ly	33	[956]
50.58	Luhman 16 distance	6.5102 ly	33	[939]
50.58	Luhman 16	6.5102 ly	34	[843]
50.70	WISE 0855−0714 distance	7.43 ly	33	[939]
50.70	WISE 0855-0714	7.430 ly	34	[843]
50.70	Mean spacing (computed) (solar neighbourhood)	2.3 pc	34	[960]
50.75	Wolf 359 distance	7.856 ly	33	[939]
50.75	Wolf 359	7.856 ly	34	[843]
50.80	Lalande 21185 distance	8.3044 ly	33	[939]
50.80	Lalande 21185	8.3044 ly	34	[843]
50.83	Sirius distance	2.639 ± 0.010 pc (8.61 ly)	27	[757]
50.84	Sirius distance	8.7094 ly	33	[939]
50.84	Sirius	8.7094 ly	34	[843]
50.85	Hyades core radius	2.7 pc	34	[985]
51.01	eps Eri b distance	3.2026 pc	33	[867]
51.03	GJ 887 b distance	3.28679 pc	33	[867]
51.03	GJ 887 c distance	3.28679 pc	33	[867]
51.03	GJ 887 d distance	3.28679 pc	33	[867]
51.03	GJ 887 e distance	3.28679 pc	33	[867]
51.05	Ross 128 b distance	3.37454 pc	33	[867]
51.41	GMC diameter min (giant molecular clouds)	5 pc	27	[735]
51.58	Nearest HZ rocky planet (G/K) (Sun-like stars)	6 pc	33	[945]
51.58	Nearest HZ planet G/K (nearby planets)	6 pc	34	[945]
51.97	Local Interstellar Cloud size (LIC)	9.2 pc	29	[824]
51.97	LIC size (Local Interstellar Cloud)	9.2 pc	34	[824]
52.04	Hyades tidal radius	10 pc	34	[985]

52.41	51 Peg distance (51 Pegasi)	15 pc	34	[994]
52.43	51 Peg distance (51 Pegasi)	50 ly	33	[941]
52.71	Height above midplane (Sun in Galaxy)	20.8 ± 0.3 pc	29	[841]
52.71	Sun height above midplane	20.8 ± 0.3 pc	34	[841]
53.00	Depth 53 length (closure depth 53)	93.40 ly = 28.64 pc = 8.836e17 m	34	[29]
53.04	Most probable cloud radius (molecular clouds)	30 pc	27	[734]
53.06	GMC diameter (giant molecular clouds)	100 ly	27	[736]
53.26	K2-18b distance	38.025 pc	33	[951]
53.41	Super-thin bar scale height (Milky Way bar)	45 pc	34	[969]
53.44	Hyades distance Hipparcos	46.34 ± 0.27 pc	34	[801]
53.45	Hyades distance Gaia DR2	47.03 ± 0.20 pc	34	[984]
53.51	Molecular scale height min (Milky Way)	50 pc	27	[735]
53.65	HD 140283 distance	58.3 pc	34	[679]
53.86	MoM-z14 effective radius	74 (+15, −12) pc	26	[717]
53.88	Molecular scale height max (Milky Way)	75 pc	27	[735]
54.13	Vertical excursion (Sun in Galaxy)	99 pc	29	[133]
54.14	Crystallisation sample radius (white dwarfs)	100 pc	27	[754]
54.31	Pleiades Hipparcos distance	120.2 ± 1.5 pc	34	[986]
54.42	Pleiades VLBI distance	136.2 ± 1.2 pc	34	[986]
54.42	Pleiades Gaia DR3	135.74 ± 0.10 pc	34	[987]
54.57	Radcliffe Wave amplitude	160 pc	34	[989]
54.59	Local Bubble radius	165 ± 6 pc	28	[808]
54.67	Thin bar scale height (Milky Way bar)	180 pc	34	[969]
54.77	GMC diameter max (giant molecular clouds)	200 pc	27	[735]
54.86-55.51	Thin disc thickness (Milky Way thin disc)	220-450 pc	34	[967]
54.86	Radcliffe Wave amplitude fit	219.88 pc	34	[983]
55.01	JADES-GS-z14-0 radius	260 pc	26	[718]
55.14	Sun to Radcliffe Wave	< 300 pc	34	[983]
55.40	PSR J0901−4046 distance	400 ± 100 pc	27	[770]
55.75	Gaia BH3 distance	590 pc	27	[775]
55.92	PSR B1257+12 distance	2300 ly	33	[940]
56.87	Radcliffe Wave period	2 kpc	34	[989]
56.96	Cygnus X-1 distance	2.22 kpc	27	[774]
57.10	Thick disc thickness (Milky Way thick disc)	2.6 ± 0.5 kpc	34	[967]
57.14	Radcliffe Wave length	2.7 kpc	34	[989]

57.37	Molecular ring inner radius (Milky Way)	3.5 kpc	27	[735]
57.37-58.07	Molecular ring (Milky Way molecular clouds)	3.5-7.5 kpc	34	[997]
57.70	Bar half-length (Milky Way bar)	5.0 ± 0.2 kpc	34	[969]
58.07	Molecular ring outer radius (Milky Way)	7.5 kpc	27	[735]
58.15	Galactic Centre distance (Sgr A*)	8178 ± 13 ± 22 pc	27	[784]
58.15	Distance to Galactic Centre R0 (Sun in Galaxy)	8178 ± 13 ± 22 pc	29	[784]
58.15	R0 geometric (Sun-Galactic Centre)	8178 ± 13 ± 22 pc	34	[784]
58.15	R0 mass model (Sun-Galactic Centre)	8.20 ± 0.09 kpc	34	[971]
58.30	Fermi bubbles reach (computed)	9.7 kpc	34	[977]
58.57	SGR 1806−20 distance	13 kpc	27	[773]
58.64	eROSITA bubbles reach	14 kpc	34	[978]
58.90	M33 D25	61100 ly	35	[980]
58.96	Sagittarius dwarf distance	20 kpc	34	[979]
59.20	Disc stars beyond 26 kpc (Milky Way disc)	26 kpc	34	[968]
59.23	D25 diameter (Milky Way disc)	26.8 ± 1.1 kpc	34	[967]
59.23	Milky Way D25	87400 ly	35	[980]
59.36	Disc stars beyond 31 kpc (Milky Way disc)	31 kpc	34	[968]
59.73	Andromeda D25	152000 ly	35	[980]
59.77	LMC distance	48.5 kpc	34	[979]
59.79	R136a1 distance (LMC)	49970 pc	27	[749]
59.82	SN 1987A distance	51.4 kpc	27	[762]
59.98	SMC distance	61 kpc	34	[979]
59.99	Stellar disc diameter (computed) (Milky Way disc)	62 kpc	34	[968]
61.40	Halo splashback edge (Milky Way dark halo)	292 ± 61 kpc	34	[967]
61.79	Barycentre distance (Local Group)	447 ± 26 kpc	35	[980]
61.81	Leo M distance	459 kpc	34	[979]
62.03	Halo diameter (Milky Way dark halo)	584 ± 122 kpc	34	[967]
62.08	Halo diameter simulations (Milky Way dark halo)	613 kpc	34	[967]
62.28	Andromeda distance	765 kpc	35	[999]
62.32	Lobes apart (Local Group)	800 kpc	35	[980]
64.01	Local Group diameter	5.11 Mpc	35	[980]
64.62-66.71	Void diameters (cosmic web)	10-100 Mpc	35	[1022]
65.07	Virgo distance (Virgo Cluster)	16.5 ± 0.1 Mpc	35	[1018]
65.88	GW170817 distance	40 Mpc	27	[782]
66.08-66.51	Filaments length	50-80 Mpc	35	[1023]

	(cosmic web)			
66.28	Boötes Void radius	62 Mpc	35	[1021]
66.48	Great Attractor (Laniakea)	77 Mpc	35	[1020]
66.71-66.85	Homogeneity WiggleZ (cosmic web)	70-81 h-1 Mpc	35	[1028]
66.84-68.04	D2 within 1% of 3 (cosmic web)	80-300 h-1 Mpc	35	[1028]
66.88	Laniakea size 2023	120 Mpc	35	[1020]
67.04	Simulated filaments (cosmic web)	> 100 h-1 Mpc	35	[1024]
67.04	BAO first peak (SDSS LRG)	100 h-1 Mpc	35	[710]
67.05	Comoving sound horizon at z* (sound waves)	144.43 ± 0.26 Mpc	25	[25]
67.05	Sound horizon r* (BAO)	144.43 ± 0.26 Mpc	35	[25]
67.06	Sound horizon at drag epoch r_d (DESI reference) (sound waves)	147.05 Mpc	25	[125]
67.06	Standard ruler today (BAO)	150 Mpc	35	[1030]
67.06	Sound horizon r_d (BAO)	147.05 Mpc	35	[125]
67.14	Laniakea size 2014	160 Mpc	35	[1019]
67.41	Boötes Void distance	700 Mly	35	[1021]
67.55	CfA2 Great Wall (cosmic web)	251 Mpc	35	[1023]
67.91	Homogeneity upper limit (cosmic web)	260 h-1 Mpc	35	[1029]
67.98	Quipu (cosmic web)	400 Mpc	35	[1023]
67.98	Big Ring (cosmic web)	400 Mpc	35	[1027]
68.00	GW150914 distance	410 Mpc	27	[776]
68.05	Sloan Great Wall (cosmic web)	433 Mpc	35	[1023]
68.48	GW231123 distance min	0.7 Gpc	27	[778]
68.81	Giant Arc (cosmic web)	1 Gpc	35	[1026]
68.93	Bullet Cluster distance	1.141 Gpc	35	[1013]
69.01	Huge-LQG (cosmic web)	1.24 Gpc	35	[1023]
69.44-69.81	Her-CrB Great Wall (cosmic web)	2000-3000 Mpc	35	[1025]
70.09	GW231123 distance max	4.1 Gpc	27	[778]
70.10	Hubble length, SH0ES (universe)	1.267e26 m	24	[25]
70.17	Hubble length c/H0 (computed) (cosmology)	1.37e26 m	9	[238]
70.17	Hubble length, Planck (universe)	1.372e26 m	24	[25]
70.17	Hubble radius (computed) (observable universe)	1.37e26 m	35	[238]
70.26	Cosmic event horizon today (observable universe)	16 Gly	24	[677]
70.26	Event horizon (observable universe)	16 Gly	35	[1002]

70.33	GW190521 distance	5.3 Gpc	27	[777]
71.21	Distance to the last-scattering surface (background light)	45.7 Gly	25	[677]
71.23	Comoving radius (observable universe)	14.26 Gpc	35	[1002]
71.86	Diameter (observable universe)	28.5 Gpc	35	[1002]

Durations

1116 positions.

Position	What	Value	Chapter	Source
-59.77	Stoney time (Stoney units)	4.605448e-45 s	8	[1; 214]
-57.53	Planck time (Planck units)	5.391247e-44 s	8	[1]
-42.30	Inflation start (table) (early universe)	1e-36 s	24	[693]
-36.01	Inflation start (text) (early universe)	1e-33 s	24	[693]
-33.92	Inflation end (early universe)	1e-32 s	24	[693]
-18.36	Z lifetime (Z boson)	2.64e-25 s	5	[113]
-18.36	Z: from width (boson)	2.638e-25 s (from Γ = 2495.5 MeV)	10	[7]
-18.25	W (ATLAS 2024): from width (boson)	2.989e-25 s (from Γ = 2202 MeV)	10	[165]
-18.22	W lifetime from PDG 2025 width (W boson)	3.08e-25 s	5	[113]
-18.22	W (PDG 2025): from width (boson)	3.076e-25 s (from Γ = 2140 MeV)	10	[113]
-18.20	W lifetime from PDG 2024 width (W boson)	3.16e-25 s	5	[7]
-18.20	W (PDG 2024): from width (boson)	3.157e-25 s (from Γ = 2085 MeV)	10	[7]
-17.85	Top quark lifetime hbar/Gamma (t quark)	4.64e-25 s	3	[59]
-17.85	Top quark lifetime	4.6e-25 s	5	[59]
-17.85	top quark: from width (boson)	4.635e-25 s (from Γ = 1420 MeV)	10	[59]
-17.78	Hydro initial time 0.15 fm/c (quark-gluon plasma)	5.00e-25 s	3	[71]
-16.84	$K^*_0(700)$: from width (light meson)	1.406e-24 s (from Γ = 468 MeV)	10	[92]
-16.83	$f_2(1950)$: from width (light meson)	1.419e-24 s (from Γ = 464 MeV)	10	[92]
-16.78	$f_0(2020)$: from width (light meson)	1.496e-24 s (from Γ = 440 MeV)	10	[92]
-16.52	Hydro initial time 0.6 fm/c (quark-gluon plasma)	2.00e-24 s	3	[71]
-16.09	P_c(4380)+ lifetime from width 205 MeV (mass 4380 ± 8 ± 29 MeV)	3.21e-24 s	3	[97]
-16.01	X(2370) lifetime from width 188 MeV (mass 2395 ± 11 +26/-94 MeV)	3.5e-24 s	3	[100]

-15.79	rho(770)0 lifetime from width 147.4 MeV (mass 775.26 ± 0.23 MeV)	4.47e-24 s	3	[92]
-15.79	rho(770) lifetime (rho meson)	4.47e-24 s	5	[92]
-15.79	ρ(770)⁰: from width (light meson)	4.465e-24 s (from Γ = 147.4 MeV)	10	[92]
-15.58	Delta(1232) lifetime from width 117 MeV	5.63e-24 s	3	[69]
-15.58	Delta(1232) lifetime (Delta baryon)	5.63e-24 s	5	[69]
-15.58	Δ(1232): from width (baryon)	5.626e-24 s (from Γ = 117 MeV)	10	[69]
-15.57	Light crossing time of proton diameter	5.67e-24 s	3	[85]
-14.83	K*(892)± (hadroproduced): from width (light meson)	1.281e-23 s (from Γ = 51.4 MeV)	10	[92]
-14.75	K*(892)⁰: from width (light meson)	1.392e-23 s (from Γ = 47.3 MeV)	10	[92]
-14.73	K*(892)± (τ decays): from width (light meson)	1.425e-23 s (from Γ = 46.2 MeV)	10	[92]
-14.59	Σ(1385)⁻: from width (baryon)	1.671e-23 s (from Γ = 39.4 MeV)	10	[69]
-14.58	P_c(4450)+ lifetime from width 39 MeV (mass 4449.8 ± 1.7 ± 2.5 MeV)	1.69e-23 s	3	[97]
-14.51	Σ(1385)⁺: from width (baryon)	1.818e-23 s (from Γ = 36.2 MeV)	10	[69]
-14.50	Σ(1385)⁰: from width (baryon)	1.828e-23 s (from Γ = 36 MeV)	10	[69]
-14.35	η_c(1S): from width (quarkonium)	2.158e-23 s (from Γ = 30.5 MeV)	10	[101]
-13.99	Upsilon(4S) lifetime from width 20.5 MeV (mass 10579.4 ± 1.2 MeV)	3.21e-23 s	3	[108]
-13.99	Υ(4S): from width (quarkonium)	3.211e-23 s (from Γ = 20.5 MeV)	10	[249]
-13.40	χ_c0(1P): from width (quarkonium)	6.152e-23 s (from Γ = 10.7 MeV)	10	[101]
-13.34	η_b(1S): from width (quarkonium)	6.582e-23 s (from Γ = 10 MeV)	10	[249]
-13.21	omega(782) lifetime (omega meson)	7.58e-23 s	5	[92]
-13.21	ω(782): from width (light meson)	7.583e-23 s (from Γ = 8.68 MeV)	10	[92]
-13.09	hydrogen-5: half-life (nucleus)	8.6e-23 s (half-life)	10	[255]
-12.76	Σ_b⁻: from width (baryon)	1.242e-22 s (from Γ = 5.3 MeV)	10	[252]
-12.71	Σ_b⁺: from width (baryon)	1.316e-22 s (from Γ = 5 MeV)	10	[252]
-12.66	hydrogen-4: half-life (nucleus)	1.39e-22 s (half-life)	10	[255]
-12.56	φ(1020): from width (light meson)	1.549e-22 s (from Γ = 4.249 MeV)	10	[92]
-12.53	Higgs lifetime, SM width (Higgs boson)	1.61e-22 s	6	[174]
-12.53	Higgs (Standard Model value): from	1.605e-22 s (from Γ = 4.1 MeV)	10	[177]

	width (boson)			
-12.43	Higgs lifetime, PDG width (Higgs boson)	1.78e-22 s	6	[113]
-12.43	Higgs (PDG 2024 average): from width (boson)	1.779e-22 s (from Γ = 3.7 MeV)	10	[7]
-12.30	Higgs lifetime, CMS width (Higgs boson)	2.06e-22 s	6	[177]
-12.30	Higgs (CMS 2022): from width (boson)	2.057e-22 s (from Γ = 3.2 MeV)	10	[177]
-11.98	hydrogen-6: half-life (nucleus)	2.94e-22 s (half-life)	10	[255]
-11.92	$D^*(2007)^0$ (Γ < 2.1 MeV): lower limit (from width bound) (heavy meson)	>3.134e-22 s	10	[108]
-11.86	χ_c2(1P): from width (quarkonium)	3.324e-22 s (from Γ = 1.98 MeV)	10	[101]
-11.83	D*_s± (Γ < 1.9 MeV): lower limit (from width bound) (heavy meson)	>3.464e-22 s	10	[244]
-11.82	$\Sigma_c(2455)^{++}$: from width (baryon)	3.483e-22 s (from Γ = 1.89 MeV)	10	[250]
-11.79	$\Sigma_c(2455)^0$: from width (baryon)	3.597e-22 s (from Γ = 1.83 MeV)	10	[250]
-11.25	hydrogen-7: half-life (nucleus)	6.52e-22 s (half-life)	10	[255]
-11.08	χ_c1(1P): from width (quarkonium)	7.836e-22 s (from Γ = 840 keV)	10	[101]
-10.12	ψ(2S): from width (quarkonium)	2.246e-21 s (from Γ = 293 keV)	10	[101]
-9.72	η′(958): from width (light meson)	3.501e-21 s (from Γ = 188 keV)	10	[92]
-9.08	J/psi(1S) lifetime from width 0.0926 MeV (mass 3096.900 ± 0.006 MeV)	7.11e-21 s	3	[101]
-9.08	J/ψ(1S): from width (quarkonium)	7.108e-21 s (from Γ = 92.6 keV)	10	[101]
-8.98	D*(2010)±: from width (heavy meson)	7.892e-21 s (from Γ = 83.4 keV)	10	[108]
-8.59	Upsilon(1S) lifetime from width 0.05402 MeV (mass 9460.40 ± 0.10 MeV)	1.22e-20 s	3	[108]
-8.59	Υ(1S): from width (quarkonium)	1.218e-20 s (from Γ = 54.02 keV)	10	[249]
-8.11	Υ(2S): from width (quarkonium)	2.058e-20 s (from Γ = 31.98 keV)	10	[249]
-7.70	Υ(3S): from width (quarkonium)	3.239e-20 s (from Γ = 20.32 keV)	10	[249]
-6.94	Sigma0 mean life (mass 1192.642 ± 0.024 MeV)	7.4e-20 s	3	[69]
-6.94	Σ^0: mean life (baryon)	7.4e-20 s	10	[69]
-5.20	eta lifetime (electromagnetic) (eta meson)	5.02e-19 s	5	[92]
-5.20	η: from width (light meson)	5.025e-19 s (from Γ = 1.31 keV)	10	[92]
-1.85	Photoemission delay, Schultze 2010 (photon)	20 as	1	[11]

-1.67	Atomic unit of time (hydrogen)	2.4188843265864(26)e-17 s	2	[1]
-1.11	Photoemission delay, Ossiander 2018 (photon)	45 as	1	[11]
-0.56	8Be half-life (beryllium-8)	8.19e-17 s	28	[788]
-0.54	pi0 mean life (mass 134.9768 ± 0.0005 MeV)	8.43e-17 s	3	[92]
-0.54	Neutral pion mean life	(8.43 ± 0.13)e-17 s	5	[113]
-0.54	π^0: mean life (light meson)	8.43e-17 s	10	[92]
-0.38	Photoemission delay, Cavalieri 2007 (photon)	100 as	1	[11]
0.00	Unit T0 = 1/(2R_H c) vs Larson 1.520655e-16 (net)	1.520658e-16 s	1	[26]
-0.00	Unit T0 with R_inf (net)	1.519830e-16 s	1	[29]
-0.00	Classical Bohr orbit period = T0 (identity) (hydrogen)	1.519830e-16 s	1	[29]
0.00	Ladder unit of time from R_H	1.520658e-16 s	8	[26]
-0.00	Ladder unit of time from R_inf	1.519830e-16 s	8	[26]
-0.00	Identity Bohr orbit period = T0 (ladder unit)	1.519830e-16 s	8	[29]
0.00	Ladder time unit	1.520655e-16 s	24	[681]
6.28	Ξ_c^0: mean life (baryon)	1.504e-13 s	10	[250]
6.55	Lambda_c+ mean life (mass 2286.46 ± 0.14 MeV)	2.026e-13 s	3	[108]
6.55	Λ_c^+: mean life (baryon)	2.026e-13 s	10	[69]
6.76	Ξ_cc^{++}: mean life (baryon)	2.56e-13 s	10	[251]
6.82	Ω_c^0: mean life (baryon)	2.73e-13 s	10	[250]
6.88	Tau mean life PDG 2024	290.3(5)e-15 s	2	[35]
6.88	Tau lepton mean life	(290.3 ± 0.5)e-15 s	5	[113]
6.88	tau lepton: mean life	2.903e-13 s	10	[35]
7.06	B_s oscillation period	3.537e-13 s	10	[247]
7.19	D0 mean life (mass 1864.84 ± 0.05 MeV)	4.103e-13 s	3	[108]
7.19	D^0: mean life (heavy meson)	4.103e-13 s	10	[108]
7.28	Ξ_c^+: mean life (baryon)	4.53e-13 s	10	[250]
7.37	D_s±: mean life (heavy meson)	5.012e-13 s	10	[244]
7.39	B_c+- mean life (mass 6274.47 ± 0.32 MeV)	5.1e-13 s	3	[108]
7.39	B_c±: mean life (heavy meson)	5.1e-13 s	10	[248]
8.03	D±: mean life (heavy meson)	1.033e-12 s	10	[108]

8.35	Lambda_b0 mean life (mass 5619.60 ± 0.17 MeV)	1.471e-12 s	3	[108]
8.35	Λ_b^0: mean life (baryon)	1.471e-12 s	10	[252]
8.36	Ξ_b^0: mean life (baryon)	1.48e-12 s	10	[252]
8.38	B0 mean life (mass 5279.63 ± 0.20 MeV)	1.517e-12 s	3	[108]
8.38	B0_s mean life (mass 5366.93 ± 0.10 MeV)	1.52e-12 s	3	[108]
8.38	B^0: mean life (heavy meson)	1.517e-12 s	10	[246]
8.38	B^0_s: mean life (heavy meson)	1.52e-12 s	10	[247]
8.41	Ξ_b^-: mean life (baryon)	1.572e-12 s	10	[252]
8.45	Omega_b- mean life (mass 6045.8 ± 0.8 MeV)	1.64e-12 s	3	[108]
8.45	$B^\pm$: mean life (heavy meson)	1.638e-12 s	10	[245]
8.45	Ω_b^-: mean life (baryon)	1.64e-12 s	10	[252]
11.99	Sigma+ mean life (mass 1189.37 ± 0.07 MeV)	8.018e-11 s	3	[69]
11.99	Σ^+: mean life (baryon)	8.018e-11 s	10	[69]
12.01	Omega- mean life (mass 1672.45 ± 0.29 MeV)	8.21e-11 s	3	[69]
12.01	Ω^-: mean life (baryon)	8.21e-11 s	10	[69]
12.09	K0_S mean life	8.954e-11 s	3	[92]
12.09	K_S mean life (neutral kaon)	(0.8954 ± 0.0004)e-10 s	5	[113]
12.27	Caesium period (defines the second)	1.088e-10 s	8	[1]
12.40	Para-positronium lifetime, experiment	125.14 ps	7	[199]
12.40	Para-positronium lifetime, theory	125.16 ps	7	[199]
12.40	para-positronium (exp., 7990.9 μs^{-1}): mean life (bound)	1.25142e-10 s	10	[199]
12.40	para-positronium (theory, 7989.50 μs^{-1}): mean life (bound)	1.25164e-10 s	10	[199]
12.55	Sigma- mean life (mass 1197.449 ± 0.029 MeV)	1.479e-10 s	3	[69]
12.55	Σ^-: mean life (baryon)	1.479e-10 s	10	[69]
12.64	Xi- mean life (mass 1321.71 ± 0.07 MeV)	1.639e-10 s	3	[69]
12.64	Ξ^-: mean life (baryon)	1.639e-10 s	10	[69]
13.07	Lambda mean life (mass 1115.683 ± 0.006 MeV)	2.617e-10 s	3	[69]
13.07	Λ: mean life (baryon)	2.617e-10 s	10	[69]

13.16	Xi0 mean life (mass 1314.86 ± 0.20 MeV)	2.9e-10 s	3	[69]
13.16	Ξ^0: mean life (baryon)	2.9e-10 s	10	[69]
16.58	K+ mean life (mass 493.677 ± 0.015 MeV)	1.238e-08 s	3	[92]
16.58	K±: mean life (light meson)	1.238e-08 s	10	[92]
17.26	pi+ mean life (mass 139.57039 ± 0.00018 MeV)	2.603e-08 s	3	[92]
17.26	Charged pion mean life	(2.6033 ± 0.0005)e-8 s	5	[113]
17.26	π±: mean life (light meson)	2.6033e-08 s	10	[92]
17.87	K0_L mean life	5.116e-08 s	3	[92]
17.87	K_L mean life (neutral kaon)	(5.116 ± 0.021)e-8 s	5	[113]
18.02	Three Gorges Dam (Earth rotation)	0.06 μs	16	[458]
18.80	Ortho-positronium lifetime 2007	142.05 ± 0.02 ns	7	[200]
18.80	ortho-positronium (Ann Arbor, gas, 7.0514 μs^{-1}): mean life (bound)	1.41816e-07 s	10	[199]
18.80	ortho-positronium (Ann Arbor, vacuum, 7.0482 μs^{-1}): mean life (bound)	1.4188e-07 s	10	[199]
18.80	ortho-positronium (London, gas, 7.0450 μs^{-1}): mean life (bound)	1.41945e-07 s	10	[199]
18.80	ortho-positronium (Tokyo, powder, 7.0398 μs^{-1}): mean life (bound)	1.42049e-07 s	10	[199]
18.80	ortho-positronium (2007): mean life (bound)	1.4205e-07 s	10	[200]
18.80	ortho-positronium (theory, 7.0382 μs^{-1}): mean life (bound)	1.42082e-07 s	10	[199]
18.80	ortho-positronium (Mainz, vacuum, 7.0310 μs^{-1}): mean life (bound)	1.42227e-07 s	10	[199]
19.32	AEgIS pulsed source time spread (antihydrogen)	250 ns	7	[191]
20.66	Positronium 2S lifetime	1100 ns	7	[200]
20.66	positronium 2S: mean life (bound)	1.1e-06 s	10	[200]
21.11	Tōhoku day shortening (Earth rotation)	1.8 μs	18	[523]
21.29	Muon mean life PDG 2024	2.1969811(22)e-6 s	2	[35]
21.29	Muon mean life MuLan 2013	2196980.3(2.2)e-12 s	2	[45]
21.29	Muon lifetime MuLan 2013	2196980.3(2.2) ps	5	[45]
21.29	Muon mean life PDG 2025	(2.1969811 ± 0.0000022)e-6 s	5	[113]

21.29	muon, MuLan 2013: mean life (lepton)	2.19698e-06 s	10	[45]
21.29	muon: mean life (lepton)	2.19698e-06 s	10	[35]
21.47	Sumatra day shortening, model (Earth rotation)	2.68 µs	18	[522]
21.58	2004 earthquake day shortening	3 µs	12	[320]
21.58	2004 earthquake day change (Earth rotation)	3 µs	16	[458]
21.58	Sumatra day shortening, other account (Earth rotation)	3 µs	18	[320]
24.23	Fizeau 1849 light time (half notch at 12.6 rev/s, 720 notches)	5.51e-5 s	1	[5]
25.74	Semiannual LOD amplitude (Earth)	0.29 ms	12	[319]
25.74	LOD semiannual term (Earth rotation)	0.29 ms	16	[319]
25.88	Annual LOD amplitude (Earth)	0.34 ms	12	[319]
25.88	LOD annual term (Earth rotation)	0.34 ms	16	[319]
26.54	Og-294 half-life (oganesson)	0.7 ms	3	[90]
26.54	oganesson-294: half-life (nucleus)	0.0007 s (half-life)	10	[90]
26.76	Og-294 half-life (calculated) (oganesson)	0.89 ms	3	[90]
27.29	Shortest day 2022 under 24 h (Earth)	1.59 ms	12	[320]
27.29	Shortest day 2022 (Earth rotation)	1.59 ms	16	[458]
27.29	First millisecond pulsar period (B1937+21)	1.6 ms	27	[771]
27.35	Day longer than a century ago (Earth rotation)	1.7 ms	16	[458]
27.40	LOD trend observed (Earth rotation)	1.8 ms per century	16	[316]
27.62	LOD trend tidal (Earth rotation)	2.3 ms per century	16	[316]
28.53	PSR B1257+12 spin	6.21853194840048 ms	33	[940]
31.32	Light around circumference (Earth)	0.134 s	15	[277]
31.55	ALPHA 2010 confinement time (antihydrogen)	0.172 s	7	[193]
33.15	Relic neutrino decoupling (relic neutrinos)	~2 MeV, ~1 s	4	[114]
33.15	One second (ladder)	1 s	24	[681]
33.15	Weak freeze-out of n ↔ p (early universe)	T ~ 1 MeV at t ~ 1 s	24	[202]
33.42	First pulses period (PSR B1919+21)	1.337 s	27	[771]

33.64	GRB 170817A delay (GW170817)	1.7 s	27	[782]
33.78	Magnetar period min (magnetars)	2 s	27	[772]
33.91	Neutrino escape from Sun	2.3 s	4	[133]
33.91	Neutrino escape time (Sun)	2.3 s	29	[133]
34.78	Electron-positron annihilation (table) (early universe)	6 s	24	[693]
34.99	SGR 1806−20 period	7.5 s	27	[773]
35.25	Electron-positron annihilation (text) (early universe)	about 10 s	24	[693]
35.25	Nucleosynthesis window (table) (light nuclei)	10 s – 1000 s	24	[693]
35.25	Magnetar period max (magnetars)	10 s	27	[772]
35.49	Burst duration (SN 1987A)	<13 s	4	[123]
35.88	VLF period (slow slip)	20 s	18	[528]
36.28	Venezuela events apart (earthquakes 2026)	31 s	18	[516]
37.09	Slowest radio NS period (PSR J0901−4046)	75.88554711 s	27	[770]
37.51	OTD view per pass (lightning)	2 min	15	[418]
37.88	Light-element abundances fixed (light nuclei)	~180 s	24	[202]
37.88	Nucleosynthesis window (text) (light nuclei)	3 – 20 min s	24	[693]
38.34	Five-minute oscillation period (Sun)	300 s	29	[811]
38.51	Tōhoku duration (Tōhoku 2011)	6 minutes	18	[523]
38.80	Bradley 1729 Sun-Earth light time	492 s	1	[3]
38.81	Modern Sun-Earth light time (computed)	499 s	1	[1]
38.81	Light time over 1 AU (computed) (Earth orbit)	499.0 s	29	[133]
38.98	Antihydrogen hold time 2016-17	600 s	7	[191]
38.98	Balser & Wagner detection interval (Schumann resonance)	10 min	15	[420]
38.98	Valdivia duration	10 minutes	18	[520]
38.98	Sumatra duration (Sumatra 2004)	10 (at least) minutes	18	[522]
38.98	net ladder tsunami	10–60 minutes	18	[29]
39.02	Th-229m fluorescence lifetime in crystal	630(15) s	8	[221]
39.02	thorium-229m, in crystal (fluorescence lifetime): mean life	630 s	10	[221]

	(nucleus)			
39.14	damaging tsunami duration	12 minutes	18	[525]
39.32	Neutron mean life PDG 2024	878.4 ± 0.5 s	3	[69]
39.32	Neutron lifetime bottle UCNtau 2021	877.75 ± 0.28 +0.22/-0.16 s	3	[81]
39.32	neutron, UCNτ 2021 (stored): mean life (baryon)	877.75 s	10	[253]
39.32	neutron (PDG 2024): mean life (baryon)	878.4 s	10	[69]
39.33	Neutron lifetime beam NIST 2005	886.3 ± 1.2 ± 3.2 s	3	[80]
39.33	Neutron lifetime beam NIST 2013	887.7 ± 1.2 ± 1.9 s	3	[80]
39.33	neutron, beam 2005: mean life (baryon)	886.3 s	10	[254]
39.33	neutron, NIST beam 2013: mean life (baryon)	887.7 s	10	[254]
39.34	Wu experiment observing time (cobalt-60)	900 s	5	[155]
39.34	Average flare duration (Sun)	15 min	29	[817]
39.44	Light time across 2 AU (computed)	998 s	1	[1]
39.44	ALPHA 2011 confinement time (antihydrogen)	1000 s	7	[193]
39.61	tsunami cycle	20–30 minutes	18	[525]
39.69	Rømer: light time across diameter of Earth’s orbit	1320 s	1	[4]
39.94	Th-229m half-life isolated (extrapolated)	1740(50) s	8	[221]
39.94	thorium-229m, isolated nucleus (extrapolated half-life): half-life	1740 s (half-life)	10	[221]
40.86	Sunlight age at Saturn	79.6 minutes	31	[847]
40.89	Shortest MOA event (free-floating planets)	0.057 days	33	[872]
41.00	Depth 41 as time (closure depth 41)	92.4 minutes	31	[29]
41.24–41.61	Pre-impact day (Ćuk & Stewart 2012) (Earth)	2–3 h	12	[293]
41.24	Stability limit of rotation (Earth)	about 2 h	12	[293]
41.50	Sunlight age at Uranus	159.4 minutes	31	[847]
41.61	Neutrino lead over light (SN 1987A)	2–3 h	4	[123]
41.93	Bennu rotation	4.276 hours	32	[905]
42.03	Rotation period min (Kepler stars)	0.2 d	28	[804]
42.13	Vesta rotation	5.342 hours	32	[905]
42.46	Phobos period (Mars)	7.654 hours	31	[847]
42.48	Pallas rotation	7.813 hours	32	[905]

42.50	Main phase (geomagnetic storms)	2–8 h	16	[443]
42.53	ʻOumuamua period (1I/ʻOumuamua)	8.26 hours	32	[928]
42.61	Ceres rotation	9.074 hours	32	[905]
42.70	Jupiter sidereal rotation	9.925 hours	31	[847]
42.75	Saturn rotation ring seismology	10.5606 hours	31	[894]
42.76	Saturn sidereal rotation	10.656 hours	31	[847]
42.87	Solar tide period	12 h	14	[374]
42.87	Short events (free-floating planets)	0.5 days	33	[873]
42.88	Itokawa rotation	12.13 hours	32	[905]
42.90	M2 tidal period (tides)	44,712 s	12	[310]
42.90	M2 tide period	44712 s	14	[374]
43.13	Arrokoth rotation	15.938 hours	32	[926]
43.14	Neptune sidereal rotation	16.11 hours	31	[847]
43.16	Voyager 2 signal light time (heliosphere)	16.5 h	29	[823]
43.20	Uranus sidereal rotation	17.24 hours	31	[847]
43.21	Carrington CME transit (Sun)	17.5 h	29	[836]
43.22	Carrington CME transit (geomagnetic storms)	17.6 h	16	[444]
43.27	1.4 Ga day (Earth)	18.68 ± 0.25 h	12	[324]
43.27	Day length 1.4 Ga (1.4 Ga rhythmites)	18.68 ± 0.25 h	19	[324]
43.29	Mid-Proterozoic day stall (Earth)	about 19 h for about 1 Gyr	12	[325]
43.42	Devonian day (computed) (Earth)	21.9 h	12	[321; 322]
43.42	620 Ma day (Earth)	21.9 ± 0.4 h	12	[290; 315]
43.44	Carboniferous day (computed) (Earth)	22.5 h	12	[321]
43.45	Mimas period	0.942422 days	31	[877]
43.48	Late Cretaceous day (Earth)	about 23.5 (23.6 computed) h	12	[290]
43.50	Sidereal rotation (Earth)	23.9345 h	11	[277]
43.50	Day on the ladder (half step) (Earth)	86,400 s	12	[29]
43.50	Slot-region electron lifetime (radiation belts)	1–2 d	16	[442]
43.50	Mean solar day (Earth rotation)	86400 s	16	[458]
43.50	Sidereal day (Earth rotation)	86164.09053083288 s	16	[458]
43.50	Day (ladder)	86,400 s	24	[681]
43.50	CME travel time to Earth (Sun)	1–5 d	29	[835]
43.50	Earth sidereal rotation	23.9345 hours	31	[847]
43.52	Mars sidereal rotation	24.6229 hours	31	[847]
43.71	Deimos period (Mars)	30.3 hours	31	[847]

43.79	Enceladus period	1.370218 days	31	[877]
43.88	TRAPPIST-1 b period	1.510826 d	30	[867]
43.92	Cordón Caulle delay (Valdivia)	38 hours	18	[520]
44.02	Io period	1.762732 days	31	[877]
44.08	Tethys period	1.887802 days	31	[877]
44.09	TOI-178 planet period	1.91 d	30	[871]
44.09	TOI-178 planet b period	1.91 days	33	[871]
44.27	Barnard d period (found 2025)	2.3402 days	33	[867]
44.30	TRAPPIST-1 c period	2.421937 d	30	[867]
44.42	Dione period	2.736916 days	31	[877]
44.55	Barnard b period (found 2024)	3.1542 days	33	[867]
44.57	TOI-178 planet period	3.24 d	30	[871]
44.57	TOI-178 planet c period	3.24 days	33	[871]
44.65	Europa period	3.525463 days	31	[877]
44.77	TRAPPIST-1 d period	4.049219 d	30	[867]
44.79	Barnard c period (found 2025)	4.1244 days	33	[867]
44.81	51 Peg b period (51 Pegasi)	4.2307966 days	33	[941]
44.85	GJ 887 e period (found 2026)	4.4249 days	33	[867]
44.87	GRS rotation (Jupiter)	4.5 days	31	[898]
44.96	Tambora onset to climax	5 days	18	[505]
44.96	Fast cool dwarf rotation (cool dwarfs)	<5 d	28	[807]
44.99	Proxima Cen d period (found 2025)	5.12338 days	33	[867]
45.04	Toutatis rotation	130 hours	32	[905]
45.15	TRAPPIST-1 e period	6.101013 d	30	[867]
45.19	Pluto sidereal rotation	153.2928 hours	31	[847]
45.19	Pluto rotation = Charon period (Pluto, Charon)	153.2928 hours	31	[847]
45.19	Charon period (1 Charon periods)	6.3872 days	31	[847]
45.21	TOI-178 planet period	6.56 d	30	[871]
45.21	TOI-178 planet d period	6.56 days	33	[871]
45.24	Barnard e period (found 2025)	6.7392 days	33	[867]
45.27	Spring–neap interval (tides)	about 7 days	12	[310]
45.27	Spring–neap interval (tide)	7 d	14	[374]
45.27	Kepler-90 planet 1 period	7.008151 d	30	[867]
45.29	Ganymede period	7.155588 days	31	[877]
45.32	Kepler-223 b period	7.38449 d	30	[867]
45.39	Water residence time in air	8 d	15	[382]

45.39	Residence atmosphere	8 days	20	[606]
45.47	Kepler-90 planet 2 period	8.719375 d	30	[867]
45.50	July 2012 CME miss (geomagnetic storms)	9 d	16	[444]
45.52	TRAPPIST-1 f period	9.20754 d	30	[867]
45.53	GJ 887 b period (found 2020)	9.2619 days	33	[867]
45.55	Residence atmosphere (computed)	9.5 days	20	[590]
45.58	Kepler-223 c period	9.84564 d	30	[867]
45.58	Ross 128 b period (found 2017)	9.8658 days	33	[867]
45.59	TOI-178 planet period	9.96 d	30	[871]
45.59	TOI-178 planet e period	9.96 days	33	[871]
45.60	LOD 10-day fluctuations (Earth rotation)	0.1 ms	16	[319]
45.70	Proxima b period (2016) (Proxima Centauri)	11.2 days	33	[948]
45.70	Proxima b period (Proxima Centauri)	11.18465 days	33	[949]
45.79	TRAPPIST-1 g period	12.352446 d	30	[867]
45.90	Cascadia episode tremor (slow slip)	2 weeks	18	[527]
45.90	Cascadia episode at a GPS station (slow slip)	2–4 weeks	18	[528]
45.93	Kepler-90 planet 3 period	14.44912 d	30	[867]
45.95	Kepler-223 d period	14.78869 d	30	[867]
45.98	TOI-178 planet period	15.23 d	30	[871]
45.98	TOI-178 planet f period	15.23 days	33	[871]
46.02	Titan period	15.945448 days	31	[877]
46.06	Callisto period	16.69044 days	31	[877]
46.10	Mathilde rotation	417.7 hours	32	[905]
46.17	TRAPPIST-1 h period	18.772866 d	30	[867]
46.21	Kepler-223 e period	19.72567 d	30	[867]
46.23	Residence rivers	12–20 days	20	[606]
46.23	Styx period (3.16 Charon periods)	20.16 days	31	[847]
46.26	TOI-178 planet period	20.71 d	30	[871]
46.26	TOI-178 planet g period	20.71 days	33	[871]
46.28	Hyperion period	21.276658 days	31	[877]
46.30	GJ 887 c period (found 2020)	21.784 days	33	[867]
46.41	Equatorial sidereal (alt.) (Sun)	24.47 d	29	[814]
46.42	Nix period (3.89 Charon periods)	24.85 days	31	[847]
46.44	Sidereal rotation at 16 deg (Sun)	25.38 d	29	[733]
46.44	Draugr period (PSR	25.262 days	33	[940]

	B1257+12)			
46.45	Doppler equatorial rotation (computed) (Sun)	25.63 d	29	[811]
46.47	Hunga onset to climax (Hunga Tonga)	26 days	18	[511]
46.51	Sidereal month (Earth–Moon)	27.3217 days	12	[278]
46.51	Carrington synodic rotation (Sun)	27.2753 d	29	[814]
46.51	Moon synchronous rotation	27.32 days	31	[847]
46.53	Third belt duration 2013 (radiation belts)	4 weeks	16	[442]
46.57	Antiproton lifetime bound LEAR	>0.08 yr	7	[187]
46.57	antiproton, LEAR bound: lower limit (stable)	>2.525e+06 s	10	[243]
46.58	Synodic month (Earth–Moon)	29.53 days	12	[278]
46.66	Kerberos period (5.04 Charon periods)	32.17 days	31	[847]
46.68	K2-18b period	32.940045 days	33	[951]
46.70	Equator/pole rotation (Sun)	25.6/33.5 d	29	[133]
46.73	2MASS J1808−5104 period (2MASS J18082002−5104378)	34.757 ± 0.010 d	28	[803]
46.74	Cascadia 1999 event (slow slip)	35 days	18	[528]
46.77	Doppler polar rotation (computed) (Sun)	36.2 d	29	[811]
46.81	Polar synodic (alt.) (Sun)	almost 38 d	29	[814]
46.82	Hydra period (5.98 Charon periods)	38.2 days	31	[847]
47.00	dysprosium-163, all 66 electrons removed: half-life (nucleus)	4.0608e+06 s (half-life)	10	[263]
47.07	GJ 887 d period (found 2026)	50.77 days	33	[867]
47.11	beryllium-7 inside C_{60}: half-life (nucleus)	4.55155e+06 s (half-life)	10	[263]
47.12	beryllium-7, ordinary: half-life (nucleus)	4.58957e+06 s (half-life)	10	[263]
47.21	Cordón Caulle duration (Valdivia)	59 days	18	[520]
47.21	Mercury sidereal rotation	1407.6 hours	31	[847]
47.22	Kepler-90 planet 4 period	59.73667 d	30	[867]
47.32	Poltergeist period (PSR B1257+12)	66.5419 days	33	[940]
47.37	Rotation period max (Kepler stars)	70 d	28	[804]
47.37	Kepler rotation periods (stars)	0.2–70 (34,030 stars) d	29	[804]
47.52	Proxima rotation (Proxima Centauri)	83 days	33	[948]

47.57	Mercury orbital period (Solar System)	88.0 d	30	[847]
47.61	Kepler-90 planet 5 period	91.93913 d	30	[867]
47.67	Phobetor period (PSR B1257+12)	98.2114 days	33	[940]
47.70	Tambora eruption length	101 days	18	[505]
47.71	Antiproton lifetime bound Gabrielse	>0.28 yr	7	[187]
47.71	antiproton, Gabrielse et al. bound: lower limit (stable)	>8.836e+06 s	10	[243]
47.83	Venus solar day	116.75 days	31	[847]
47.89	Kepler-90 planet 6 period	124.9144 d	30	[867]
48.21	Mercury solar day	4222.6 hours	31	[847]
48.24	Shikoku SSE period (slow slip)	6 months	18	[528]
48.37	Kepler-90 planet 7 period	210.73514 d	30	[867]
48.43	Venus orbital period (Solar System)	224.7 d	30	[847]
48.44	Spotless days 1958–1968 (Sun)	227 d	29	[832]
48.48	O4a duration (computed) (LVK O4a)	237 d	27	[780]
48.50	Venus sidereal rotation	5832.5 hours	31	[847]
48.50	Venus rotation on half-layer	243.0 days	31	[29]
48.56	KATRIN data	36 million electrons, 259 days	4	[122]
48.63	Residence soil moisture	280 days	20	[606]
48.66	thallium-205, fully ionized: half-life (nucleus)	2.51424e+07 s (half-life)	10	[263]
48.71	Euler period (Chandler wobble)	305 d	16	[459]
48.78	Kepler-90 planet 8 period	331.60296 d	30	[867]
48.87	Wellington SSE duration (slow slip)	1 year	18	[527]
48.87	Year (ladder)	3.15576e7 s	24	[681]
48.87	Earth orbital period (Solar System)	365.2 d	30	[847]
48.87	Earth orbital period	365.256 days	31	[847]
48.87	5 kt impact rate (Earth impacts)	1 years	32	[916]
48.94	Cascadia ETS interval range (slow slip)	13–16 months	18	[528]
48.96	Antiproton storage record (TRAP)	405 days	7	[188]
48.96	antiproton, stored in a Penning trap: lower limit (stable)	>3.499e+07 s	10	[243]
49.01	Cascadia ETS period (slow slip)	14 months	18	[527]
49.03	Chandler period (Chandler wobble)	433 d	16	[459]

49.03	Chandler period (polar motion) (Chandler wobble)	435 d	16	[460]
49.04	Cascadia ETS period, Brudzinski & Allen (slow slip)	14.5 months	18	[528]
49.07	Lake residence median (lakes)	456 days	20	[602]
49.22	Super-K atmospheric exposure (Super-Kamiokande)	33.0 kt yr (535 days)	4	[116]
49.22	Borexino 2010 geoneutrinos	9.9 of 15 in 537 days (4.2 sigma)	4	[134]
49.22	Borexino 2010 live time (geoneutrinos)	537 days	11	[134]
49.24	BASE campaign span (antiproton)	1.5 yr	7	[196]
49.35	IceCube live time 2013	615.9 days	4	[140]
49.45	Mars orbital period (Solar System)	687.0 d	30	[847]
49.50	Interval 2017–2019 (interstellar objects)	2 years	32	[927]
49.52	KamLAND 2005 events / geoneutrinos	152 / 4.5–54.2 in 749 days	4	[134]
49.52	KamLAND 2005 live time (geoneutrinos)	749 days	11	[134]
49.60	Spotless days 2001–2014 (Sun)	817 d	29	[832]
49.64	Spotless days 2014–2024 (Sun)	849 d	29	[832]
49.81	Spotless days 1870–1883 (Sun)	1028 d	29	[832]
49.81	Spotless days 1906–1917 (Sun)	1023 d	29	[832]
49.85	Borexino Phase III duration	1072 (71.3 t) days	4	[132]
49.87	Tokai SSE duration (slow slip)	3 years	18	[528]
49.87	Younger Dryas onset time	≤3 years	19	[556]
49.96	2P/Encke period	3.3 years	32	[906]
50.02	Borexino Phase II duration	1291.51 days	4	[131]
50.06	Borexino 2013 geoneutrinos	14.3 ± 4.4 in 1353 days	4	[134]
50.06	Borexino 2013 live time (geoneutrinos)	1353 days	11	[134]
50.13	Atacama rainless periods	up to 4 years	20	[594]
50.22	Mean rise / fall (computed) (Sun)	4.4 / 6.7 yr	29	[832]
50.26	Ceres period	4.6 years	32	[905]
50.34	IGRF secular variation interval (geomagnetic field)	5 yr	16	[424]
50.34	rotation lag (earthquake triggering)	5 years	18	[524]
50.34	Wellington SSE period (slow slip)	5 years	18	[527]
50.34	Lake residence mean (lakes)	1,834 days	20	[602]

50.42	9P/Tempel 1 period	5.51 years	32	[906]
50.44	Borexino 2015 geoneutrinos	24 of 77 in 2056 days	4	[134]
50.44	Borexino 2015 live time (geoneutrinos)	2056 days	11	[134]
50.49	Intradecadal LOD oscillation (Earth core)	5.9 years	12	[317]
50.49	LOD 5.9-yr oscillation (Earth rotation)	5.9 yr	16	[317]
50.50	Increased LOD power near (Earth)	6 years	12	[316]
50.50	Beat of the two lunar months (half step) (Earth–Moon)	2190.35 (1.0015 × 3^7) days	12	[29]
50.50	Lunar beat derived 1/8.85 + 1/18.61 (Earth–Moon)	6.00 years	12	[29]
50.50	LOD 6-yr power (Earth rotation)	6 yr	16	[316]
50.50	Cascadia crustal-motion record (slow slip)	6 years	18	[529]
50.50	Interval 2019–2025 (interstellar objects)	6 years	32	[931]
50.56	81P/Wild 2 period	6.39 years	32	[906]
50.58	67P/Churyumov–Gerasimenko period	6.57 years	32	[906]
50.64	Cycles 7 yr (solar-type stars)	7 yr	28	[807]
50.64	Cycles in solar-type stars	7–18 yr	29	[807]
50.68	eps Eri b period (found 2000)	2680 days	33	[867]
50.86	Borexino 2020 duration	3262.74 days	4	[137]
50.86	Borexino 2020 live time (geoneutrinos)	3262.74 days	11	[137]
50.86	Line of apsides period (Earth–Moon)	8.85 years	12	[29]
50.87	Consecutive OHC records (ocean)	9 years	23	[387]
50.87	Solar cycle 2: min 1766 Jun (SN 18.6), max 1769 Sep (SN 193), rise 3.2 yr (Sun)	9.00 yr length	29	[832]
50.90	Solar cycle 3: min 1775 Jun (SN 12.0), max 1778 May (SN 264), rise 2.9 yr (Sun)	9.25 yr length	29	[832]
50.92	New Horizons launch to Pluto (spacecraft)	9.48 years	31	[904]
50.94	Valdivia in 2025-years (seismic moment)	9.7 years	18	[516]
50.94	Solar cycle 8: min 1833 Nov (SN 12.2), max 1837 Mar (SN 245), rise 3.3 yr (Sun)	9.67 yr length	29	[832]
50.96	Solar cycle 22: min 1986 Sep (SN 13.5), max 1989 Nov (SN 213), rise 3.2 yr (Sun)	9.92 yr length	29	[832]
50.97	Galactic plane neutrinos (Milky	4.5 sigma (10 yr)	4	[146]

	Way)			
50.97	Core–mantle coupling time (Earth rotation)	10 yr	16	[319]
50.97	s capture interval 10 yr (s-process)	10 yr	28	[791]
50.97	Solar cycle 15: min 1913 Jul (SN 2.5), max 1917 Aug (SN 176), rise 4.1 yr (Sun)	10.08 yr length	29	[832]
50.97	Solar cycle 16: min 1923 Aug (SN 9.3), max 1928 Apr (SN 130), rise 4.7 yr (Sun)	10.08 yr length	29	[832]
50.98	Antiproton lifetime bound BASE	>10.2 yr	7	[187]
50.98	antiproton, BASE trap bound: lower limit (stable)	>3.219e+08 s	10	[243]
50.98	Solar cycle 18: min 1944 Feb (SN 12.9), max 1947 May (SN 219), rise 3.2 yr (Sun)	10.17 yr length	29	[832]
51.00	Solar cycle 17: min 1933 Sep (SN 5.8), max 1937 Apr (SN 199), rise 3.6 yr (Sun)	10.42 yr length	29	[832]
51.01	Solar cycle 7: min 1823 May (SN 0.1), max 1829 Nov (SN 119), rise 6.5 yr (Sun)	10.50 yr length	29	[832]
51.01	Solar cycle 19: min 1954 Apr (SN 5.1), max 1958 Mar (SN 285), rise 3.9 yr (Sun)	10.50 yr length	29	[832]
51.05	Schwabe cycle (Sun)	11 (9–14) yr	29	[446]
51.05	Solar cycle 24: min 2008 Dec (SN 2.2), max 2014 Apr (SN 116), rise 5.3 yr (Sun)	11.00 yr length	29	[832]
51.06	Mean cycle length, cycles 1–24 (computed) (Sun)	11.03 ± 1.16 yr	29	[832]
51.07	Solar cycle 10: min 1855 Dec (SN 6.0), max 1860 Feb (SN 186), rise 4.2 yr (Sun)	11.25 yr length	29	[832]
51.08	Solar cycle 1: min 1755 Feb (SN 14.0), max 1761 Jun (SN 144), rise 6.3 yr (Sun)	11.33 yr length	29	[832]
51.09	Schwabe cycle (Sun)	9–14 yr	16	[446]
51.09	Sunspot cycle (fact sheet)	11.4 yr	29	[733]
51.09	Solar cycle 14: min 1902 Jan (SN 4.5), max 1906 Feb (SN 107), rise 4.1 yr (Sun)	11.50 yr length	29	[832]
51.09	Solar cycle 20: min 1964 Oct (SN 14.3), max 1968 Nov (SN 157), rise 4.1 yr (Sun)	11.42 yr length	29	[832]
51.10	Gaia BH3 period	11.6 yr	27	[775]
51.11	Solar cycle 11: min 1867 Mar (SN 9.9), max 1870 Aug (SN 234), rise 3.4 yr (Sun)	11.75 yr length	29	[832]

51.12	Solar cycle 13: min 1890 Mar (SN 8.3), max 1894 Jan (SN 147), rise 3.8 yr (Sun)	11.83 yr length	29	[832]
51.12	Jupiter orbital period (Solar System)	4331 d	30	[847]
51.12	Jupiter orbital period	4332.589 days	31	[847]
51.13	7 to 8 billion (humanity)	12 years	23	[657]
51.13	Voyager 2 launch to Neptune (spacecraft)	12.0 years	31	[903]
51.15	Solar cycle 5: min 1798 Apr (SN 5.3), max 1805 Feb (SN 82), rise 6.8 yr (Sun)	12.25 yr length	29	[832]
51.16	tritium: half-life (nucleus)	3.8879e+08 s (half-life)	10	[255]
51.16	Solar cycle 9: min 1843 Jul (SN 17.6), max 1848 Feb (SN 220), rise 4.6 yr (Sun)	12.42 yr length	29	[832]
51.16	Solar cycle 23: min 1996 Aug (SN 11.2), max 2001 Nov (SN 180), rise 5.2 yr (Sun)	12.33 yr length	29	[832]
51.17	Recurrence of May-2024-size storms (Sun)	12.5 yr	29	[833]
51.19	Solar cycle 6: min 1810 Jul (SN 0.0), max 1816 May (SN 81), rise 5.8 yr (Sun)	12.83 yr length	29	[832]
51.21	Ozone hole growth to 20 million km2	13 yr	15	[412]
51.24	Solar cycle 4: min 1784 Sep (SN 15.9), max 1788 Feb (SN 235), rise 3.4 yr (Sun)	13.58 yr length	29	[832]
51.33 to 51.38	Soil carbon to 1 m / respiration	14.9-15.8 years	22	[640]
51.34	8 to 9 billion (projected, 2037) (humanity)	about 15 years	23	[657]
51.38	Atmosphere / land NPP turnover	15.8 years	22	[636]
51.39	S2 orbit	16 yr	27	[784]
51.39	S2 orbital period (Galactic Centre)	16 yr	29	[784]
51.50	Saros (half step) (Earth–Moon)	6585.32 (1.0037×3^8) days	12	[29]
51.50	Cycles 18 yr (solar-type stars)	18 yr	28	[807]
51.53	Line of nodes period (Earth–Moon)	18.61 years	12	[29]
51.59	Jupiter–Saturn conjunction (Jupiter, Saturn)	19.87 years	31	[701]
51.60	8.2 ka cooling in Greenland (8.2 ka event)	3.3 °C in <20 years	19	[568]
51.60	Human-made mass doubling time (technosphere)	~20 years	23	[664]
51.60	Grand minimum centred 5710 BC (Sun)	20 yr duration	29	[829]

51.68	Hale cycle (Sun)	22 yr	16	[446]
51.72	Previous record held (B1937+21)	23 yr	27	[769]
51.84	Proposal to detection interval (neutrino)	26 yr	4	[109]
51.87	S2 followed	27 yr	27	[784]
51.89	Rotation slows every (Earth rotation)	25–30 yr	16	[458]
51.95	Saturn orbital period (Solar System)	10747 d	30	[847]
51.97	D-O warming, common (Dansgaard–Oeschger events)	5 °C in 30–40 years	19	[573]
51.97	Grand minimum centred 7305 BC (Sun)	30 yr duration	29	[829]
52.05	rhenium-187, fully ionized: half-life (nucleus)	1.03825e+09 s (half-life)	10	[263]
52.05	55P/Tempel–Tuttle period	32.92 years	32	[906]
52.08	Years since first exoplanet (census)	34 years	33	[867]
52.11	Halley next perihelion (1P/Halley)	35 years from now	32	[923]
52.16	23 ZJ in years of primary energy (ocean)	37 yr	14	[387]
52.21	Nobel Prize Reines (neutrino)	1995 year	4	[109]
52.23	D-O warming, extreme (Dansgaard–Oeschger events)	~8 °C in 40 years	19	[573]
52.23	Grand minimum centred 5620 BC (Sun)	40 yr duration	29	[829]
52.25	Recurrence of a storm of that length (Sun)	41 yr	29	[833]
52.29	Copper reserves / production	43 years	21	[624]
52.37	CC SN interval low (Milky Way)	47 yr	27	[758]
52.39	Cassini Permanent Spot 1665–1713 (Jupiter)	48 years	31	[888]
52.43	Younger Dryas termination warming	50–60 years	19	[556]
52.43	Search for natural bridgmanite	half a century years	21	[619]
52.43	Reservoir building period (reservoirs)	past 50 years	23	[611]
52.43	Sirius orbital period (Sirius AB)	50.13 yr	27	[756]
52.43	Grand minimum centred 7035 BC (Sun)	50 yr duration	29	[829]
52.44	Chiron period	50.7 years	31	[905]
52.44	95P/Chiron period	50.7 years	32	[906]
52.57	Inclination period (geomagnetic field)	58 ± 5 yr	16	[318]
52.60	60-year signal in rotation (Earth core)	about 60 years	12	[318]

52.60	Angular velocity 60-yr (Earth rotation)	60 yr	16	[318]
52.60	Mount Wilson start (Mount Wilson HK)	1966 year	28	[806]
52.60	Grand minimum centred 5460 BC (Sun)	60 yr duration	29	[829]
52.61	CC SN mean interval (Milky Way)	61 (+24/−14) yr	27	[758]
52.61	Milky Way core-collapse SN interval	61 (+24/−14) yr	28	[758]
52.61	Core-collapse supernova interval (Milky Way)	61 (+24/-14) yr	34	[758]
52.63	Declination period (geomagnetic field)	62 ± 3 yr	16	[318]
52.68	OHC 2025 highest in 66-year record (ocean)	66 yr	14	[385]
52.68	OHC 2025 highest of record (ocean)	66 years	23	[385]
52.71	Chandler damping (Chandler wobble)	68 yr	16	[459]
52.74	Inner-core oscillation (inner core)	70 yr	16	[456]
52.74	Grand minimum centred 3335 BC (Sun)	70 yr duration	29	[829]
52.81	1P/Halley period	76.1 years	32	[906]
52.86	Long brightness cycles (cool dwarfs)	80 yr	28	[807]
52.86	Grand minimum centred 6400 BC (Sun)	80 yr duration	29	[829]
52.86	Long brightness cycles of fast cool dwarfs (stars)	up to 80 yr	29	[807]
52.90	Uranus orbital period (Solar System)	30589 d	30	[847]
52.91	CC SN interval high (Milky Way)	85 yr	27	[758]
52.97	Grand minimum centred 765 BC (Sun)	90 yr duration	29	[829]
52.97	Gleissberg cycle (Sun)	90 (60–120) yr	29	[446]
53.00	Closure depth 53 occupant: long solar cycle (ladder)	80–100 yr	29	[29]
53.00	Depth 53 in time between Uranus and Neptune years (closure depth 53)	93.4 years	31	[847]
53.00	Depth 53 time (closure depth 53)	93.40 yr	34	[29]
53.01	Years since positron discovery	94 yr	7	[184]
53.06–55.16	Mixing after impact (Pahlevan & Stevenson 2007) (Earth–Moon)	100–1000 years	12	[269]
53.06	4.2 ka event	~100 (22nd century BC) years	19	[569]
53.06	Residence fresh lakes	1–100 years	20	[606]
53.06	s capture interval 100 yr (s-process)	100 yr	28	[791]

53.15	Grand minimum centred 8215 BC (Sun)	110 yr duration	29	[829]
53.37	Grand minimum centred 5260 BC (Sun)	140 yr duration	29	[829]
53.43	8.2 ka event duration	~150 (core 60) years	19	[568]
53.43	Grand minimum centred 9165 BC (Sun)	150 yr duration	29	[829]
53.49	Grand minimum centred AD 1470 (Spörer) (Sun)	160 yr duration	29	[829]
53.51	survey span (Everest)	164 years	18	[492]
53.51	Neptune orbital period (Solar System)	59800 d	30	[847]
53.64	Hamersley iron in years of 2024 mining (Hamersley, Western Australia)	188 years	22	[625]
53.67	GRS observed since 1831 (Jupiter)	195 years	31	[898]
53.69	Holocene oscillation period (sea level)	>=200 yr	14	[366]
53.73	de Vries/Suess cycle (Sun)	205–210 yr	29	[446]
53.89	Pluto orbital period (Solar System)	90560 d	30	[847]
53.90	Laschamp transition (geomagnetic field)	250 yr	16	[436]
53.90	H4 duration (Heinrich event 4)	250 ± 150 years	19	[579]
54.03	MWP-1A other reconstruction (sea level)	13.5 m over 290 yr	14	[365]
54.03	MWP-1A (other reconstruction) (meltwater pulse 1A)	13.5 m over ~290 years	19	[365]
54.04	Arrokoth period	294 years	32	[926]
54.06	Residence groundwater	300 years	20	[606]
54.06 to 62.73	Hawaiian chronosequence span (Hawaii soils)	300 yr to 4.1 Myr years	22	[644]
54.18	MWP-1A window (meltwater pulse 1A)	≤340 years	19	[367]
54.29	Time per cm of soil at median	385 years	21	[627]
54.32	Direct observation span (geomagnetic field)	400 yr	16	[424]
54.32	MWP-1A (summary) (meltwater pulse 1A)	16–25 m over 400–500 years	19	[564]
54.37	Last Galactic SN seen (Kepler 1604)	1604 year	27	[760]
54.41	Laschamp reversed state (geomagnetic field)	440 yr	16	[436]
54.53	Outer-core diffusion time (outer core)	<=500 yr	16	[431]
54.53	Heinrich layer deposition (Heinrich events)	500 ± 250 years	19	[578]
54.60	Glacier lifetime at	~540 years	19	[587]

	present loss (glaciers)			
54.95	South Asian drought cycles (Indus)	200–800 years	19	[571]
55.16	Deep water age (AMOC)	1000 yr	14	[371]
55.16	North Pacific transit time (thermohaline circulation)	1000 yr	14	[373]
55.16	Radiocarbon age contrast (ocean)	1000 yr	14	[372]
55.16	Melting time (model) (Snowball exit)	~1,000 years	19	[480]
55.16	Aberrations (Cenozoic climate)	~10^3 years	19	[542]
55.16	Bond period (revised) (North Atlantic ice rafting)	~1,000 years	19	[577]
55.16	Residence salt lakes	10–1,000 years	20	[606]
55.16 to 55.79	Subsurface turnover (deep biosphere)	1,000-2,000 years	22	[652]
55.16	Age of MWC 349	1000 yr	27	[736]
55.16	s-process duration	thousands yr	28	[791]
55.16	Youngest star MWC 349 age	1000 yr	29	[736]
55.16	Tunguska-class rate (Earth impacts)	1000 years	32	[916]
55.24	Eddy-type variations (Sun)	600–700 or 1000–1200 yr	29	[446]
55.32	Younger Dryas duration	1,150–1,300 years	19	[556]
55.41	Bond gaps (North Atlantic ice rafting)	800–2,300 (mean 1,325) years	19	[577]
55.51	D-O spacing GISP2 (Dansgaard–Oeschger events)	~1,470 (±12 %, 23 cycles) years	19	[574]
55.51	Bond cycle (North Atlantic ice rafting)	1470 ± 500 years	19	[576]
55.53	LOD oscillation of roughly (Earth)	1500 years	12	[316]
55.53	LOD 1500-yr oscillation (Earth rotation)	1500 yr	16	[316]
55.59	Time to zero dipole	1600 yr	16	[428]
55.62	Time to remove 1 m on cropland	1,670 years	21	[626]
55.74	Sun leaves LIC	<=1900 yr	29	[824]
55.74	Sun exits LIC	<= 1900 yr ahead	34	[824]
55.79	Full reversal duration (Glatzmaier & Coe) (geomagnetic field)	2000–12000 yr	16	[431]
55.79	IBE and LE duration (geomagnetic field)	<2000 yr	16	[438]
55.79	Fast sea-level fall at ~30 ka (LGM sea level)	~40 m in <2,000 years	19	[366]
55.88	Hallstatt cycle (Sun)	2000–2400 yr	29	[446]
55.90	Halley first record (1P/Halley)	2265 years	32	[923]
55.99	Whole-ocean turnover at 17 Sv	2480 yr	14	[369]
55.99	Ocean volume constant (Holocene	2.5 ka to 100–150 years ago	19	[366]

	sea level)			
56.06	Eclipse record span (Earth rotation)	2700 yr	16	[316]
56.16	MIS 16 below 180 ppmv (ice-core air)	3000 yr	15	[405]
56.16	Inner-core diffusion time (inner core)	3000 yr	16	[431]
56.16	CO2 below 180 ppmv in MIS 16 (ice-core CO2)	~3,000 years	19	[405]
56.16	Green period build-up (Sahara)	2–3 kyr	20	[599]
56.16	Green period end (Sahara)	2–3 kyr	20	[599]
56.19	Ocean residence time of water	3100 yr	14	[382]
56.19	Residence ocean	3,100 years	20	[606]
56.22	Residence ocean (computed)	~3,200 years	20	[590]
56.27	Obliquity lag before 3 Ma (LR04)	~3,400 years	19	[552]
56.29	Greenlandian (Holocene stages)	3,464 years	19	[565]
56.31	Drift time at Jupiter (computed, 300 orbits) (disk solids)	3600 yr	30	[847]
56.42	Northgrippian (Holocene stages)	3,986 years	19	[565]
56.42	Hale–Bopp period	4000 years	32	[906]
56.48	Meghalayan (Holocene stages)	4,250 years	19	[565]
56.62	K–Pg carbon-cycle disruption (carbon cycle)	5 (less than) kyr	18	[489]
56.79	~6 kyr activity trend (Sun)	6000 yr	29	[828]
56.90	Obliquity lag in Pleistocene (LR04)	~6,800 years	19	[552]
56.93	Mean duration last four reversals (geomagnetic field)	7000 yr	16	[431]
56.93	Present strength average for (dipole)	7000 yr	16	[428]
56.93	Heinrich spacing (Heinrich events)	~7,000 years	19	[579]
57.04	Th-229 ground-state alpha half-life	7916 yr	8	[221]
57.04	thorium-229 ground state: half-life (nucleus)	2.4981e+11 s (half-life)	10	[221]
57.05	Slow fall to −134 m (LGM sea level)	29–21 ka (8,000 years)	19	[366]
57.05	Green period peak (Sahara)	4–8 kyr	20	[599]
57.08	Main deglaciation	16.5–8.2 ka (8,300 years)	19	[366]
57.16	African Humid Period duration (Sahara)	~9,000 years	20	[600]
57.25	Photon escape from Sun	1e4–1.7e5 yr	4	[133]
57.25	PETM carbon release duration (ocean carbon)	10 kyr	14	[376]

57.25	Rhythms (orbital) (Cenozoic climate)	$10^{4–10}$6 years	19	[542]
57.25	Greenland turnover at present loss (Greenland ice sheet)	1.0 × 10^4 years	19	[585]
57.25	Age of VLA 1623	<10000 yr	27	[736]
57.25	Magnetar active life (magnetars)	1e4 yr	27	[772]
57.25	Youngest star VLA 1623 age	<10000 yr	29	[736]
57.25	Photon escape time (Sun)	10000–170000 yr	29	[133]
57.34	B–M precursor lead (geomagnetic field)	11 kyr	16	[435]
57.37	Marcott record span (Holocene temperature)	11,300 (73 records) years	19	[566]
57.37	Vela pulsar age (PSR J0835−4510)	0.0113 Myr	27	[771]
57.42	Holocene span in GVP count (volcanoes)	12000 years	18	[502]
57.56	One green period (Sahara)	8–14 kyr	20	[599]
57.68	Residence glaciers	16,000 years	20	[606]
57.69	Time to remove 1 m at present natural rate (continents)	16,100 years	21	[626]
57.88	PETM onset duration	<20 kyr	19	[543]
57.93	Climatic precession now (Earth orbit)	21,000 years	19	[550]
57.97	B–M process duration (geomagnetic field)	22 kyr	16	[435]
58.01	Climatic precession mean (Earth orbit)	23,000 years	19	[550]
58.01	Spectral peak, precession (Southern Ocean cores)	~23,000 (10 % variance) years	19	[551]
58.01	Monsoon pacing (East Asian monsoon)	23,000 years	20	[598]
58.12	pH unprecedented for (ocean pH)	26000 yr	14	[375]
58.12	Present pH unprecedented for (ocean)	at least 26,000 years	23	[375]
58.19	Interglacial after Termination V (ice-core air)	28000 yr	15	[407]
58.22	Climatic precession range (Earth orbit)	20,800–29,000 years	19	[550]
58.25	Deccan duration, short (Deccan Traps)	30 (less than) kyr	18	[487]
58.25	Productive ecosystem in crater (Chicxulub)	30000.0 years	32	[920]
58.34	Chicxulub impact to extinction	33 (within) kyr	18	[489]
58.39	Lambeck record span (sea level)	35000 yr	14	[366]
58.39	Mean spacing of green periods (Sahara)	≤34,800 years	20	[599]
58.52	Simulated field duration (geodynamo model)	>40000 yr	16	[451]

58.52	CCD jumps (equatorial Pacific)	2 × ~40 kyr	19	[547]
58.52	Hyakutake period	40000 years	32	[906]
58.54	Obliquity cycle (Earth orbit)	41,000 (22.1–24.5°) years	19	[550]
58.56	Spectral peak, obliquity (Southern Ocean cores)	~42,000 (25 % variance) years	19	[551]
58.72	Antiproton lifetime bound APEX mu X	>50000 yr	7	[187]
58.72	antiproton, APEX bound ($\bar{p} \to \mu^- X$): lower limit (stable)	>1.578e+12 s	10	[243]
58.72	Two reversals within (geomagnetic field)	50000 yr	16	[431]
58.74	Age at matter–radiation equality (universe)	51.0 ± 0.8 kyr	25	[25]
58.88	end-Permian extinction interval	60 ± 48 kyr	18	[483]
58.92	Time to remove 1 m at Phanerozoic mean (continents)	62,500 years	21	[626]
59.03	PETM acidification duration (ocean pH)	70 kyr (at least)	14	[376]
59.03	Longest reversal (Yamamoto) (geomagnetic field)	70000 yr	16	[431]
59.07	Toba age, Storey 2012	73880 ± 320 years	18	[500]
59.07	Toba age, Mark 2017	73700 ± 300 years	18	[500]
59.15	GW170817 false-alarm	<1 per 8.0e4 yr	27	[782]
59.15	Hoba fall age (upper)	80000.0 years	32	[934]
59.30	Eccentricity component (Earth orbit)	95,000 years	19	[550]
59.35	Spectral peak, 100 kyr (Southern Ocean cores)	~100,000 (50 % variance) years	19	[551]
59.35	GRIP/GISP2 climate span (Greenland cores)	~100,000 years	19	[558]
59.39	Mean spacing of terminations (glacial terminations)	104,600 (93,000–118,300) years	19	[556]
59.48	Duration of decoupling (background light)	roughly 115,000 yr	25	[704]
59.54	NGRIP data span	123,000 years	19	[558]
59.55	Eccentricity component (Earth orbit)	124,000 years	19	[550]
59.72	end-Triassic crisis after CAMP onset (extinction)	150 (less than) kyr	18	[485]
59.72	Organic P maximum (Hawaii soils)	about 150,000 years	22	[644]
59.78	Permian event duration, short (extinction)	160 kyr	18	[484]
59.83	PETM total duration	170 kyr	14	[381]
59.83	PETM duration (air)	170 kyr	15	[381]

59.83	PETM duration, precession chronology	~170 kyr	19	[381]
59.83	Photon escape time upper (Sun)	170000 yr	29	[133]
59.88	Antarctic turnover at present loss (Antarctic ice sheet)	1.8 × 10^5 years	19	[585]
59.98	PETM duration	~200 (170 orbital) kyr	19	[543]
59.99	GW150914 false-alarm	<1 per 203000 yr	27	[776]
60.08	Chinese cave record span (East Asian monsoon)	224,000 years	20	[598]
60.35	Antiproton lifetime bound APEX e gamma	>300000 yr	7	[187]
60.35	antiproton, APEX bound ($\bar{p} \to e^- \gamma$): lower limit (stable)	>9.467e+12 s	10	[243]
60.35	Cluster age span (young clusters)	0.3–30 Myr	30	[857]
60.44	Dome Fuji first hole age	~330,000 years	19	[558]
60.46–62.03	Solar system older than previously thought, by	0.34–1.91 Myr	11	[266]
60.49	Gaskiers glaciation duration	0.35 Myr	19	[480]
60.55	Age at last scattering t* (background light)	371.8 ± 1.0 kyr	25	[25]
60.56	Age at last scattering, Wikipedia CMB (background light)	approximately 379,000 yr	25	[704]
60.61	Green period clusters (Sahara)	100 and 400 kyr	20	[599]
60.62	Eccentricity main (Earth orbit)	405,000 years	19	[550]
60.66	Vostok cycles (ice-core air)	4 in 420 kyr	15	[407]
60.66	Vostok record (Vostok ice core)	420,000 (4 cycles) years	19	[557]
60.72	Hays record span (Southern Ocean cores)	450,000 years	19	[551]
60.73	Mean reversal interval (geomagnetic field)	454 kyr	16	[431]
60.81	carbon-cycle volatility after P–Tr (carbon cycle)	500 kyr	18	[483]
60.81	EOT earlier estimate (Eocene–Oligocene transition)	500 kyr	19	[546]
60.81	Naica crystals maximum U-Th age (Naica gypsum)	about 500,000 years	21	[622]
60.87	Datura cluster age (main belt)	530000 years	32	[910]
60.90	MPT length (Pleistocene ice)	~550,000 years	19	[554]
60.90	Proxima orbital period (Proxima Centauri)	547000 yr	34	[993]

60.98	CAMP pulse span	600 kyr	18	[486]
60.98	Deccan duration, long (Deccan Traps)	600–800 kyr	18	[487]
61.08	Yellowstone interval 2	0.67 Myr	18	[499]
61.15	Dome Fuji second hole age	720,000 years	19	[558]
61.17	EPICA 2004 record (EPICA Dome C)	~740,000 years	19	[555]
61.22	Yellowstone interval 1	0.78 Myr	18	[499]
61.23	EOT duration (Eocene–Oligocene transition)	~790 kyr	19	[546]
61.24	Vesta mean accretion time	0.8 ± 0.8 Myr	11	[268]
61.24	Azolla duration (air)	800 kyr	15	[404]
61.24	Azolla interval duration (Eocene Arctic Ocean)	~800 kyr	19	[544]
61.24	EPICA usable data (EPICA Dome C)	800,000 years	19	[558]
61.24	Span of the record, highest levels (atmosphere)	800,000 years	23	[384]
61.24	Vesta mean accretion time	0.8 ± 0.8 (two-stage 2.6) Myr after CAI	30	[268]
61.35	Difference of the two CAI ages (solar system)	0.9 Myr	11	[265; 266]
61.35	Difference of CAI ages (computed) (Solar System)	0.9 Myr	30	[266]
61.45	one million years (time)	1 Myr	17	[467]
61.45	LIP pulse duration, short (large igneous provinces)	1 Myr	18	[481]
61.45	Siberian Traps duration, ref	1 Myr	18	[482]
61.45	Greenland oldest ice in summit core	~1,000,000 years	19	[549]
61.45	Age of the largest crystals (secondary) (Naica gypsum)	about 1 million years	21	[622]
61.45	NC/CC reservoirs separated (Solar nebula)	~1 to 3–4 Myr after CAI	30	[856]
61.45	Jupiter core ~20 Earth masses	<1 Myr after CAI	30	[856]
61.45	Disk time, stars >1.3 M_sun (young stars)	~1 Myr	30	[858]
61.45	Jupiter core 20 M⊕ within 1 Myr	1000000.0 years	31	[856]
61.46	R136a1 age	1.02 ± 0.16 Myr	27	[749]
61.56	Time to grow 0.5 m on one face (Naica gypsum)	1.13e6 years	21	[623]
61.68	Gliese 710 time to approach	1290000.0 years	32	[939]
61.68	Gliese 710 time	1.29-1.30 Myr ahead	34	[843]
61.75	Camp Century melted at least once (Greenland)	1.4 Myr	19	[549]

61.78	Yellowstone three discharges span	1.45 Myr	18	[499]
61.81	R136 / NGC 3603 ages	1.5 Myr	27	[748]
61.85	Sun crosses 28.64 pc at 18 km/s	1.56 Myr	34	[840]
61.93	Antiproton lifetime bound cosmic rays	>~1.7e6 yr	7	[187]
61.93	antiproton, cosmic-ray bound: lower limit (stable)	>5.365e+13 s	10	[243]
61.93	Disk half-life (young stars)	1.7 Myr	30	[858]
62.08	Mars shergottite source mean time	2 (+3/−2) Myr	11	[268]
62.08	Mars half its present size within	≤2 Myr	11	[273]
62.08	CO2 highest in at least (air)	2 Myr	15	[383]
62.08	Siberian Traps duration, intro	2 Myr	18	[482]
62.08	CO2 2019 highest in (atmosphere)	at least 2 million years	23	[383]
62.08	Population III lifetime, model (first stars)	2–5 Myr	26	[720]
62.08	Mars half-grown	<=2 Myr	30	[273]
62.08	Olympus youngest flows (young end) (Mars)	2000000.0 years	31	[899]
62.28	Disk e-folding time (young stars)	~2.5 Myr	30	[858]
62.31	Span CAI to youngest dated chondrule (solar system)	2.59 Myr	11	[265]
62.31	First CAI to youngest chondrule (computed) (Solar System)	2.59 Myr	30	[265]
62.31	CAI to youngest chondrule (first solids)	2590000.0 years	32	[265]
62.32	Vesta two-stage core time	2.6 Myr	11	[268]
62.35	Soil under Greenland ice covered	~2.7 Myr	19	[549]
62.35	Allan Hills blue ice age	2.7 Myr	19	[558]
62.38	Permian event duration, long (extinction)	2.8 Myr	18	[484]
62.45	Duration of CAI formation (solar system)	about 3 Myr	11	[265]
62.45	Basaltic lava on Vesta within	3 Myr	11	[275]
62.45	Duration from iridium anomaly (Cryogenian)	≥3 Myr	19	[480]
62.45	Lifetime most massive stars	few (3) Myr	27	[745]
62.45	Duration of chondrule formation (Solar System)	3 Myr	29	[265]
62.45	CAI/chondrule	3 Myr	30	[265]

	process duration (Solar System)			
62.45	Half of disks lost (young clusters)	<~3 Myr	30	[857]
62.45	Disk time, brown dwarfs <0.08 M_sun (young stars)	~3 Myr	30	[858]
62.45	Chondrule formation duration from CAI time (first solids)	3000000.0 years	32	[265]
62.53	Mars shergottite source two-stage time	3.3 Myr	11	[268]
62.71	Mars nakhlite–chassignite source mean time	4 ± 1 Myr	11	[268]
62.71	Jupiter core ~50 Earth masses	>=3–4 Myr after CAI	30	[856]
62.73	Marinoan duration	≥4 (4.08) Myr	19	[533]
62.75	Early Eocene Climatic Optimum (EECO)	53.3–49.1 Ma (4.2 Myr)	19	[543]
62.75	Tc longest half-life bound (technetium)	4.2 Myr	28	[791]
62.77	C/1999 F1 period (Oort cloud)	4300000.0 years	32	[924]
62.81	Atacama humid interval (Atacama, Tiliviche palaeolake)	10.86–6.4 Ma (4.46 Myr)	20	[594]
62.91	LIP pulse duration, long (large igneous provinces)	5 Myr	18	[481]
62.91	MoM-z14 star-formation rise	~10× in last 5 Myr	26	[717]
62.96	LR04 stack (benthic δ18O)	57 records, 5.3 Myr	19	[552]
62.96	PSR J0901−4046 age	5.3 Myr	27	[770]
63.03	Karin family age (main belt)	5700000.0 years	32	[910]
63.08	Stage 1 duration (solar nebula)	6 Myr	21	[272]
63.08	Overall disk lifetime (young clusters)	~6 Myr	30	[857]
63.37	Veritas family age (main belt)	8300000.0 years	32	[910]
63.45	182Hf half-life (Hf–W clock)	9 Myr	11	[268]
63.45	Moon Hf–W mean time	9.0 ± 0.7 Myr	12	[268]
63.51	Mars nakhlite–chassignite source two-stage time	9.7 Myr	11	[268]
63.54	Earth main accumulation	about 10 Myr	11	[268]
63.54	Main growth of terrestrial planets	about 10 Myr	11	[275]
63.54–64.54	Earth core formation, three groups (press)	10–30 Myr	11	[269]
63.54–65.64	Earth later evolution (press, Chambers 2004)	10–100 Myr	11	[269]
63.54	GOE transition duration (one record) (air)	10 Myr	15	[391]

63.54	Superchron definition (geomagnetic field)	>=10 Myr	16	[431]
63.54	Trends (tectonic) (Cenozoic climate)	$10^{5–10}$7 years	19	[542]
63.54	Cloud lifetime (molecular clouds)	10 Myr	27	[735]
63.54	Radio pulsar fade min (pulsars)	10 Myr	27	[771]
63.54	Cloud dispersal time (molecular clouds)	10 Myr	29	[735]
63.54–65.64	Ring age (Cassini mass) (Saturn rings)	10–100 million years	31	[897]
63.54	TRAPPIST-1 stability	10000000.0 years	33	[947]
63.63	Earth mean time of accretion	11 ± 1 Myr	11	[268]
63.63	Earth mean accretion time	11 ± 1 Myr after CAI	30	[268]
63.63–65.66	Ring lifetime from Cassini inflow (Saturn rings)	11–102 million years	31	[897]
63.67	Earth core time, 9:1 giant-impact model	11.5 Myr	11	[268]
63.81	Earth core time, 7:3 model	13.5 Myr	11	[268]
63.85	Star formation on shell (Local Bubble)	14 Myr	34	[808]
63.87	Local Bubble age	14.4 Myr	28	[808]
63.87	Local Bubble age	14.4 (+0.7/-0.8) Myr	34	[808]
63.91	Earlier estimates of Mars accretion time	0–15 Myr	11	[273]
63.97	Vesta formation, earlier estimate	about 16 Myr	11	[275]
63.97	Stage 2 duration (planetesimals)	16 Myr	21	[272]
64.08	Greenland glaciers and ice caps	≥18 Myr	19	[549]
64.17–64.80	Serenitatis older than Imbrium (bombardment)	20–40 Myr	13	[336]
64.17	Hamersley deposition span (Hamersley, Western Australia)	about 20 Myr	22	[346]
64.20	Cryogenian nonglacial interlude	≤20 (20.7) Myr	19	[533]
64.48	Moon Hf–W two-stage time	28.1 Myr	12	[268]
64.51	slab descent time at 10 cm/yr (slabs)	28.9 Myr	17	[462]
64.53	Earth two-stage core-formation time (Earth core)	29.5 Myr	11	[268]
64.54	End of Earth accretion	about 30 Myr after T_0	11	[268]
64.54	Core formation of Vesta, Mars and Earth within (terrestrial planets)	≤30 Myr	11	[274]
64.54	Metal–silicate separation completed within (solar system)	<30 Myr	11	[275]
64.54–66.27	Range of lunar age estimates (Moon)	30–200 Myr after T_0	12	[298]
64.54	Moon formation (Hf–W 2005)	about 30 Myr after T_0	12	[268]

64.54–65.01	Moon formation, earlier Hf–W	30–50 Myr after T_0	12	[269]
64.54	CNS (BGS) (geomagnetic field)	30 Myr	16	[424]
64.54	CO2 accumulation time (model) (Snowball exit)	4–30 Myr	19	[480]
64.54	Energy transport time (Sun)	3e7 yr	29	[133]
64.54	Cores of Vesta, Mars, Earth formed (rocky bodies)	first ~30 Myr	30	[274]
64.54-65.01	Gould’s Belt age	30-50 Myr	34	[988]
64.63	hotspot drift interval (Hawaii hotspot)	33 Myr	18	[491]
64.70	Popigai age	35700000.0 years	32	[922]
64.73	CNS duration (geomagnetic field)	37 Myr	16	[431]
64.80	First preserved lunar crust pushed back by (Moon)	about 40 Myr	12	[301]
64.97	Sun plane crossing	48 (+6/-5) Myr	34	[983]
64.99	Temagami deposition span (Temagami, Canada)	49 Myr	22	[346]
65.01	Moon formation (Hf–W 2019)	about 50 Myr after T_0	12	[298]
65.01–66.01	Moon-forming impact (Dauphas & Pourmand)	50–150 Myr after T_0	12	[273]
65.01	Kiaman duration (geomagnetic field)	>50 Myr	16	[431]
65.01	LIP maximum lifespan (large igneous provinces)	50 Myr	18	[481]
65.01	Grand Tack terrestrial formation (rocky planets (model))	30–50 Myr	30	[860]
65.09	LMO duration if start 152 Myr (Moon)	about 55 Myr	12	[300]
65.09	Namib aridity	55–80 Myr	20	[593]
65.11	Oldest lunar zircon minus oldest terrestrial (computed) (Earth–Moon)	56 Myr	13	[301; 326]
65.13	Sturtian glaciation duration	57 Myr	19	[532]
65.17	Earlier Hf–W core age (Earth core)	≥60 Myr	11	[274]
65.17	182Hf extant period (Hf–W clock)	60 Myr	12	[298]
65.17–65.64	Moon formation (Touboul 2007)	≥60, up to 100 Myr after T_0	12	[269]
65.17	Pannotia span (table)	60 Myr	17	[475]
65.20	Older terrestrial-planet timescale (terrestrial planets)	62 Myr	11	[275]
65.25	K–Pg age (Schulte) (Chicxulub)	65500000.0 years	32	[919]
65.26	CENOGRID span (Cenozoic)	66 Myr	19	[541]
65.26	Chicxulub age	66051000.0 years	32	[922]

65.26	Chicxulub age	66043000.0 years	32	[917]
65.47	Vertical period (Sun in Galaxy)	83 Myr	29	[133]
65.47	Vertical period model (Sun)	83 Myr	34	[133]
65.52	ocean floor renewal at 3.41 km²/yr	88 Myr	17	[463]
65.52	Vertical period visible + halo (Sun)	88.2 Myr	34	[983]
65.59	Moon age from simulations (Jacobson 2014)	about 95 Myr after T_0	12	[292]
65.59	Sun vertical period	95 (+12/-10) Myr	34	[983]
65.64	Only hydrogen, helium and lithium (universe)	100 Myr	24	[700]
65.64	Radio pulsar fade max (pulsars)	100 Myr	27	[771]
65.64	Only H, He, Li for 100 Myr (early universe)	100 Myr	28	[700]
65.64–66.90	Ring exposure age (dust) (Saturn rings)	100–400 million years	31	[883]
65.64	Sagittarius dwarf disc passage	100 Myr ahead	34	[979]
65.64	Pleiades age accepted	100 Myr	34	[987]
65.67	Zircon to hydrosphere (computed) (Hadean water)	104 Myr	13	[326; 330]
65.72	Minimum Moon age within	110 Myr after T_0	12	[301]
65.73	ocean floor renewal at 2.7 km²/yr	111 Myr	17	[468]
65.76	Olympus youngest flows (old end) (Mars)	115000000.0 years	31	[899]
65.76	Pleiades age lithium	115 Myr	34	[987]
65.80	Lunar crust by Sm–Nd (Carlson & Lugmair 1988) (Moon)	about 120 Myr after T_0	12	[269]
65.85	Sirius B cooling age	126 Myr	27	[756]
65.90	Core formation to oldest zircon (computed) (Hadean crust)	133 Myr	13	[326]
65.94	Spacing of climate optima (Phanerozoic)	~140 Myr	19	[537]
65.98	Gap from Earth formation to oldest water zircon	146 Myr	14	[326]
65.98	Morokweng age	146060000.0 years	32	[922]
66.01	Time since core passage (Bullet Cluster)	150 Myr	35	[1013]
66.04	LMO duration if start 52 Myr (Moon)	about 155 Myr	12	[300]
66.07	Pangaea span (table)	161 Myr	17	[475]
66.07	Pangaea existed	160 Myr	17	[479]
66.08	First solids to oldest zircon (computed) (Hadean crust)	163 Myr	13	[326]

66.17	First Lyα photons from stars (EDGES) (first stars)	by 180 Myr	25	[712]
66.17	Lyα starlight by (EDGES) (first stars)	180 Myr	26	[712]
66.27	Oldest ocean floor (crust)	about 200 Myr	11	[281]
66.27	Solidification after solar system formation (editorial) (Moon)	about 200 Myr	12	[302]
66.27	Wet minimum melting within (Hadean crust)	200 Myr after T_0	13	[328]
66.27	Strong cataclysm interval (excluded) (bombardment)	≤200 Myr	13	[336]
66.27	GOE oscillation duration (air)	200 Myr	15	[392]
66.27	Next starburst (Galactic Centre)	200 Myr ahead	34	[976]
66.28	Galactic year (computed, 248.5 km/s) (Sun in Galaxy)	202 Myr	29	[839]
66.28-66.35	Galactic year computed (Sun)	202-219 Myr	34	[784]
66.34	Manicouagan age	215560000.0 years	32	[922]
66.38	Galactic year (quoted) (Sun in Galaxy)	225–250 Myr	29	[133]
66.39	Sirius system age	228–230 Myr	27	[757]
66.43	Ahuna Mons max age (Ceres)	240000000.0 years	32	[911]
66.47	Mineral diversity established within (minerals)	250 Myr	13	[272]
66.47	Rodinia span (table)	250 Myr	17	[475]
66.47	Pangaea Proxima (continents)	250 Myr ahead	17	[475]
66.47	Pleiades remaining life	250 Myr	34	[987]
66.53	First solids to first water (computed) (Hadean water)	267 Myr	13	[330]
66.54	FAN age spread (Moon)	270 Myr	12	[300]
66.57	Gas heated (EDGES) (intergalactic gas)	less than 100 Myr after 180 Myr	25	[712]
66.60	slab descent time at 1 cm/yr (slabs)	289 Myr	17	[462]
66.61	Ring lifetime from ring rain (Saturn rings)	292000000.0 years	31	[897]
66.63	interval Pannotia to Pangaea (supercontinent cycle)	297 Myr	17	[475]
66.64	Acidification events over 300 Myr (ocean pH)	300 Myr	14	[377]
66.64	supercontinent cycle, short	300 Myr	17	[474]
66.72	Nectaris dates difference (computed)	330 Myr	13	[336]

	(bombardment)			
66.82	interval Rodinia to Pannotia (supercontinent cycle)	367 Myr	17	[475]
66.82	Gyro median age active stars (gyrochronology)	365 Myr	28	[805]
66.84	Oldest zircon to Acasta (computed)	374 Myr	13	[326]
66.84	Gondwana span (table)	375 Myr	17	[475]
66.85	Siljan age	380900000.0 years	32	[922]
66.89	Ur span (table)	395 Myr	17	[475]
66.90	GOE span (air)	400 Myr	15	[390]
66.90	Delay photosynthesis to atmospheric O2 (air)	400 (at least) Myr	15	[390]
66.90	Vaalbara stability, short	0.4 Gyr	17	[476]
67.05	Nuna/Columbia span (table)	470 Myr	17	[475]
67.07	PhanDA span (Phanerozoic temperature)	485 Myr	19	[535]
67.10	Two clocks difference (computed) (Nuvvuagittuq)	500 Myr	13	[343; 344]
67.10	supercontinent cycle, long	500 Myr	17	[474]
67.10	Time to main sequence below 0.13 M_sun (low-mass stars)	5e8 yr	27	[738]
67.10	Starburst recurrence (Galactic Centre)	500 Myr	34	[976]
67.17	Scotese model span (Phanerozoic temperature)	540 Myr	19	[536]
67.24	Acraman age	580000000.0 years	32	[922]
67.28	Kenorland span (table)	606 Myr	17	[475]
67.31	Hyades age	625 ± 50 Myr	28	[801]
67.31	Hyades age Hipparcos	625 ± 50 Myr	34	[801]
67.33	Hyades age Gaia DR2	640 (+67/-49) Myr	34	[984]
67.40	Age at half reionization	690 ± 90 Myr	25	[25]
67.41	U-235 half-life (radiogenic heat)	0.704×10^9 years	11	[150]
67.41	Nice-model spike after planets formed (bombardment)	about 700 (3,867 Ma) Myr	13	[337]
67.41	LHB spike after planet formation (model) (inner Solar System)	~700 Myr	30	[337]
67.41	LHB spike in model (Earth impacts)	700000000.0 years after formation	32	[337]
67.47 to 69.57	Geological carbon / slow cycle (rock)	7.5e8-7.5e9 years	22	[634]
67.53	Thick disk start after BB (Milky Way)	0.8 Gyr	28	[726]

67.53	Thick disc start after Big Bang (Milky Way thick disc)	0.8 Gyr	34	[726]
67.55	interval Nuna to Rodinia (supercontinent cycle)	820 Myr	17	[475]
67.57	Vaalbara span (table)	833 Myr	17	[475]
67.64	interval Kenorland to Nuna (supercontinent cycle)	900 Myr	17	[475]
67.73	LLSVP age (Earth mantle)	>1 Gyr	12	[306]
67.73	High-temperature overgrowth after core (Hadean crust)	about 1 Gyr	13	[297]
67.73	Vaalbara stability, long	1 Gyr	17	[476]
67.73	Overgrowth after core, atom-probe zircon (Hadean zircon)	about 1 Gyr	21	[297]
67.73	Red giant phase 1 M_sun (red giants)	1 Gyr	27	[751]
67.73	Crystallisation cooling delay (white dwarfs)	1 Gyr	27	[754]
67.73	Red-giant phase (Sun)	1 Gyr	29	[751]
67.73	Rheasilvia age (Vesta)	1000000000.0 years	32	[912]
67.73	Flora family (upper) age (main belt)	1000000000.0 years	32	[910]
67.82	Time to undisputed field (geomagnetic field)	1.1 Gyr	16	[425]
67.90	Gyro median age Pizzolato (gyrochronology)	1.2 Gyr	28	[805]
67.94	K-40 half-life	1.25e9 yr	4	[150]
67.94	potassium-40: half-life (nucleus)	3.93839e+16 s (half-life)	10	[30]
67.94	K-40 half-life (radiogenic heat)	1.25×10^{9} years	11	[150]
67.94	Interval without a new mode, 1.85-0.6 Ga (Earth surface)	1.25 Gyr	21	[272]
68.10	Fracture fluid minimum mean residence (deep crust)	~1.5 Gyr	20	[592]
68.10	Cooling to 7140 K (white dwarfs)	1.5 Gyr	27	[753]
68.29	Sudbury age	1849000000.0 years	32	[922]
68.34	Main BIF span (banded iron formation)	1.95 Gyr	22	[346]
68.37	Vredefort age	2023000000.0 years	32	[922]
68.46	Yarrabubba age	2229000000.0 years	32	[922]
68.62	Fracture fluid pockets residence (deep crust)	1.5–2.64 Gyr	20	[592]
68.73	Mars surface water >3 Ga	3000000000.0 years	31	[891]
68.73	Ring age upper	several billion years	31	[885]

	(pollution resistance) (Saturn rings)			
68.87	S1-Warrawoona spherule bed (Earth impacts)	3472000000.0 years	32	[922]
68.97	85% of Earth age (plate tectonics)	3.88 Gyr	17	[354]
68.97	M31 first pericentre (Local Group)	3.87 Gyr ahead	29	[844]
68.97	LHB spike, years before now (computed 4,567 − 700) (Earth impacts)	3867000000 years	32	[337]
68.97	First pericentre (Andromeda-Milky Way)	3.87 (+0.42/-0.32) Gyr ahead	35	[844]
69.10	U-238 half-life	4.47e9 yr	4	[150]
69.10	uranium-238 (α): half-life (nucleus)	1.40999e+17 s (half-life)	10	[30]
69.10	U-238 half-life (radiogenic heat)	4.47×10^9 years	11	[150]
69.10	Sun time passed	4.5 Gyr	27	[745]
69.10	Main-sequence time passed (Sun)	4.5 Gyr	29	[745]
69.10	Mars early water epoch	4500000000.0 years	31	[890]
69.11	Earth–Moon angular momentum nearly conserved	4.5 Gyr	12	[291]
69.12	Age of oldest solids (CAIs) (Solar System)	4567.30 ± 0.16 Myr	29	[265]
69.12	Sun age from stellar models	4.6 Gyr	29	[133]
69.12	CAI age (U-corrected Pb–Pb) (Solar System)	4567.30 ± 0.16 Myr	30	[265]
69.12	CAI age NWA 2364 (Solar System)	4568.2 Myr	30	[266]
69.12	CAI age (first solids)	4567300000.0 years	32	[265]
69.12	CAI NWA 2364 age (first solids)	4568200000.0 years	32	[266]
69.12	Youngest dated chondrule (first solids)	4564710000.0 years	32	[265]
69.17	Proxima age (Proxima Centauri)	4.85 Gyr	34	[993]
69.20	Turn to acceleration, other account (universe)	about 5 Gyr ago	26	[690]
69.20	Sun leaves main sequence in	5 Gyr	27	[751]
69.34	M31 merger (Local Group)	5.86 Gyr ahead	29	[844]
69.34	Merger (Andromeda-Milky Way)	5.86 (+1.61/-0.72) Gyr ahead	35	[844]
69.38	Turn to acceleration, before now (computed) (universe)	6.10 Gyr	26	[25]
69.48	Uniform-speed closing time (computed) (Andromeda)	6.8 Gyr	35	[1015]
69.58	Oldest pulsar age in	7580 Myr	27	[771]

	table (PSR J0030+0451)			
69.58–70.14	3I/ATLAS age (thick disk)	7.6–14 Gyr	32	[931]
69.59	Age at the turn to acceleration (universe)	7.70 ± 0.10 Gyr	26	[25]
69.63	Disk age from WD cooling (Milky Way disk)	8 Gyr	27	[753]
69.63	Thin disc age (white dwarfs) (Milky Way thin disc)	8 Gyr	34	[842]
69.73	Proton waiting time (Sun core)	9e9 yr	28	[787]
69.73	Average proton wait before fusion (Sun core)	9e9 yr	29	[787]
69.83	Sun main-sequence life	1e10 yr	27	[745]
69.83	Main-sequence lifetime of the Sun	1e10 yr	29	[745]
69.92	Most thick-disk stars formed (Milky Way)	11 Gyr ago	26	[726]
70.00	Sun hydrogen burning	12 Gyr	27	[745]
70.00	Hydrogen burning total (Sun)	12 Gyr	29	[745]
70.05	Oldest globular clusters (Milky Way)	as old as 12.7 Gyr	26	[727]
70.05	Oldest globular clusters (Milky Way globular clusters)	12.7 Gyr	34	[966]
70.12	Age of the universe	13.797 ± 0.023 Gyr	4	[25]
70.12	Age of the universe (cosmology)	13.787±0.020 Gyr	9	[239]
70.12	Age of the universe, Planck 2015	13.813 ± 0.038 Gyr	24	[676]
70.12	Age of the universe, WMAP nine-year	13.772 ± 0.059 Gyr	24	[676]
70.12	Age of BD +17°3248, radioactive dating	13.8 ± 0.4 Gyr	24	[676]
70.12	Age of the universe used for comparison	13.77 ± 0.06 Gyr	24	[679]
70.12	Age of universe in Bond 2013	13.77 ± 0.06 Gyr	28	[679]
70.12	Age of universe	13.797 ± 0.023 Gyr	35	[25]
70.14	Th-232 half-life	14.0e9 yr	4	[150]
70.14	thorium-232: half-life (nucleus)	4.43384e+17 s (half-life)	10	[30]
70.14	Th-232 half-life (radiogenic heat)	14.0×10^9 years	11	[150]
70.17	Age of HD 140283	14.46 ± 0.31 (± 0.8 total) Gyr	24	[679]
70.17	HD 140283 age	14.46 ± 0.31 (± 0.8) Gyr	28	[679]
70.19	Age of the universe, 42 type Ia supernovae	14.9 (+1.4, −1.1) × 0.63/h Gyr	24	[678]
71.16	rhenium-187, neutral atom: half-life (nucleus)	1.35698e+18 s (half-life)	10	[263]
74.02	Lifetime below 0.1	>1e12 yr	27	[745]

	M_sun (red dwarfs)			
76.47	Whole-mass conversion time at present rate (computed) (Sun)	1.48e13 yr	29	[733]
86.60	Massive photon lifetime bound (Heeck 2013)	>1e18 years	1	[9]
86.60	photon (massive-photon bound): lower limit (stable)	>3.156e+25 s	10	[151]
88.38	Two-neutrino double-beta half-life 100Mo	7.06e+18 yr	4	[127]
88.38	molybdenum-100 (2νββ): half-life (nucleus)	2.22797e+26 s (half-life)	10	[256]
88.63	Two-neutrino double-beta half-life 150Nd	9.34e+18 yr	4	[127]
88.63	neodymium-150 (2νββ): half-life (nucleus)	2.94748e+26 s (half-life)	10	[256]
89.33	bismuth-209 (α): half-life (nucleus)	6.34308e+26 s (half-life)	10	[257]
89.45	Two-neutrino double-beta half-life 96Zr	2.3e+19 yr	4	[127]
89.45	zirconium-96 (2νββ): half-life (nucleus)	7.25825e+26 s (half-life)	10	[256]
89.59	Two-neutrino double-beta half-life 116Cd	2.69e+19 yr	4	[127]
89.59	cadmium-116 (2νββ): half-life (nucleus)	8.48899e+26 s (half-life)	10	[256]
90.21	Two-neutrino double-beta half-life 48Ca	5.3e+19 yr	4	[127]
90.21	calcium-48 (2νββ): half-life (nucleus)	1.67255e+27 s (half-life)	10	[256]
90.66	Two-neutrino double-beta half-life 82Se	8.7e+19 yr	4	[127]
90.66	selenium-82 (2νββ): half-life (nucleus)	2.74551e+27 s (half-life)	10	[256]
92.67	Two-neutrino double-beta half-life 130Te	7.91e+20 yr	4	[127]
92.67	tellurium-130 (2νββ): half-life (nucleus)	2.49621e+28 s (half-life)	10	[256]
93.46	Two-neutrino double-beta half-life 76Ge	1.88e+21 yr	4	[127]
93.46	germanium-76 (2νββ): half-life (nucleus)	5.93283e+28 s (half-life)	10	[256]
93.52	Two-neutrino double-beta half-life 238U	2e+21 yr	4	[127]
93.52	uranium-238 (2νββ, radiochemical): half-life (nucleus)	6.31152e+28 s (half-life)	10	[256]
93.59	Two-neutrino double-beta half-life 136Xe	2.18e+21 yr	4	[127]
93.59	xenon-136 (2νββ): half-life (nucleus)	6.87956e+28 s (half-life)	10	[256]
93.60	barium-130 (2νεε): half-life (nucleus)	6.94267e+28 s (half-life)	10	[256]
94.90	krypton-78 (2νεε, BAKSAN): half-life (nucleus)	2.9033e+29 s (half-life)	10	[261]
95.07	xenon-124 (2νεε, XENON1T 2022):	3.47134e+29 s (half-life)	10	[261]

	half-life (nucleus)			
95.52	xenon-124 (2νεε, XENON1T 2019): half-life (nucleus)	5.68037e+29 s (half-life)	10	[260]
95.56	krypton-78 (2νεε, recommended): half-life (nucleus)	5.99594e+29 s (half-life)	10	[256]
99.71	tellurium-128 (geochemical, 1.8 × 10^{24}): half-life (nucleus)	5.68037e+31 s (half-life)	10	[261]
99.91	Two-neutrino double beta half-life, tellurium-128 (recommended)	2.25 ± 0.09e24 years	4	[127]
99.91	tellurium-128 (2νββ, recommended): half-life (nucleus)	7.10046e+31 s (half-life)	10	[256]
100.97	tellurium-128 (geochemical, 7.2 × 10^{24}): half-life (nucleus)	2.27215e+32 s (half-life)	10	[261]
101.03	tellurium-128 (IAEA): half-life (nucleus)	2.42994e+32 s (half-life)	10	[262]
104.58	0nubb half-life limit 136Xe	>3.8e26 yr	4	[126]
104.58	0νββ half-life limit Xe-136 (neutrino)	>3.8e26 yr	7	[126]
104.58	xenon-136 (0νββ, limit): lower limit (nucleus)	>1.199e+34 s	10	[126]
109.27	Electron mean life lower bound (Borexino 2015)	>6.6e28 years	2	[36]
109.27	electron: lower limit (stable)	>2.083e+36 s	10	[36]
111.65	Proton partial lifetime limit invisible (90% CL)	>9e+29 yr = 2.84e+37 s	3	[69]
111.65	proton, invisible mode: lower limit (stable)	>2.84e+37 s	10	[69]
111.71	Antiproton lifetime bound infobox	>0.96e30 yr	7	[187]
117.18	Proton partial lifetime limit nubar pi+ (90% CL)	>3.9e+32 yr = 1.23e+40 s	3	[69]
117.18	proton, p → ν̄π⁺ (τ/B): lower limit (stable)	>1.231e+40 s	10	[69]
117.67	Proton partial lifetime limit e+gamma (90% CL)	>6.7e+32 yr = 2.11e+40 s	3	[69]
117.67	proton, p → e^{+}γ (τ/B): lower limit (stable)	>2.114e+40 s	10	[69]
118.04	Proton partial lifetime limit e+K0 (90% CL)	>1e+33 yr = 3.16e+40 s	3	[69]
118.04	proton, p → $e^{+}K^{0}$ (τ/B): lower limit (stable)	>3.156e+40 s	10	[69]
119.44	Proton partial lifetime limit mu+eta (90% CL)	>4.7e+33 yr = 1.48e+41 s	3	[69]
119.44	proton, p → μ^{+}η (τ/B): lower limit (stable)	>1.483e+41 s	10	[69]
119.65	Proton partial	>5.9e+33 yr =	3	[69]

	lifetime limit nubar K+ (90% CL)	1.86e+41 s		
119.65	proton, p → ν̄K⁺ (τ/B): lower limit (stable)	>1.862e+41 s	10	[69]
120.13	Proton partial lifetime limit e+eta (90% CL)	>1e+34 yr = 3.16e+41 s	3	[69]
120.13	proton, p → e⁺η (τ/B): lower limit (stable)	>3.156e+41 s	10	[69]
120.56	Proton partial lifetime limit mu+pi0 (90% CL)	>1.6e+34 yr = 5.05e+41 s	3	[73]
120.56	proton, p → μ⁺π⁰ (τ/B): lower limit (stable)	>5.049e+41 s	10	[73]
120.93	Proton partial lifetime limit e+pi0 (90% CL)	>2.4e+34 yr = 7.57e+41 s	3	[73]
120.93	proton, p → e⁺π⁰ (τ/B): lower limit (stable)	>7.574e+41 s	10	[73]
121.24	Proton partial lifetime limit e+e+e- (90% CL)	>3.4e+34 yr = 1.07e+42 s	3	[69]
121.24	proton, p → e⁺e⁺e⁻ (τ/B): lower limit (stable)	>1.073e+42 s	10	[69]
170.43	Vacuum lifetime 95% lower bound	>1e58 yr	6	[180]
170.43	Vacuum lifetime (calculated, 95% lower) (vacuum stability)	>1e58 yr	9	[180]
170.43	vacuum state, calculated (95 % lower bound): calculated, lower limit	>3.156e+65 s	10	[180]
340.20	Vacuum lifetime central	1e139 yr	6	[180]
340.20	vacuum state, calculated (central): calculated	3.15576e+146 s	10	[180]

Ages

390 positions, youngest first.

Position	What	Value	Chapter	Source
50.34	Inner-core super-rotation (inner core)	2003–2008 AD	16	[457]
51.34	Inner-core backtracking (inner core)	2008–2023 AD	16	[457]
52.81	Oort proposal (Oort cloud)	76 years ago	32	[924]
53.60	Neptune telescope discovery	180 years ago	31	[896]
54.53	Bond event at ~0.5 ka (North Atlantic ice rafting)	0.5 ka	19	[577]
55.46	Bond event at ~1.4 ka (North Atlantic ice rafting)	1.4 ka	19	[577]

55.99	End of slowing rise (sea level)	2.5 ka	14	[366]
56.10	Bond event at ~2.8 ka (North Atlantic ice rafting)	2.8 ka	19	[577]
56.46	Bond event at ~4.2 ka (North Atlantic ice rafting)	4.2 ka	19	[577]
56.71	African Humid Period end (Sahara, Sahel)	6,000–5,000 (Sahel ~5,500) years ago	20	[600]
56.77	Bond event at ~5.9 ka (North Atlantic ice rafting)	5.9 ka	19	[577]
56.79	East Asian monsoon peak	~6,000 years ago	20	[597]
57.07	Bond event at ~8.2 ka (North Atlantic ice rafting)	8.2 ka	19	[577]
57.20	Bond event at ~9.4 ka (North Atlantic ice rafting)	9.4 ka	19	[577]
57.25	Green period 6–10 ka (Sahara)	6–10 ka	20	[599]
57.25	Sun entered LIC	<10000 yr ago	29	[824]
57.25	Sun enters LIC	< 10000 yr ago	34	[824]
57.28	Bond event at ~10.3 ka (North Atlantic ice rafting)	10.3 ka	19	[577]
57.35	Bond event at ~11.1 ka (North Atlantic ice rafting)	11.1 ka	19	[577]
57.37	No MWP-1B at 11.3 ka (sea level)	11.3 ka	14	[366]
57.40	Holocene base	11,700 years b2k	19	[565]
57.46	Younger Dryas slower rise (sea level)	12.5–11.5 ka	14	[366]
57.48	Younger Dryas (AMOC)	12800–11700 yr ago	14	[371]
57.48	Younger Dryas NH onset	12,870 ± 30 years ago	19	[556]
57.58	MWP-1A end (sea level)	14310 yr ago (before)	14	[367]
57.60	MWP-1A start (sea level)	14650 yr ago (no earlier than)	14	[367]
57.60	Dansgaard–Oeschger event 1 (AMOC)	14690 yr ago	14	[371]
57.62	West Antarctic decline (West Antarctica)	15–14 ka	19	[560]
57.62	African Humid Period onset (Sahara)	15,000–14,500 years ago	20	[600]
57.74	Fennoscandian ice at LGM extent	~17 ka	19	[560]
57.88	All ice sheets at LGM positions	19–20 ka	19	[559]
58.12	LGM (summary)	26–20 ka	19	[560]
58.14	Oruanui VEI 8 age	26.5 ka	18	[498]
58.16	Oruanui other date age (VEI 8)	27 ka	18	[498]

58.22	LGM fall interval (sea level)	29–21 ka	14	[366]
58.25	Glacial state reached (sea level)	30 ka	14	[366]
58.34	Ice sheets at maximum (LGM)	33.0–26.5 ka	19	[559]
58.54	Laschamp radiocarbon age (geomagnetic field)	41 ka	16	[437]
58.56	Laschamp age (geomagnetic field)	42.2–41.5 ka	16	[436]
59.03	Yellowstone last lava	70 ka	18	[499]
59.08	Toba VEI 8 age	74 ka	18	[498]
59.16	Green period 77–81 ka (Sahara)	77–81 ka	20	[599]
59.42	Green period 102–108 ka (Sahara)	102–108 ka	20	[599]
59.57	Green period 122–128 ka (Sahara)	122–128 ka	20	[599]
59.59	Termination II (glacial terminations)	~130 ka	19	[556]
60.16	Termination III (glacial terminations)	~243 ka	19	[556]
60.46	Termination IV (glacial terminations)	~337 ka	19	[556]
60.61	Hawaiian Islands, young (Hawaii hotspot)	0.4 Ma	18	[470]
60.61	South Greenland ice-free (MIS 11)	~400 ka	19	[549]
60.61	Obliquity pacing of WAIS until (West Antarctica)	~400 ka	19	[554]
60.68	Termination V (glacial terminations)	~430 ka	19	[555]
60.90	Mid-Pleistocene Transition (Pleistocene ice)	1,250–700 ka	19	[553]
61.03	Lava Creek age (Yellowstone)	0.63 Ma	18	[499]
61.04	Yellowstone VEI 8 age	0.64 Ma	18	[498]
61.21	Brunhes–Matuyama final reversal (geomagnetic field)	773 ka	16	[435]
61.22	B–M precursor excursion (geomagnetic field)	784 ka	16	[435]
61.22	B–M round value (geomagnetic field)	780 ka	16	[425]
61.24	B–M onset of weakening (geomagnetic field)	795 ka	16	[435]
61.35	Abrupt Antarctic ice-volume increase (Antarctica)	~900 ka	19	[553]
61.35	Green periods less frequent after	~0.9 Ma	20	[599]

	(Sahara)			
61.49	Tropical African change	1.05 Ma	19	[554]
61.68	Mesa Falls age (Yellowstone)	1.3 Ma	18	[499]
61.87	Precession phase jump (LR04)	~1.6 Ma	19	[552]
61.93	60Fe/53Mn peak young start (Earth record)	1.7 Myr ago	28	[809]
61.93-62.50	60Fe/53Mn peak young (Earth record)	1.7-3.2 Myr ago	34	[991]
61.97	zeta Oph / PSR B1706−16 supernova (zeta Ophiuchi)	1.78 ± 0.21 Myr ago	28	[809]
61.97	zeta Oph supernova (zeta Ophiuchi / PSR B1706-16)	1.78 ± 0.21 Myr ago	34	[991]
62.08	Sahara conventional age	2–3 Ma	20	[596]
62.11	Huckleberry Ridge age (Yellowstone)	2.08 Ma	18	[499]
62.12	Yellowstone VEI 8 age	2.1 Ma	18	[498]
62.28	Large Northern Hemisphere ice sheets	2.5 Ma	14	[363]
62.28	Large Northern Hemisphere ice sheets (sea-level record)	2.5–0 Ma	19	[363]
62.32	monsoon intensification end	2.6 Ma	18	[496]
62.32	Greenland single ice sheet	2.6–2.7 Ma	19	[549]
62.32	Variable summer, strong winter monsoon since (East Asia)	2.6 Ma	20	[496]
62.50	60Fe/53Mn peak young end (Earth record)	3.2 Myr ago	28	[809]
62.61	monsoon intensification start	3.6 Ma	18	[496]
62.61	East Asian monsoon strengthening	3.6–2.6 Ma	20	[496]
62.81	Sun enters Local Bubble	4.5 Myr ago	34	[991]
62.93	Hawaiian Islands, old (Hawaii hotspot)	5.1 Ma	18	[470]
63.15	60Fe peak old start (Earth record)	6.5 Myr ago	28	[809]
63.15-63.41	60Fe peak old (Earth record)	6.5-8.7 Myr ago	34	[991]
63.22	Sahara oldest dunes (Chad Basin)	~7 Ma	20	[595]
63.34	monsoon onset, late	8 Ma	18	[496]
63.34	Strong Indian	~8 Ma	20	[597]

	monsoon (many geologists)			
63.41	60Fe peak old end (Earth record)	8.7 Myr ago	28	[809]
63.45	monsoon onset, early	9 Ma	18	[496]
63.45	Asian monsoon onset	9–8 Ma	20	[496]
63.54	Greenland coherent ice sheet	~10 Ma	19	[549]
63.63	Tethys shrinkage (Tortonian, model) (Sahara)	7–11 Ma	20	[596]
63.91	Marinoan (alternative dating)	650–635 (15 Myr) Ma	19	[480]
63.91	Indian monsoon start (newer studies)	15–20 Ma	20	[597]
64.02	Columbia River Basalt age (LIP)	17–6 Ma	18	[481]
64.02	Columbia River plume track (hotspot)	17 Ma	18	[471]
64.42	La Garita age (VEI 8)	26.3 Ma	18	[498]
64.54	Afar plume track (hotspot)	30 Ma	18	[471]
64.54	Wah Wah Springs age (VEI 8)	30 Ma	18	[498]
64.63	Large Antarctic ice sheets	33–2.5 Ma	14	[363]
64.63	MM25 polarity time scale span, young end (ocean floor)	33 Ma	17	[433]
64.63	Atacama hyperaridity onset	~33 Ma	20	[594]
64.65	Top of EOIS (Eocene–Oligocene transition)	33.65 Ma	19	[546]
64.66	First global glaciation window (Paleoproterozoic glaciation)	2.460–2.426 Ga	19	[392]
64.68	collision claim assessed (Himalaya)	35 Ma	18	[495]
64.80	Neotethys closed (Himalaya)	40 Ma	18	[469]
64.87	end of Pacific-over-Hawaii interval (plate)	43 Ma	17	[470]
64.87	bend, trench jam account (Pacific plate)	43 Ma	18	[470]
64.95	Pacific motion change, Torsvik (Pacific plate)	47 Ma	18	[491]
64.98	Azolla bloom age (Lomonosov Ridge)	48.5 Ma	19	[545]
65.01	Azolla interval (air)	50–48.5 Ma	15	[404]
65.01	Hawaiian–Emperor bend, Sharp & Clague (Pacific plate)	50 Ma	18	[490]

65.02	youngest marine facies Qumiba, young (Himalaya)	50.6 Ma	18	[495]
65.06	youngest marine facies Qumiba, old (Himalaya)	52.8 Ma	18	[495]
65.09	Eocene control (Earth)	about 55 Ma	12	[324]
65.11	PETM age (ocean carbon)	56 Ma	14	[376]
65.11	PETM (climate)	56 Ma	18	[379]
65.11	PETM onset age	55.8 Ma	19	[543]
65.17	Norwegian Sea opening (Atlantic)	60–55 Ma	17	[479]
65.17	India–Asia collision, Paleocene (Himalaya)	60 Ma	18	[469]
65.17	First Antarctic ice (Antarctica)	60–45.5 Ma	19	[548]
65.20	North Atlantic Igneous Province age (LIP)	62–55 Ma	18	[481]
65.25	Deccan main window end (Deccan Traps)	65.6 Ma	18	[487]
65.26	Deccan Traps age (LIP)	66 Ma	18	[481]
65.26	Deccan onset (Deccan Traps)	66.25 Ma	18	[487]
65.26	Deccan main window start (Deccan Traps)	66.3 Ma	18	[487]
65.26	K–Pg extinction	66 Ma	18	[489]
65.27	Deccan first pulse (Deccan Traps)	67 Ma	18	[487]
65.29	Deccan plume track (hotspot)	68.5 Ma	18	[471]
65.31	Rudist age (Earth)	about 70 Ma	12	[290]
65.43	hotspot drift start (Hawaii hotspot)	80 Ma	18	[491]
65.43	Late Paleozoic ice age (Permo-Carboniferous icehouse)	340–260 Ma	19	[401]
65.45	start of Pacific-over-Hawaii interval (plate)	81 Ma	17	[470]
65.45	Detroit Seamount age (Hawaii hotspot)	81 Ma	18	[470]
65.47	MM25 polarity time scale span, old end (ocean floor)	83 Ma	17	[433]
65.59	Caribbean plume track (hotspot)	95 Ma	18	[471]
65.64	Ephemeral Antarctic ice sheets	100–33 Ma	14	[363]
65.64	Hawaiian plume head plateau (Hawaii hotspot)	100 Ma	18	[471]
65.65	Cretaceous Normal Superchron	120–83 Ma	16	[431]

	(geomagnetic field)			
65.82	Ontong Java Plateau age (LIP)	c. 122 Ma	18	[481]
65.84	Ontong Java plume track (hotspot)	125 Ma	18	[471]
65.88	Kerguelen plume track (hotspot)	130 Ma	18	[471]
65.89	Paraná-Etendeka plume track (hotspot)	132 Ma	18	[471]
65.90	Paraná–Etendeka age (LIP)	134–129 Ma	18	[481]
66.01	Mesozoic Dipole Low (geomagnetic field)	170–130 Ma	16	[431]
66.01	Gondwana separation	150–140 Ma	17	[479]
66.07	Jurassic Quiet Zone age (ocean floor)	160 (older than) Ma	17	[432]
66.12	oldest sea floor found today (ocean floor)	170 Ma	17	[474]
66.15	Gondwana breakup (table)	175 Ma	17	[475]
66.15	Pangaea breakup (table)	175 Ma	17	[475]
66.15	North Atlantic rifting (Pangaea)	175 Ma	17	[479]
66.19	Karoo–Ferrar age (LIP)	183–180 Ma	18	[481]
66.19	Karoo-Ferrar plume track (hotspot)	183 Ma	18	[471]
66.27	oldest large-scale ocean crust (ocean floor)	180–200 Ma	17	[472]
66.27	Atlantic opening	200 Ma	17	[467]
66.27	CAMP age (LIP)	201–197 Ma	18	[481]
66.27	CAMP plume track (hotspot)	200 Ma	18	[471]
66.33	Pangaea breakup began (table text)	215 Ma	17	[475]
66.40	Pangaea first breakup, late Ladinian	230 Ma	17	[479]
66.47	Siberian Traps age (LIP)	250 Ma	18	[481]
66.48	Emeishan age (LIP)	253–250 Ma	18	[481]
66.48	Permian–Triassic boundary (time scale)	251.9 Ma	18	[482]
66.48	end-Permian extinction start	251.941 ± 0.037 Ma	18	[483]
66.48	end-Permian extinction end	251.880 ± 0.031 Ma	18	[483]
66.54	eastern Mediterranean Tethys remnant (ocean floor)	270 Ma	17	[472]
66.57	Pangaea formation, other date	280 Ma	17	[479]

66.60	Kiaman Reverse Superchron (geomagnetic field)	312–262 Ma	16	[431]
66.64	Huronian Supergroup deposition (Huronian glaciation)	2.4–2.1 Ga	19	[531]
66.67	Pangaea formation, other date	310 Ma	17	[479]
66.74	Pangaea formation (table)	336 Ma	17	[475]
66.74	Pangaea formed	335 Ma	17	[479]
66.75	Herodotus Basin ocean crust (ocean floor)	340 Ma	17	[473]
66.94	Charcoal continuous from (air)	419 Ma	15	[396]
66.99	Late Ordovician glaciation (Ordovician icehouse)	444 Ma	19	[538]
67.05	Moyero Reverse Superchron (geomagnetic field)	485–463 Ma	16	[431]
67.10	Inner core age, Bono 2019	about 0.5 Ga	11	[288]
67.10–68.36	Earlier inner-core nucleation estimates (Biggin 2015) (inner core)	<0.5 to nearly 2 Ga	11	[286]
67.10–68.57	Published inner-core onset span (inner core)	about 0.5 to >2.5 Ga	11	[288]
67.10	Inner-core age Bono 2019 (inner core)	0.5 Ga	16	[448]
67.18	Phanerozoic sea-level review start (sea level)	543 Ma	14	[363]
67.18	Stage 10 (2008) after 0.542 Ga (biosphere)	<0.542 Ga	21	[612]
67.19	Gondwana formation (table)	550 Ma	17	[475]
67.21	Sept-Îles intrusive suite age (geomagnetic field)	about 565 Ma	11	[288]
67.23	Pannotia breakup (table)	573 Ma	17	[475]
67.24	Deep ocean ferruginous until	580 Ma	15	[390]
67.24	Deep ocean still ferruginous	580 Ma	22	[390]
67.27	Piper first breakup (continents)	0.6 Ga	17	[474]
67.27	Pannotia (second list)	600 Ma	17	[474]
67.28	Gondwana assembled by	608 Ma	17	[475]
67.30	Rhythmite age, South Australia (Earth)	about 620 Ma	12	[315]

67.31	Ocean oxygenation after Marinoan (Doushantuo shales)	635–630 Ma	19	[395]
67.32	Ocean oxygenation after Marinoan	635–630 Ma	15	[395]
67.32	Pannotia formation (table)	633 Ma	17	[475]
67.32	Rodinia breakup end	633 Ma	17	[478]
67.32	Marinoan glaciation end (ice)	635 Ma	17	[480]
67.32	Ghaub Formation ash age, upper (Marinoan, Namibia)	635.21 ± 0.59 Ma	19	[533]
67.32	Sheepbed Formation base, end of Marinoan (NW Canada, Laurentia)	632.3 ± 5.9 Ma	19	[532]
67.32 to 67.31	Ocean oxygenation after Marinoan	635-630 Ma	22	[395]
67.33	Ghaub Formation ash age, lower (Marinoan, Namibia)	639.29 ± 0.26 Ma	19	[533]
67.34	Inner core age, Driscoll & Bercovici 2014	0.65 Ga	11	[285]
67.34	Marinoan glaciation start (ice)	650 Ma	17	[480]
67.35	Above Maikhan-Uul diamictite (Mongolia)	659.0 ± 4.5 Ma	19	[532]
67.36	Sturtian glaciation end (ice)	660 Ma	17	[480]
67.41	Inner core age, Ohta 2016	<0.7 Ga	11	[287]
67.41	Inner core age, Labrosse 2015	<0.7 Ga	11	[285]
67.43	Sturtian glaciation start (ice)	717 Ma	17	[480]
67.43	Sturtian onset	717 Ma	19	[532]
67.44	Below Grand Conglomerate (Congo craton)	727.3 ± 4.9 Ma	19	[532]
67.47	Rodinia breakup (table)	750 Ma	17	[475]
67.47	Rodinia breakup start	750 Ma	17	[478]
67.47	Callison Lake Formation base (nonglacial) (Yukon, Laurentia)	752.7 ± 5.5 Ma	19	[532]
67.47	Neoproterozoic minor BIF (banded iron formation)	about 750 Ma	22	[346]
67.53	late onset, blueschists (plate tectonics)	0.8 Ga	17	[354]
67.56	Rodinia superplume	825–800 Ma	17	[478]
67.59	Neoproterozoic Oxygenation Event	850–540 Ma	15	[390]

	(air)			
67.64	Rodinia assembly end	0.90 Ga	17	[478]
67.73–68.10	Inner core age, Biggin 2015	1–1.5 Ga	11	[286]
67.73	Inner core age, Labrosse 2001	1 ± 0.5 Ga	11	[285]
67.73	Rodinia formation (table)	1000 Ma	17	[475]
67.90	Youngest basalts (crater counts) (Moon)	about 1.2 Ga	12	[309]
67.92	Rodinia formed (Zhao)	1.23 Ga	17	[478]
67.93	Sudbury dykes (Columbia)	1.24 Ga	17	[477]
67.94	Field transition (Biggin) (geomagnetic field)	1.0–1.5 Ga	16	[286]
67.94	Rodinia assembly start	1.26 Ga	17	[478]
67.94	Rodinia formed (second list)	1.25 Ga	17	[474]
67.95	Mackenzie dykes (Columbia)	1.27 Ga	17	[477]
67.97	Palaeointensity rise noted by Ohta 2016 (geomagnetic field)	around 1.3 Ga	11	[287]
67.97	Columbia final breakup	1.3–1.2 Ga	17	[477]
68.01	Nuna/Columbia breakup (table)	1350 Ma	17	[475]
68.04	Rhythmite sequence age (Earth)	about 1.4 Ga	12	[324]
68.10	Columbia growth end	1.5 Ga	17	[477]
68.10	Columbia fragmentation start	1.5–1.35 Ga	17	[477]
68.27	modern-style subduction (plate tectonics)	1.8 Ga	17	[462]
68.27	Columbia assembly end	1800 Ma	17	[477]
68.28	Mean crust age (loess) (continental crust)	1.82 ± 0.07 Ga	13	[351]
68.28	Nuna/Columbia formation (table)	1820 Ma	17	[475]
68.28	Columbia final assembly	1.82 Ga	17	[477]
68.29	Banded iron formation peak / end (ocean)	2.5 / 1.85 Ga	15	[390]
68.29	Orosirian BIF peak (banded iron formation)	about 1,850 Ma	22	[346]
68.29	End of main BIF deposition (banded iron formation)	about 1.85 Ga	22	[346]
68.32	eclogite subduction-driven	1.9–2.0 Ga	17	[462]

	assembly (plate tectonics)			
68.32	Trans-Hudson, Penokean, Svecofennian orogens (Columbia)	1.9–1.8 Ga	17	[477]
68.36–68.87	Inner core age, Smirnov 2011	2–3.5 Ga	11	[285]
68.36	Inner core age, Labrosse 2003	about 2 Ga	11	[285]
68.36–68.57	Impact spherules to (bombardment)	about 2.0–2.5 Ga	13	[336]
68.36	Mean crust age (continental crust)	about 2.0 Ga	13	[281]
68.36	Inner-core age Labrosse 2003 (inner core)	2 Ga	16	[448]
68.38	Bushveld intrusion (Kaapvaal)	2.045 Ga	17	[476]
68.38	Vredefort impact (Kaapvaal)	2.025 Ga	17	[476]
68.39	End of Lomagundi excursion (air)	2060 Ma	15	[392]
68.39	Vaalbara separated before	2.05 Ga	17	[476]
68.40	Sulphur cycle change (air)	2450–2090 Ma	15	[389]
68.41	Kenorland breakup (table)	2114 Ma	17	[475]
68.41	Columbia assembly start	2100 Ma	17	[477]
68.41	Transamazonian and Eburnean orogens (Columbia)	2.1–2.0 Ga	17	[477]
68.45	Modern plate tectonics at least	2.2 Ga	13	[354]
68.47	GOE oscillation end (air)	2250–2240 Ma	15	[392]
68.47	Makganyene Formation age (South Africa)	2.25 Ga	19	[480]
68.49	Gowganda Formation age (Huronian glaciation)	2.3 Ga	19	[531]
68.50	GOE in Transvaal cores (air)	2.33 Ga	15	[391]
68.50	Sclavia broke off (cratons)	2312 Ma	17	[475]
68.50	Great Oxidation Event (atmosphere)	about 2.33 Ga	21	[391]
68.53	Ur breakup (table)	2408 Ma	17	[475]
68.54	Ongeluk Formation date (air)	2426 ± 3 Ma	15	[392]
68.54	Ongeluk Formation U–Pb age (Kaapvaal craton)	2.426 ± 0.003 Ga	19	[392]
68.55	BIF age (Earth)	about 2450 Ma	12	[315]
68.55	Sulphur mass-independent fractionation before (Archean	2450 Ma	15	[389]

	air)			
68.55	GOE onset (air)	2460–2426 Ma	15	[392]
68.55 to 68.54	Great Oxidation Event onset (atmosphere)	2.460-2.426 Ga	21	[392]
68.56	Superia broke off (cratons)	2480 Ma	17	[475]
68.56 to 68.55	Hamersley BIF age (Hamersley, Western Australia)	2,470-2,450 Ma	22	[346]
68.57	Jaspilite host age (Lan 2022) (Nuvvuagittuq)	ca. 2500 Ma	13	[343]
68.57	modern upper crust after Archean	2.5 Ga	17	[461]
68.57	Archean end (time scale)	2.5 Ga	17	[380]
68.57	mineral stage initiation of plate tectonics, end (minerals)	2.5 Ga	17	[272]
68.57	Global glaciation (Kopp 2005) (Paleoproterozoic glaciation)	2.5–2.2 Ga	19	[480]
68.64	Cyanobacteria present (biosphere)	2.7 (probably) Ga	15	[390]
68.64	Vaalbara craton crust, young	2.7 Ga	17	[476]
68.64	Kenorland formation (table)	2720 Ma	17	[475]
68.64	Piper single supercontinent start (continents)	2.7 Ga	17	[474]
68.64	Host rock age (Timmins, Ontario)	2.7 Ga	20	[592]
68.65 to 68.63	Temagami BIF age (Temagami, Canada)	2,736-2,687 Ma	22	[346]
68.66	Vaalbara 30° apart	2.78–2.77 Ga	17	[476]
68.67	Vaalbara breakup (table)	2803 Ma	17	[475]
68.67	Ur formation (table)	2803 Ma	17	[475]
68.67 to 68.57	Late Archaean BIF peak (banded iron formation)	2,800-2,500 Ma	22	[346]
68.73	Host conglomerate age (Jack Hills)	about 3.0 Ga	13	[327]
68.73	Growth-rate decrease at (continental crust)	about 3 Ga	13	[352]
68.73	Crustal destruction rise (continental crust)	starting about 3 Ga	13	[352]
68.73	crustal destruction rises (continental crust)	3 Ga	17	[352]
68.73	start of supercontinent cycle (continents)	3 Ga	17	[474]
68.78	Mare basalts age (as printed) (Moon)	about 3.16 Ga	12	[309]

68.82, 68.70, 68.64	Acasta intrusions	3.30, 2.88, 2.70 Ga	13	[341]
68.86	Field duration (undisputed) (geomagnetic field)	>=3.45 Ga	16	[430]
68.87–69.04	Elevated flux (bombardment)	about 3.5 to 4.0–4.2 Ga	13	[336]
68.87	Dynamo before 3.5 Ga unknown (Jack Hills zircons)	3.5 Ga	16	[334]
68.87	mineral stage initiation of plate tectonics, start (minerals)	3.5 Ga	17	[272]
68.87	Vaalbara spherule layers	3.5 Ga	17	[476]
68.87	Oldest impact spherule bed (Earth)	~3472 Ma	30	[862]
68.90	Isua folding (Isua Supracrustal Belt)	3.6 Ga	16	[348]
68.90	Vaalbara craton crust, old	3.6 Ga	17	[476]
68.91	Vaalbara formation (table)	3636 Ma	17	[475]
68.92–68.97	Orientale age (bombardment)	about 3.7–3.9 Ga	13	[336]
68.92–68.95	Isua banded iron formations	3700–3800 Ma	13	[346]
68.92	Isua field age (geomagnetic field)	3.7 Ga	13	[348]
68.92 to 68.95	Isua BIF (Isua, Greenland)	3,700-3,800 Ma	22	[346]
68.94–68.98	Impact-melt age cluster (bombardment)	3.75–3.95 Ga	13	[336]
68.94	Cross-cutting granites U–Pb (minimum) (Nuvvuagittuq)	3750 Ma	13	[343]
68.94	Detrital zircon maximum (Nuvvuagittuq)	3780 Ma	13	[343]
68.94	Felsic bands U–Pb (Nuvvuagittuq)	>3.768 Ga	13	[341]
68.94–69.06	Putative microfossils (Nuvvuagittuq)	≥3770, possibly 4280 Ma	13	[345]
68.94 to 69.06	Putative microfossils, Nuvvuagittuq (hydrothermal vent precipitates, Quebec)	at least 3,770, possibly 4,280 Ma	22	[345]
68.95	Isua pillow basalts	about 3.8 Ga	13	[276]
68.95	Isua BIF with light carbon	about 3800 Ma	13	[347]
68.95	Subduction as early as (plate tectonics)	3.8 Ga	13	[354]
68.95	Isua pillow basalts (Isua Greenstone Belt)	3.8 Ga	14	[276]
68.95	Nuvvuagittuq Greenstone Belt age	3.8 or 4.28 Ga	14	[276]
68.95	Archean liquid	3.8–2.5 Ga	15	[380]

	water and life (Earth surface)			
68.95	subduction onset, early (plate tectonics)	3.8 Ga	17	[354]
68.95	Archean start (time scale)	3.8 Ga	17	[380]
68.96	Spike date from first solids (computed) (bombardment)	3867 Ma	13	[337]
68.96	Akilia	possibly >3850 Ma	13	[347]
68.96	Akilia rock possibly older (Akilia, Greenland)	>3,850 Ma	22	[347]
68.97–69.06	Jack Hills zircons 3,910–4,280 Myr (Hadean water)	3910–4280 Ma	13	[330]
68.97	Cataclysm pulse as defined (bombardment)	3.9 ± 0.1 Ga	13	[336]
68.97–68.98	Imbrium age (bombardment)	3.91–3.94 Ga	13	[336]
68.97	Vaalbara palaeomagnetic link	3.87 Ga	17	[476]
68.98 / 69.05	Nectaris age, two readings (bombardment)	3.92 or 4.25 ± 0.05 Ga	13	[336]
68.98–68.57	Typical Archaean rocks (Archaean crust)	3.9–2.5 Ga	13	[342]
68.98	Acasta polyphase (Mojzsis 2014)	about 3920 Ma	13	[341]
68.99	Acasta gneisses (Bowring 1989)	3.96 Ga	13	[341]
69.00–69.04	Inclusion-bearing zircon ages (Hadean crust)	4.02–4.19 Ga	13	[329]
69.00	Acasta oldest components	4030 Ma	13	[326]
69.00–69.08	Relative quiescence (bombardment)	about 4.0–4.2 to 4.4 Ga	13	[336]
69.00–69.04	Hybrid late instability (bombardment)	about 4.0 to 4.2 Ga	13	[336]
69.00	Acasta orthogneisses	4.00–4.03 Ga	13	[340]
69.00	Idiwhaa tonalitic gneiss (Acasta)	4.02 (4.03 summary) Ga	13	[342]
69.00	inclusion-bearing zircons, younger age	4.02 Ga	17	[329]
69.00	Hadean onset (plate tectonics)	4 Ga	17	[354]
69.01	Strong Hadean field (Jack Hills zircons)	4.1–4.0 Ga	16	[333]
69.02	Zircon with graphite inclusions (Hadean crust)	4.10 ± 0.01 Ga	13	[331]
69.02–69.00	High field strength period (geomagnetic field)	4.1–4.0 Ga	13	[333]

69.02–68.95	Bombardment window in habitability model	4.1–3.8 Ga	13	[338]
69.02	Sawtooth second wave (bombardment)	4.1 Ga	13	[336]
69.03	Gabbroic dike (Sole 2025) (Nuvvuagittuq)	4157 Ma	13	[343]
69.04	Inner core age, Konôpková 2016	<4.2 Ga	11	[285]
69.04 / 68.92 / 68.57	Lunar meteorite clast ages (bombardment)	oldest ~4.2, peak ~3.7, to ~2.5 Ga	13	[336]
69.04	Descartes clast event (bombardment)	4.22 ± 0.01 Ga	13	[336]
69.04	inclusion-bearing zircons, older age	4.19 Ga	17	[329]
69.06	FAN 62236 Sm–Nd (Moon)	4.29 ± 0.06 Ga	12	[300]
69.06	Earlier oldest Yilgarn zircons (Hadean crust)	about 4276 Ma	13	[326]
69.06	Narryer Gneiss terrane zircon (Hadean crust)	as great as 4.3 Ga	13	[281]
69.06	Hydrosphere interacting with crust by (Hadean water)	4300 Ma	13	[330]
69.06	Nuvvuagittuq 146Sm–142Nd isochron	4280 (+53/−81) Ma	13	[344]
69.06	Nuvvuagittuq crystallization Sm–Nd (O'Neil 2019)	4.313 Ga	13	[341]
69.06	Earlier oldest zircon (Jack Hills zircons)	4276 Ma	14	[326]
69.06	Zircons with δ18O to 15.0 per mil (Jack Hills zircons)	3910–4280 Ma	14	[330]
69.06	Near-surface water by (Earth surface)	4300 Ma	14	[330]
69.07	FAN 60025 crystallization (Moon)	4360 ± 3 Ma	12	[302]
69.07	Crust formation, erosion, recycling by (Hadean crust)	4.35 Ga	13	[328]
69.07 / 69.08	Nuvvuagittuq gabbro Sm–Nd	4321 (also c. 4388 printed) Ma	13	[343]
69.08	Silicate Earth mixed before (atom probe)	4.4 Ga	12	[297]
69.08	ur-KREEP model age (Moon)	4.368 ± 0.029 Ga	12	[300]
69.08	Ferroan anorthosites age (Moon)	circa 4.4 Ga	12	[309]
69.08	Oldest detrital zircon, Jack Hills (Hadean crust)	4404 ± 8 Ma	13	[326]
69.08	Oldest zircon recording water,	4404 ± 8 Ma	14	[326]

	Jack Hills (Jack Hills zircon)			
69.08	Oldest zircon marked by water (Jack Hills zircon)	4404 ± 8 Ma	15	[326]
69.08	Oldest Jack Hills zircon	4404 ± 8 Ma	16	[326]
69.08	Oldest terrestrial zircon, Jack Hills (detrital zircon, Yilgarn Craton)	4,404 ± 8 Ma	21	[326]
69.08	Hadean zircon examined by atom-probe tomography	4.4 Ga	21	[297]
69.09	Oldest lunar zircon (72255) (Moon)	4460 ± 31 Ma	12	[301]
69.09	Lunar anorthosites Sm–Nd (Moon)	4440 Ma	12	[269]
69.09	Highland rocks age (Moon)	up to about 4.44 Ga	12	[309]
69.10	Lunar crust differentiated (zircon Hf) (Moon)	4.51 (± 0.01) Ga	12	[299; 300]
69.10	Impact heating in meteorites (Bottke 2015) (Moon)	4.47 Ga	12	[292]
69.10	Moon age (Halliday 2008)	about 4.48 Ga	12	[292]
69.10	Accretion of icy planetesimals (Earth)	4.5 Ga	14	[276]
69.11	End of core formation (computed) (Earth core)	4537 Ma	11	[268; 274]
69.11	Moon age (Taylor 1998)	4.527 ± 0.010 Ga	12	[292]
69.11	FAN 67016 Sm–Nd (Moon)	4.56 ± 0.07 Ga	12	[300]
69.12	Age of CAIs, first solids (U-corrected Pb–Pb) (solar system)	4567.30 ± 0.16 Ma	11	[265]
69.12	Age of CAI in NWA 2364 (Pb–Pb) (solar system)	4568.2 Ma	11	[266]
69.12	Chondrule ages (solar system)	4567.32 ± 0.42 to 4564.71 ± 0.30 Ma	11	[265]
69.12	Solar system start used in Hf–W review	4567 Ma	11	[268]
69.12	Solar system origin from uranium decay in meteorites (press)	4567 Ma	11	[269]
69.63	Split of age-metallicity sequences (Milky Way disc)	8 Gyr ago	34	[726]
69.63-69.92	Accretion epoch (Gaia-Enceladus)	8-11 Gyr ago	34	[965]
69.83	Gaia-Enceladus merger time	10 Gyr ago	34	[964]
69.92	Most thick-disk stars formed (Milky Way)	11 Gyr ago	28	[726]

69.92	Most thick-disc stars formed (Milky Way thick disc)	11 Gyr ago	34	[726]
70.07	Thick disk start (Milky Way)	13 Gyr ago	28	[726]
70.07	Thick-disc star formation begins (Milky Way thick disc)	13 Gyr ago	34	[726]

What the ladder shows

The ladder holds this whole book on one scale. In length it runs from the Stoney length, at −59.77, and the Planck length, at −57.53, to the diameter of the observable universe, 28.5 Gpc, at 71.86. That is about 130 positions: a factor of three, 130 times over.

The three parts stand on it one after another. The proton’s charge radius, 0.8409 fm, stands at −16.21 and the Bohr radius at −6.15. The Earth’s mean radius, 6,371 km, stands at 29.65, its circumference at 31.32, and the Moon’s distance at 33.38.

The Sun’s radius, 695,700 km, stands at 33.92 and the heliopause, 119 AU, at 43.16. The stellar disc of the Galaxy, about 62 kpc across, stands at 59.99. Laniakea follows at 66.88 and the edge of the observable universe at 71.86.

Several positions below the atom are identities of the ladder’s units. The unit of length is half the inverse of the Rydberg constant of hydrogen. The Bohr radius is $(\alpha/2\pi)\cdot S_0$ at −6.15 and the electron’s Compton wavelength $\alpha^2\cdot S_0$ at −8.96.

Two closure depths stand in the sky. Depth 41, 11.11 AU, lies between Saturn’s aphelion at 40.91 and Uranus’s perihelion at 41.45, where only the centaur Chiron crosses. Depth 53, 93.40 light-years, encloses the Sun’s neighbourhood; the Hyades lie beyond it.

In time the ladder runs from the shortest measured lives, the Z boson at −18.36 and the top quark at −17.85, to the age of the universe, 13.787 Gyr, at 70.12. The muon lives at 21.29 and the free neutron at 39.32. Today’s day stands at 43.50 and the day of 1.4 Ga, 18.68 h, at 43.27.

The long rhythms of the Earth climb above. The last reversal of the field, 773 ka, stands at 61.21 and the half-life of uranium-238 at 69.10, beside the first solids, 4,567.30 Ma, at 69.12. Light set free at last scattering, 371.8 kyr after the beginning, stands at 60.55.

What closes, stays. The proton and the electron hold through every bound measured, the oldest zircon holds its age of 4,404 Ma, and the disc of the Galaxy holds its shape while stars are born and die in it. The form lasts while its carriers are replaced.

The ladder does not end at the top row of these tables. “A ladder driven by a rest cannot end.” The last closure depth, 306, stands far above every position written here.

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