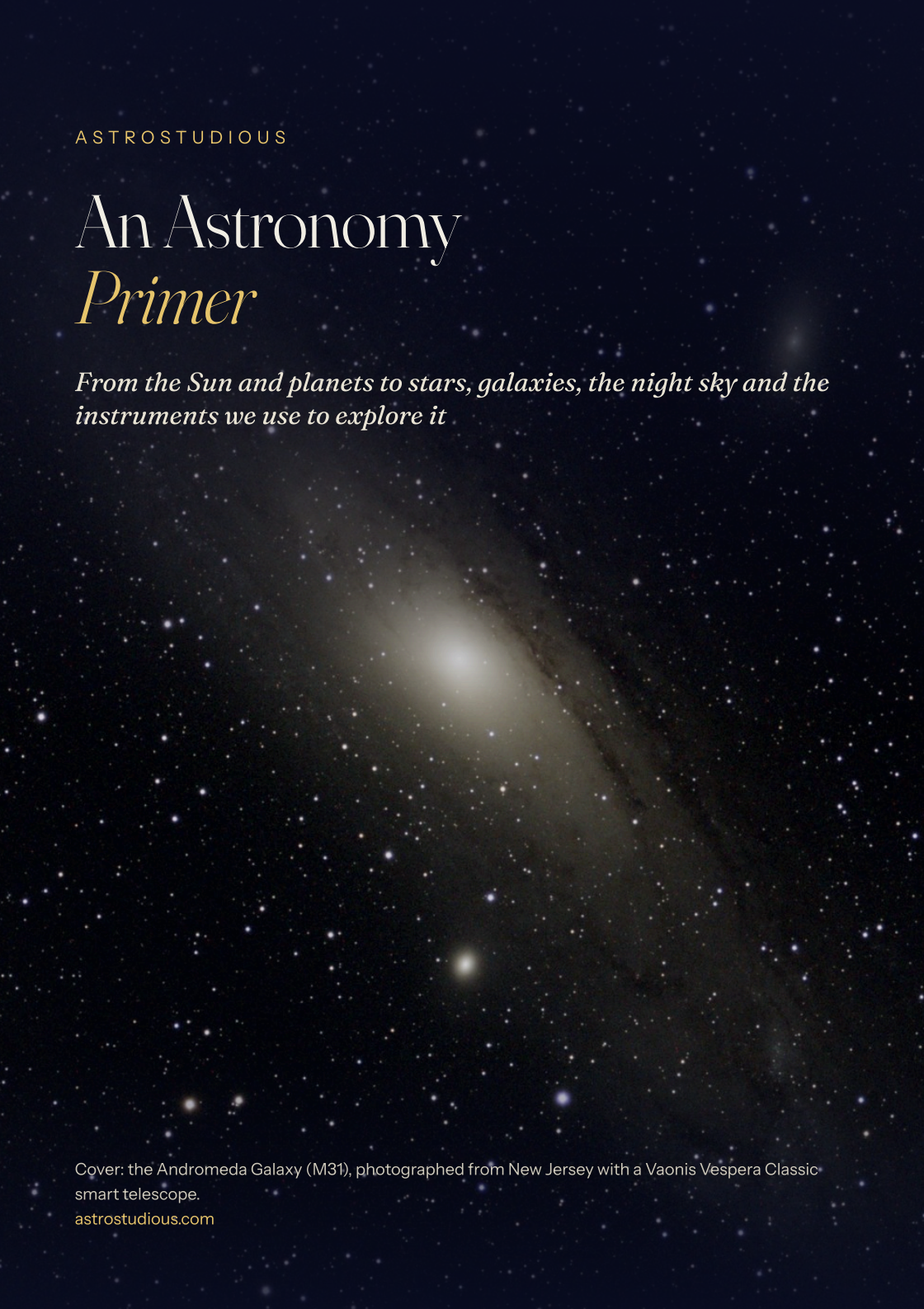
ASTROSTUDIOUS

An Astronomy *Primer*

From the Sun and planets to stars, galaxies, the night sky and the instruments we use to explore it



Cover: the Andromeda Galaxy (M31), photographed from New Jersey with a Vaonis Vespera Classic smart telescope.

astrostudious.com

AstroStudious Astronomy Primer

A simple primer for anyone who has looked up at the night sky and wondered.

The text, diagrams and photographs of the AstroStudious website astrostudious.com

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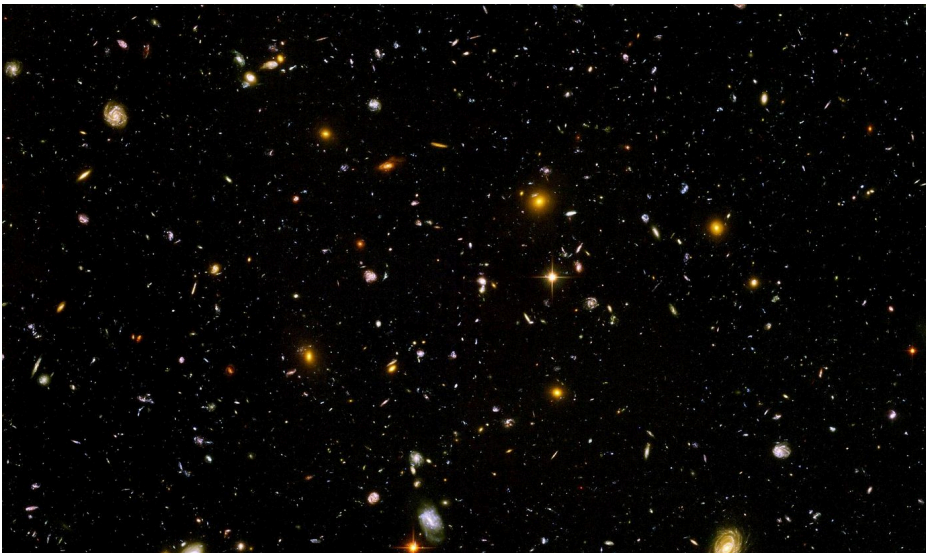
INTRODUCTION

A sense of scale

A simple primer for anyone who has looked up at the night sky and wondered. It covers the basics, goes deeper in a few places, and hopes to leave you curious enough to keep exploring.



Hubble Ultra Deep Field — NASA/ESA (public domain)

A sense of scale before we begin

Light takes eight minutes to reach Earth from the Sun, four hours to reach Neptune, and more than a year to clear the Oort cloud. The next star is four years away at that speed. The centre of the Milky Way is about 26,000 years

away; the Andromeda Galaxy, 2.5 million. The faintest galaxies in the image above sent their light toward us some 13 billion years ago.

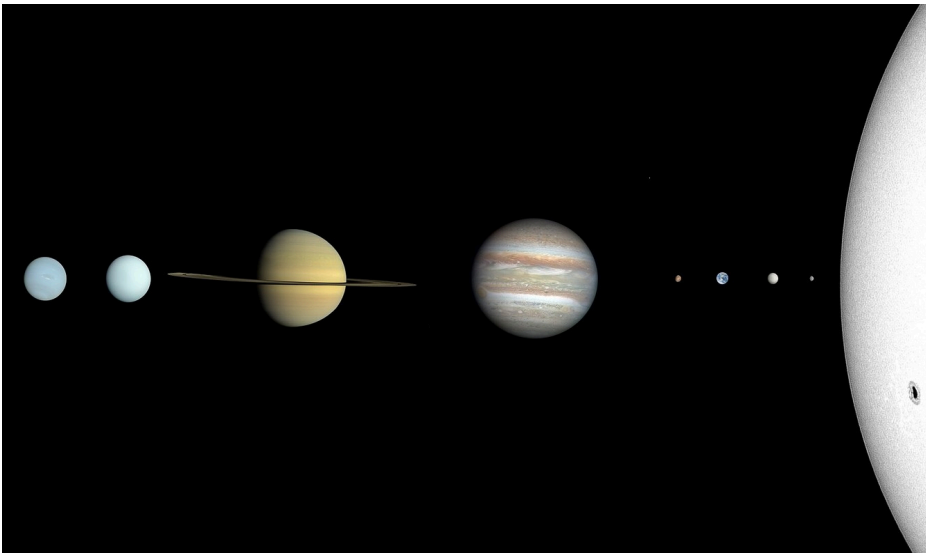
This book works outward along that path. It begins with our own Solar System and the Sun, moves on to how stars are born, live and die, and then to galaxies and the expanding universe. Two chapters bring it back to the backyard: how astronomers map the sky and how it slowly shifts, and the constellations and the seasons. A final chapter explains the telescopes and instruments used to observe it all.

SUN TO EARTH 8.3 light-minutes	SUN TO NEPTUNE 4.2 light-hours
EDGE OF OORT CLOUD ~1–1.5 light-years	NEAREST STAR 4.2 light-years
GALACTIC CENTRE ~26,000 light-years	ANDROMEDA 2.5 million light-years

CHAPTER 1

The Solar System

One ordinary star, eight planets, a scattering of dwarf planets, and two vast reservoirs of ice that reach a good fraction of the way to the next star.



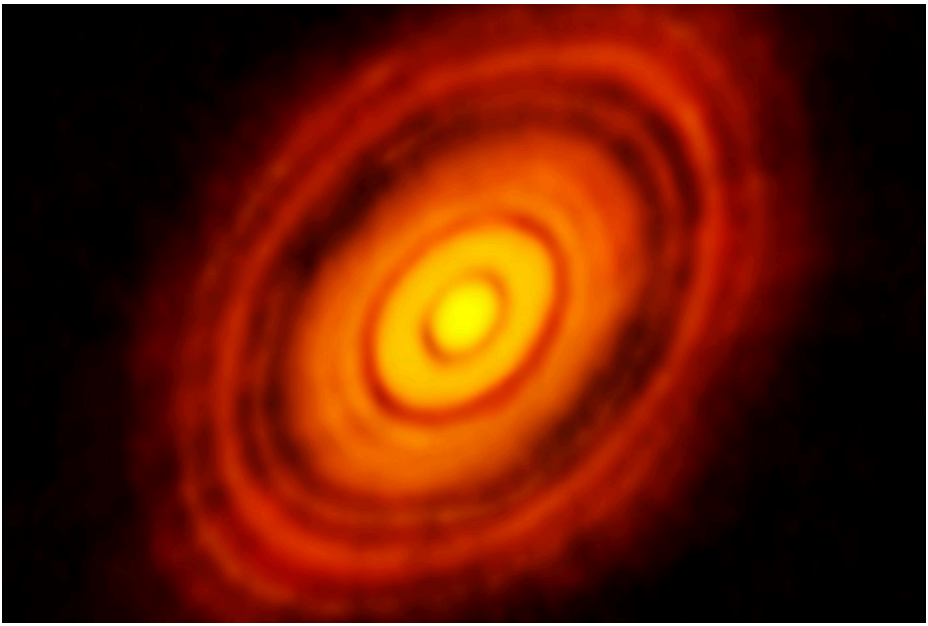
The planets in true colour, to scale — CactiStaccingCrane, CC BY-SA 4.0

Where it came from

About 4.6 billion years ago a cold fragment of a molecular cloud, a few light-years across, began to collapse under its own weight. Almost everything fell to the centre and became the Sun. The small fraction of material with too much sideways motion to fall in flattened into a spinning disc, and that disc is where the rest of the solar system was built.

Close to the young Sun the disc was hot, and only rock and metal could condense. Farther out, past what astronomers call the frost line (roughly where the asteroid belt is now), water, ammonia and methane froze too, so there was far more solid material to gather. That single temperature gradient explains the basic layout: small rocky worlds inside, giants outside, ice everywhere beyond them.

Dust grains stuck together into pebbles, pebbles into planetesimals kilometres across, and planetesimals collided and merged into planets. The giant planets grew fast enough to pull in the surrounding gas before the Sun's early wind blew the disc away, a window of only a few million years. Whatever was left over — never swept up, never flung out — is what we see today as asteroids, comets and the Kuiper belt.



Another solar system in the making. ALMA's image of the young star HL Tauri shows a dusty disc with dark gaps where planets are probably sweeping up material — a snapshot of what our own system looked like in its first million years.

ALMA (ESO/NAOJ/NRAO), CC BY 4.0

The Sun

The Sun holds 99.8% of the mass of the solar system. It is a G-type main-sequence star, middle-aged and thoroughly average, which is exactly what makes it useful: everything we learn about it applies to hundreds of billions of stars like it.

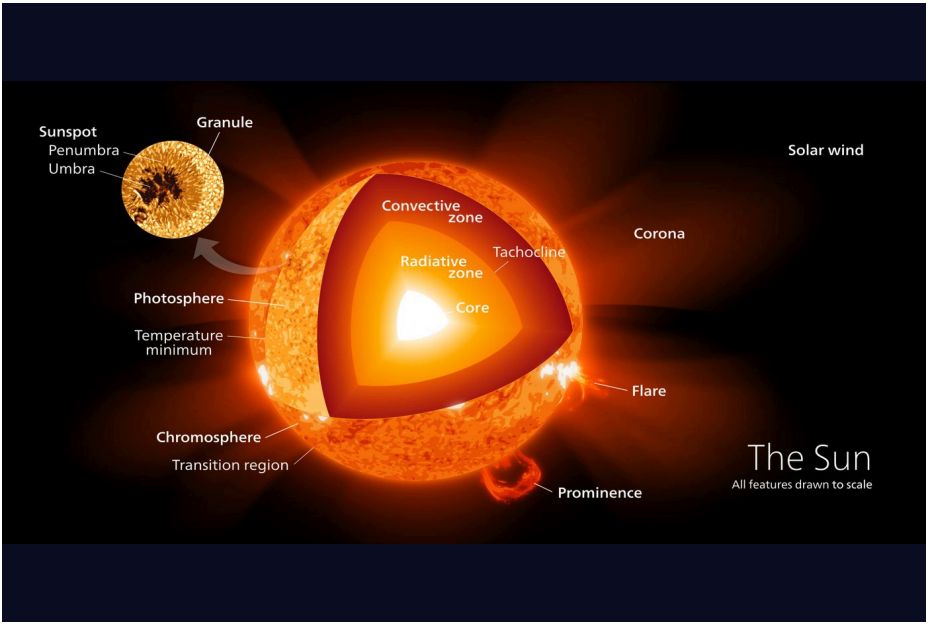
At the centre, 15 million kelvin and a density thirteen times that of lead let hydrogen nuclei fuse into helium through the proton–proton chain. About 600 million tonnes of hydrogen become helium every second, and 4 million tonnes of that mass disappears as energy, in accordance with $E = mc^2$. The energy leaks outward as radiation through the deep interior, then is carried by boiling convection cells through the outer third, arriving at the visible surface — the photosphere — roughly 100,000 years after it was made.

The photosphere is only about 5,800 K, but the tenuous corona above it is over a million degrees, a puzzle that has driven decades of solar physics and is now attributed largely to magnetic waves and small-scale reconnection events. The corona streams away as the solar wind, a flow of charged particles that inflates a bubble around the whole solar system called the heliosphere. Sunspots, flares and coronal mass ejections all follow an approximately eleven-year magnetic cycle.

MASS 333,000 Earths	DIAMETER 1.39 million km
CORE TEMPERATURE 15 million K	SURFACE TEMPERATURE 5,800 K
AGE 4.6 billion yr	MAIN-SEQUENCE LIFE ~10 billion yr

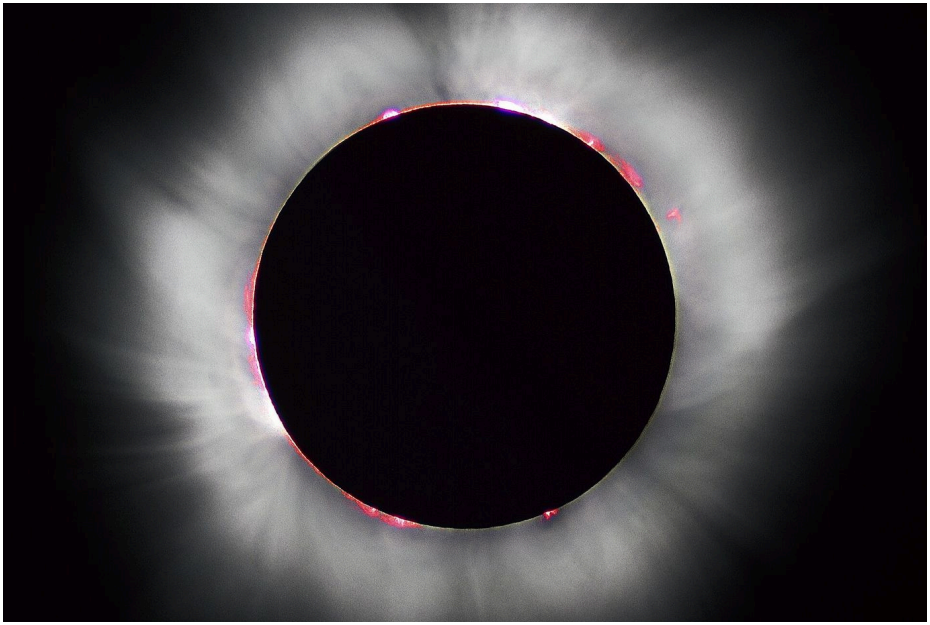
The Sun's surface is constantly changing. Sunspots, plage, filaments, prominences, flares and coronal mass ejections are all driven by its magnetic field; see Features of the Sun for a guide to each, with Earth shown to scale.

Its future is covered in the Stars chapter: in about five billion years the Sun will swell into a red giant, shed its envelope as a planetary nebula, and settle down as a white dwarf.



The layered Sun. Fusion happens only in the core, roughly the inner quarter by radius.

Kelvinsong, CC BY-SA 3.0

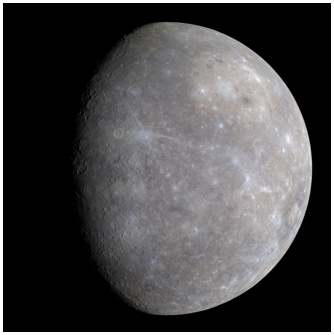


The corona, visible only when the Moon blocks the photosphere. The 1999 total eclipse from France.

Luc Viatour, CC BY-SA 3.0

The rocky planets

Four small, dense worlds formed inside the frost line from rock and metal, each with an iron core and a silicate mantle. Their differences come down to size and distance from the Sun.

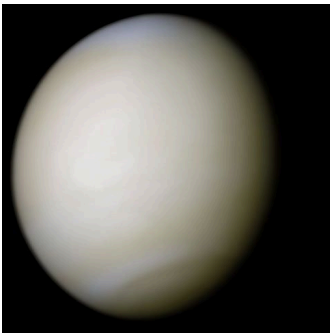


NASA/JHUAPL (public domain)

Mercury *0.39 AU*

The smallest planet and the fastest, completing an orbit in 88 days. It is oddly dense: its iron core makes up more than 60% of its mass, perhaps because a giant impact stripped away much of its original mantle. With almost no atmosphere, the surface swings from 430 °C at noon to −180 °C at night. Mercury's day is peculiar too: it rotates exactly three times for every two orbits, so a single day–night cycle lasts 176

Earth days. The MESSENGER and BepiColombo missions found water ice in permanently shadowed polar craters and a surprisingly active magnetic field.



NASA/Mariner 10 (public domain)

Venus *0.72 AU*

Almost Earth's twin in size and mass, and a lesson in how differently a planet can turn out. A carbon-dioxide atmosphere 90 times denser than ours traps heat so effectively that the surface sits at 465 °C everywhere, hotter than Mercury. Sulphuric-acid clouds hide the ground completely; radar mapping reveals volcanic plains, a few thousand volcanoes and evidence of recent eruptions. Venus rotates backwards and very slowly — a Venusian day is longer than its year. It is the brightest object in our sky after the Sun and Moon.



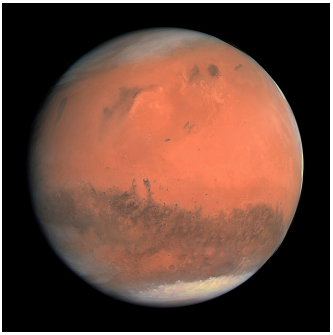
NASA/Apollo 17 (public domain)

Earth *1 AU*

The only world known to have liquid water on its surface, plate tectonics, and life. Its distance from the Sun is part of that, but so is its nitrogen–oxygen atmosphere, its magnetic field (generated by convection in a liquid iron outer core), and its unusually large Moon, which stabilises the tilt of the axis and drives the tides. The Moon is thought to have formed from debris after a Mars-sized body struck the young Earth about 4.5 billion years ago. Earth's 23.4° axial tilt gives us the seasons; its 24-hour rotation and 365.25-day orbit are the base units of every calendar.

Mars *1.5 AU*

Half Earth's diameter, a tenth its mass, with a thin CO_2 atmosphere and an average temperature of −60 °C. Its colour is iron oxide — rust. Mars has the



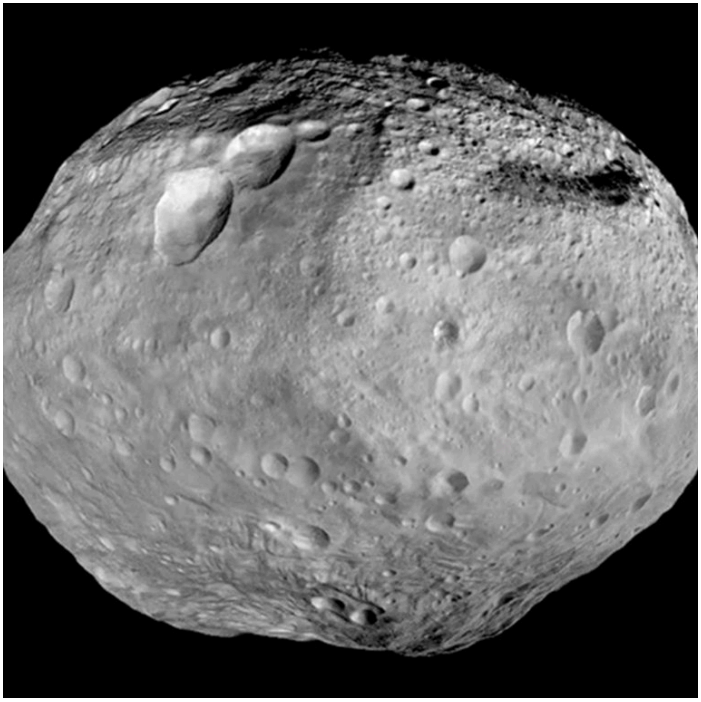
ESA/Rosetta, CC BY-SA 3.0 IGO

tallest volcano in the solar system (Olympus Mons, 22 km high) and a canyon system, Valles Marineris, that would stretch across the United States. Rovers and orbiters have found dry river valleys, lake beds, clay minerals and buried ice: three to four billion years ago Mars was wetter and warmer, before it lost most of its atmosphere to space once its magnetic field died. Two small captured asteroids, Phobos and Deimos, serve as moons.

The asteroid belt

Between Mars and Jupiter lies a zone where Jupiter's gravity stirred the planetesimals too violently for them ever to assemble into a planet. What remains is the asteroid belt: more than a million rocky and metallic bodies larger than a kilometre, with a total mass of only about 3% of the Moon. Despite film depictions, it is mostly empty space; spacecraft cross it without special manoeuvres.

The largest member, Ceres, is nearly 1,000 km across and round enough to count as a dwarf planet (see below). Vesta, the second-largest, has a basaltic crust and a huge impact basin at its south pole; fragments of it fall to Earth as a recognised class of meteorite. Asteroids are the nearest thing we have to leftover building blocks from the original disc, which is why sample-return missions such as Hayabusa2 and OSIRIS-REx went to fetch pieces.



Vesta, 525 km across, imaged by NASA's Dawn spacecraft in 2011.

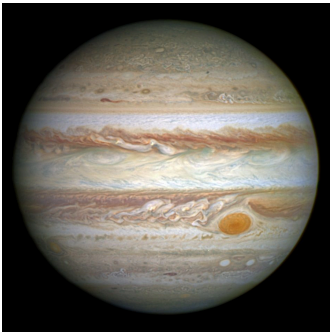
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA (public domain)

The giant planets

Beyond the frost line, ice was plentiful and the planets grew large enough to capture hydrogen and helium directly from the disc. Jupiter and Saturn are gas giants, mostly hydrogen and helium down to their cores. Uranus and Neptune, farther out and slower to form, are ice giants, richer in water, ammonia and methane. All four have rings and large families of moons.

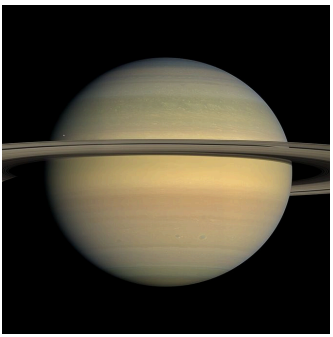
Jupiter *5.2 AU*

More than twice as massive as all the other planets combined. Its banded clouds of ammonia crystals race around the planet in under ten hours, driven by heat still escaping from Jupiter's formation. The Great Red Spot is an anticyclone larger than Earth that has persisted for at least 190 years. Deep inside, hydrogen is squeezed into a liquid metallic state, generating the



NASA/ESA/Hubble (public domain)

strongest magnetic field of any planet. Jupiter has 95 confirmed moons; the four Galilean moons — Io, Europa, Ganymede and Callisto — are worlds in their own right, and Europa's subsurface ocean is a leading candidate for life elsewhere in the solar system.



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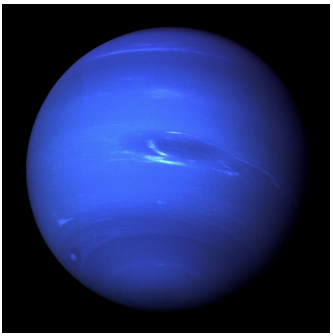
Saturn *9.6 AU*

The least dense planet — it would float in water — and the owner of the solar system's great rings. The rings are almost pure water ice, spanning 280,000 km but in places only ten metres thick, and they may be surprisingly young, perhaps only a few hundred million years old. Saturn has 146 known moons, more than any other planet. Titan, the largest, has a thick nitrogen atmosphere and lakes of liquid methane; tiny Enceladus sprays water vapour from geysers over a subsurface ocean. A hexagonal jet stream circles the north pole.



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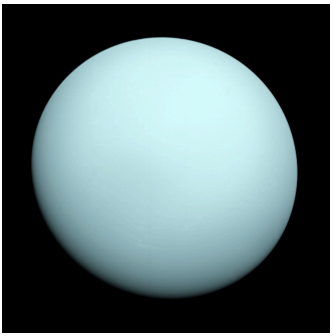
Uranus *19 AU*

The first planet discovered with a telescope (William Herschel, 1781). Uranus is tipped on its side, its axis tilted 98°, so each pole gets 42 years of continuous daylight followed by 42 of darkness — probably the result of a giant collision early in its history. Methane in the upper atmosphere absorbs red light and gives the planet its aquamarine colour. It is the coldest planet, with cloud-top temperatures near −224

°C, and radiates almost no internal heat. Voyager 2 in 1986 remains the only spacecraft to visit. It has 13 faint rings and 28 known moons named after characters from Shakespeare and Pope.



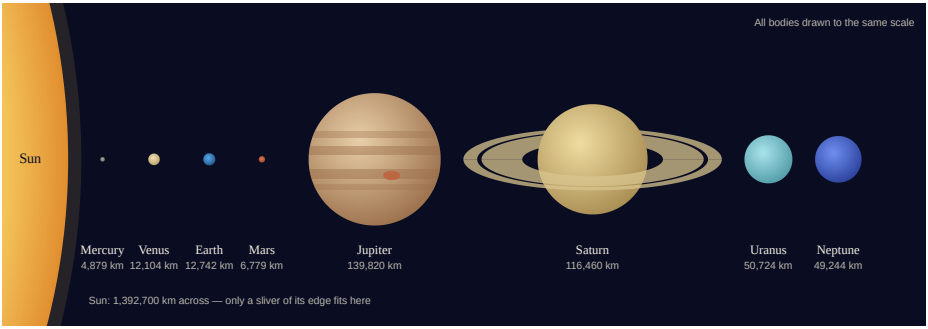
NASA/JPL (public domain)

Neptune *30 AU*

Found in 1846 not by searching but by calculation: irregularities in the orbit of Uranus pointed to an unseen planet, and Neptune was where the mathematics said it should be. It has the fastest winds in the solar system, over 2,000 km/h, and radiates 2.6 times the energy it receives from the Sun. Its large moon Triton orbits backwards and is almost certainly a captured Kuiper belt object; it has nitrogen geysers and a surface of frozen nitrogen at −235 °C. Neptune's gravity shapes the entire Kuiper belt beyond it, herding Pluto and thousands of other bodies into resonant orbits.

The planets at a glance

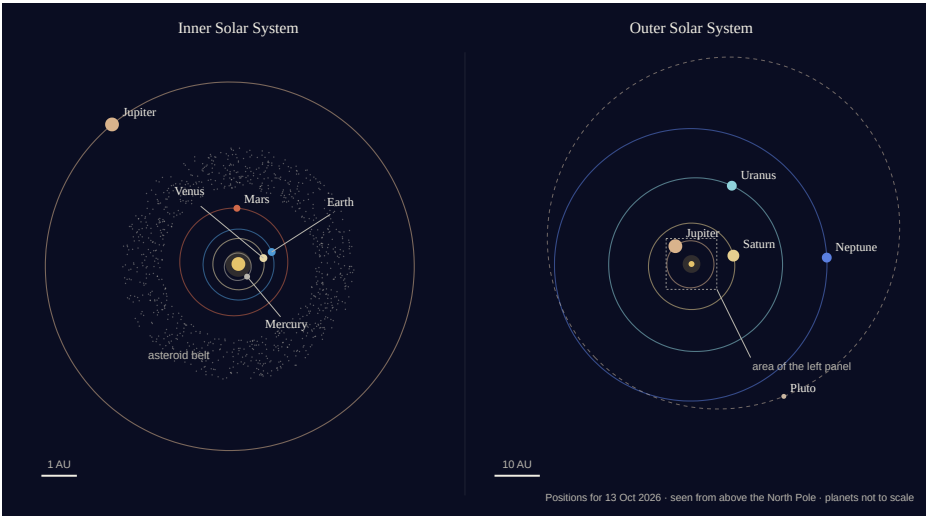
Planet	Distance (AU)	Diameter (Earth = 1)	Mass (Earth = 1)	Year	Day	Known moons
Mercury	0.39	0.38	0.055	88 d	59 d	0
Venus	0.72	0.95	0.82	225 d	243 d (retrograde)	0
Earth	1.00	1.00	1.00	365 d	24 h	1
Mars	1.52	0.53	0.11	687 d	24.6 h	2
Jupiter	5.20	11.2	318	11.9 yr	9.9 h	95
Saturn	9.58	9.45	95	29.5 yr	10.6 h	146
Uranus	19.2	4.0	14.5	84 yr	17.2 h (retrograde)	28
Neptune	30.1	3.9	17.1	165 yr	16.1 h	16



The planets in order from the Sun, all drawn to the same scale. Jupiter is about 11 times wider than Earth, and the Sun is about 10 times wider than Jupiter — only a sliver of its edge fits at the left. Distances between the planets are not to scale; see how far apart everything is.

The planets in their orbits

Seen from above, the orbits are nearly circular and almost all in one plane, and the planets all travel the same way around the Sun — counter-clockwise when viewed from above the North Pole. Here the orbits are drawn to scale in two panels, because the outer system is so much larger than the inner one: the whole left panel fits inside the small dotted square at the centre of the right one. Each planet is shown where it is in October 2026. Notice that Pluto's tilted, stretched orbit brings it closer to the Sun than Neptune for 20 years of its 248-year circuit; the two never collide because Pluto is locked in step with Neptune (see the Kuiper belt).



The orbits of the planets to scale, with each planet at its approximate position on 13 October 2026. The planets themselves are drawn hugely enlarged; at this scale even Jupiter would be far smaller than a pixel. 1 AU is the Earth–Sun distance.

Spin, tilt, days and years

Every planet does two things at once: it **revolves** around the Sun, and it **rotates** on its own axis. The time to go once around the Sun is the planet's year; the time to turn once on its axis is its rotation period. The angle between that axis and a line perpendicular to the orbit is its **axial tilt**, and the tilt is what gives a planet seasons.

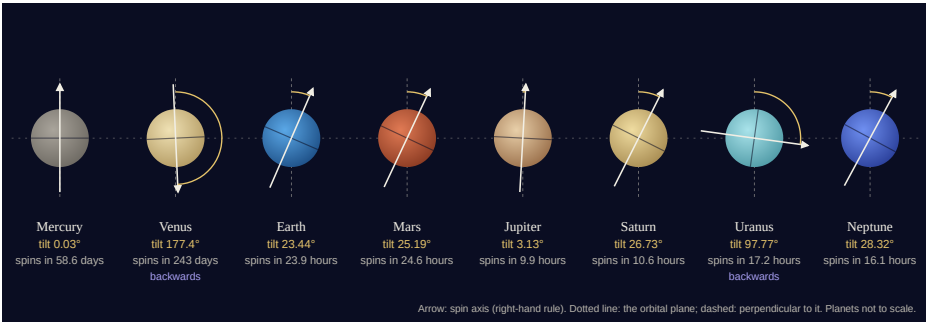
The cloud of gas and dust the planets formed from was itself turning, so the planets all orbit in the same direction and most also spin that way. Two do not. **Venus** turns backwards, and so slowly that one rotation (243 Earth days) takes longer than its year (225 days); from its surface the Sun would rise in the west and set in the east, about 117 days later. **Uranus** is tipped 98°, so it rolls around the Sun on its side. Each pole gets about 42 years of continuous sunlight followed by 42 years of darkness. A collision with an Earth-sized body early in its history is the likely cause.

Mercury stands almost perfectly upright and is locked into an unusual rhythm by the Sun's gravity: it turns exactly three times for every two orbits. The result is that a full day, from one sunrise to the next, lasts 176 Earth days — two Mercury years.

Earth and **Mars** are near-twins in this respect: tilts of 23.4° and 25.2°, and days of 24 hours and 24 hours 40 minutes. Mars therefore has seasons like ours, each roughly twice as long. Our large Moon steadies Earth's tilt; Mars, with no such moon, has swung between roughly 10° and 60° over tens of millions of years, rearranging its ice caps and climate.

The giant planets spin fastest of all. **Jupiter** turns in under ten hours, so quickly that it bulges about 7% wider at its equator than through its poles; **Saturn**, in about 10 hours 34 minutes, is flattened by 10% — easily visible in a small telescope. Neither has a solid surface, so their rotation periods are measured from their magnetic fields and radio emissions, and for Saturn from waves in its rings recorded by the Cassini spacecraft. Jupiter's tilt is only 3°, so it has almost no seasons; Saturn and Neptune are tilted much like Earth, and their seasons each last decades.

The length of the year follows a simple rule that Johannes Kepler found in 1619: the square of a planet's orbital period is proportional to the cube of its distance from the Sun. Double the distance and the year lengthens almost threefold. Farther planets also move more slowly — Mercury races along at 47 km/s, Earth at 30 km/s and Neptune at just 5.4 km/s — so Neptune, 30 times farther out than Earth, takes 165 years to complete one orbit. It has gone around the Sun only once since its discovery in 1846.



Each planet's axial tilt drawn to the true angle, with its rotation period. A tilt above 90° means the planet spins backwards (retrograde) compared with its orbit. Venus, at 177°, is effectively upside down; Uranus, at 98°, lies on its side.

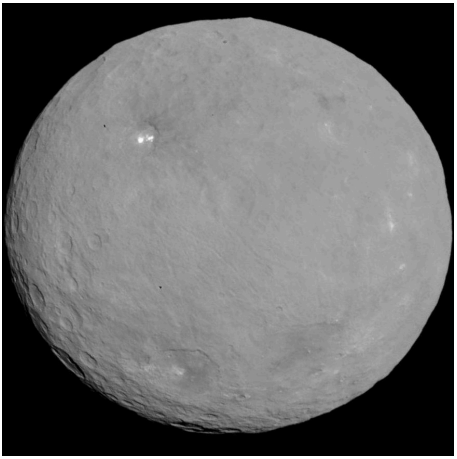
Rotation and revolution of the planets

Planet	Axial tilt	Rotation period	Sunrise to sunrise	Orbital period (year)	Orbital speed
Mercury	0.03°	58.6 days	176 days	88 days	47.4 km/s
Venus	177.4°	243 days (backwards)	117 days	225 days	35.0 km/s
Earth	23.44°	23 h 56 m	24 h	365.26 days	29.8 km/s
Mars	25.19°	24 h 37 m	24 h 40 m	687 days (1.88 yr)	24.1 km/s
Jupiter	3.13°	9 h 56 m	9 h 56 m	11.9 years	13.1 km/s
Saturn	26.73°	10 h 34 m	10 h 34 m	29.5 years	9.7 km/s
Uranus	97.77°	17 h 14 m (backwards)	17 h 14 m	84.0 years	6.8 km/s
Neptune	28.32°	16 h 6 m	16 h 6 m	164.8 years	5.4 km/s

The rotation period is measured against the distant stars. "Sunrise to sunrise" is the solar day, which differs from it because the planet moves along its orbit while it turns; for the fast-spinning giants the two are practically the same.

Dwarf planets and the lesser worlds

In 2006 the International Astronomical Union settled a long argument by defining a planet as a body that orbits the Sun, is massive enough for gravity to pull it round, and has cleared its orbital neighbourhood of other objects. A body that meets the first two tests but not the third is a dwarf planet. Five are officially recognised — Ceres, Pluto, Haumea, Makemake and Eris — and several dozen more Kuiper belt objects are probably large enough to qualify.



Ceres (2.8 AU, 940 km). The only dwarf planet in the asteroid belt. Its bright spots are salt deposits left by briny water that seeped up from a subsurface reservoir.

NASA/JPL-Caltech/UCLA/MPS/DLR/IDA (public domain)



Pluto (39.5 AU, 2,377 km). Discovered in 1930, visited by New Horizons in 2015. Nitrogen-ice glaciers flow across Sputnik Planitia, mountains of water ice rise 3 km, and a thin blue haze surrounds the planet. Its moon Charon is half its size.

NASA/JHUAPL/SwRI (public domain)



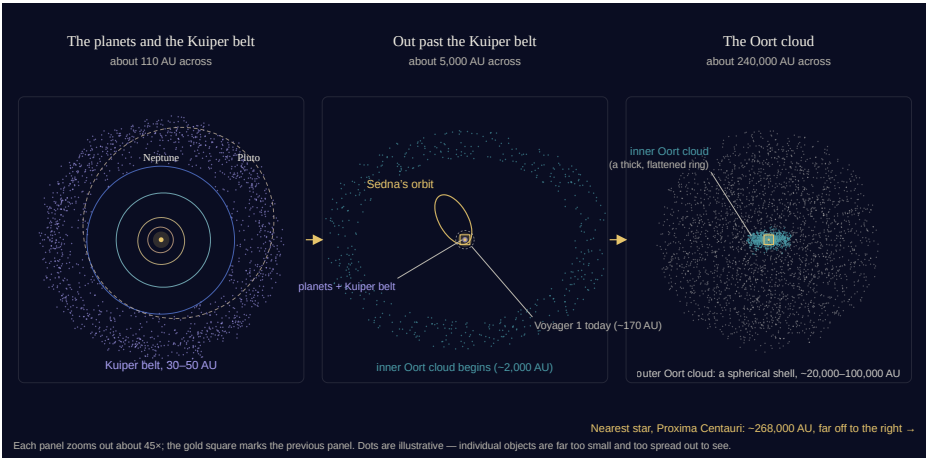
Charon, Pluto's largest moon, 1,212 km across. Pluto and Charon orbit a point between them; some astronomers regard them as a double dwarf planet.

NASA/JHUAPL/SwRI (public domain)

Dwarf planet	Region	Mean distance	Diameter	Notes
Ceres	Asteroid belt	2.8 AU	940 km	Water-rich; possible remnant subsurface brine
Pluto	Kuiper belt	39.5 AU	2,377 km	Five moons; 3:2 resonance with Neptune
Haumea	Kuiper belt	43 AU	~1,600 km (long axis ~2,100)	Spins every 4 hours, stretched into an ellipsoid; has a ring
Makemake	Kuiper belt	45.8 AU	~1,430 km	Methane-frost surface; one known moon
Eris	Scattered disc	68 AU	2,326 km	Slightly more massive than Pluto; its discovery in 2005 forced the planet definition

Beyond the planets: the Kuiper belt and the Oort cloud

The planets are only the inner core of the Sun's domain. Just past Neptune lies the Kuiper belt, a flat, doughnut-shaped disc of icy bodies in the same plane as the planets, from about 30 to 50 AU. Beyond it is a sparse scattered region where a few objects such as Sedna follow long, stretched orbits reaching hundreds of AU out. Then comes the Oort cloud: first a thick, flattened inner cloud starting around 2,000 AU, then an enormous, roughly spherical outer shell of comets reaching perhaps 100,000 AU — more than a third of the way to the nearest star. The three panels below zoom out step by step, and the next two sections look at each region in turn; in each, the gold square marks the whole of the panel before it.



Three views, each about 45 times wider than the last. The Kuiper belt is a flat disc in the plane of the planets; the outer Oort cloud is a sphere surrounding the Sun on all sides, which is why long-period comets arrive from every direction. The dots only show the shape of each region — the real objects are tiny and millions of kilometres apart.

The Kuiper belt

EXTENT 30–50 AU	TOTAL MASS ~2% of Earth
LARGEST MEMBER Pluto	TEMPERATURE ~40 K

Beyond Neptune, from about 30 to 50 AU, the solar system flattens out into a second, far larger belt of debris. The Kuiper belt is to comets what the asteroid belt is to asteroids: a disc of icy bodies left over from formation, never gathered into a planet because there was too little material spread over too great a volume, and because Neptune's gravity kept it stirred. It was predicted in the 1940s and 1950s, notably by Gerard Kuiper, but the first object other than Pluto was not found until 1992.

Several thousand Kuiper belt objects (KBOs) are now catalogued, and the belt probably holds more than 100,000 larger than 100 km. They fall into families. **Classical** objects follow nearly circular orbits in the main belt. **Resonant** objects, including Pluto, are locked into rhythms with Neptune —

Pluto orbits twice for every three Neptune orbits, which is why the two can never collide despite Pluto's crossing orbit. **Scattered-disc** objects like Eris were flung onto stretched, tilted orbits by Neptune and reach hundreds of AU.

The belt is the source of the short-period comets, and studying it tells us how the giant planets migrated. The leading model, called the Nice model, proposes that Neptune formed closer to the Sun and moved outward, ploughing through the primordial disc and scattering it — which explains the belt's sharp outer edge, its excited orbits and the resonant families.



Arrokoth (2014 MU69), the most distant object ever visited by a spacecraft, 6.6 billion km from the Sun. The red colour comes from complex organic molecules produced by radiation acting on ices.

NASA/JHUAPL/SwRI (public domain)

In 2019 New Horizons flew past Arrokoth, a 36-km classical KBO, and found two smooth lobes gently joined together — direct evidence that planetesimals formed by soft accumulation of pebbles rather than by violent collisions.

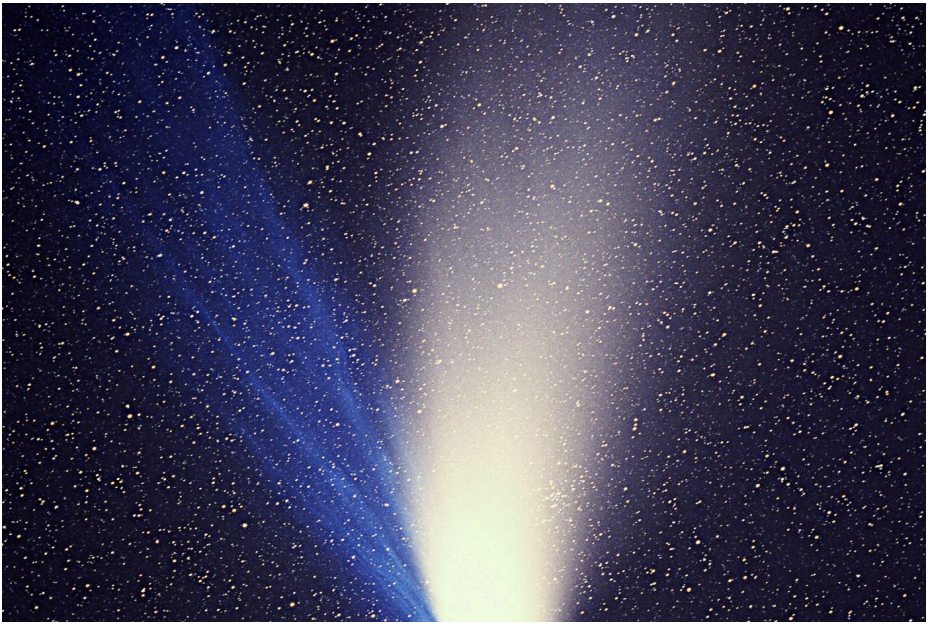
The Oort cloud

The Oort cloud has never been seen. It is inferred from the comets that fall out of it. In 1950 Jan Oort noticed that long-period comets arrive from every direction in the sky, not just from the plane of the planets, and that their orbits trace back to distances of tens of thousands of AU. He concluded the Sun must be surrounded by a vast spherical shell of icy bodies, only occasionally nudged inward.

The picture today: an inner, doughnut-shaped region (sometimes called the Hills cloud) from about 2,000 to 20,000 AU, and an outer spherical shell from 20,000 to perhaps 100,000 AU or more — a substantial fraction of the 4.2-light-year distance to the nearest star. It may contain trillions of objects larger than a kilometre, with a combined mass of a few Earths. These are the most distant things that still belong to the Sun.

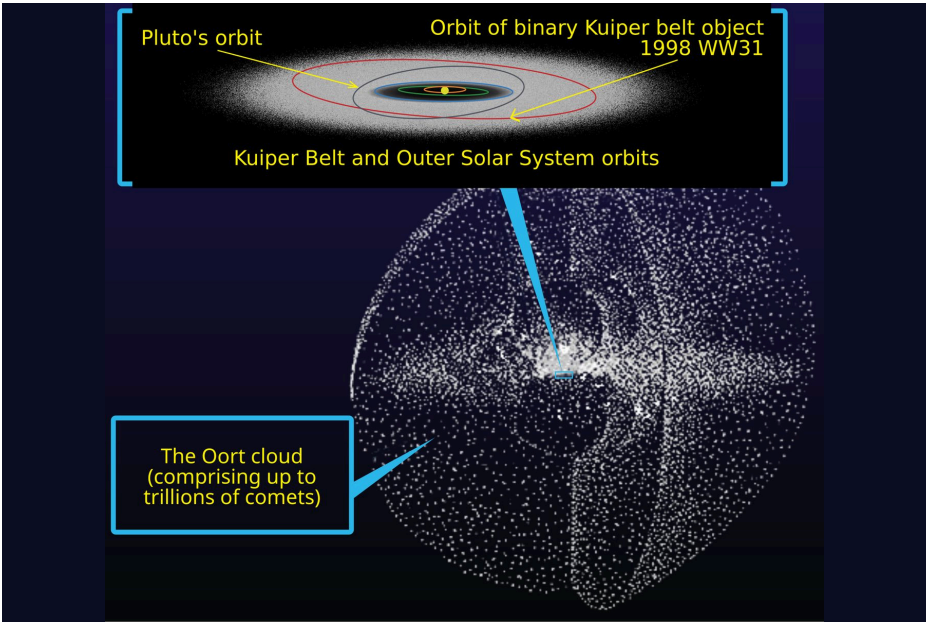
The cloud's members did not form out there. They were planetesimals from the giant-planet region that were slung outward by close encounters with Jupiter and Saturn, then had their orbits circularised and randomised by the gravity of the whole Milky Way and by passing stars. That same galactic tide, plus occasional stellar flybys, is what dislodges a few of them each year and sends them falling toward the Sun to appear as long-period comets — Hale–Bopp, Hyakutake, and the "new" comets that appear with no warning.

> **Why it matters.** The Oort cloud preserves the most pristine material from the solar system's birth, and it is the natural boundary of the Sun's domain: the point where the Sun's gravity gives way to the pull of the rest of the galaxy. Beyond it, the next stop is another star.



Comet Hale–Bopp in 1997 — a visitor from the Oort cloud, with a white dust tail and a blue ion tail. It will not return for another 2,500 years or so.

E. Kolmhofer & H. Raab, Johannes-Kepler-Observatory, Linz, CC BY-SA 3.0



The flattened Kuiper belt and the spherical Oort cloud, not to scale.

cmglee, ESA, NASA, CC BY-SA 4.0

How far apart everything is

Sunlight takes 8 minutes to reach Earth, more than 4 hours to reach Neptune, and over a year to reach the outer edge of the Oort cloud. Distances like that are hard to picture, so this section lays them out along lines running from the Sun. For the orbits seen from above, see the planets in their orbits; for a zoom out past the planets to the edge of the Sun's reach, see beyond the planets.

The inner Solar System, drawn to scale

Distances here are linear: one astronomical unit is the same width everywhere on the line. Notice how much of it is empty.

Object	Distance from the Sun
Sun	—
Mercury	0.39 AU
Venus	0.72 AU
Earth	1 AU
Mars	1.5 AU
Ceres	2.8 AU
Jupiter	5.2 AU

The whole system, on a logarithmic scale

To fit the Oort cloud on the same line the scale has to change: each step to the right now multiplies the distance by ten. The rocky planets, which filled the table above, are crowded into the first fifth of this one.

Object	Distance from the Sun
Sun	0
Mercury	0.39 AU
Venus	0.72 AU
Earth	1 AU
Mars	1.5 AU
Ceres	2.8 AU
Jupiter	5.2 AU
Saturn	9.6 AU
Uranus	19 AU
Neptune	30 AU
Kuiper belt	30–50 AU
Voyager 1	~170 AU
Inner Oort cloud	~2,000 AU

Object	Distance from the Sun
Outer Oort cloud	~100,000 AU

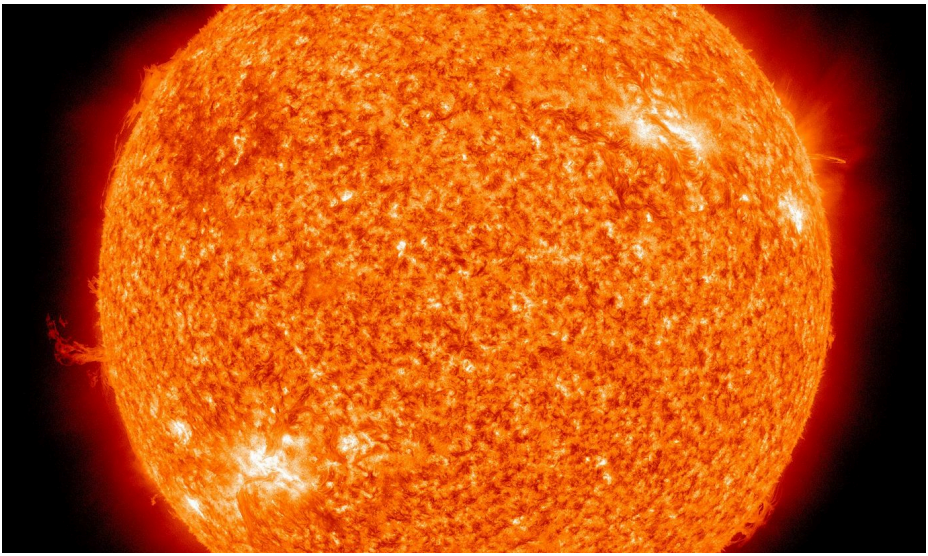
1 AU (astronomical unit) is the average Earth–Sun distance, about 150 million km. Light covers it in 8 minutes 20 seconds. Voyager 1, launched in 1977 and the most distant human-made object, is only now approaching 170 AU — well short of the inner Oort cloud.

All of it is held together, lit and warmed by one ordinary star. Take a closer look at it next: continue to the Sun.

CHAPTER 2

Features of the Sun

The Sun's face is never quite the same two days in a row. Its tangled magnetic field produces dark spots, bright patches, floating clouds of gas, sudden flashes and vast eruptions that can reach all the way to Earth.



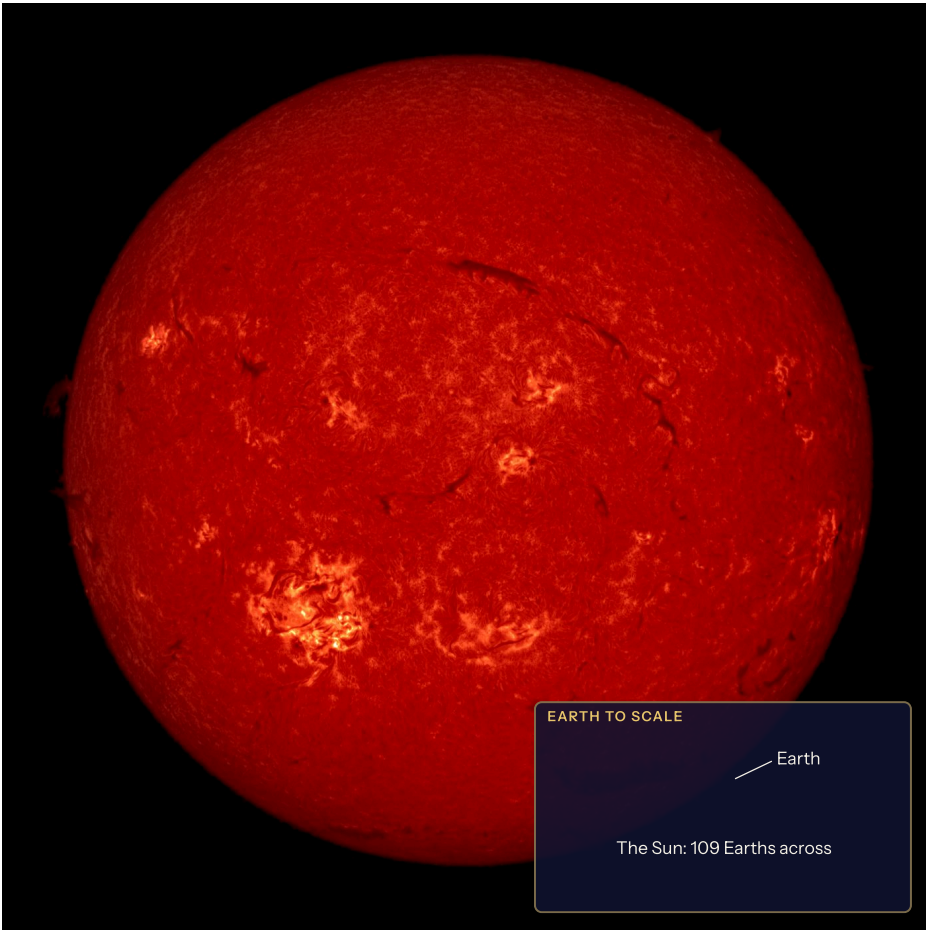
The Sun at 304 Å, Aug. 2010 — NASA/SDO (public domain)

> **Safety first:** Never look at the Sun directly or through any telescope, binoculars or camera without a certified solar filter fitted over the front of the instrument. Hydrogen-alpha and calcium-K views require dedicated solar telescopes or filter systems.

A magnetic star

All of these features share a single cause: the Sun's **magnetic field**. The Sun is a ball of electrically charged gas (plasma) that rotates faster at its equator than near its poles. That uneven spin twists and concentrates the magnetic field until bundles of it break through the visible surface. Where they emerge, astronomers find an *active region* — and that is where sunspots, plage, filaments, flares and coronal mass ejections tend to cluster. Activity rises and falls over an average 11-year **solar cycle**.

To give a sense of scale, most photos in this chapter carry a small **Earth to scale** inset. Earth is about 12,700 km (7,900 miles) across; the Sun is about 1.39 million km, so roughly 109 Earths would fit side by side across its face. The insets compare Earth with the true physical size of each feature.



The whole Sun seen in hydrogen-alpha light, which reveals the chromosphere just above the visible surface. The bright patches are plage; the dark thread-like lines are filaments; small prominences stick out from the edge of the disk.

Image: Big Bear Solar Observatory / New Jersey Institute of Technology — Public Domain. Via IAU Office of Astronomy for Education.

The layers of the Sun

FROM THE CORE TO THE CORONA

The Sun has no solid surface. It is a ball of hot plasma, about 73% hydrogen and 25% helium by mass, that gets steadily hotter and denser toward the centre. Even so, it has distinct layers, each defined by how energy moves

through it. The features described in this chapter all live in the outer layers, but their energy and their magnetism come from deep inside.

The core. The inner quarter of the Sun's radius is its power plant. At about 15 million K, and squeezed to roughly 150 times the density of water, hydrogen nuclei fuse into helium, converting about 4 million tonnes of matter into energy every second. Almost all of the Sun's energy is made here.

The radiative zone. From the edge of the core out to about 70% of the radius, the gas is too dense and hot to boil, so energy moves outward as light. Each photon travels only a tiny distance before it is absorbed and re-emitted in a random direction, so the energy staggers outward in an aimless walk. Estimates of how long it takes to cross this zone range from tens of thousands to a few hundred thousand years.

The tachocline. At the outer edge of the radiative zone is a thin boundary layer. Below it the Sun turns like a solid ball; above it the equator spins faster than the poles. The shearing between the two is thought to wind up the Sun's magnetic field and drive the solar dynamo behind the 11-year cycle.

The convective zone. In the outer 30% of the Sun, about 200,000 km deep, the gas is cool enough that it can no longer pass the energy along as light. Instead it boils, like a pot on a stove: hot plasma rises, cools at the top, and sinks again, carrying energy to the surface in a matter of weeks. The tops of these cells show on the surface as **granulation**, a pattern of bright grains each about the size of Texas that form and fade within ten or twenty minutes.

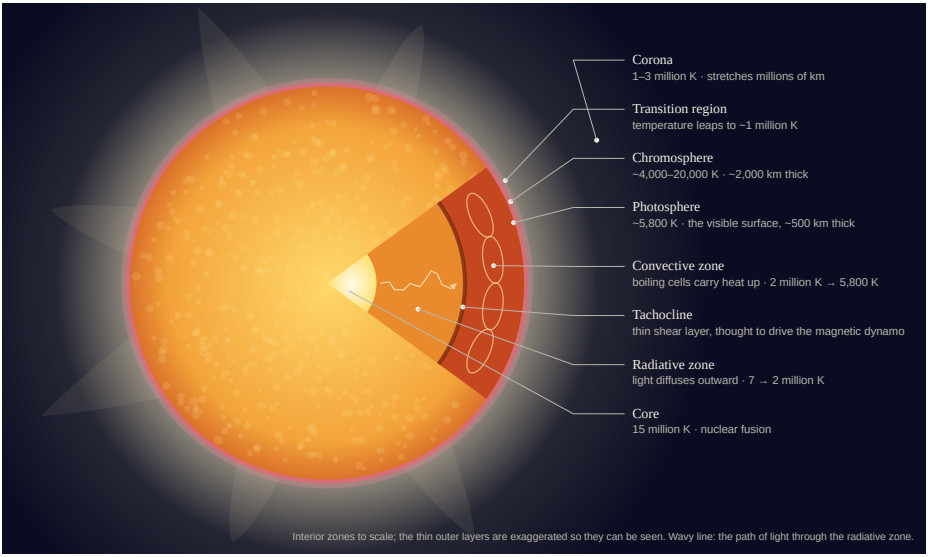
The photosphere. This is the visible "surface" — the layer, only about 500 km thick, where the gas finally becomes transparent and light escapes into space. Its temperature is about 5,800 K. Sunspots, granulation and the bright faculae near the Sun's edge are all photospheric features. The disc looks darker toward its edge (limb darkening) because there we see only the cooler upper part of the photosphere.

The chromosphere. Above the photosphere lies a thin, irregular layer about 2,000 km thick. Strangely, the temperature rises again here, from about 4,000 K to around 20,000 K. Its light is swamped by the photosphere except in special filters such as hydrogen-alpha, or for a few seconds at a total eclipse, when it flashes into view as a pinkish-red rim — the colour that gives it its

name, from the Greek for "colour sphere". Plage, filaments and the bases of prominences are chromospheric features, and its surface bristles with jets of gas called spicules.

The transition region. In a layer only a few hundred kilometres thick the temperature leaps from tens of thousands of degrees to about a million. It is seen only in ultraviolet light from spacecraft.

The corona. The Sun's outer atmosphere is a million times fainter than the photosphere and extremely thin, yet it is heated to 1–3 million K, hotter still above active regions. Why the corona is hundreds of times hotter than the surface beneath it is one of the great puzzles of solar physics; the leading explanations involve magnetic waves and countless small magnetic explosions. The corona is normally hidden by the glare of the photosphere, but during a total solar eclipse it appears as a pearly white halo with long streamers shaped by the magnetic field. It has no outer edge: it flows continuously away from the Sun as the **solar wind**, at 400–800 km/s, out past all the planets. In 2021 NASA's Parker Solar Probe became the first spacecraft to fly through the corona.



The layers of the Sun. The core, radiative zone and convective zone are drawn to scale; the photosphere, chromosphere and transition region are far too thin to show at this size and have been exaggerated.

The Sun from the inside out

Layer	Where	Temperature	How energy moves
Core	Centre to 25% of the radius	~15 million K	Made by nuclear fusion
Radiative zone	25–70% of the radius	~7 to 2 million K	Carried by light, absorbed and re-emitted countless times
Convective zone	Outer 30%, ~200,000 km deep	~2 million K to 5,800 K	Carried by rising and sinking plasma
Photosphere	The visible surface, ~500 km thick	~5,800 K	Escapes into space as sunlight
Chromosphere	~2,000 km above the surface	~4,000 to 20,000 K	Heated by magnetic waves and shocks
Transition region	A few hundred km thick	~20,000 K to 1 million K	Sharp jump in temperature
Corona	Outward for millions of km	1–3 million K	Flows away as the solar wind

Sunspots

LAYER: PHOTOSPHERE (THE VISIBLE SURFACE) · SEEN IN: WHITE LIGHT

Sunspots are the easiest solar feature to see — with a proper solar filter, even a small telescope shows them. They look black, but only by contrast: a sunspot is roughly 1,500–2,000 degrees cooler than the surrounding surface, which glows at about 5,800 K. Seen on its own, a sunspot would still shine brighter than an arc welder.

The cause is magnetism. Inside a sunspot the magnetic field is thousands of times stronger than Earth's, strong enough to choke off the churning convection that normally carries heat up from below. Less heat arriving means a cooler, darker patch.



A sunspot group photographed on June 7, 2023. Each spot shows a dark central *umbra* surrounded by a lighter, filamentary *penumbra*.

Image: Juliebern, via Wikimedia Commons — CC0 1.0.

QUICK FACTS

- Sunspots usually come in pairs or groups of opposite magnetic polarity, like the two ends of a bar magnet.
- Large spots can be several times the diameter of Earth and last for weeks.
- Their number rises and falls with the 11-year solar cycle; counting them is one of the longest-running records in science.
- The Sun's rotation carries spots across the disk in about two weeks.

Plage

LAYER: CHROMOSPHERE · SEEN IN: HYDROGEN-ALPHA AND CALCIUM-K LIGHT

Plage (pronounced "plahzh") are bright, cloud-like patches that surround sunspot groups. They are nearly invisible in ordinary white light but stand out clearly through narrow-band filters tuned to hydrogen-alpha (deep red) or ionized calcium's "K line" (violet).

Plage mark places where the magnetic field is concentrated, but not concentrated enough to form a spot. Instead of blocking heat, these smaller magnetic bundles let extra energy leak upward, so the chromosphere above them glows brighter than its surroundings. Their counterparts lower down, in the photosphere, are called *faculae* — bright specks seen most easily near the Sun's edge.

The name comes from the French *plages brillantes*, "bright regions," a phrase used by the astronomer Henri Deslandres in the 1890s. (It is often said to mean "beach," but that's a later misreading.)

QUICK FACTS

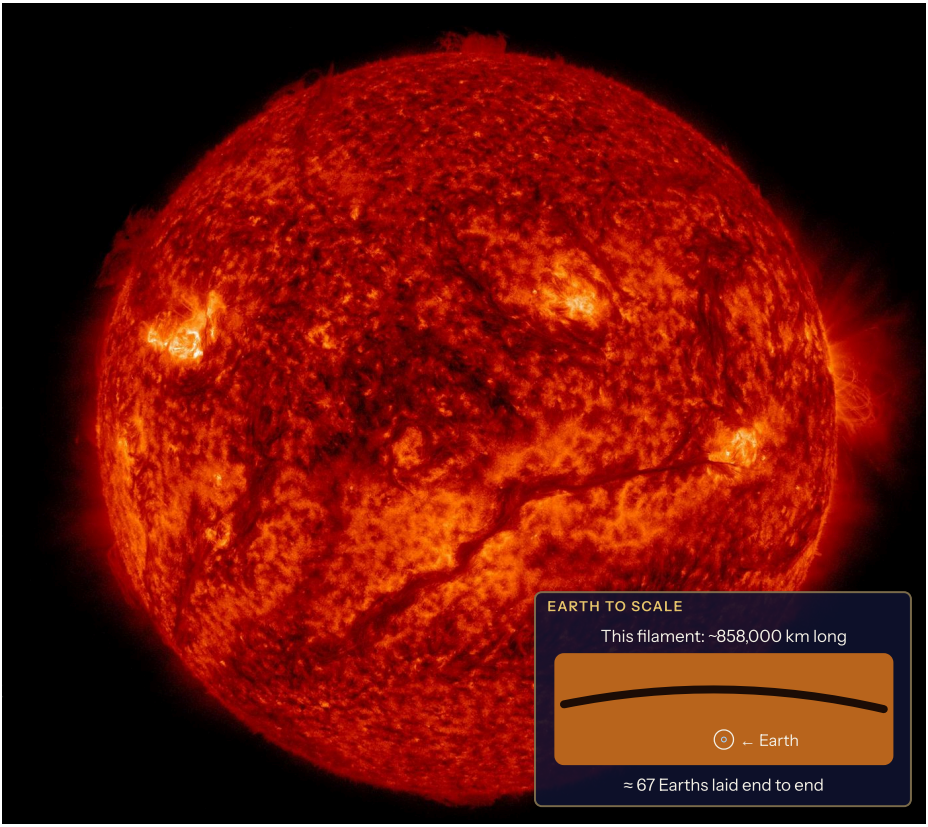
- Plage often appear before sunspots form and linger after the spots fade.
- They are a reliable map of the Sun's magnetic activity, even on days with no spots at all.
- Plage and faculae slightly *raise* the Sun's total brightness at solar maximum, more than offsetting the dimming from sunspots.
- In the hydrogen-alpha image under “A magnetic star,” the bright blotches are plage.
- A single plage region can sprawl across 100,000 km or more, wide enough to line up about eight Earths side by side.

Filaments

LAYER: CHROMOSPHERE AND CORONA · SEEN IN: HYDROGEN-ALPHA AND EXTREME ULTRAVIOLET

Filaments are long, dark ribbons stretched across the face of the Sun. Each one is a vast cloud of relatively cool, dense plasma — around 10,000 K — floating in the corona, where the surrounding gas is more than a million degrees. Magnetic field lines cradle the material like a hammock, holding it aloft against the Sun's gravity.

Because the filament is cooler than what lies behind it, it absorbs light and looks dark against the bright disk. When the same kind of structure sits at the Sun's edge, seen against black space, it glows instead and is called a **prominence**. Filaments and prominences are the same phenomenon viewed from different angles.



A giant filament snakes across the lower half of the Sun in this extreme-ultraviolet image from NASA's Solar Dynamics Observatory, February 10, 2015. Stretched out straight, it would be more than 500,000 miles long.

Image: NASA/Goddard/SDO — Public Domain (NASA imagery is not copyrighted). Via NASA.

QUICK FACTS

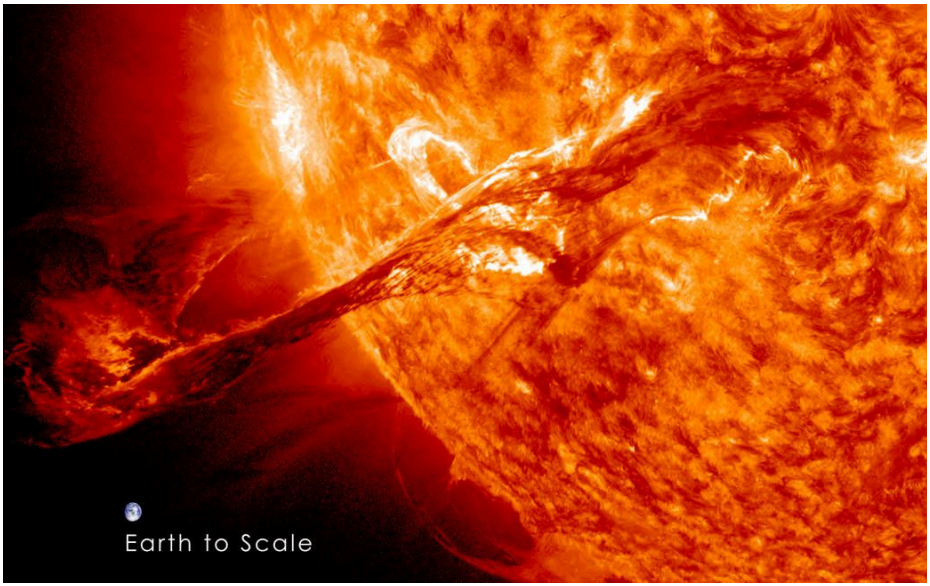
- Filaments form above the boundary line between regions of opposite magnetic polarity.
- Quiet filaments far from active regions can survive for weeks or even months.
- When a filament becomes unstable it can collapse back down or erupt outward, often launching a coronal mass ejection.

Prominences

LAYER: CHROMOSPHERE INTO THE CORONA · SEEN IN: HYDROGEN-ALPHA, EXTREME ULTRAVIOLET, AND AT TOTAL SOLAR ECLIPSES

A prominence is a filament seen side-on. When the Sun's rotation carries one of those dark ribbons to the edge of the disk, it is no longer silhouetted against the bright surface. Instead it glows against the blackness of space as a luminous arch, plume or hedgerow of plasma standing high above the surface.

Like filaments, prominences are made of gas at roughly 10,000 K, about a hundred times cooler than the corona around them, held up by magnetic fields that act as both support and insulation. During a total solar eclipse, when the Moon blocks the bright disk, prominences can be seen with the naked eye as vivid pink-red flames around the black edge of the Moon. Their color comes from hydrogen's red H-alpha light.



A long filament erupts from the Sun's edge as a towering prominence on August 31, 2012, seen in extreme-ultraviolet light from NASA's Solar Dynamics Observatory. NASA added the Earth image to scale; the eruption dwarfs our planet many times over.

Image: NASA/SDO/AIA — Public Domain. Via NASA.

Astronomers sort prominences by how they behave:

- **Quiescent prominences** form far from active regions, often at high latitudes. They are calm and long-lived, sometimes lasting for months, and can reach great heights.
- **Active-region prominences** sit in the strong magnetic fields near sunspots. They live for hours to days and are far more likely to erupt.
- **Eruptive prominences** are those that break loose, rising at hundreds to more than 1,000 km per second and lifting off into space.

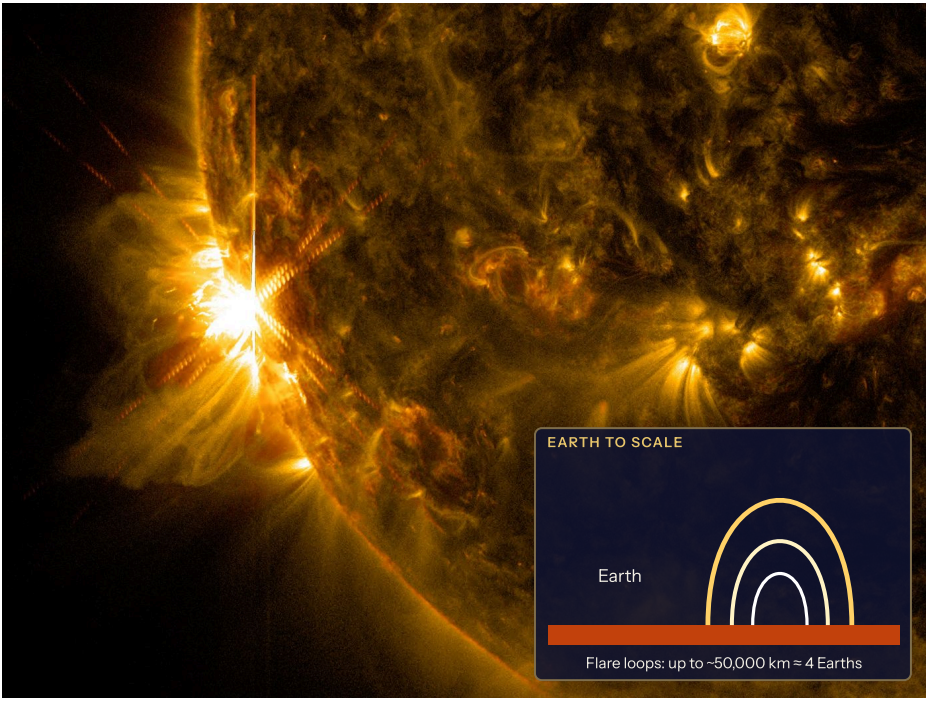
QUICK FACTS

- Prominence and filament are two names for the same structure: "filament" on the disk, "prominence" at the edge.
- The largest on record stretched more than 800,000 km, well over half the Sun's diameter.
- At least 70% of prominence eruptions are accompanied by a coronal mass ejection.
- The first detailed written description of a prominence dates to the total solar eclipse of May 1, 1185, recorded in a Russian chronicle.

Flares

LAYER: ALL LAYERS, FROM PHOTOSPHERE TO CORONA · SEEN IN: X-RAYS, ULTRAVIOLET, HYDROGEN-ALPHA, RADIO

A solar flare is a sudden, intense burst of light from an active region — the most powerful explosions in the solar system. Over minutes, tangled magnetic field lines above a sunspot group snap and reconnect into a simpler shape, releasing stored energy all at once. A large flare can release as much energy as millions of hydrogen bombs, heating gas to tens of millions of degrees and flinging particles to nearly the speed of light.

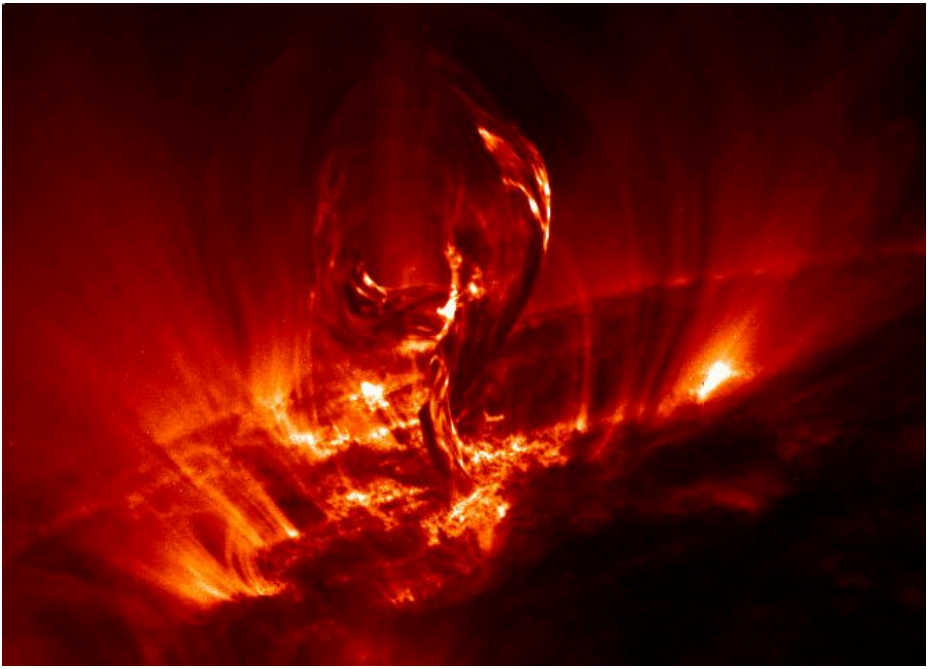


An X2.2-class flare bursts from the left edge of the Sun on June 10, 2014, shown in a blend of two extreme-ultraviolet wavelengths from NASA's Solar Dynamics Observatory.

Image: NASA/SDO/Goddard/Wiessinger — Public Domain. Via NASA.

Flares are ranked by how much X-ray energy reaches Earth. Each letter class is ten times stronger than the one before it, and a number refines the strength within a class (an X2 is twice an X1).

Class	Strength	Typical effect on Earth
A, B	Background	None
C	Small	Little or none
M	Medium	Brief radio blackouts near the poles
X	Major	Planet-wide radio blackouts; radiation storms



Flares and filaments are often linked. Here NASA's TRACE spacecraft caught a filament erupting during a flare, its dark threads tangled among bright, superheated loops.

Image: TRACE, NASA — Public Domain. Via Wikimedia Commons.

QUICK FACTS

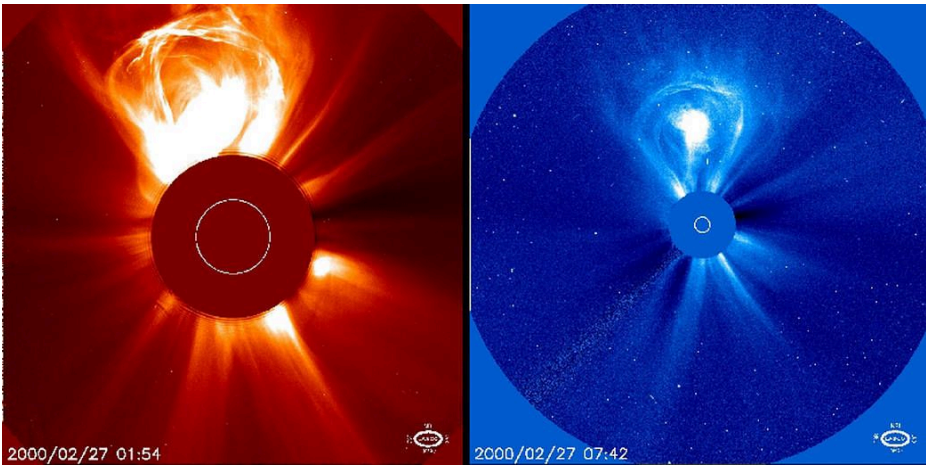
- The first flare ever recorded was seen in white light by Richard Carrington and Richard Hodgson on September 1, 1859. The geomagnetic storm that followed, the "Carrington Event," remains the strongest on record.
- Flare light reaches Earth in about 8 minutes; Earth's atmosphere blocks the X-rays, so flares are no danger to people on the ground.
- Strong flares can disrupt shortwave radio and GPS, and pose radiation risks to astronauts.
- Through a hydrogen-alpha telescope, flares appear as suddenly brightening ribbons inside plage.

Coronal mass ejections (CMEs)

LAYER: CORONA AND OUT INTO THE SOLAR SYSTEM · SEEN IN: CORONAGRAPHS (INSTRUMENTS THAT BLOCK THE SUN'S DISK)

A coronal mass ejection is exactly what its name says: a huge mass of the Sun's outer atmosphere, the corona, hurled out into space. A large CME can carry billions of tons of magnetized plasma and expand to become wider than the Sun itself within hours, eventually sweeping out a region many millions of kilometres across as it crosses the solar system.

CMEs are often confused with flares, and the two frequently happen together, but they are different things. A flare is a flash of *light* that reaches Earth in about eight minutes. A CME is a cloud of *matter* that travels far more slowly, at roughly 250 to 3,000 km per second, so it usually takes one to three days to cover the 150 million km to Earth. Many CMEs begin when a filament or prominence erupts, carrying its cool plasma along inside the expanding cloud.



A coronal mass ejection billows away from the Sun on February 27, 2000, seen by the LASCO C2 and C3 coronagraphs on the SOHO spacecraft. The dark central disk is the instrument's mask, which blocks the Sun's glare so the faint corona shows up; the Sun itself is hidden behind it.

Image: SOHO (ESA & NASA). Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. Via NASA.

When a CME reaches Earth

Most CMEs head off in other directions, but when one is aimed at Earth its magnetic field can couple with our planet's magnetic field and set off a **geomagnetic storm**. The results can include:

- **Auroras** spreading far beyond the polar regions. During the strong storm of May 10–11, 2024, the northern lights were seen across much of the United States, including New Jersey.
- **Power-grid problems.** A storm on March 13, 1989, knocked out the Hydro-Québec grid, leaving millions without power for about nine hours.
- **Satellite and GPS disruption**, as the upper atmosphere heats, swells and drags on spacecraft in low orbit.

QUICK FACTS

- CMEs are watched with coronagraphs, telescopes that create an artificial eclipse by blocking the Sun's disk so the faint corona can be seen.
- Near solar maximum the Sun can produce several CMEs a day; near minimum, about one every few days.
- The CME behind the 1859 Carrington Event reached Earth in under 18 hours, extraordinarily fast.
- A CME that appears as an expanding ring all the way around the Sun, called a "halo CME", is coming either straight toward Earth or directly away from it.

Prominence, flare or CME?

THREE DIFFERENT THINGS THAT OFTEN HAPPEN TOGETHER

These three are easy to mix up because they so often occur in the same eruption, but they are different kinds of things. A **prominence** is a *structure*, a **flare** is a *flash of energy*, and a **CME** is a *cloud of matter* thrown into space.

- **Prominence:** a cloud of relatively cool plasma (about 10,000 K) held above the surface by magnetic fields. It can sit quietly for days or even months.

Against the bright disk it looks dark and is called a filament; at the edge, against space, it glows.

- **Flare:** a sudden burst of light and radiation, from radio waves to X-rays, released when tangled magnetic fields snap and reconnect. It lasts minutes to hours, and its light reaches Earth in about 8 minutes. It is mostly energy; little material leaves the Sun.
- **CME:** billions of tons of magnetized plasma blasted out of the corona. It travels far slower than light, taking 1 to 3 days to reach Earth. That is why CMEs, not flares, cause most geomagnetic storms and auroras.

	Prominence	Flare	CME
What it is	Cool plasma held up by magnetism	Burst of light and radiation	Ejected cloud of plasma
Duration	Days to months	Minutes to hours	Hours to leave the Sun, days to cross space
Reaches Earth?	No, unless it erupts as part of a CME	Its light arrives in about 8 minutes	Its matter arrives in 1 to 3 days
Main effect on Earth	None	Radio blackouts	Geomagnetic storms, auroras, power-grid trouble

They don't always come as a set. Many flares happen with no CME, and some CMEs launch from quiet prominence eruptions with only a weak flare, or none at all. The August 31, 2012 eruption pictured in the Prominences section is a good example of a prominence becoming a CME.

How they fit together

Picture a typical active region rotating into view. In white light you see a **sunspot** group. Switch to a hydrogen-alpha filter and the spots are wrapped in glowing **plage**, with a dark **filament** lying along the dividing line between magnetic polarities. As the Sun turns, that filament reaches the edge and becomes a **prominence**. If the magnetic field becomes stressed enough, it can snap in a **flare** and tear the prominence loose, sending it off into space inside a **coronal mass ejection**. Days later, that CME may arrive at Earth and light up the sky with auroras. All six are chapters of the same magnetic story.

CHAPTER 3

The lives of stars

A star is a balancing act between gravity pulling in and pressure pushing out. Everything about its life — how bright it is, what colour, how long it lasts, how it dies — follows from a single number: its mass.



Pillars of Creation, M16 — NASA/ESA/Hubble (public domain)

Stellar nurseries

Stars are born in giant molecular clouds: cold (10–20 K), dark, and enormous, spanning tens to hundreds of light-years and holding up to a million solar masses of gas, mostly molecular hydrogen with a dusting of heavier atoms

and soot-like grains. The Orion complex is the nearest large example, about 1,300 light-years away.

Such a cloud sits in a fragile equilibrium between its own gravity and the outward push of thermal pressure, turbulence and magnetic fields. A shock — the blast from a nearby supernova, the passage of a spiral arm, a collision with another cloud — can tip a region past the point where gravity wins. The cloud fragments into dense cores, and each core collapses toward its centre. As the core contracts it heats, and after a few hundred thousand years a protostar glows at the centre of a rotating disc of infalling material.

When the core temperature reaches a few million kelvin, hydrogen fusion begins and the outward flow of energy halts the collapse. The object is now a star. The remaining gas is blown away by its radiation and wind — the process that has carved the Pillars of Creation above into their present shapes — and the nursery is revealed as a young open cluster, like the Pleiades, whose members will drift apart over the next few hundred million years.

Because the cloud fragments unevenly, stars come in a range of masses, and small ones are far more common than large ones. For every star of ten solar masses there are hundreds of red dwarfs.



The Orion Nebula (M42), a stellar nursery 1,300 light-years away lit by the Trapezium, four hot young stars at its heart. Hubble has photographed dozens of protoplanetary discs among the newborn stars here.

NASA/ESA/M. Robberto (public domain)



The Pleiades (M45), an open cluster about 100 million years old. The blue haze is dust reflecting the light of the hot young stars.

NASA/ESA/AURA/Caltech (public domain)

Glowing clouds: emission, reflection and dark nebulae

The gas and dust of a stellar nursery can show up in three quite different ways, depending on how it meets the light of the stars around it. The names describe where the light comes from, not what the cloud is made of — and a single cloud often shows all three at once.

Emission nebulae

When a newborn star is hot enough — an O or early B star with a surface above about 25,000 K — its ultraviolet light strips the electrons from the surrounding hydrogen. The cloud becomes an **H II region**, a bubble of ionised gas. Each time an electron is recaptured by a proton it cascades down the atom's energy levels, releasing light at a few exact wavelengths. The strongest is **hydrogen-alpha** at 656 nm, a deep red that gives emission nebulae their colour in photographs; ionised oxygen adds a green-blue glow at 501 nm. The gas makes its own light, so the spectrum is a set of bright emission lines

rather than a continuous rainbow. The Orion Nebula (M42), the Lagoon (M8), the Omega (M17) and the Eagle (M16) are all emission nebulae. Planetary nebulae and supernova remnants also glow this way, though their gas was thrown off by dying stars rather than gathered for new ones.

Reflection nebulae

Where the nearby stars are too cool to ionise the gas, or the cloud lies too far from them, the dust simply scatters their light, like fog around a streetlight. Small grains scatter blue light more strongly than red — for much the same reason the daytime sky is blue — so reflection nebulae look blue. Their spectrum is the spectrum of the star they reflect, absorption lines and all; in 1912 Vesto Slipher used exactly that to show that the nebulosity around the Pleiades was lit by the cluster's own stars. M78 in Orion and the haze around the Pleiades (M45) are the best-known examples.

Dark nebulae

A cloud dense enough in dust blocks the light of whatever lies behind it and appears as a black silhouette against a brighter background — a glowing nebula or the star fields of the Milky Way. The Horsehead in Orion, the Coalsack beside the Southern Cross and the dark rifts that split the summer Milky Way are dark nebulae. The smallest, called **Bok globules**, are compact knots of gas and dust, many of them collapsing to form stars. Infrared telescopes such as Webb see straight through them to the stars forming inside.

Type	Where the light comes from	Typical colour	Examples
Emission	Gas ionised by hot young stars glows at its own wavelengths	Red (hydrogen-alpha), with green-blue from oxygen	M42, M8, M16, M17
Reflection	Dust scatters the light of nearby stars	Blue	M78, the Pleiades (M45)
Dark	Dense dust blocks light from behind	Black against a bright background	Horsehead, Coalsack, Bok globules



Emission: the Lagoon Nebula (M8). The red glow is hydrogen-alpha; the small dark patches are Bok globules. From the AstroStudious gallery.



Reflection: M78 in Orion, dust lit by the young stars embedded in it, with dark dust beside it. From the AstroStudious gallery.



All three: the Trifid Nebula (M20) — a red emission lobe split by dark dust lanes, with a blue reflection nebula above it. From the AstroStudious gallery.

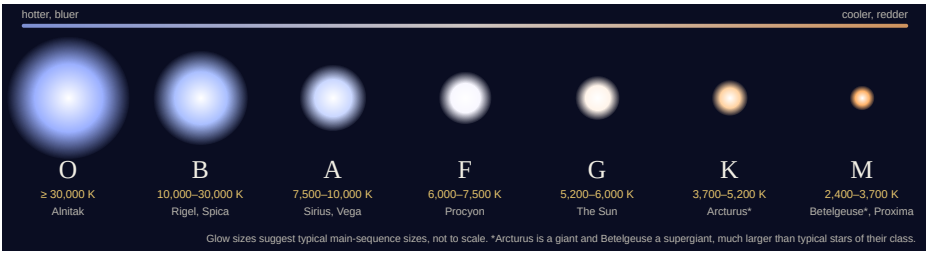
> The difference matters when photographing them. The narrowband and dual-band filters that cut through light pollution pass only a few emission lines, so they make emission nebulae stand out but dim reflection nebulae almost to nothing. Reflection nebulae, with their continuous starlight spectrum, need broadband colour and the darkest sky you can find.

Sorting the stars

Look up on a clear night and the stars seem much alike — points of light, some brighter, a few tinted orange or blue. In fact they differ enormously. The faintest give off less than a ten-thousandth of the Sun's light; the brightest, more than a million times as much. The smallest are about the size of

Jupiter; the largest would swallow the orbit of Mars. Some will burn for trillions of years, others for only a few million.

Colour is temperature. A star's colour tells you how hot its surface is, just as a heated poker glows red, then orange, then white as it gets hotter. Betelgeuse, in Orion's shoulder, is a cool red at about 3,500 K; Rigel, at Orion's knee, is blue-white at about 12,000 K. Around 1900 a team of women at Harvard College Observatory, led by Annie Jump Cannon, sorted hundreds of thousands of stellar spectra into a sequence of classes, now ordered from hottest to coolest as **O, B, A, F, G, K, M** — remembered by generations of students as "Oh Be A Fine Girl (or Guy), Kiss Me". In 1925 Cecilia Payne showed that the differences between the classes come from temperature, not composition, and that stars are made overwhelmingly of hydrogen and helium.



The seven main spectral classes, hottest to coolest. Hotter stars are bluer and, on the main sequence, larger and far more luminous.

Astronomers group stars into a handful of families:

- **Red dwarfs** — small, cool M-class stars with a tenth to half the Sun's mass. They are by far the most common stars, about three in every four, yet not one is visible to the naked eye. The nearest star to the Sun, Proxima Centauri, is a red dwarf. They burn so slowly that none has yet died of old age.
- **Sun-like stars** — G- and K-class stars, the "yellow" and "orange dwarfs". The word dwarf here only means an ordinary star in the long, stable hydrogen-burning stage of life; the Sun is one, and is brighter than about 90% of the stars in the Milky Way.
- **Hot blue stars** — massive O, B and A stars, rare but brilliant, which dominate the light of young clusters and spiral arms. They live only a few million to a few hundred million years.

- **Giants and supergiants** — stars near the end of their lives that have swollen to tens, hundreds or even more than a thousand times the Sun's diameter: orange Arcturus and Aldebaran, red Betelgeuse and Antares, blue-white Rigel and Deneb.
- **Stellar remnants** — the dead cores left behind: white dwarfs, neutron stars and black holes.
- **Brown dwarfs** — "failed stars" of about 13 to 80 Jupiter masses, too small ever to sustain hydrogen fusion. They glow dimly from the heat of their formation and slowly fade.

Many stars do not live alone. About half of Sun-like stars, and most massive stars, have one or more companions orbiting them in binary or multiple systems. Some stars also change in brightness — pulsating variables such as Cepheids, eclipsing binaries in which one star passes in front of another, and flare stars. Nearly all of this variety comes back to one property, a star's **mass**, and the clearest way to see it is to plot stars on a single chart.

The Hertzsprung–Russell diagram

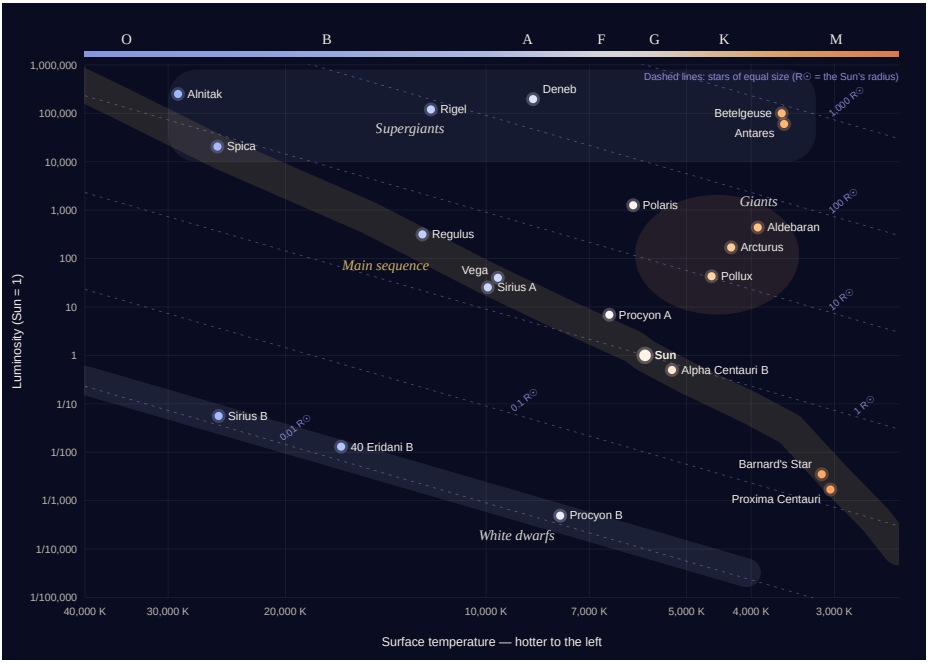
Around 1910 Ejnar Hertzsprung and Henry Norris Russell independently plotted stars' luminosities against their colours (or equivalently, temperatures) and found that the points did not scatter randomly. Most stars fell along a diagonal band running from hot-and-bright to cool-and-faint: the **main sequence**. A smaller group sat in the upper right — cool but very luminous, so they had to be huge: the **giants** and **supergiants**. A few sat in the lower left, hot but faint, so tiny: the **white dwarfs**.

The H–R diagram is the single most important tool in stellar astronomy because position on it encodes the physics. A star on the main sequence is burning hydrogen in its core, and where it sits along the sequence is set entirely by its mass: a 20-solar-mass star is a hot blue O star at the top, the Sun is a yellow G star in the middle, a 0.2-solar-mass red dwarf sits at the bottom. Luminosity climbs steeply with mass (roughly as the 3.5 power), so massive stars burn through their fuel far faster and live shorter lives — a few million years at the top of the sequence, trillions at the bottom.

When a star exhausts its core hydrogen it leaves the main sequence and moves across the diagram: rightward and upward as it swells into a giant,

then, for a Sun-like star, down and left to become a white dwarf. The evolutionary track a star follows is a curve drawn on this one diagram, and the age of a star cluster can be read from the point where its main sequence "turns off": the massive stars have already left, and only the lower part remains.

Spectral classes run O, B, A, F, G, K, M from hottest to coolest (with L, T and Y added for brown dwarfs). Luminosity classes run from I (supergiants) through III (giants) to V (main sequence, sometimes called dwarfs). The Sun is a G2V star.



The H–R diagram, with well-known stars plotted at their measured temperatures and luminosities. Temperature runs backwards along the bottom by historical convention — the hottest, bluest stars are on the left. The dashed lines show that stars of the same size lie along diagonals: the supergiants at top right are hundreds of times the Sun's width, the white dwarfs at bottom left about the size of Earth.

Main-sequence stars by spectral class

Class	Surface temperature	Colour	Mass (Sun = 1)	Luminosity (Sun = 1)	Main-sequence lifetime	Example
O	> 30,000 K	Blue	16–100+	30,000–1,000,000	1–10 million yr	Alnitak (Orion's belt)
B	10,000–30,000 K	Blue-white	2.1–16	25–30,000	10–400 million yr	Rigel, Spica
A	7,500–10,000 K	White	1.4–2.1	5–25	0.4–3 billion yr	Sirius, Vega
F	6,000–7,500 K	Yellow-white	1.04–1.4	1.5–5	3–7 billion yr	Procyon
G	5,200–6,000 K	Yellow	0.8–1.04	0.6–1.5	7–15 billion yr	The Sun, Alpha Centauri A
K	3,700–5,200 K	Orange	0.45–0.8	0.08–0.6	15–70 billion yr	Alpha Centauri B, Epsilon Eridani
M	2,400–3,700 K	Red	0.08–0.45	< 0.08	Trillions of years	Proxima Centauri, Barnard's Star

Evolution by mass

The four tracks below follow the life that results from each range of starting mass. The boundaries are approximate — composition and rotation shift them — but the overall pattern is one of the best-understood results in astrophysics.

Below about 0.08 solar masses

1. **Collapse** — A cloud fragment contracts but never reaches the ~3 million K core needed for sustained hydrogen fusion.
2. **Deuterium burning** — Trace deuterium fuses briefly, then the object simply cools for the rest of time.

End state: Brown dwarf. Not a true star. Cools forever without ever fusing hydrogen steadily.

0.08 to 0.5 solar masses

1. **Protostar** — Contraction heats the core; the star settles onto the bottom of the main sequence as a red dwarf.
2. **Main sequence** — Fully convective and frugal: hydrogen burns so slowly that the lifetime exceeds a trillion years — longer than the current age of the universe.
3. **Blue dwarf (theoretical)** — Late in life the star should heat and brighten slightly before contracting into a helium white dwarf.

End state: Helium white dwarf, eventually. No star this small has yet had time to die — the universe is not old enough.

0.5 to 8 solar masses — stars like the Sun

1. **Protostar** — A rotating disk forms; planets may condense in it while the star reaches the main sequence.
2. **Main sequence (~10 billion years)** — Hydrogen fuses to helium in the core through the proton–proton chain.
3. **Subgiant, then red giant** — The core exhausts hydrogen, contracts, and a hydrogen shell ignites. The envelope swells past the orbit of Mercury.
4. **Helium flash & horizontal branch** — Degenerate helium ignites explosively; the star burns helium to carbon and oxygen for ~100 million years.
5. **Asymptotic giant branch** — Double-shell burning, thermal pulses and strong winds shed most of the envelope.
6. **Planetary nebula** — The exposed hot core ionises the cast-off gas, which glows for a few tens of thousands of years.

End state: Carbon–oxygen white dwarf. About the mass of the Sun packed into a sphere the size of Earth, cooling for eternity.

Above about 8 solar masses

1. **Rapid formation** — Reaches the main sequence in under a million years and burns hydrogen through the CNO cycle.
2. **Main sequence (a few million years)** — A hot O or B star, radiating fiercely and driving a strong wind.
3. **Supergiant** — Successive shells fuse helium, carbon, neon, oxygen and silicon in an onion-like structure — each stage faster than the last.
4. **Iron core** — Fusion of iron consumes energy instead of releasing it. Within a day the core reaches the Chandrasekhar limit.
5. **Core collapse supernova** — The core collapses at a quarter the speed of light; the rebound and neutrino flood blow the star apart and forge elements heavier than iron.

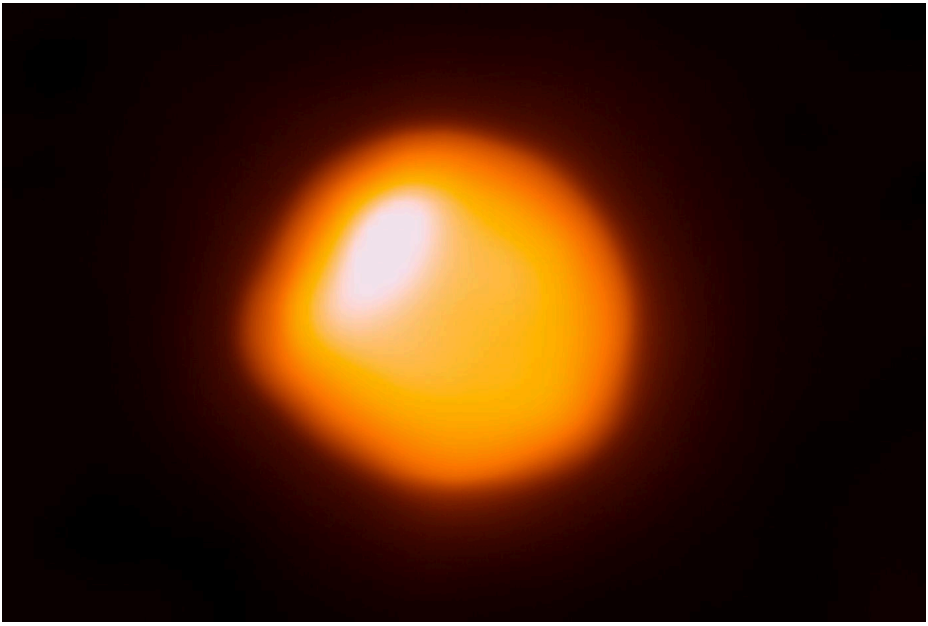
End state: Neutron star (8–20 solar masses) or black hole (above about 20–25). The core survives as a city-sized ball of neutrons, often seen as a pulsar. Above roughly 20–25 solar masses, nothing halts the collapse. A stellar-mass black hole remains.

Red giants

When a star has fused the hydrogen in its core to helium, the core has no source of energy and begins to contract under gravity. Paradoxically, this makes the star grow. The contracting core heats the hydrogen-rich layer just outside it, which ignites as a shell. The shell burns furiously and dumps energy into the envelope, which expands enormously and cools. The star has become a red giant: cooler at the surface, but so large that its total luminosity has climbed a hundredfold or more. On the H–R diagram it moves up and to the right.

The Sun will do this in about five billion years. It will swell to roughly 200 times its present radius — engulfing Mercury and Venus and possibly Earth — and shine 2,000 times as brightly. Its surface will cool to about 3,000 K, an orange-red.

Eventually the helium core, compressed and heated to 100 million K, ignites. In stars below about two solar masses the core is electron-degenerate and the ignition is a runaway called the helium flash, releasing in minutes as much energy as the Sun does in a hundred million years, all of it absorbed by the star's own layers. The star shrinks somewhat and settles into helium burning on the horizontal branch, then swells again as an asymptotic-giant-branch star when the helium runs out. AGB stars are unstable, pulsing every few tens of thousands of years and driving off their outer layers in a strong wind laden with carbon dust — the source of much of the carbon in the universe.



The red supergiant Betelgeuse, resolved by ALMA. About 15–20 solar masses and roughly 750 times the Sun's radius, it would reach past Jupiter's orbit if placed at the centre of our solar system. It is expected to explode as a supernova within the next 100,000 years.

ALMA (ESO/NAOJ/NRAO)/E. O'Gorman/P. Kervella, CC BY 4.0

Planetary nebulae

The name is an eighteenth-century mistake: through William Herschel's telescope these round glowing discs resembled the planet Uranus he had just

discovered. They have nothing to do with planets. A planetary nebula is the last breath of a Sun-like star.

At the end of the asymptotic giant branch the star's pulses and wind have stripped away most of its envelope, leaving a cloud of gas expanding outward at 20–30 km/s. What remains at the centre is the bare core: a ball of carbon and oxygen the size of Earth with a surface temperature of 30,000 to over 100,000 K. It floods the departing gas with ultraviolet light, ionising it, and the gas glows — hydrogen in red, oxygen in green and blue, nitrogen in red. The shells, rings, jets and bipolar lobes seen in the images record the star's final episodes of mass loss, often shaped by a binary companion or a magnetic field.

A planetary nebula is a brief affair. The gas thins and fades within 10,000 to 50,000 years, and the star at the centre, no longer able to ionise it, dims into a white dwarf. There are perhaps 3,000 planetary nebulae in the Milky Way at any moment. Most of the material returned to interstellar space this way — enriched in carbon, nitrogen and s-process elements — will eventually be swept into the next generation of stars and planets.



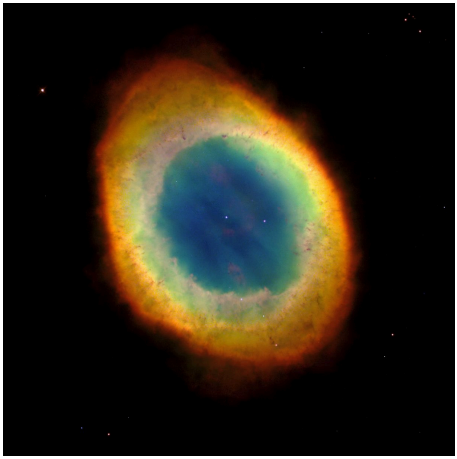
The Helix Nebula (NGC 7293), 650 light-years away, the nearest bright planetary nebula. About 2.5 light-years across.

NASA/ESA/C. R. O'Dell (public domain)



The Cat's Eye Nebula (NGC 6543). Its concentric rings were ejected at intervals of about 1,500 years.

NASA/ESA/HEIC/Hubble Heritage (public domain)



The Ring Nebula (M57) in Lyra — a favourite in amateur telescopes and one of the objects in the deep-sky catalog.

NASA/ESA/Hubble Heritage (public domain)

White dwarfs

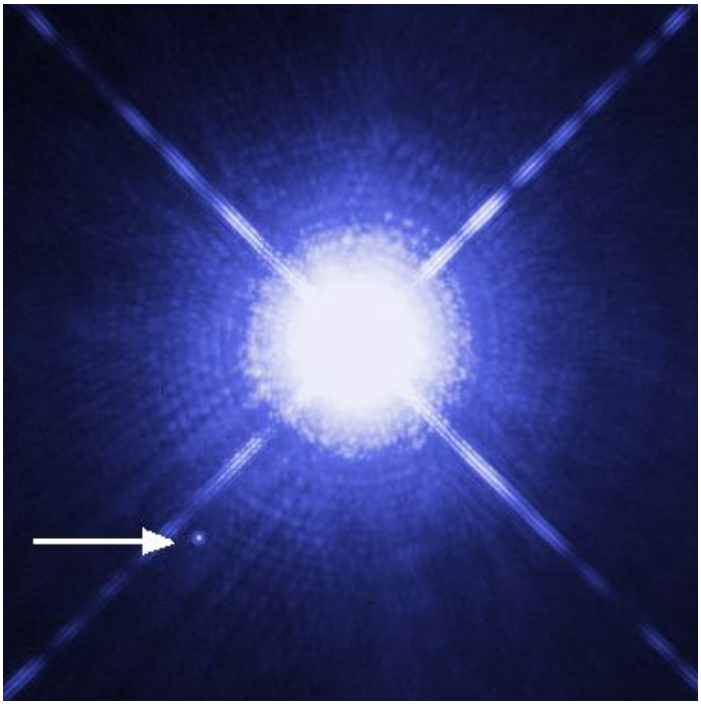
A white dwarf is what remains after a low- or intermediate-mass star (anything below roughly eight solar masses at birth — 97% of all stars) has shed its envelope. It is the old core, typically 0.6 solar masses, compressed into a sphere about the size of Earth. A teaspoon of its material would weigh several tonnes.

No fusion happens inside. What holds it up against gravity is not heat but quantum mechanics: electrons cannot be squeezed into the same states, and the resulting electron degeneracy pressure supports the star indefinitely. Because of this, a white dwarf's fate is simply to cool. It starts at over 100,000 K and glows white, then yellow, then red, over tens of billions of years, eventually becoming a cold black dwarf — though the universe is not yet old enough for any to have done so.

Degeneracy pressure has a limit. Subrahmanyan Chandrasekhar showed in 1930 that a white dwarf more massive than about 1.4 solar masses cannot support itself. A white dwarf in a binary that gains mass from its companion and approaches this limit detonates as a Type Ia supernova, releasing a nearly fixed amount of energy — which makes these explosions superb "stan-

dard candles" for measuring cosmic distances, and led to the discovery of the accelerating universe in 1998.

Sirius B, the companion of the brightest star in the sky, was the first white dwarf discovered (1862) and is still the best studied: as massive as the Sun, slightly smaller than Earth, and 10,000 times fainter than Sirius A.



Sirius A and, at lower left, the white dwarf Sirius B. Their brightness ratio is 10,000 to 1; the dwarf is only visible because Hubble's optics are so clean.

NASA/ESA/H. Bond/M. Barstow (public domain)

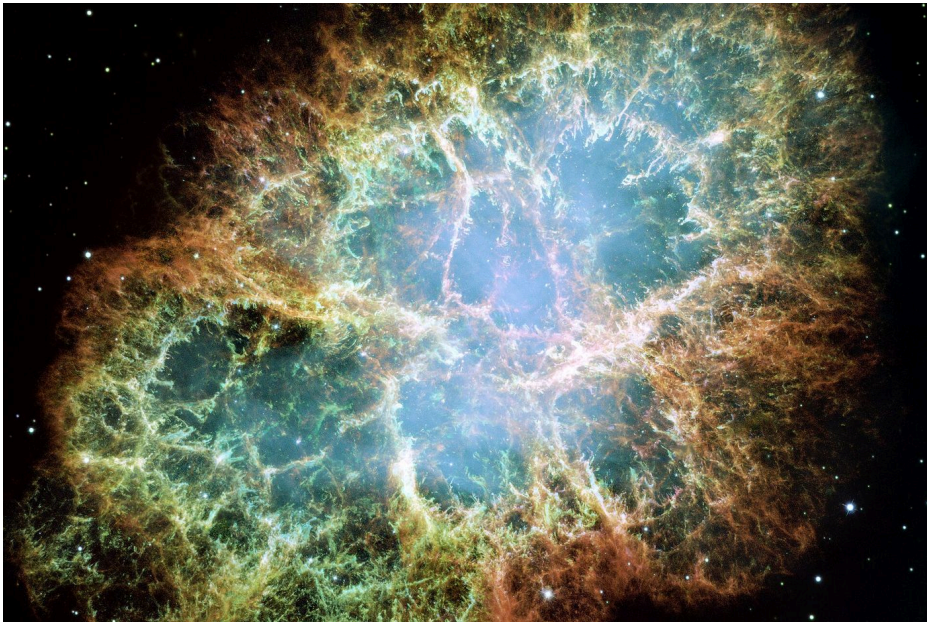
Supernovae and neutron stars

For stars above about eight solar masses, the end is violent. When silicon burning fills the core with iron, energy production stops and the core, now roughly 1.4 solar masses and the size of Earth, collapses in less than a second to a ball 20 km across. Protons and electrons are crushed together into neutrons, releasing a torrent of neutrinos carrying away 99% of the energy — a

hundred times more than the light. The infalling outer layers rebound off the incompressible neutron core, and the neutrino flood drives the shock outward, tearing the star apart at 10,000 km/s.

For a few weeks the supernova outshines its whole galaxy. The debris, laced with newly made oxygen, silicon, calcium, iron and r-process elements, expands into space as a supernova remnant and seeds the next generation of stars. Astronomers saw this happen close to home in 1987, when SN 1987A exploded in the Large Magellanic Cloud and neutrino detectors in Japan, the US and Russia registered its burst three hours before the light arrived.

What remains is a **neutron star**: 1.4 to about 2.3 solar masses packed into a sphere the size of a city, with a density like that of an atomic nucleus and a surface gravity 100 billion times Earth's. Conservation of angular momentum spins it up to many rotations per second, and its magnetic field is compressed to trillions of times Earth's. Beams of radio emission sweep past us with each rotation, and we see a pulsar. Jocelyn Bell Burnell detected the first one in 1967. The pulsar in the Crab Nebula, born in a supernova recorded by Chinese astronomers in 1054, flashes 30 times per second.



The Crab Nebula (M1), the remnant of the supernova of 1054. The filaments are the shredded star; the blue glow at the centre is synchrotron radiation powered by the pulsar.

NASA/ESA/J. Hester/A. Loll (public domain)

Kinds of supernova

Not every supernova is the collapse of a massive star. There are two quite different ways for a star to explode, and astronomers label them by what their light shows. The system goes back to 1941, when Rudolph Minkowski noticed that some supernovae show hydrogen in their spectra (Type II) and others do not (Type I). Type I was later split by the other elements present.

Thermonuclear supernovae (Type Ia). These come from white dwarfs, not massive stars. A carbon–oxygen white dwarf in a close binary gains mass, either by pulling gas from a companion star or by merging with a second white dwarf. As it nears the Chandrasekhar limit of about 1.4 solar masses, carbon ignites in its core and a runaway nuclear burn destroys the whole star in seconds, leaving no remnant at all. Because the exploding stars are so similar, Type Ia supernovae reach nearly the same peak brightness, about five billion times the Sun's; that makes them the "standard candles" used to

measure the expansion of the universe (see the distance ladder). They also forge much of the iron in the cosmos — including the iron in your blood.

Core-collapse supernovae (Types II, Ib and Ic). These are the deaths of stars above about eight solar masses, described above. What they look like depends on how much of its outer layers the star still had when it exploded. A star that kept its thick hydrogen envelope, such as a red supergiant, produces a **Type II**, with strong hydrogen lines and often a long "plateau" of steady brightness lasting months. Stars that lost their hydrogen to fierce stellar winds or to a companion star produce a **Type Ib**, showing helium; stars stripped of both hydrogen and helium produce a **Type Ic**. A few of the most energetic Type Ic explosions launch jets that we see as long gamma-ray bursts, the most luminous explosions known. All core-collapse supernovae leave behind a neutron star or a black hole.

In a galaxy like the Milky Way, supernovae of all kinds occur roughly twice a century, but most are hidden from us by dust. The last one seen with the naked eye in our own galaxy was Kepler's Supernova of 1604. The nearest observed since then was SN 1987A, just outside the Milky Way, in the Large Magellanic Cloud.

The main types of supernova

Type	What explodes	Spectrum shows	What is left	Famous examples
Ia	A white dwarf in a binary, pushed past its mass limit	No hydrogen; strong silicon	Nothing — the star is destroyed	Tycho's Supernova (1572); SN 2011fe in the Pinwheel Galaxy, M101
II	A massive star that kept its hydrogen envelope	Strong hydrogen	Neutron star or black hole	SN 1987A; SN 2023ixf, also in the Pinwheel Galaxy
Ib	A massive star stripped of its hydrogen	Helium, no hydrogen	Neutron star or black hole	SN 2008D
Ic	A massive star stripped of hydrogen and helium	Neither hydrogen nor helium	Neutron star or black hole	SN 1998bw, linked to a gamma-ray burst

Black holes

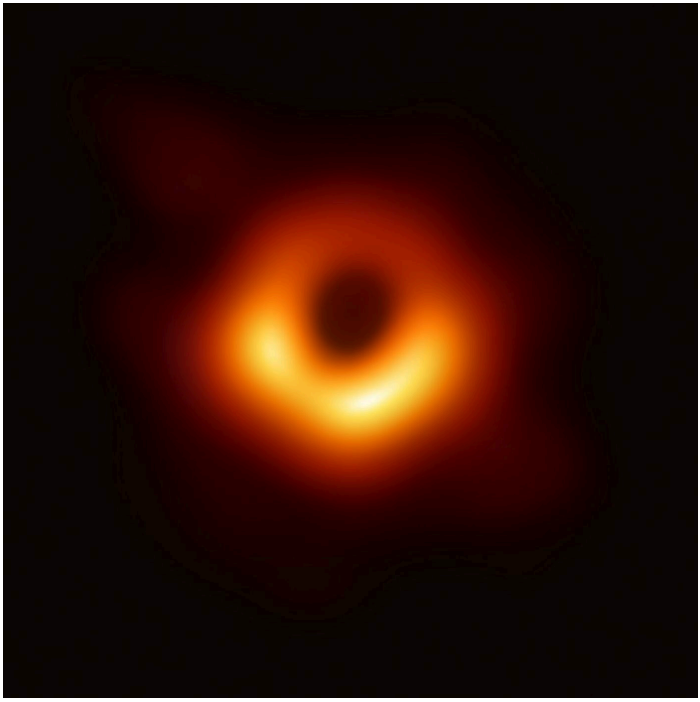
Neutron degeneracy pressure also has a ceiling, somewhere between two and three solar masses. If the collapsing core of a very massive star exceeds

it, no known force can stop the collapse, and general relativity predicts that the matter falls inward without end. Around it forms an event horizon — the surface at which the escape velocity reaches the speed of light — and nothing inside can ever communicate with the outside again. This is a black hole.

A black hole is defined by only three numbers: mass, spin and (in principle) electric charge. Its size follows directly from mass: the Schwarzschild radius is about 3 km per solar mass, so a 10-solar-mass black hole is 60 km across. Time slows near the horizon relative to distant observers, and light is bent so strongly that a hole casts a "shadow" about 2.6 times larger than the horizon itself.

Stellar-mass black holes are detected in binaries, where gas stolen from a companion star spirals inward through an accretion disc heated to millions of degrees and blazes in X-rays; Cygnus X-1 was the first convincing case, in 1971. Since 2015 the LIGO and Virgo observatories have detected the gravitational waves from dozens of pairs of black holes spiralling together and merging, some with masses of 50–100 Suns.

Supermassive black holes — millions to billions of solar masses — sit at the centres of nearly all large galaxies. The Milky Way's, Sagittarius A*, has 4 million solar masses; its presence was established by tracking stars orbiting it at thousands of km/s, work that earned the 2020 Nobel Prize in Physics. In 2019 the Event Horizon Telescope produced the first image of a black hole's shadow, the 6.5-billion-solar-mass giant at the heart of the galaxy M87, followed in 2022 by Sagittarius A* itself. How such monsters grew so large so early in cosmic history is an open question taken up in the Galaxies chapter.



The shadow of the supermassive black hole at the centre of M87, imaged by the Event Horizon Telescope in 2019. The bright ring is light from hot gas bent around the hole; the dark centre is about 40 billion km across.

Event Horizon Telescope Collaboration, CC BY 4.0

Dark matter

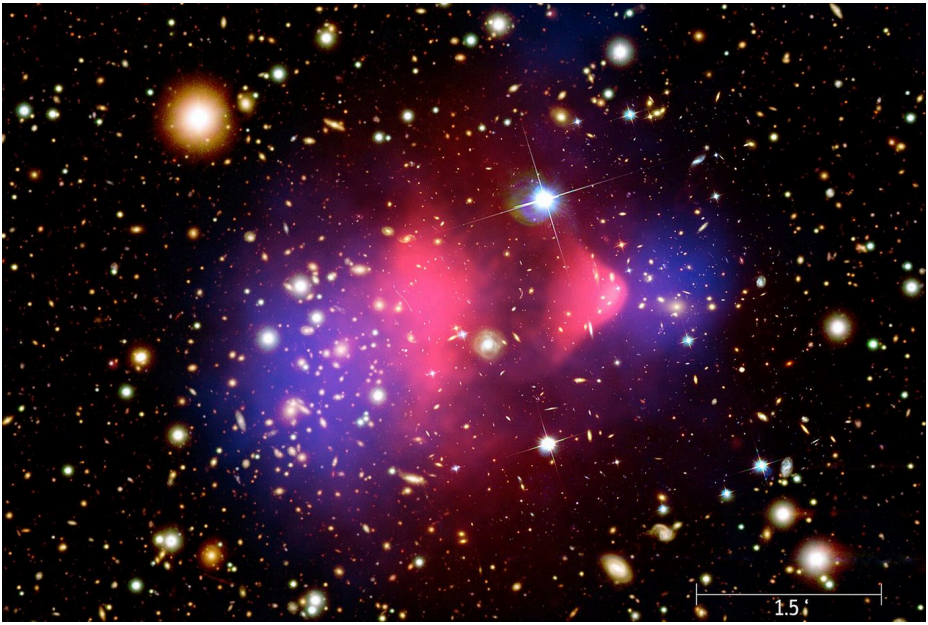
Add up all the stars, gas and dust in a galaxy and you get its visible mass. Watch how fast the galaxy rotates and you get its actual mass, from Newton's laws. The two numbers disagree, by a factor of five or more. Something we cannot see is supplying most of the gravity.

The first hint came in 1933, when Fritz Zwicky found that the galaxies in the Coma Cluster were moving far too fast to be held together by their visible mass. The decisive evidence came in the 1970s from Vera Rubin and Kent Ford, who measured the rotation speeds of stars and gas in spiral galaxies. If mass were concentrated where the light is, orbital speeds should fall off with distance from the centre, as the planets' do around the Sun. Instead the rota-

tion curves stayed flat out to the faintest measurable edges: the galaxies were embedded in vast invisible halos of matter extending far beyond their visible discs.

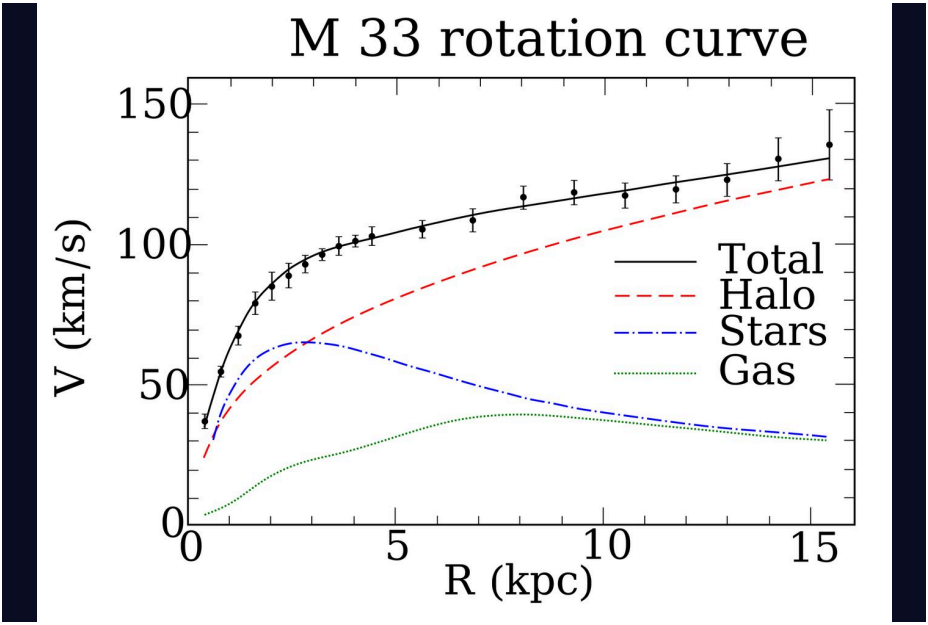
The evidence has since become overwhelming and comes from independent directions. Galaxy clusters bend the light of background galaxies (gravitational lensing) far more than their visible mass allows. In the Bullet Cluster, two clusters have collided; the hot gas — most of the ordinary matter — has been slowed and left in the middle, while the lensing shows the mass has sailed straight through with the galaxies, exactly as collisionless dark matter should. The pattern of temperature ripples in the cosmic microwave background can be fitted only if about 85% of the matter in the universe is dark, non-atomic and cold. And no simulation of cosmic structure formation produces galaxies at all without it.

What dark matter *is* remains unknown. It is not ordinary atoms, not black holes in significant numbers, and not the known neutrinos. The leading candidates are undiscovered particles — weakly interacting massive particles or ultralight axions — and dozens of experiments deep underground and in space are searching for them. Dark matter accounts for about 27% of the energy content of the universe; ordinary matter, everything on the periodic table, is about 5%. The rest is dark energy, the subject of the next page.



The Bullet Cluster. Pink: hot X-ray gas seen by Chandra — most of the normal matter. Blue: where the mass actually is, mapped by gravitational lensing. The mass and the gas have separated in the collision, which is very hard to explain without dark matter.

NASA/CXC/CfA/STScI/Magellan/ESO (public domain)



The rotation curve of M33, the Triangulum Galaxy. The points are the observed speeds; the solid line is the best fit, built from three parts — stars, gas and a dark matter halo (red dashed). Stars and gas alone fall far short in the outer galaxy.

Vallastro, CC BY-SA 4.0

Nucleosynthesis: how stars make the elements

The Big Bang produced hydrogen, helium and a trace of lithium — nothing heavier. Every other element in your body was made inside a star or in the death of one. This is nucleosynthesis, and it is the reason stars shine: fusing light nuclei into heavier ones releases the binding energy that holds the star up.

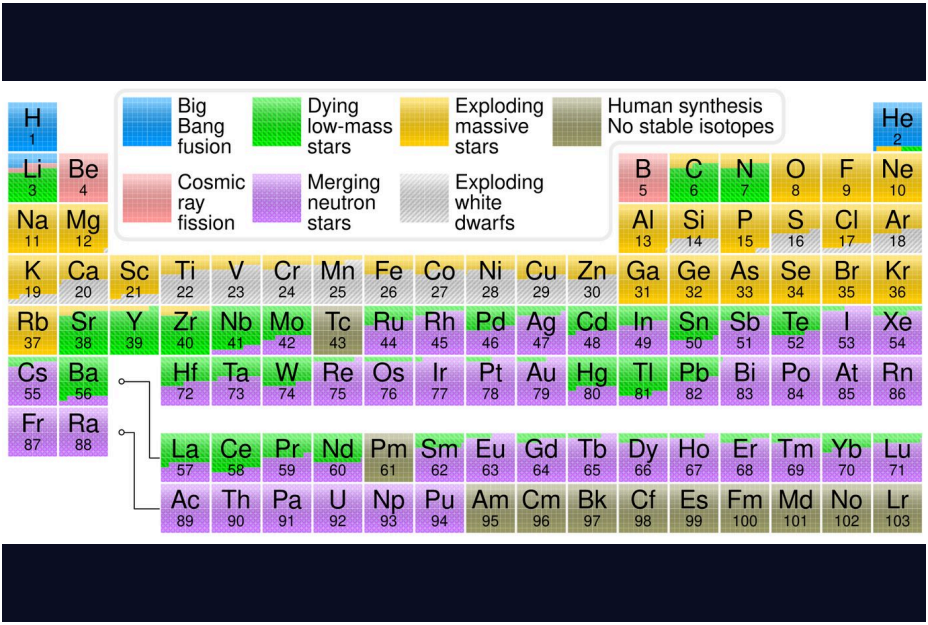
Hydrogen burning. In stars up to about 1.3 solar masses the dominant route is the proton–proton chain: four protons become one helium-4 nucleus in three steps, releasing two positrons, two neutrinos and 26.7 MeV of energy. In hotter, more massive stars the CNO cycle takes over, using carbon, nitrogen and oxygen nuclei as catalysts to achieve the same result far faster. Either way, 0.7% of the mass involved is converted to energy.

Helium burning. Once hydrogen is exhausted the core contracts and heats to 100 million K, and helium fuses by the triple-alpha process: two helium nuclei form fleeting beryllium-8, and a third arrives before it decays, producing carbon-12. Some carbon captures a fourth helium to make oxygen-16. Carbon and oxygen are thus the ash of helium burning, and for a Sun-like star that is the end of the line.

Advanced burning. Stars above about eight solar masses keep going: carbon burns to neon and magnesium at 600 million K, neon to oxygen and magnesium, oxygen to silicon and sulphur, and finally silicon to iron and nickel at 3 billion K. Each stage is shorter than the last — millions of years for hydrogen, a year for oxygen, a day for silicon. The star develops an onion-like structure with iron at the centre.

The iron wall. Iron-56 has the most tightly bound nucleus of all. Fusing it releases no energy; it costs energy. When a massive star's core turns to iron, the furnace goes out, and within seconds the star collapses (see supernovae).

Beyond iron. Elements heavier than iron are built not by fusion but by neutron capture. The slow *s-process* happens in the outer shells of ageing giants over thousands of years and makes elements such as strontium, barium and lead. The rapid *r-process* needs an extraordinary flood of neutrons — a core-collapse supernova or, as the 2017 gravitational-wave event GW170817 confirmed, the merger of two neutron stars — and makes gold, platinum, uranium and most of the heaviest elements in a matter of seconds.



Where the elements come from. Hydrogen and helium from the Big Bang; carbon and nitrogen largely from dying low-mass stars; oxygen and the alpha elements from massive-star supernovae; iron mostly from exploding white dwarfs; gold and the heaviest elements from merging neutron stars.

Cmglee, CC BY-SA 3.0

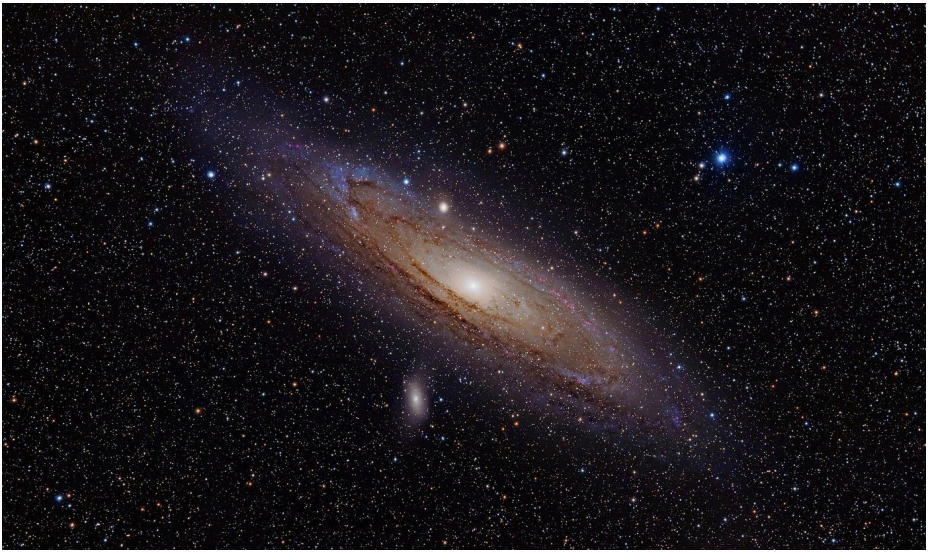
HYDROGEN BURNING 15 million K	HELIUM BURNING 100 million K
CARBON BURNING 600 million K	SILICON BURNING 3 billion K

Stars gather in their hundreds of billions. Continue to galaxies and the large-scale universe.

CHAPTER 4

Galaxies and the large-scale universe

Gravity, given thirteen billion years and a little dark matter to work with, gathers stars into galaxies, galaxies into clusters, and clusters into a foam of filaments and voids that spans everything we can see.



Andromeda Galaxy, M31 — Adam Evans, CC BY 2.0

What a galaxy is

A galaxy is a gravitationally bound system of stars, gas, dust and dark matter, ranging from dwarfs of a few million stars to giants of several trillion.

The Milky Way is a large one, with perhaps 200–400 billion stars in a disc 100,000 light-years across. The observable universe holds something like two trillion galaxies.

Until a century ago no one knew galaxies existed. The fuzzy "spiral nebulae" catalogued by Messier and Herschel might have been gas clouds inside the Milky Way, or "island universes" far beyond it; the Great Debate of 1920 between Harlow Shapley and Heber Curtis argued both sides. Edwin Hubble settled it in 1924 by finding Cepheid variables in Andromeda and measuring its distance at nearly a million light-years (we now know it is 2.5 million) — far beyond any star in our galaxy. Suddenly the universe was vastly larger than anyone had imagined, and full of other Milky Ways.

Most of a galaxy's mass is dark matter, arranged in a roughly spherical halo that extends several times farther than the visible stars.

GALAXIES IN OBSERVABLE UNIVERSE ~2 trillion	STARS IN THE MILKY WAY 200–400 billion
MILKY WAY DISC DIAMETER ~100,000 ly	DARK MATTER HALO ~85% of mass
DISTANCE TO ANDROMEDA 2.5 million ly	MOST DISTANT CONFIRMED GALAXY ~13.5 billion ly (light-travel)

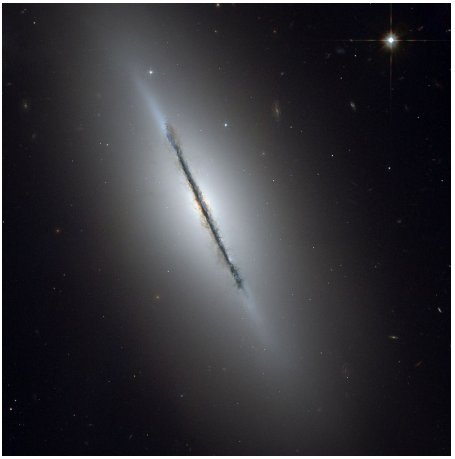
Kinds of galaxy

Hubble sorted galaxies by appearance into a scheme still used today, though his idea that it was an evolutionary sequence from elliptical to spiral turned out to be wrong. We now believe that mergers of spiral galaxies contribute significantly to the formation of ellipticals. Over time, the trend has been one-directional. Over the last several billion years, the share of massive “red and dead” ellipticals has steadily grown, while star-forming spirals have become comparatively rarer.



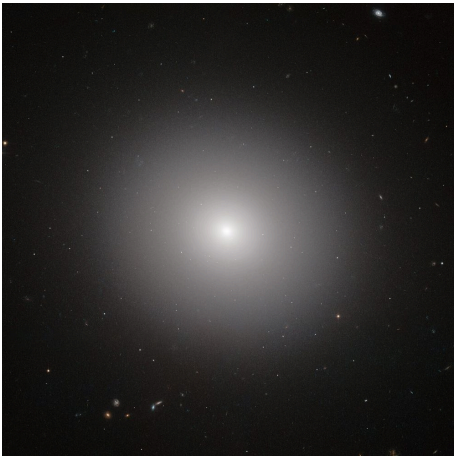
Spirals (like M51, the Whirlpool). A flat rotating disc of stars and gas with arms of active star formation, wrapped around a central bulge of older stars. About two-thirds of large nearby galaxies, including the Milky Way and Andromeda, are spirals; many, including ours, have a central bar.

NASA/ESA/S. Beckwith/Hubble Heritage (public domain)



Lenticulars (like NGC 5866, seen edge-on). The in-between type, S0 in Hubble's scheme: a disc and bulge like a spiral, but with no arms and almost no new stars. They are disc galaxies that have used up or been stripped of their gas, and they are common in crowded galaxy clusters.

NASA/ESA/Hubble Heritage (public domain)



Ellipticals (like IC 2006). Smooth, featureless, and old: little gas, little dust, no new stars, with stars swarming on random orbits rather than circling in a disc. The largest galaxies in the universe, such as M87, are giant ellipticals at the centres of clusters. Their star formation shut down billions of years ago, starting in the core and spreading outward.

ESA/Hubble & NASA, J. Schmidt, J. Blakeslee (public domain)



Irregulars and mergers (like the Antennae, NGC 4038/4039). Galaxies distorted by collision or too small to organise themselves. The Magellanic Clouds are irregular dwarfs; the Antennae are two spirals in mid-collision, with a burst of star formation lit by the encounter.

NASA/ESA/Hubble Heritage (public domain)



Dwarfs (like the Fornax dwarf spheroidal, a satellite of the Milky Way). Small, faint galaxies of a few million to a few billion stars. They vastly outnumber the giants and come in spheroidal and irregular varieties; many are so dominated by dark matter that they barely shine at all. Fornax is a dim haze of old stars that can only be seen through a telescope.

ESO/Digitized Sky Survey 2, CC BY 4.0

How galaxies form

Let's begin around 380,000 years after the Big Bang, when the universe had cooled enough for atoms to form and light to travel freely. That light is the cosmic microwave background, and it shows a universe that was almost perfectly uniform — but not quite. Regions were denser than average by about one part in 100,000. Those tiny ripples were the seeds of everything.

Dark matter went first. Not feeling radiation pressure, it could begin collapsing into the overdense regions while ordinary matter was still coupled to light. Over the next few hundred million years dark matter gathered into halos, small ones first, which merged into larger ones — a **hierarchical** or bottom-up process. Ordinary gas then fell into the gravitational wells the dark matter had dug, cooled by radiating away energy, and sank to the centres, where it fragmented into the first stars.

Those first stars, around 100–200 million years after the Big Bang, were probably huge, hot and short-lived, made of pure hydrogen and helium. Their ul-

traviolet light re-ionised the gas around them, ending the "cosmic dark ages," and their supernovae seeded the surrounding gas with the first heavy elements. The James Webb Space Telescope has now photographed galaxies as they were 300–400 million years after the Big Bang, and they are surprisingly bright and numerous — a genuine puzzle for models of how quickly stars could form.

Whether a galaxy becomes a disc or a spheroid depends largely on how it acquired its gas. Gas that flowed in smoothly along cold streams, carrying angular momentum, settled into a rotating disc and became a spiral. Halos assembled by violent, rapid mergers scrambled their stars' orbits and became ellipticals. Supermassive black holes grew in the centres alongside their galaxies, feeding on infalling gas; the energy they released as quasars and jets heated and expelled gas, throttling star formation in the largest galaxies — which is why the most massive galaxies are "red and dead" today.



The Hubble eXtreme Deep Field, assembled from 23 days of exposure on a patch of sky smaller than the full Moon. About 5,500 galaxies are visible; the reddest, faintest smudges are seen as they were some 13.2 billion years ago.

NASA/ESA/G. Illingworth et al. (public domain)

How galaxies move

Within a spiral galaxy, stars orbit the centre. The Sun travels at about 230 km/s and takes roughly 225 million years to complete one circuit — a "galactic year"; it has made about twenty since it formed. The flat rotation curves described in the Stars chapter show that the mass responsible extends far beyond the visible disc.

Spiral arms are not fixed streams of stars. If they were, differential rotation — inner stars orbiting faster than outer ones — would wind them up tightly within a few rotations. Instead the arms are **density waves**: slowly rotating patterns of compression through which stars and gas pass, like cars bunching at a slow spot on a highway. Gas entering an arm is compressed and forms stars; the bright blue stars and pink nebulae that outline the arms are simply the newest and shortest-lived, which die before they drift out the other side.

Galaxies also move relative to one another. Within groups and clusters they orbit a common centre of mass at hundreds to thousands of km/s. Andromeda and the Milky Way are falling toward each other at about 110 km/s and will collide in roughly 4.5 billion years, eventually merging into a single elliptical galaxy. Our Local Group as a whole is falling toward the Virgo Cluster, and the whole region moves at about 600 km/s relative to the cosmic microwave background, pulled by a concentration of mass called the Great Attractor and, beyond it, the Shapley Supercluster.

Above all this local motion sits the expansion of the universe itself: on the largest scales, every galaxy recedes from every other, at a speed proportional to its distance. That is the subject of the section on the expanding universe.



The Sombrero Galaxy (M104), seen nearly edge-on, shows the two components of a disc galaxy: the flattened rotating disc with its dust lane, and the bright bulge of older stars on more random orbits. The bulge here is unusually large, and the galaxy is thought to be a spiral inside the body of an elliptical.

NASA/ESA/Hubble Heritage (public domain)

How galaxies change

Galaxies are not static. Over billions of years they consume their gas, merge with their neighbours, and are shaped by their environment.

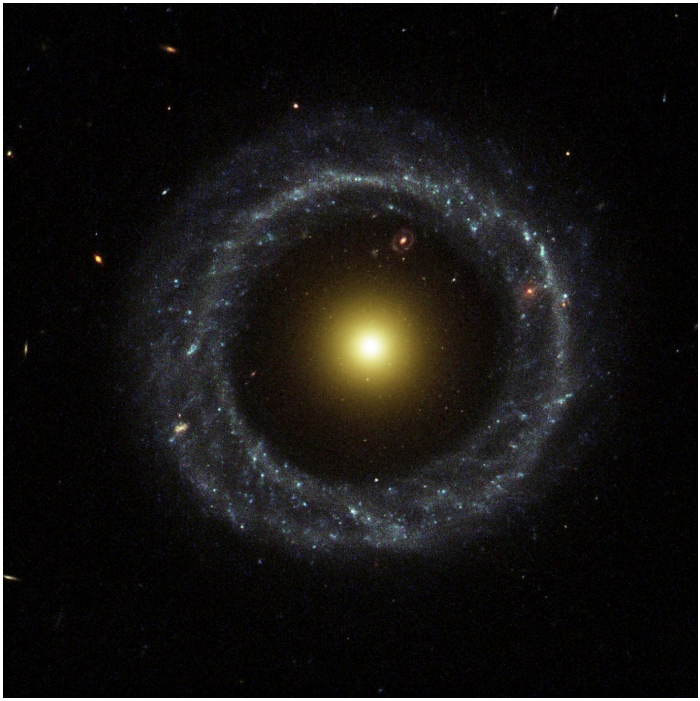
Mergers. When two galaxies of similar size collide, the individual stars almost never hit one another — they are far too widely spaced — but gravity throws them onto new orbits, and the gas clouds do collide, compressing and igniting intense starbursts. The tidal tails of the Antennae Galaxies are stars slung out in this way. After a billion years or so the two discs have been scrambled into a single spheroid: an elliptical galaxy. Large galaxies also grow by swallowing many small ones; the Milky Way is currently digesting the Sagittarius dwarf galaxy, and streams of its stars wrap around our halo.

Quenching. A galaxy forms stars only while it has cold gas. Gas can run out, be blown away by supernovae or by the galaxy's central black hole, or be

stripped by the hot gas of a cluster as the galaxy falls through it. Once quenched, a galaxy reddens as its blue massive stars die, and it drifts from the "blue cloud" of star-forming galaxies to the "red sequence" of dead ones. The universe's overall star-formation rate peaked about 10 billion years ago and has been declining ever since; most of the stars that will ever exist have already been born.

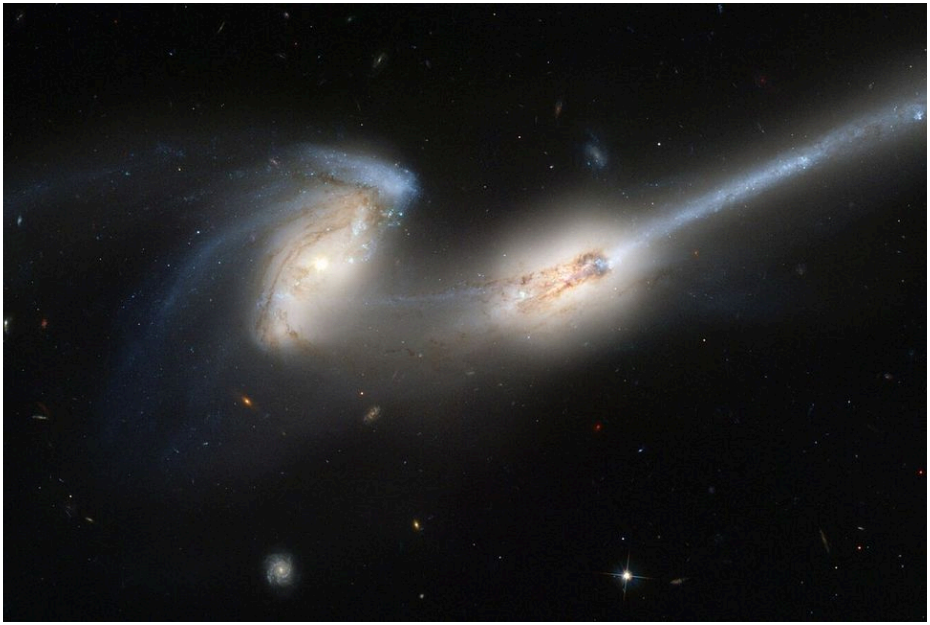
Environment. Where a galaxy lives shapes what it becomes. Cluster cores are dominated by ellipticals and lenticulars, stripped and merged; spirals are found in the quieter outskirts and in loose groups. Isolated galaxies in the voids between filaments are mostly small, blue and still forming stars.

The Milky Way's own future is written in this: a merger with Andromeda, a burst of star formation, and finally a quiet red elliptical — provisionally named "Milkomeda" — settling into old age.



Hoag's Object, a ring galaxy 600 million light-years away. The ring of young blue stars around an old yellow core is probably the result of a collision that rippled through the disc like a stone dropped in a pond.

NASA/Hubble Heritage (public domain)



The Mice (NGC 4676), two spirals partway through a collision. The long tails are stars pulled out by tidal forces; the pair will merge over the next billion years.

NASA/ESA/H. Ford et al. (public domain)

The Milky Way

We see our galaxy from inside, as a band of light across the summer sky — the combined glow of billions of distant stars in the disc, cut by dark lanes of dust. Mapping it has been like mapping a forest from beneath the trees, and the modern picture owes much to radio and infrared surveys that penetrate the dust and to the Gaia spacecraft, which has measured precise positions and motions for nearly two billion stars.

The Milky Way is a barred spiral about 100,000 light-years across, with four major arms and a thin disc roughly 1,000 light-years thick. The Sun lies in the Orion Spur, a minor arm segment, about 26,000 light-years from the centre and slightly above the mid-plane — a good vantage point, out of the worst of the dust. At the centre is a dense bulge of old stars, a bar, and the 4-million-solar-mass black hole Sagittarius A*. Around the whole thing is a sparse halo of ancient stars and about 150 globular clusters, spherical swarms of hun-

dreds of thousands of stars that are among the oldest objects known, some 12–13 billion years old. Many Messier objects — M13, M22, M5 — are globulars.

The Milky Way belongs to the Local Group, a loose gathering of about 80 galaxies spanning 10 million light-years, dominated by itself and Andromeda, with Triangulum (M33) a distant third and everything else a dwarf. The Large and Small Magellanic Clouds, visible from the southern hemisphere, are the largest of our satellites.



The Milky Way from the inside: a panorama assembled by ESO's Serge Brunier. The bulge is toward Sagittarius; the dark rifts are dust in the plane of the disc.

ESO/S. Brunier, CC BY 4.0

Cepheid variables and the cosmic distance ladder

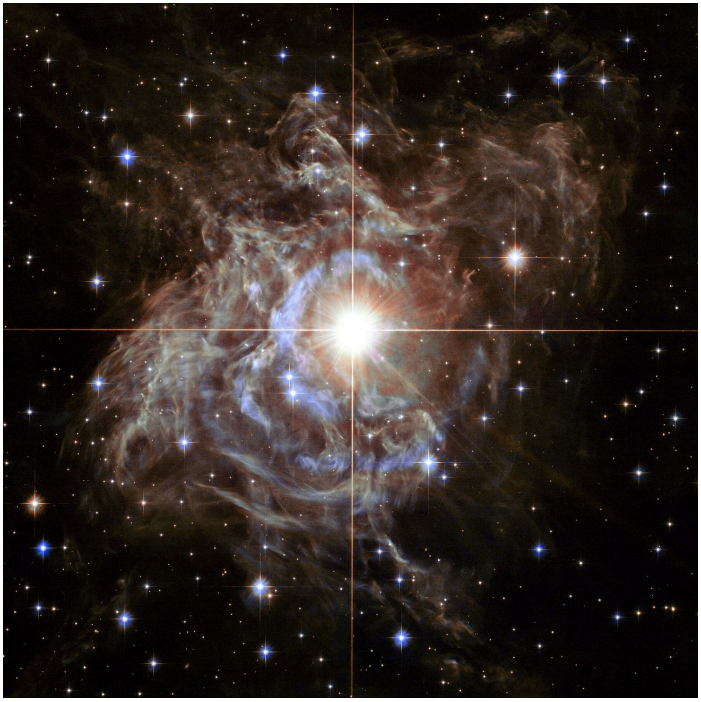
A Cepheid is a yellow supergiant, 4 to 20 times the Sun's mass, passing through a phase of its post-main-sequence life in which it pulsates: the whole star swells and shrinks, brightening and dimming with clockwork regularity every 1 to 100 days. The mechanism is a valve of ionised helium in the star's outer layers. When compressed, the layer absorbs more light and

heats, pushing the star outward; as the star expands the layer becomes transparent, the pressure releases, and gravity pulls the star back in. This oscillation is stable and self-sustaining while the star is in a narrow band of the H–R diagram called the instability strip.

In 1908–1912 Henrietta Swan Leavitt, studying Cepheids in the Small Magellanic Cloud at Harvard, discovered that the brighter a Cepheid, the longer its period. Since all the stars in the Cloud are at essentially the same distance, this had to be a relation between period and true luminosity — the **period–luminosity relation**, now called the Leavitt law. Its significance is hard to overstate. Measure a Cepheid's period, and you know how luminous it is. Compare that with how bright it appears, and you know how far away it is.

Cepheids were the tool that Edwin Hubble used in 1924 to show that the "spiral nebula" in Andromeda was an entire galaxy far outside the Milky Way, and in 1929 to show that galaxies recede from us at speeds proportional to their distance — the expanding universe. Today they remain the critical middle rung of the distance ladder: parallax calibrates nearby Cepheids, Cepheids calibrate the distances to galaxies hosting Type Ia supernovae, and those supernovae reach across the observable universe. The Hubble Space Telescope was designed with Cepheids in mind, and the current disagreement between Cepheid-based measurements of the expansion rate and those from the early universe — the "Hubble tension" — is one of the liveliest problems in cosmology.

The prototype, Delta Cephei, varies between magnitudes 3.5 and 4.4 every 5.37 days and is easy to follow with the naked eye. Polaris, the North Star, is a low-amplitude Cepheid too.



RS Puppis, one of the most luminous Cepheids in the Milky Way, wrapped in a dust cloud. Its pulsations send light echoes rippling through the nebula every 41.4 days, which allowed a direct geometric measurement of its distance: 6,500 light-years.

NASA/ESA/Hubble Heritage (public domain)

The expanding universe

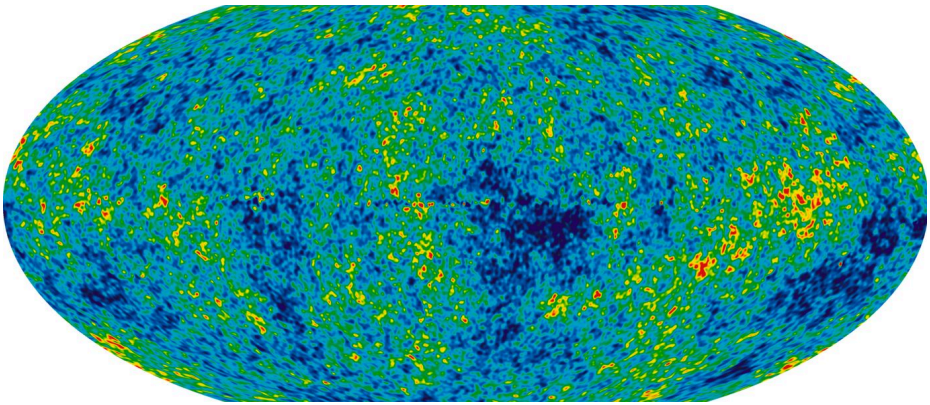
In 1929 Hubble, using Cepheid distances and the spectra measured by Vesto Slipher, showed that galaxies' light is shifted to the red — they are receding — and that the farther a galaxy is, the faster it recedes. Georges Lemaître had reached the same conclusion two years earlier from Einstein's equations. The relation, velocity = H_0 × distance, is the Hubble–Lemaître law, and its meaning is that space itself is expanding: the galaxies are not flying through space so much as being carried apart by it, like raisins in a rising loaf.

Run the expansion backwards and everything converges 13.8 billion years ago in a hot, dense state — the Big Bang. The theory makes specific predictions that have all been confirmed: the cosmic microwave background, dis-

covered in 1965 as a faint glow of 2.7 K filling the sky from every direction; the abundances of helium, deuterium and lithium, forged in the first three minutes; and the growth of structure from the tiny ripples in that background into the galaxies we see.

Gravity should slow the expansion. In 1998 two teams measuring Type Ia supernovae in distant galaxies found the opposite: the expansion is speeding up. Something is pushing space apart, and it has been named **dark energy**. Its simplest form is Einstein's cosmological constant, an energy inherent to space itself. It now makes up about 68% of the energy content of the universe, and it will dominate ever more as expansion dilutes the matter. The universe's fate, on current evidence, is to expand forever, growing colder, darker and emptier.

The current value of H_0 is disputed. Measurements built on the Cepheid distance ladder give about 73 km/s per megaparsec; those inferred from the cosmic microwave background give about 67. The gap is far larger than the stated uncertainties and may be pointing to new physics.



The cosmic microwave background as mapped by WMAP. The whole sky, in microwaves, 380,000 years after the Big Bang. The colour differences are temperature variations of a few hundred-thousandths of a degree — the seeds from which all galaxies grew.

NASA/WMAP Science Team (public domain)

Large-scale structure: the cosmic web

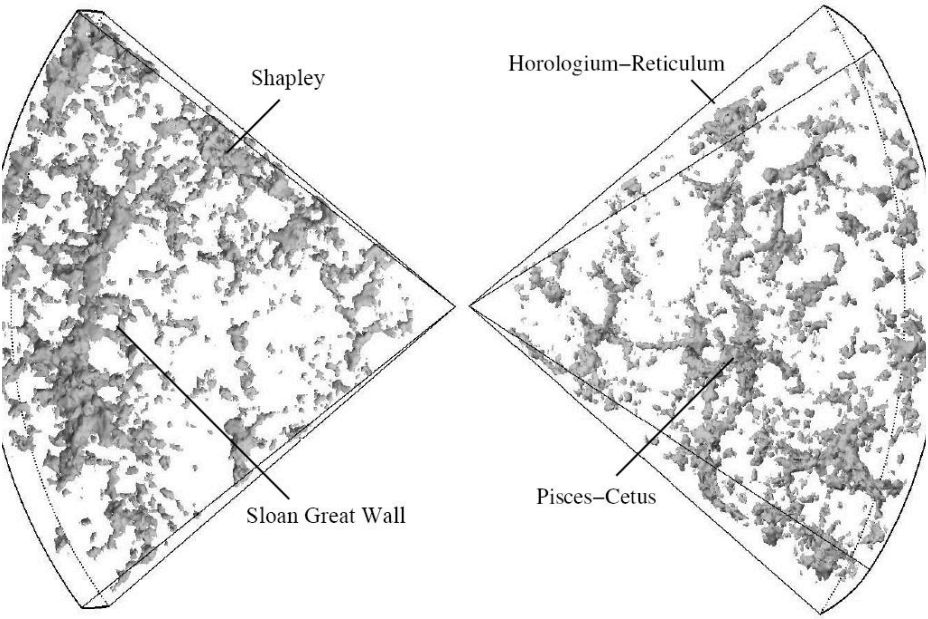
Galaxies are not scattered evenly through space. Surveys that measure the redshifts of millions of galaxies — the 2dF survey, the Sloan Digital Sky

Survey, and now DESI — reveal that they are arranged in a pattern like a sponge or a foam: long **filaments** and flat **sheets** of galaxies surrounding enormous nearly empty **voids**, with dense **clusters** where the filaments meet. This is the cosmic web, and it is the largest structure in the universe.

The hierarchy runs like this. Galaxies gather in *groups* of a few dozen (like our Local Group) and *clusters* of hundreds to thousands, spanning 10–30 million light-years and filled with hot X-ray-emitting gas; the Virgo Cluster, 55 million light-years away, is the nearest large one. Clusters and groups link into *superclusters* hundreds of millions of light-years long; the Local Group lies on the outskirts of the Virgo Supercluster, which is itself a lobe of the far larger Laniakea Supercluster identified in 2014. Between the filaments are voids 100–300 million light-years across containing almost nothing. Beyond about 300 million light-years the universe finally looks the same in every direction and every place — statistically homogeneous, as the Big Bang model requires.

The web is what gravity makes out of nearly uniform matter. Computer simulations that start from the ripples in the cosmic microwave background and let gravity act on cold dark matter for 13.8 billion years reproduce it in detail: the slight overdensities pull in matter, empty the regions around them into voids, and channel infalling material along filaments into the nodes that become clusters. Galaxies form where the dark matter is densest; the pattern of light traces the pattern of unseen mass. The remarkable thing is how few ingredients this needs — dark matter, ordinary matter, dark energy, and general relativity — to produce a universe that looks like ours.

> **Looking back out.** The dwarf planets of the Kuiper belt, the Sun's nuclear furnace, the Cepheids that gave us the distance to Andromeda, the dark matter halos that hold galaxies together, and the filaments that string those galaxies across the sky are all governed by the same handful of laws acting on different scales of time and size. That continuity, from the pebbles that built Arrokoth to the cosmic web, is the whole point of looking outward — and of studying it.



The cosmic web as mapped by the 2dF Galaxy Redshift Survey. Each dot is a galaxy; Earth is at the apex. Filaments, walls and voids are plain to see.

Willem Schaap, CC BY-SA 3.0



The galaxy cluster Abell S740, 450 million light-years away, dominated by the giant elliptical ESO 325-G004. Clusters are the nodes where the filaments of the cosmic web meet.

NASA/ESA/Hubble Heritage (public domain)

Now bring it back to the eyepiece. The gallery holds images of many of these objects taken from a backyard telescope.

CHAPTER 5

Celestial coordinates and the moving sky

To find anything in the night sky you need an address for it. Astronomers have several address systems, each suited to a different job, and every one of them has to account for the fact that the sky itself is slowly moving.



Star trails around the north celestial pole, Pennsylvania — Tyler Savitski, CC BY-SA 4.0

The celestial sphere

The stars are at wildly different distances — the nearest a little over four light-years away, the faintest naked-eye stars thousands. But to the eye they

all seem pinned to the inside of a great dome. Astronomers keep that illusion as a working tool: the **celestial sphere**, an imaginary sphere of unlimited size centred on the Earth, onto which every object is projected. Distance is set aside; what matters is direction.

Extend the Earth's axis outward and it pierces the sphere at the **north and south celestial poles**. Extend the Earth's equator and it traces the **celestial equator**. Because the Earth spins, the whole sphere appears to turn around those poles once a day, carrying the stars from east to west.

Every coordinate system in this chapter works the same way as latitude and longitude on a globe: pick a reference circle, pick a starting point on it, then give two angles — one measured around the circle, one measured away from it. The systems differ only in which circle they choose.

FULL CIRCLE 360°	1 DEGREE 60′ (arcminutes)
1 ARCMINUTE 60″ (arcseconds)	FULL MOON about 0.5°
FIST AT ARM'S LENGTH about 10°	WHOLE SKY 41,253 sq. degrees

An arcsecond is tiny — the width of a coin seen from about 4 km away. Many of the motions described below are measured in arcseconds per year or per century.

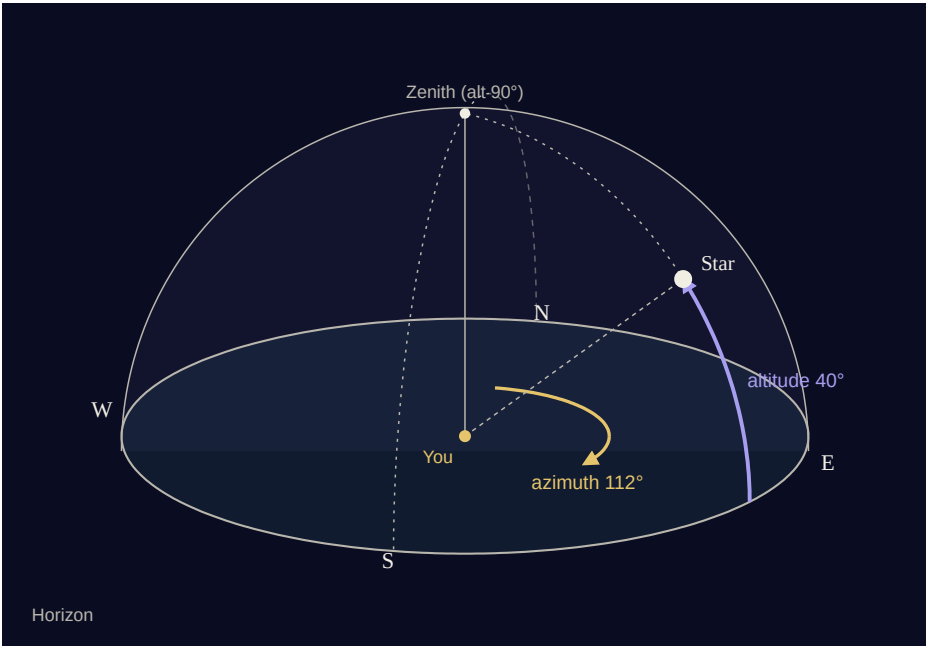
Altitude and azimuth: the sky from where you stand

The simplest system uses your own horizon as the reference circle. **Altitude** is the angle of an object above the horizon, from 0° at the horizon to 90° at the **zenith** directly overhead. **Azimuth** is the compass direction, measured clockwise from north: 0° north, 90° east, 180° south, 270° west.

This is the system of everyday observing — "Jupiter is 30° up in the south-east" — and it is how most telescope mounts, including smart telescopes, physically point. The line running from due north through the zenith to due south is the **meridian**; an object is highest in the sky when it crosses it,

which is why observers try to catch faint targets near the meridian, where they shine through the least atmosphere.

The catch is that altitude and azimuth belong to one place at one moment. As the Earth turns, every star's altitude and azimuth change continuously, and an observer in another town sees different numbers at the same instant. For a catalogue or a star chart, a coordinate system fixed to the sky itself is needed.



The horizon system. Azimuth runs around the horizon from north through east; altitude climbs from the horizon toward the zenith.

Right ascension and declination: addresses on the sky

The **equatorial system** projects the Earth's latitude and longitude onto the sky, and it is the standard for star catalogues, charts and telescope "go-to" databases.

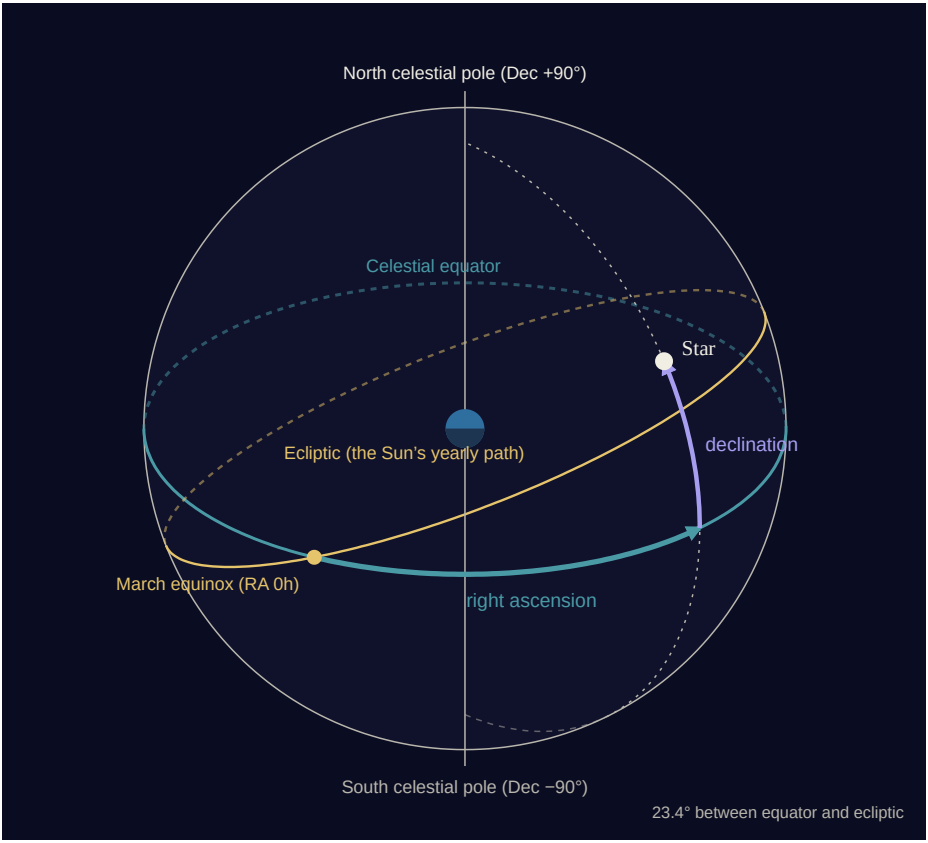
Declination (Dec) is celestial latitude: degrees north (+) or south (−) of the celestial equator, from +90° at the north celestial pole to −90° at the south.

Polaris sits at about +89°; the Orion Nebula at about −5°.

Right ascension (RA) is celestial longitude, but it is counted in *hours* rather than degrees, from 0h to 24h, increasing eastward. One hour of RA equals 15°. The hours are a reminder of the sky's rotation: a star with an RA one hour greater than another crosses your meridian one hour later.

Longitude on Earth starts at Greenwich; right ascension starts at the **March equinox point**, sometimes called the First Point of Aries. That is where the Sun, moving along its yearly path, crosses the celestial equator heading north around 20 March. The Andromeda Galaxy, for example, sits at RA 0h 43m, Dec +41° 16′ — about three-quarters of an hour east of that point and 41 degrees north of the equator.

Because these coordinates are tied to the Earth's axis and not to any observer, they are the same for everyone, everywhere, all night long. Almost. As the rest of this chapter explains, the axis itself drifts, so every catalogue position has to state the date — the **epoch** — for which it is valid.



Right ascension is measured eastward along the celestial equator from the March equinox; declination is measured north or south of the equator. The ecliptic — the Sun's apparent yearly path — is tilted 23.4° to the equator because the Earth's axis is tilted by the same amount.

The revolving Earth and sidereal time

The Earth turns once relative to the stars in **23 hours 56 minutes 4 seconds** — a **sidereal day**. Our 24-hour solar day is about four minutes longer, because while the Earth spins it also moves a little way along its orbit, and has to turn slightly further to bring the Sun back to the meridian. The result: every star rises about four minutes earlier each night, two hours earlier each month, and the evening sky cycles through the constellations over a year.

Observatories keep a second clock running on **sidereal time**. Local sidereal time is simply the right ascension currently on your meridian. If the sidereal clock reads 5h 35m, the Orion Nebula (RA 5h 35m) is due south and at its highest. Convert between RA/Dec and altitude/azimuth using your latitude and the sidereal time, and a go-to mount knows where to point.

Your latitude also decides which stars you see. The north celestial pole stands above your northern horizon at an altitude equal to your latitude — about 40° from New Jersey. Stars within 40° of the pole never set; they are **circumpolar**, wheeling around Polaris all night, as in the star trails at the start of this chapter. Stars within 40° of the *south* pole never rise at all. From the equator, every star rises and sets; from the North Pole, only the northern half of the sky is ever visible, and it never sets.

SIDEREAL DAY 23 h 56 m 4 s	SOLAR DAY 24 h 00 m
STARS RISE EARLIER BY ~4 min / night	ALTITUDE OF THE POLE = your latitude

> **Finding Polaris.** Follow the two stars at the end of the Big Dipper's bowl, Merak and Dubhe, about five times their separation. Polaris is not especially bright, but it is the only star that does not move.

Two more systems: ecliptic and galactic

Ecliptic coordinates

The planets all orbit in nearly the same plane, so their paths across our sky stay close to the **ecliptic**, the Sun's yearly track. For the solar system it is natural to use the ecliptic as the reference circle. **Ecliptic longitude** is measured eastward along it from the March equinox, in degrees; **ecliptic latitude** north or south of it. The Sun's ecliptic latitude is zero by definition, and its longitude advances almost one degree a day. The band of sky within a few degrees of the ecliptic is the zodiac, covered in the Constellations chapter.

The ecliptic is tilted to the celestial equator by the **obliquity** — 23.44° today. That tilt is the Earth's axial tilt, and it is the reason we have seasons.

Galactic coordinates

For studying the Milky Way, the reference circle is the galaxy's own mid-plane. **Galactic longitude** (l) is measured from 0° in the direction of the galactic centre, in Sagittarius at RA 17h 46m, Dec −29°. **Galactic latitude** (b) runs from +90° at the north galactic pole, in Coma Berenices, to −90°.

In these coordinates the Milky Way is a horizontal band along $b = 0°$, star-forming regions and open clusters crowd near it, and globular clusters and distant galaxies scatter far above and below it. Maps of the whole sky from missions such as Gaia and Planck are usually drawn this way. See the Milky Way section for the structure behind it.

Precession: the wobbling axis

Around 130 BC the Greek astronomer **Hipparchus** compared his own star positions with those recorded about 150 years earlier and found that they had all shifted by about two degrees in the same direction. He had discovered the **precession of the equinoxes**, the slowest and largest of the sky's motions.

The Earth is not a perfect sphere. Its spin makes it bulge at the equator, which is about 43 km wider than the distance between the poles. The Sun and Moon pull on that bulge, trying to straighten the tilted Earth up. A spinning top answers a sideways pull by wobbling instead of falling, and the Earth does the same: its axis sweeps out a cone, keeping its 23.4° tilt but changing the direction it points.

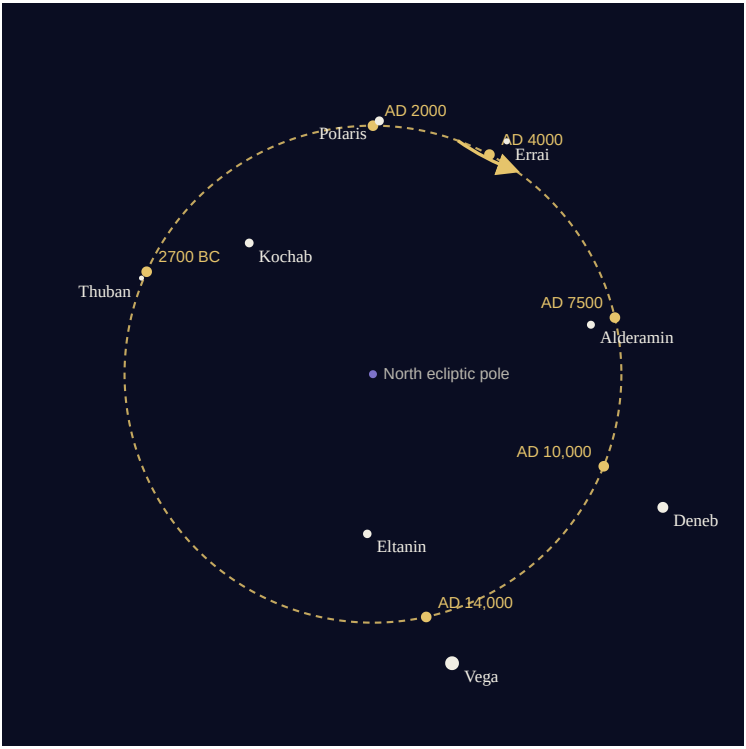
One circuit takes about **25,800 years**. The celestial poles therefore trace slow circles among the stars, and the "pole star" changes over the ages:

- **Thuban**, in Draco, was the pole star when the Egyptian pyramids were built, around 2700 BC.
- **Polaris** is the pole star now, and is still getting closer. It will pass within about 0.45° of the pole around AD 2100, then begin to drift away.
- The pole will pass near **Errai** around AD 4000, **Alderamin** around AD 7500 and **Deneb** around AD 10,000, and will come within a few degrees of brilliant **Vega** around AD 14,000.

Precession also drags the equinox points westward along the ecliptic, by about 50 arcseconds a year — one degree every 72 years. Since right ascen-

sion and ecliptic longitude are both counted from the March equinox, *every* star's catalogued coordinates slowly change. That is why positions are quoted for a standard epoch, today usually **J2000.0** (noon on 1 January 2000), and why planetarium software "precesses" them to the date of observation. A star chart printed in 1950 is already off by more than half a degree in places.

The March equinox point lay in the constellation Aries when the system was named over 2,000 years ago — hence "First Point of Aries". Precession carried it into Pisces in the first century BC, and it will cross into Aquarius around AD 2600.



The path of the north celestial pole over one precession cycle, centred on the pole of the ecliptic. The arrow shows the direction of travel. Star positions from the Hipparcos catalogue; pole positions computed for a 25,772-year period.

Nutation: a nod on top of the wobble

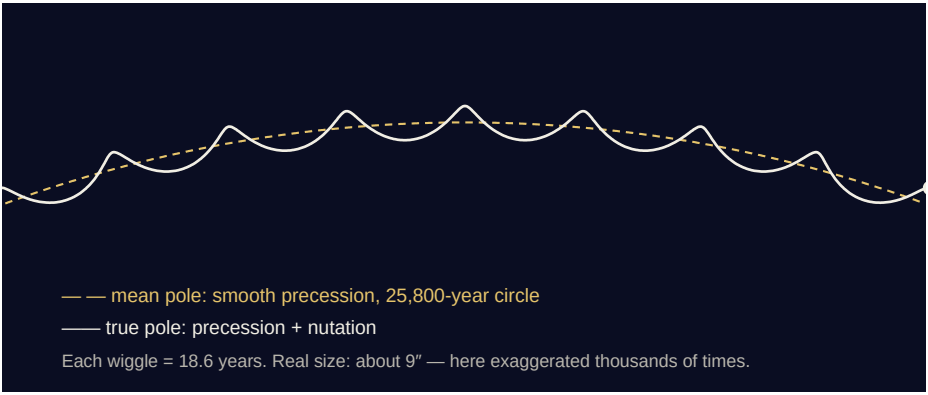
Precession would be a smooth circle if the pulls of the Sun and Moon were steady. They are not. The Moon's orbit is tilted about 5° to the ecliptic, and that tilted orbit itself slowly swivels around, completing a turn every **18.6 years**. As it does, the Moon's grip on the Earth's bulge strengthens and weakens, and the axis nods back and forth as it precesses. This is **nutation**, from the Latin for "nodding".

The main nutation shifts the pole by up to about **9 arcseconds** in the tilt direction and 17 arcseconds along the ecliptic — about a quarter of the apparent width of Jupiter. Smaller ripples follow the Sun's half-yearly and the Moon's fortnightly changes of position.

It was discovered by the English astronomer **James Bradley**, who noticed from 1727 onward that stars were drifting by small amounts his other corrections could not explain. He tracked them for a full 18.6-year lunar cycle before announcing the result in 1748.

Nutation is far too small to matter at the eyepiece, but professional catalogues, spacecraft navigation and the precise pointing of radio telescopes all correct for it. A position that includes precession *and* nutation is called a "true" position, as opposed to a "mean" one that includes precession alone.

> **Not the same thing:** the Earth's axial tilt also varies slowly between about 22.1° and 24.5° over a 41,000-year cycle, one of the Milankovitch cycles that pace the ice ages. It is decreasing now, by about half an arcsecond a year.



Nutation superimposes a small 18.6-year nod on the smooth precession circle. The wiggles are exaggerated thousands of times here; in reality the whole 25,800-year circle is about 47° across, while each nod is a few arcseconds.

Proper motion: the stars are not fixed

Precession and nutation move the coordinate grid; the stars themselves stay put relative to one another. But they are not truly fixed. Every star is orbiting the centre of the Milky Way, as the Sun is, and each has its own velocity relative to us. The sideways part of that motion, seen as a slow drift across the sky, is its **proper motion**.

In 1718 **Edmond Halley** compared modern positions of Sirius, Arcturus and Aldebaran with those recorded by Ptolemy 1,500 years earlier and found that they had shifted — Arcturus by about a degree, twice the width of the full Moon — far beyond any error in the old records. The "fixed stars" were moving.

Proper motions are tiny: most naked-eye stars shift by a small fraction of an arcsecond a year. The record holder is **Barnard's Star**, a faint red dwarf six light-years away in Ophiuchus, which crosses 10.4 arcseconds a year and covers the width of the full Moon in about 175 years. Arcturus, among the brightest stars, moves 2.3 arcseconds a year.

Proper motion is an angle; to turn it into a speed you need the distance. A star at 1 parsec (3.26 light-years) moving 1 arcsecond a year has a sideways speed of 4.74 km/s, and the numbers scale in proportion. Combine that with the **radial velocity** measured from the Doppler shift of the star's spectrum,

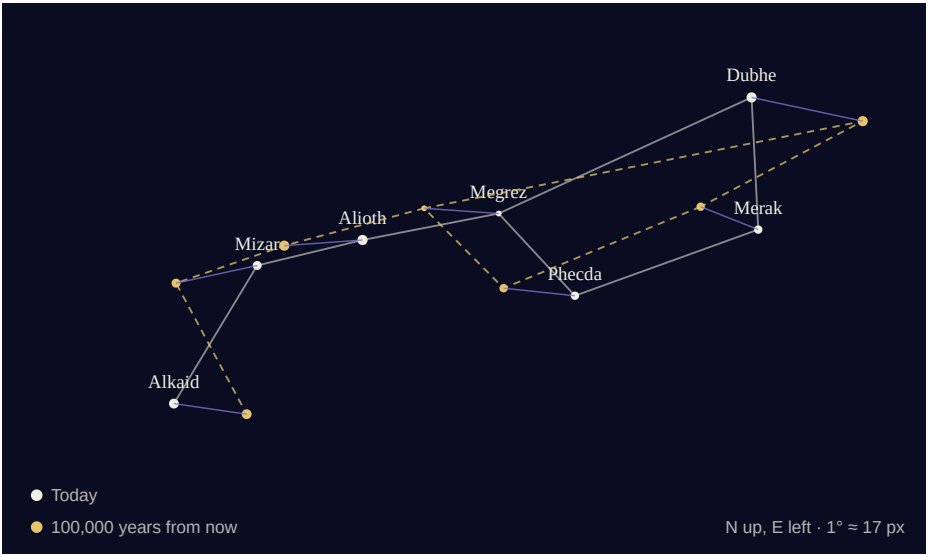
and you have its full motion through space. Barnard's Star, for example, is approaching us at about 110 km/s and will pass within about 3.8 light-years of the Sun around AD 11,800.

Given enough time, proper motion reshapes the constellations. Five of the seven Big Dipper stars belong to the **Ursa Major Moving Group**, a loose family about 80 light-years away travelling together through space. The two ends of the Dipper, Dubhe and Alkaid, are not members and are heading the other way, so the familiar shape is slowly coming apart.

The European Space Agency's **Gaia** spacecraft has measured proper motions for some 1.8 billion stars, for bright ones with a precision of a few hundredths of a thousandth of an arcsecond per year. With those measurements astronomers can run the Milky Way's clock backward and forward, tracing star streams torn from swallowed dwarf galaxies and families of stars born together long ago.

Some notable proper motions

Star	Proper motion	Distance
Barnard's Star	10.4″ / yr	6 ly
Kapteyn's Star	8.6″ / yr	13 ly
61 Cygni	5.3″ / yr	11 ly
Alpha Centauri	3.7″ / yr	4.4 ly
Arcturus	2.3″ / yr	37 ly
Sirius	1.3″ / yr	8.6 ly
Typical bright star	< 0.1″ / yr	hundreds of ly



The Big Dipper today (white) and 100,000 years from now (gold), computed from the stars' measured proper motions. The five middle stars travel together; Dubhe and Alkaid go their own way.

Other small shifts

A few more effects move a star's apparent position, each discovered as instruments improved. Together with precession, nutation and proper motion, these are the corrections that turn a catalogue position into the exact spot where a telescope must point.

Effect	Cause	Size	Timescale
Precession	Sun and Moon pull on the Earth's equatorial bulge	50″ per year; 47° circle	25,800 years
Nutation	The Moon's tilted orbit swivels, varying its pull	Up to ~9″ (tilt), ~17″ (longitude)	18.6 years, plus shorter ripples
Aberration	The Earth's orbital speed (30 km/s) tilts incoming starlight, like rain on a moving car's windscreen; found by Bradley in 1727	Up to 20.5″	1 year
Parallax	Viewing nearby stars from opposite sides of the Earth's orbit; first measured by Bessel for 61 Cygni in 1838	Under 1″ — 0.77″ for Proxima Centauri	1 year
Proper motion	The star's own motion through space	Up to 10.4″ per year	Accumulates steadily
Atmospheric refraction	Air bends light, lifting objects near the horizon	About 0.5° at the horizon; zero at the zenith	Varies with altitude and weather

Refraction is the one you can see for yourself: when the Sun's lower edge appears to touch the horizon at sunset, the whole Sun is already geometrically below it. Parallax is the most important for astronomy — it was the first direct measurement of the distance to a star, and it is still the foundation of the cosmic distance ladder described in the Galaxies chapter.

Now see how the constellations sit on this grid, and how they change through the year. Continue to the constellations and the seasons.

CHAPTER 6

The constellations, the zodiac and the seasons

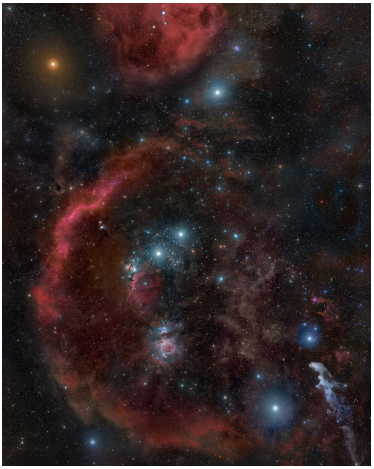
The patterns in the night sky are a human invention, but the way they march across the year is pure physics: the Earth circling the Sun, with its axis tilted, so that each season turns our night side toward a different part of the sky.



The Milky Way panorama — ESO/S. Brunier, CC BY 4.0

What a constellation is

For most of history a constellation was a figure: a hunter, a scorpion, a queen on her throne, traced out by joining bright stars. Astronomers now use the word in a stricter sense. Since 1922 the **International Astronomical Union** has recognised exactly **88 constellations**, and in 1930 the Belgian astronomer Eugène Delporte drew official boundaries between them along lines of right ascension and declination. Together they tile the whole sky like the counties of a state, with no gaps and no overlaps. Every star, galaxy and nebula lies in exactly one constellation, which is why the Andromeda Galaxy is "in Andromeda" even though it is millions of times farther away than any of that constellation's stars.



Orion from head to toe in a long-exposure photograph. Red Betelgeuse is at upper left, blue-white Rigel at lower right, and the Orion Nebula hangs below the belt. The faint red loops are hydrogen gas invisible to the eye.

Rogelio Bernal Andreo, CC BY-SA 3.0

A familiar star pattern that is not one of the 88 is an **asterism**. The Big Dipper is the best-known example; it is part of Ursa Major, the Great Bear. The Summer Triangle, the Great Square of Pegasus, the Sickle of Leo and the Teapot of Sagittarius are others.

The stars of a constellation are usually not related to one another at all. They line up only from our point of view. In Orion, Bellatrix (the western shoulder) is about 250 light-years away, Betelgeuse about 550, Rigel about 860, and the belt stars well over a thousand. Seen from a planet around another star, Orion would be scrambled beyond recognition. The constellations are a map of directions, not of neighbourhoods.

Constellations vary enormously in size. The largest, Hydra the Water Snake, covers 1,303 square degrees and stretches more than a quarter of the way around the sky; the smallest, Crux, the Southern Cross, covers just 68.

Where the constellations came from

Many of the northern constellations go back to Mesopotamia. Babylonian star lists compiled around 1000 BC, known from the clay tablets called MUL.APIN, already name a bull, a lion, a scorpion and twins, and single out the constellations "in the path of the Moon". The Greeks inherited and reworked these figures, attaching their own myths: Perseus rescuing Andromeda from the sea monster Cetus while her parents Cepheus and Cassiopeia look on is one story spread across five neighbouring constellations.

Around AD 150 the astronomer **Ptolemy** catalogued 48 constellations in his *Almagest*. Those 48 formed the core of Western star maps for 1,400 years, and nearly all survive today. The largest, the ship Argo Navis, was later split into Carina (the keel), Puppis (the stern) and Vela (the sails).

Ptolemy's list covered only the sky visible from the Mediterranean. The far southern sky was charted by Europeans from the 1590s, when Dutch navigators Pieter Keyser and Frederick de Houtman recorded southern stars and the cartographer Petrus Plancius turned them into twelve new figures, including the Toucan, the Peacock and the Bird of Paradise. In the 1750s the French astronomer **Nicolas-Louis de Lacaille**, observing from the Cape of Good Hope, filled the remaining gaps with fourteen constellations named after the instruments of science and art: the Telescope, the Microscope, the Air Pump, the Pendulum Clock, the Painter's Easel.

Other cultures saw entirely different pictures in the same stars. In China the sky was divided into 283 smaller asterisms organised around an imperial court; many Aboriginal Australian traditions read the dark dust lanes of the Milky Way as figures, such as the Emu in the Sky. The 88 IAU constellations are the Greek-and-European tradition, adopted as an international standard.

OFFICIAL CONSTELLATIONS 88	LISTED BY PTOLEMY 48
LARGEST Hydra, 1,303 sq°	SMALLEST Crux, 68 sq°
ON THE ECLIPTIC 13	BOUNDARIES FIXED 1930

The zodiac: the constellations behind the Sun

As the Earth orbits, the Sun appears to move against the background stars, completing one circuit of the sky each year along the **ecliptic**. We cannot see the stars behind the Sun in daylight, but ancient astronomers could work out where it stood by watching which stars vanished into the evening twilight and which reappeared before dawn.

Because the Moon and planets orbit in nearly the same plane as the Earth, they too stay close to the ecliptic. The band of sky they travel through — about 8° either side of it — is the **zodiac**, from the Greek for "circle of little animals". By about the 5th century BC Babylonian astronomers had divided it into twelve equal 30° sections named after the constellations they contained, to make calculating the positions of the Sun, Moon and planets easier.

The real constellations are not equal. Along the ecliptic, Virgo spans about 44°, while Scorpius spans only about 6°. And when Delporte drew the official boundaries in 1930, the ecliptic passed through a thirteenth constellation: **Ophiuchus**, the Serpent Bearer, whose feet lie between Scorpius and Sagittarius. The Sun now spends only about six days in Scorpius, and about nineteen in Ophiuchus.

Precession, described in the Sky coordinates chapter, has shifted the whole system. The twelve signs used in astrology are measured from the March equinox, which has slid westward by almost a full constellation since the zodiac was laid out. So on your birthday the Sun is usually in the constellation *before* the one your traditional sign is named after. Astronomy and astrology parted ways long ago: the constellations are simply regions of the sky, and their positions have no measurable influence on events on Earth.



The zodiacal light: sunlight scattered by dust in the plane of the solar system, glowing along the ecliptic after dusk. It traces the Sun's path through the zodiac across the sky.

ESO/Y. Beletsky, CC BY 4.0



Upper bar: the constellation behind the Sun on each date, using the official IAU boundaries. Lower bar: the traditional astrological sign dates. Precession has opened a gap of about a month between them.

The thirteen constellations of the ecliptic (dates vary by a day from year to year)

Constellation	Figure	Sun is there	Days	Brightest star	Best evening sky
Aries	Ram	18 Apr – 13 May	25	Hamal	Autumn
Taurus	Bull	13 May – 21 Jun	39	Aldebaran	Winter
Gemini	Twins	21 Jun – 20 Jul	29	Pollux	Winter

Constellation	Figure	Sun is there	Days	Brightest star	Best evening sky
Cancer	Crab	20 Jul – 10 Aug	21	Al Tarf	Late winter
Leo	Lion	10 Aug – 16 Sep	37	Regulus	Spring
Virgo	Maiden	16 Sep – 30 Oct	44	Spica	Spring
Libra	Scales	30 Oct – 23 Nov	24	Zubeneschamali	Early summer
Scorpius	Scorpion	23 Nov – 29 Nov	6	Antares	Summer
Ophiuchus	Serpent Bearer	29 Nov – 18 Dec	19	Rasalhague	Summer
Sagittarius	Archer	18 Dec – 20 Jan	33	Kaus Australis	Summer
Capricornus	Sea-goat	20 Jan – 16 Feb	27	Deneb Algedi	Late summer
Aquarius	Water Bearer	16 Feb – 11 Mar	23	Sadalsuud	Autumn
Pisces	Fishes	11 Mar – 18 Apr	38	Alpherg	Autumn

Why the night sky changes through the year

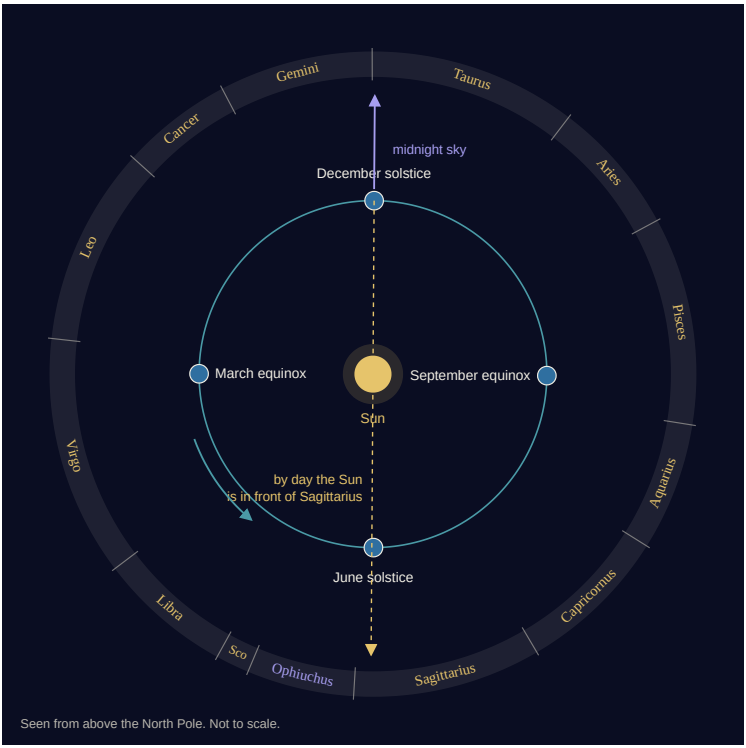
The constellations are always there, day and night, all year. What changes is which half of the sky is hidden by the Sun's glare. Whatever constellation the Sun stands in is overhead at noon and invisible. The constellation on the *opposite* side of the sky is highest around midnight, and it is the one that dominates that season's nights.

Follow the diagram around. In December the Earth is on the side of its orbit where the Sun appears in front of Sagittarius; looking away from the Sun at midnight, we face Taurus and Gemini, with Orion just to the south of them — the classic winter sky. Six months later the Earth is on the far side of the Sun. Now the Sun is in Taurus, hiding Orion in daylight, and at midnight we look out toward Sagittarius and Scorpius, low in the south on summer nights.

Because the stars rise about four minutes earlier each night (see sidereal time), the change is gradual: each constellation creeps westward night by night, until it disappears into the evening twilight and spends a few weeks behind the Sun before re-emerging in the dawn sky on the eastern side.

A useful rule of thumb follows: a constellation you see high in the south at about 10 pm will be in the same spot around 8 pm a month later, and around

2 am a few months earlier. So early risers can preview the next season's constellations before dawn — Orion is already up in the east before sunrise in late August.

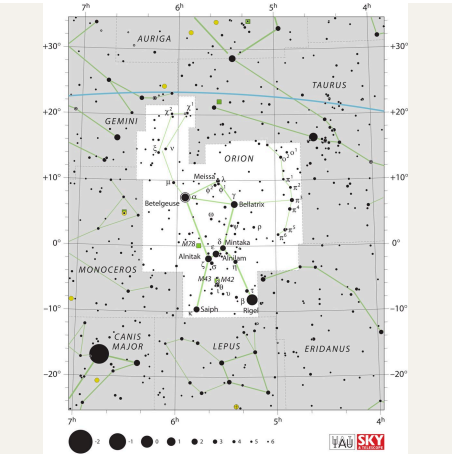


The Earth's orbit with the zodiac in the distance. At each position the Sun hides the constellation behind it, and the one on the opposite side fills the midnight sky. Not to scale — the stars are millions of times farther away than the Sun.

A sky for each season

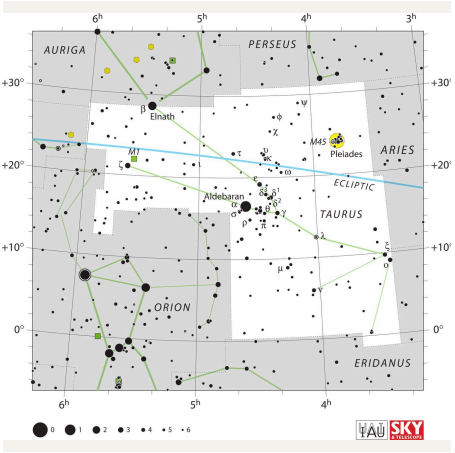
What follows is the evening sky (around 9–10 pm local time) from mid-northern latitudes such as New Jersey. Each season's sky is anchored by a few bright constellations or asterisms that make it easy to find the rest. Many of the deep-sky objects in the Gallery of the AstroStudious website sit inside them.

Season	Key constellations	Signposts	Deep-sky highlights
Winter	Orion, Taurus, Gemini, Auriga, Canis Major, Canis Minor	Orion's Belt points down to Sirius, the brightest star in the night sky, and up to Aldebaran and the Pleiades. The Winter Hexagon of Sirius, Procyon, Pollux, Capella, Aldebaran and Rigel rings the sky.	Orion Nebula (M42), Pleiades (M45), Crab Nebula (M1), clusters M35–M38
Spring	Leo, Virgo, Boötes, Cancer, Ursa Major (high overhead)	"Arc to Arcturus, speed on to Spica": follow the curve of the Big Dipper's handle to orange Arcturus, then on to Spica in Virgo. The backward question mark of the Sickle marks Leo's head.	The Virgo galaxy cluster, Leo Triplet, Beehive Cluster (M44), Whirlpool Galaxy (M51)
Summer	Scorpius, Sagittarius, Lyra, Cygnus, Aquila, Hercules, Ophiuchus	The Summer Triangle of Vega, Deneb and Altair high overhead. Red Antares marks the Scorpion's heart low in the south; the Teapot of Sagittarius sits on the brightest part of the Milky Way.	Lagoon (M8), Omega (M17) and Eagle (M16) nebulae, Ring Nebula (M57), Hercules Cluster (M13)
Autumn	Pegasus, Andromeda, Cassiopeia, Perseus, Aquarius, Pisces	The Great Square of Pegasus. From its north-east corner, a chain of stars leads through Andromeda toward Perseus; the W of Cassiopeia rides high to the north.	Andromeda Galaxy (M31), Triangulum Galaxy (M33), Double Cluster in Perseus



Winter — Orion. The hunter dominates the southern sky from December to March.

IAU and Sky & Telescope (R. Sinnott & R. Fienberg), CC BY 3.0



Winter — Taurus. Aldebaran and the V-shaped Hyades form the bull's face; the Pleiades ride on its shoulder.

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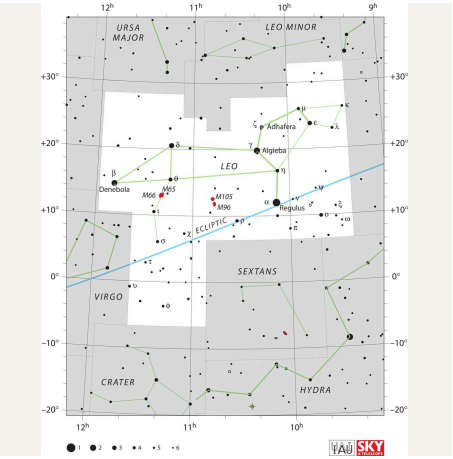

Spring — Leo. Regulus sits almost exactly on the ecliptic, so the Moon and planets often pass close by.

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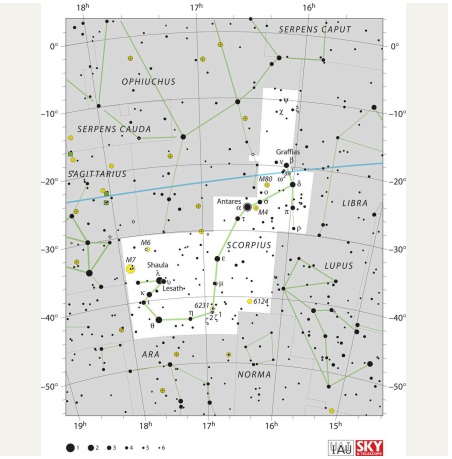

Summer — Scorpius. One of the few constellations that really looks like its namesake. From New Jersey the tail skims the southern horizon.

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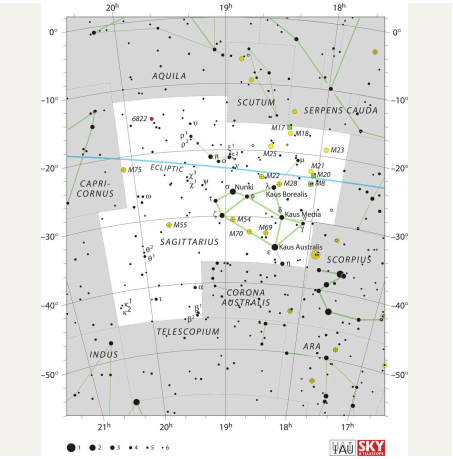

Summer — Sagittarius. The centre of the Milky Way lies just west of the Teapot's spout, and the area is packed with Messier objects.

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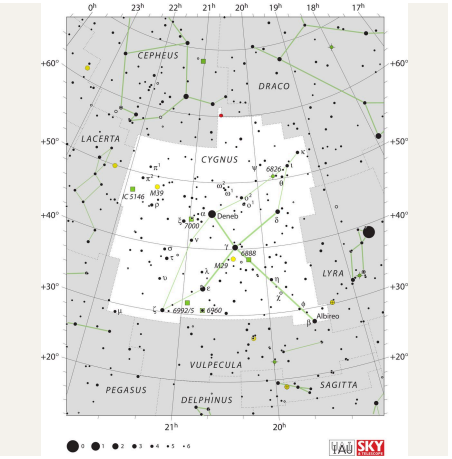

Summer — Cygnus. The swan, or Northern Cross, flies down the Milky Way with Deneb at its tail.

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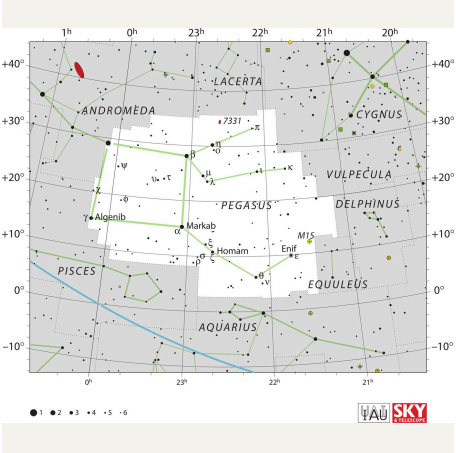
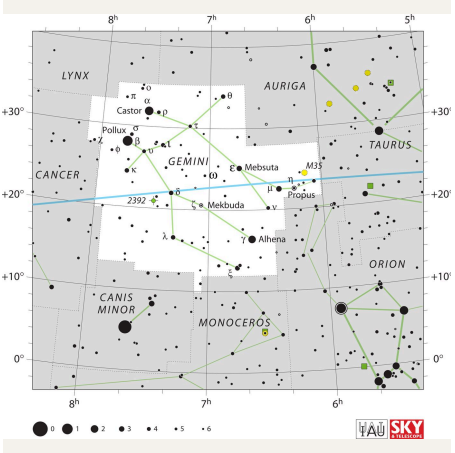


Autumn — Pegasus. The Great Square is the autumn signpost; its north-east corner star actually belongs to Andromeda.

IAU and Sky & Telescope (R. Sinnott & R. Fienberg), CC BY 3.0



Winter — Gemini. Castor and Pollux mark the twins' heads. The June solstice point now lies near the Gemini–Taurus border.

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From the gallery: one object in each season's sky



Winter: the Orion Nebula (M42), in the sword of Orion.



Spring: the Whirlpool Galaxy (M51), just below the end of the Big Dipper's handle.



Summer: the Lagoon Nebula (M8), above the spout of the Teapot in Sagittarius.



Autumn: the Andromeda Galaxy (M31), high overhead on autumn evenings.

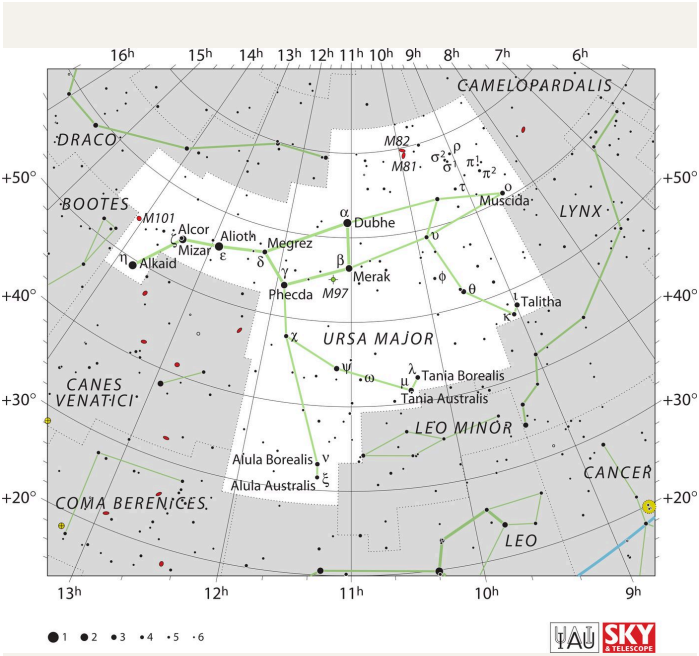
Circumpolar constellations, and the ones we never see

From New Jersey, at about 40° north, the north celestial pole stands 40° above the northern horizon. Anything within 40° of the pole circles it without ever setting. These **circumpolar** constellations are visible on every clear night of the year, though their orientation changes with the hour and the season: the Big Dipper skims low over the northern horizon on autumn evenings and swings high overhead in spring.

- **Ursa Minor**, the Little Bear, with Polaris at the end of its tail
- **Ursa Major**, the Great Bear: its Big Dipper never quite sets, though the tip of the handle grazes the horizon
- **Cassiopeia**, the W-shaped queen, opposite the Dipper across the pole
- **Cepheus**, the king, shaped like a child's drawing of a house
- **Draco**, the dragon, winding between the two bears
- **Camelopardalis**, the giraffe, large and faint

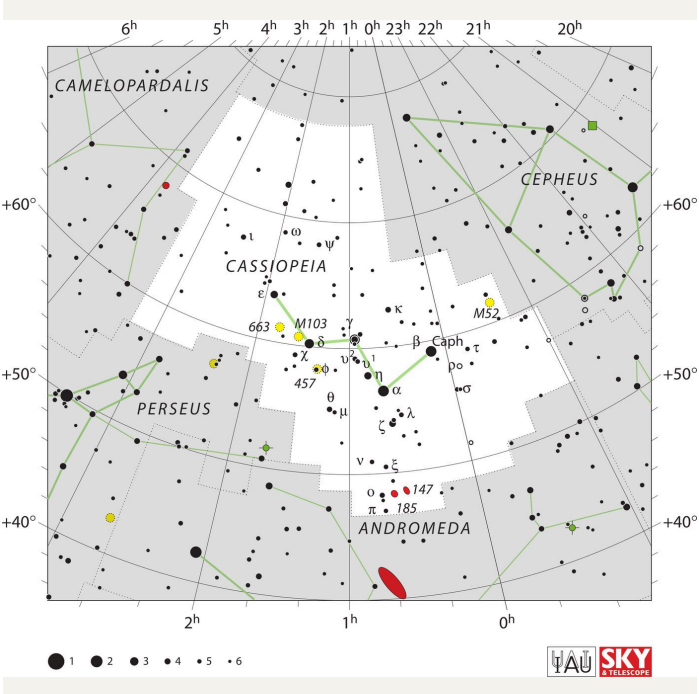
The same geometry works in reverse. Stars within 40° of the *south* celestial pole never rise above a New Jersey horizon. The Southern Cross, the bright pointer stars Alpha and Beta Centauri, the Large and Small Magellanic Clouds and constellations such as Musca, Chamaeleon, Apus and Octans can

be seen only from farther south. Florida's southern tip, at 25° north, brings the Southern Cross briefly above the horizon on spring nights.



Ursa Major. The Big Dipper is only the bear's hindquarters and tail; its legs and head extend much farther.

IAU and Sky & Telescope (R. Sinnott & R. Fienberg), CC BY 3.0



Cassiopeia, the queen, on the opposite side of Polaris from the Dipper.

IAU and Sky & Telescope (R. Sinnott & R. Fienberg), CC BY 3.0

What causes the seasons

A common belief is that summer happens when the Earth is closest to the Sun. In fact the Earth is *closest* to the Sun, at **perihelion**, in early January, at about 147 million km, and farthest, at **aphelion**, in early July, at about 152 million km. That 3% difference in distance changes the sunlight reaching us by only about 7%, and it works against northern summer, not for it.

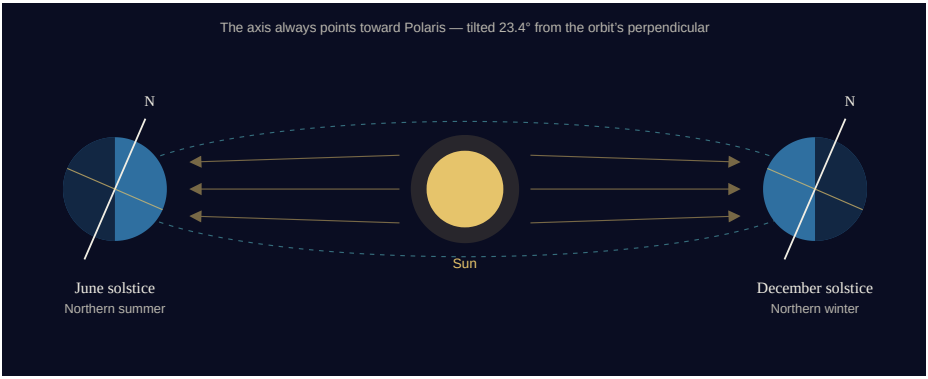
The real cause is the **23.4° tilt** of the Earth's axis. The axis keeps pointing the same way in space — toward Polaris — all the way around the orbit. In June the Northern Hemisphere leans toward the Sun: the Sun climbs high at noon, its light strikes the ground steeply and is concentrated on a smaller area, and days are long. In December the north leans away: the Sun stays low, its light arrives at a slant and is spread thin, and nights are long. The Southern Hemisphere has the opposite seasons at the same time.

The four turning points of the year are fixed by the tilt and are marked in the sky by where the Sun stands on the ecliptic:

- **March equinox** (about 20 March): the Sun crosses the celestial equator heading north. Day and night are roughly equal everywhere. The Sun is in Pisces.
- **June solstice** (about 21 June): the Sun reaches its northernmost point, Dec +23.4°, and stands overhead at noon along the Tropic of Cancer. It is at the border of Taurus and Gemini.
- **September equinox** (about 22 September): the Sun crosses the equator heading south. It is in Virgo.
- **December solstice** (about 21 December): the Sun reaches Dec −23.4°, overhead along the Tropic of Capricorn. It is in Sagittarius.

The tropics are named for the constellations the Sun stood in at the solstices about 2,000 years ago — Cancer and Capricornus. Precession has since moved the solstice points nearly 30° west, into neighbouring constellations, but the names have stuck: one more reminder that the sky we see is a snapshot of a slowly turning machine.

AXIAL TILT 23.44°	PERIHELION (EARLY JAN) 147.1 million km
APHELION (EARLY JUL) 152.1 million km	NOON SUN, NJ, JUNE about 73° high
NOON SUN, NJ, DECEMBER about 27° high	DAYLIGHT, NJ, JUNE / DEC. ~15 h / ~9 h 20 m



The axis keeps the same direction in space. In June the north leans toward the Sun and gets long days and steep sunlight; in December it leans away.

CHAPTER 7

Observational astronomy

Almost everything we know about the universe has arrived as light. Observational astronomy is the craft of catching it — with eyes, lenses, mirrors, dishes and detectors — and teasing out what it has to say.



The Pleiades (M45) — from the AstroStudious gallery

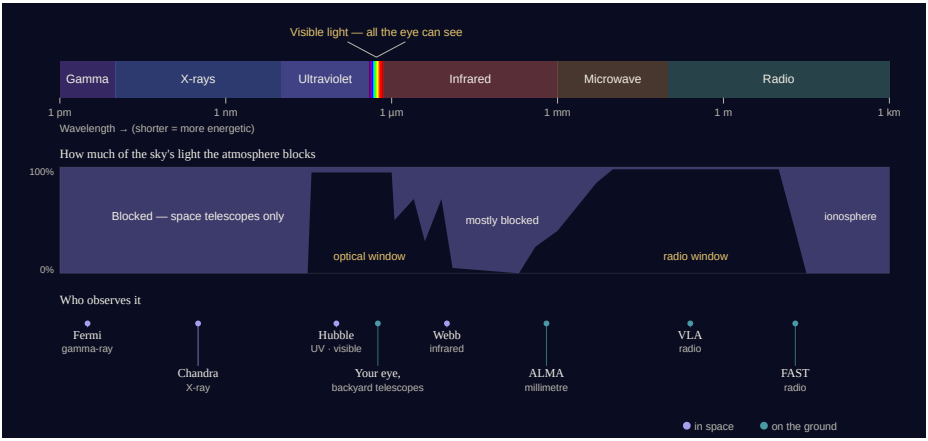
The electromagnetic spectrum

Light is a wave of electric and magnetic fields, and visible light is only a sliver of a much wider family. All of it travels at the same speed — about 300,000 km per second — but the wavelength can be anything from a trillionth of a metre to kilometres. Shorter waves carry more energy. In order of

increasing wavelength, the family runs from **gamma rays** and **X-rays** through **ultraviolet**, the narrow band of **visible light**, **infrared**, **microwaves** and finally **radio waves**.

Each band shows a different universe. Gamma rays and X-rays come from the most violent places — gas spiralling into black holes, the shock waves of supernovae, the million-degree corona of the Sun. Ultraviolet picks out the hottest young stars. Visible light shows us stars and the glowing gas around them. Infrared sees warm dust, cool stars and planets, and peers through dust clouds that hide newborn stars; it also catches the light of the most distant galaxies, stretched to longer wavelengths by the expansion of the universe. Millimetre and radio waves trace cold gas, the 21-centimetre glow of hydrogen atoms, pulsars, and the faint afterglow of the Big Bang itself.

Our atmosphere lets only some of this through. Two "windows" reach the ground: the **optical window**, roughly from the near ultraviolet to the near infrared, and the much wider **radio window**. Water vapour absorbs most of the infrared, which is why infrared and millimetre observatories are built on high, dry mountains and deserts. Gamma rays, X-rays and most ultraviolet light never reach the surface at all — fortunately for life — so those parts of the sky can be studied only from space.



The electromagnetic spectrum, how much of each band the atmosphere blocks, and some of the telescopes that observe it. Only the optical and radio windows reach the ground.

Reading starlight: spectra and spectroscopy

A picture shows where light comes from. Spreading the light into its colours — a **spectrum** — shows what made it. In 1814 Joseph von Fraunhofer noticed hundreds of fine dark lines crossing the Sun's spectrum. In 1859 Gustav Kirchhoff and Robert Bunsen worked out what they were: every chemical element, when heated, glows at its own set of precise wavelengths, and absorbs light at exactly the same wavelengths when cooler gas lies in front of a hotter source. The dark lines in sunlight are the fingerprints of hydrogen, sodium, calcium, iron and dozens of other elements in the Sun's outer layers.

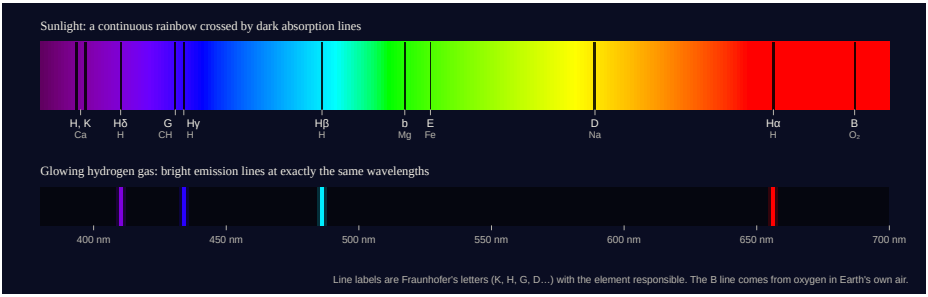
That simple idea made astrophysics possible. From a star's spectrum astronomers can read:

- **Composition** — which elements are present, and in what amounts.
- **Temperature** — from the overall colour and from which lines are strong; this is the basis of the O-B-A-F-G-K-M classes in the Stars chapter.
- **Motion** — the Doppler shift moves every line slightly toward the blue for an object approaching us and toward the red for one receding. It reveals orbiting binary stars, the rotation of galaxies, planets tugging on their stars, and the expansion of the universe.
- **Pressure, magnetism and more** — from the width and splitting of the lines.

Nebulae show the reverse pattern. Thin glowing gas produces bright *emission lines* on a dark background: the deep red of hydrogen-alpha that colours the Orion Nebula, and the green-blue of doubly ionised oxygen in planetary nebulae such as the Ring.

HYDROGEN-ALPHA 656.3 nm	HYDROGEN-BETA 486.1 nm
OXYGEN III 500.7 nm	SODIUM D 589 nm
CALCIUM K 393.4 nm	NEUTRAL HYDROGEN 21 cm (radio)

These wavelengths are also why narrowband filters for astrophotography are named "H-alpha", "OIII" and so on: each passes just one emission line and blocks almost everything else, including most light pollution.



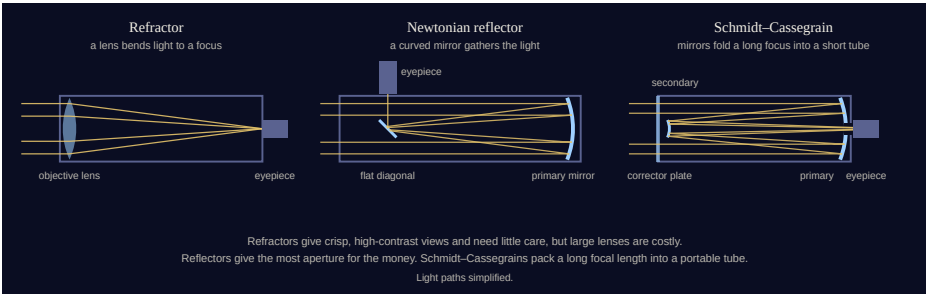
Absorption and emission. The dark lines in sunlight (top) sit at exactly the wavelengths where hot hydrogen gas glows (bottom). Each element has its own unmistakable pattern.

The spectrograph

A **spectrograph** captures spectra. Light from the telescope passes through a narrow slit, is spread out by a prism or, more usually, a **diffraction grating** — a surface ruled with thousands of fine grooves per millimetre — and is recorded by a camera. Professional spectrographs can measure a star's motion to within a metre per second, precise enough to detect the wobble caused by an orbiting planet. Some instruments record thousands of spectra at once, with optical fibres or tiny robotically positioned mirrors placed on each target; surveys built this way have mapped the motions and chemistry of millions of stars and galaxies. Amateurs take spectra too, with an inexpensive grating that screws into the eyepiece holder like a filter.

Optical telescopes

A telescope does two jobs. Its main lens or mirror gathers far more light than the eye's pupil, revealing objects too faint to see unaided; and it forms a magnified image that an eyepiece or camera can examine. The size of that main lens or mirror — the **aperture** — matters more than anything else. Almost every design is a variation on one of three ideas.



Three common designs. The light paths are simplified.

Refractors

Galileo's telescope of 1609 used lenses, and so do today's refractors. A simple lens bends different colours by different amounts, which fringes bright objects with colour; modern **achromatic** and **apochromatic** ("apo") refractors combine two to four lens elements of special glass to cancel it. Refractors are sealed, need almost no adjustment and give sharp, high-contrast images, making them favourites for wide-field astrophotography. Large lenses are expensive and heavy, though; the biggest ever built, at Yerkes Observatory in 1897, is 102 cm across.

Reflectors

Isaac Newton replaced the lens with a curved mirror in 1668. Mirrors reflect all colours equally and can be supported from behind, so they can be made far larger. A **Newtonian** reflector on a simple rocking base — the **Dobsonian** — offers the most aperture for the money and is the classic choice for viewing faint deep-sky objects. Every large research telescope is a reflector.

Catadioptrics

These combine a mirror with a thin correcting lens. The **Schmidt–Cassegrain** and **Maksutov–Cassegrain** fold a long light path into a short tube, giving the long focal length that suits planets and the Moon in a portable package. They are popular all-rounders on motorised "go-to" mounts.

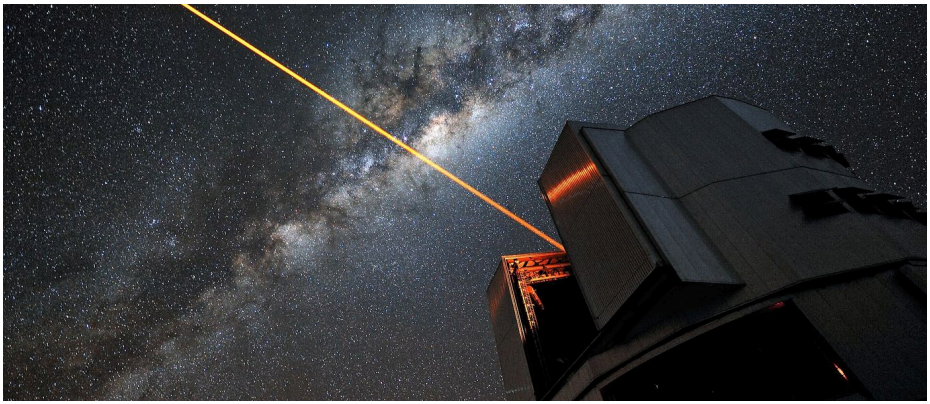
Giant telescopes

Single mirrors become impossibly heavy beyond about 8 metres, so the largest telescopes use mirrors made of many hexagonal segments held in

shape by computer-controlled actuators. The twin Keck telescopes on Mauna Kea have 10-metre mirrors of 36 segments; the Extremely Large Telescope under construction in Chile will have a 39-metre mirror of 798. To beat the blurring of the atmosphere they use **adaptive optics**: a laser excites sodium atoms 90 km up to make an artificial "guide star", and a deformable mirror changes shape hundreds of times a second to cancel the twinkling.

Smart telescopes

A recent arrival combines a small apochromatic refractor, a camera, a motorised mount and a computer in a single unit controlled from a phone. It finds its own position by recognising star patterns, then stacks many short exposures into an image that builds up in real time. The deep-sky photographs in the Gallery of the AstroStudious website were taken this way, with a Vaonis Vespera Classic.



A laser guide star at the Very Large Telescope. Measuring how the artificial star twinkles lets the adaptive optics system cancel atmospheric blurring.

ESO/G. Hüdepohl, CC BY 4.0

Cameras and other instruments

For three centuries the detector was the human eye, which takes in light for only about a tenth of a second at a time. Photographic plates, from the 1880s, could build up exposures for hours and revealed objects no eye had ever seen. Since the 1980s electronic sensors — first **CCDs**, now mostly **CMOS** chips like those in phone cameras — have taken over. They record most of

the photons that strike them rather than the 1–2% a photographic plate managed, and their output is numbers that can be measured, combined and processed.

- **Imaging cameras** are often monochrome, with colour images made by combining exposures through red, green and blue filters, or through narrowband filters that isolate single emission lines such as hydrogen-alpha and oxygen III. Professional cameras are cooled, sometimes with liquid nitrogen, to suppress electronic noise.
- **Photometers** measure brightness precisely over time. The tiny dimming as a planet crosses its star — often less than 1% — is how the Kepler and TESS missions found thousands of exoplanets.
- **Spectrographs**, described above, spread light into spectra.
- **Polarimeters** measure how light waves are aligned, revealing magnetic fields and dust.
- **Coronagraphs** block the light of a bright object — the Sun's disc, or a star — to reveal the faint corona, or planets and dust discs around other stars.
- **Interferometers** combine light from separate telescopes so they act together like a single instrument as wide as the distance between them, giving far finer detail than any one alone.

Radio telescopes

Radio astronomy began by accident. In 1932 Karl Jansky, an engineer at Bell Telephone Laboratories tracking down static that interfered with radio telephones, found a faint hiss that rose and set with the stars — radio waves from the centre of the Milky Way.

A radio telescope is usually a large dish that reflects radio waves to a receiver at its focus. Because radio wavelengths are so long, a dish must be huge to see fine detail: the resolution of a telescope depends on its width measured in wavelengths, and a 100-metre dish observing 21-centimetre waves sees detail about ten times coarser than the unaided eye. The largest single dish, China's FAST, is 500 metres across, set into a natural hollow in the karst landscape of Guizhou.

The solution is **interferometry**: many dishes spread over a wide area, their signals combined by computer to act like one telescope as large as the whole array. The Very Large Array in New Mexico has 27 dishes on Y-shaped tracks up to 36 km across. ALMA, on a 5,000-metre plateau in Chile's Atacama Desert, links 66 antennas to study the cold gas and dust where stars and planets form. Link dishes across continents and the "telescope" becomes the size of the Earth: in 2019 the Event Horizon Telescope used this technique to produce the first image of a black hole's shadow.

Radio telescopes discovered pulsars, quasars and the cosmic microwave background, and they map the cold hydrogen that fills galaxies using its 21-cm emission line. Because they do not need darkness, they work around the clock — though they need protection from radio interference, so many are built in remote "radio quiet" zones.



The Very Large Array, New Mexico. The 27 dishes move along railway tracks to change the size of the array.

CGP Grey, CC BY 2.0



ALMA antennas on the Chajnantor plateau, 5,000 metres up in the Atacama Desert, where the air is dry enough for millimetre waves to get through.

ESO/B. Tafreshi, CC BY 4.0

Solar telescopes

> **Safety first:** never look at the Sun through any telescope, binoculars or camera without a certified solar filter covering the front of the instrument. Permanent eye damage can happen in a fraction of a second.

The Sun is the one star we can study in detail, and its problem is the opposite of every other target: too much light. Solar telescopes are built to reject most of it and to cope with the heat.

- **White-light filters**, made of special film or coated glass, fit over the front of an ordinary telescope and pass about one part in 100,000 of the light. They show sunspots, faculae and the granulation of the photosphere.
- **Hydrogen-alpha telescopes** pass a band of light less than 0.1 nm wide centred on the deep-red 656.3 nm line. That reveals the chromosphere:

prominences arching off the edge, filaments, plage and flares. **Calcium-K** filters, at 393.4 nm, show the chromosphere's magnetic network in violet.

- Large research instruments such as the 4-metre Daniel K. Inouye Solar Telescope on Haleakalā, Hawaii, resolve features on the Sun as small as about 20 km. Spacecraft watch continuously from space: SOHO and the Solar Dynamics Observatory image the Sun in ultraviolet light the atmosphere blocks, and Parker Solar Probe flies through the corona itself.

See The Sun for what these telescopes show.



The Daniel K. Inouye Solar Telescope, the world's largest solar telescope, near the summit of Haleakalā. Its 4-metre mirror gathers so much sunlight that a cooling system has to carry away the heat.

NSF/NSO/AURA, CC BY 4.0

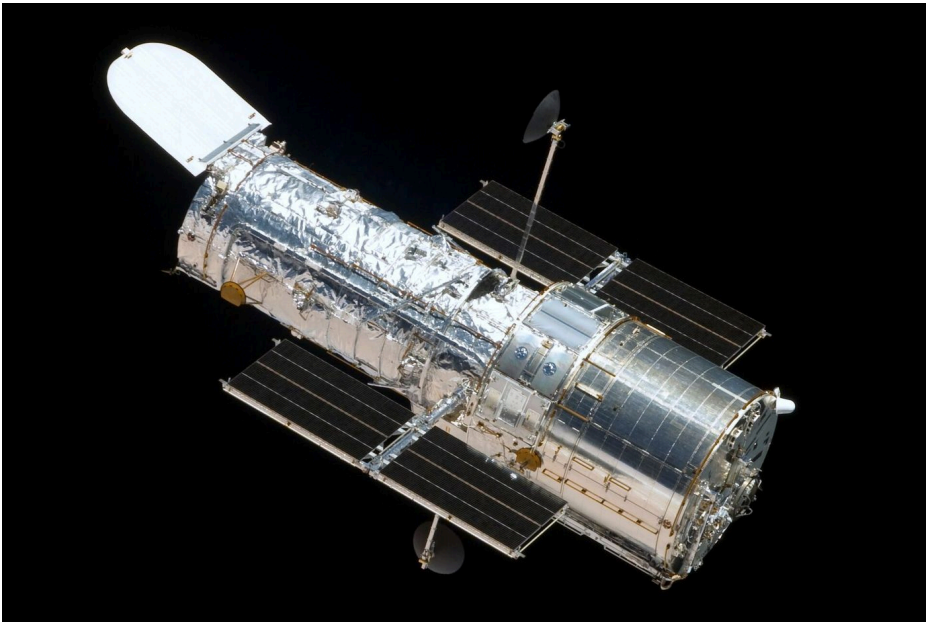
Telescopes in space

Above the atmosphere a telescope escapes both its absorption and its turbulence. Stars no longer twinkle, the sky is dark even in daylight, and the whole spectrum is open.

- The **Hubble Space Telescope**, launched in 1990 with a 2.4-metre mirror, observes in ultraviolet, visible and near-infrared light from low Earth orbit. Astronauts repaired and upgraded it on five servicing missions.
- The **James Webb Space Telescope**, launched in 2021, has a 6.5-metre mirror of 18 gold-coated beryllium segments and works in the infrared. It orbits 1.5 million km from Earth, shielded from the Sun by a tennis-court-sized sunshade that keeps it at about −230 °C, cold enough not to be blinded by its own heat.
- **Chandra** observes X-rays with nested mirrors that the rays strike at grazing angles, like stones skipping on water; ordinary mirrors would simply

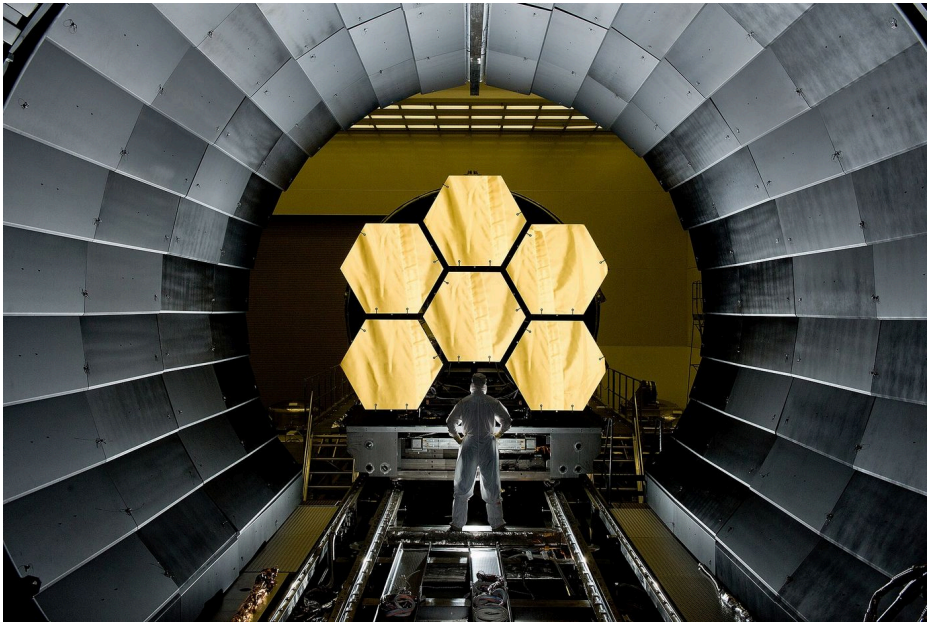
absorb them. **Fermi** detects gamma rays, which cannot be focused at all and are tracked particle by particle.

- **Gaia** has measured the positions, distances and motions of nearly two billion stars (see proper motion).



Hubble photographed from the Space Shuttle Atlantis in 2009, after its final servicing mission.

NASA, STS-125 crew (public domain)



Webb's 6.5-metre primary mirror during testing. The thin gold coating reflects infrared light efficiently.
NASA/MSFC/D. Higginbotham (public domain)

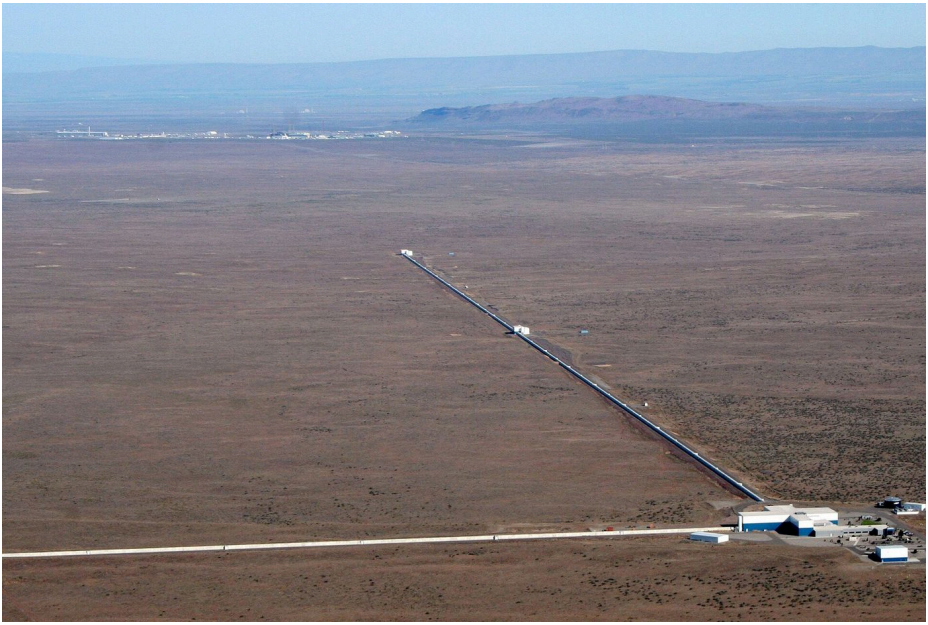
Beyond light

Light is no longer the only messenger.

Gravitational waves are ripples in space itself, set off by colliding black holes and neutron stars. LIGO's two detectors, in Washington State and Louisiana, use lasers in L-shaped arms 4 km long to measure changes in length smaller than a thousandth of the width of a proton. They made the first detection in September 2015 — two black holes merging 1.3 billion light-years away — and in 2017 caught two neutron stars colliding, an event also seen by telescopes across the whole spectrum.

Neutrinos are ghostly particles that pass through the Earth almost unhindered. Huge detectors buried deep underground or in Antarctic ice catch a tiny fraction of them, and have seen neutrinos from the Sun's core, from Supernova 1987A and from distant galaxies.

Cosmic rays — atomic nuclei striking the atmosphere at nearly the speed of light — are recorded by arrays of detectors spread over thousands of square kilometres. And spacecraft visiting the planets, comets and asteroids collect samples and bring them home: the most direct observation of all.



LIGO Hanford, Washington. Each arm is 4 km long; a passing gravitational wave stretches one and squeezes the other by far less than the width of an atomic nucleus.

LIGO Laboratory (public domain)

Optics in practice: what the numbers mean

Telescopes are described by a handful of numbers. Each one affects what the instrument does well.

Aperture

The diameter of the main lens or mirror, and the most important number of all. Light-gathering power grows with the *area*, so doubling the aperture collects four times as much light. A 200 mm (8-inch) telescope collects about 800 times more light than a dark-adapted eye, whose pupil opens to about 7 mm,

and shows stars roughly 7 magnitudes — over 600 times — fainter. Aperture also sets resolution.

Focal length

The distance from the lens or mirror to the point where it brings light to a focus. Long focal lengths give a large, magnified image of a small area of sky; short ones a smaller image of a wide area. A camera at the focus of a 200 mm lens and one behind a 2,000 mm telescope see the same sky, but the second shows a field ten times narrower in each direction.

Focal ratio

Focal length divided by aperture, written f/4, f/10 and so on. For photographing faint extended objects such as nebulae and galaxies, a "fast" low focal ratio builds up an image much more quickly: an f/4 system needs only about a sixth of the exposure time of an f/10 system for the same brightness per pixel. "Slow" high ratios suit high-magnification work on planets, double stars and the Moon.

Magnification

With an eyepiece, magnification is the telescope's focal length divided by the eyepiece's: a 1,200 mm telescope with a 25 mm eyepiece magnifies 48 times. Magnification is the least important number, and the one most often oversold. Above about twice the aperture in millimetres (50× per inch) the image just gets bigger and dimmer without showing more; in practice the steadiness of the air usually limits useful magnification to 250–300× however large the telescope.

Resolution

The finest detail a telescope can show, limited by the wave nature of light. A useful rule, Dawes' limit, says a telescope can just separate two equal stars about 116 ÷ aperture (mm) arcseconds apart: 2.3″ for a 50 mm telescope, 0.6″ for 200 mm. In practice atmospheric turbulence — astronomers call it **seeing** — smears images to between 1″ and 3″ on most nights, so large backyard telescopes rarely reach their theoretical limit.

Exit pupil

The width of the beam of light leaving the eyepiece: aperture divided by magnification. If it is wider than about 7 mm, some of the light misses the eye; if it is narrower than about 0.5 mm, the image becomes dim and floaters in the eye intrude. Faint, extended nebulae look best with a large exit pupil of 4–7 mm; planets with 0.5–1 mm.

Field of view

How much sky you see. Through an eyepiece, the true field is roughly the eyepiece's apparent field (often 50°–82°) divided by the magnification. On a camera, it is set by the sensor size and focal length. The full Moon is half a degree across; the Andromeda Galaxy spans about three degrees.

Image scale and the mount

For cameras, the image scale in arcseconds per pixel is 206 × pixel size (µm) ÷ focal length (mm). Matching it to the seeing — usually 1″–2″ per pixel — avoids wasting resolution or sensitivity. And none of it works without a steady **mount**. Simple altitude-azimuth mounts are fine for viewing; long-exposure photography needs a motorised mount that tracks the stars accurately as the Earth turns.

The equations behind the numbers

These are the formulas behind the numbers in this chapter, plus a few that astrophotographers use for cameras. D is the aperture and F the telescope's focal length, both in millimetres; f_e is the eyepiece focal length. The worked examples use an 8-inch Dobsonian (D = 203 mm, F = 1,200 mm) with a 25 mm, 52° eyepiece, and for the camera formulas the Vespera Classic (D = 50 mm, F = 200 mm, 2.9 µm pixels, 1920 × 1080 sensor).

Quantity	Formula	Example
Focal ratio	$N = F \div D$	1,200 ÷ 203 = f/5.9
Magnification	$M = F \div f_e$	1,200 ÷ 25 = 48×
True field of view	$TFOV \approx \text{apparent field} \div M$	52° ÷ 48 = 1.08°
Exit pupil	$D \div M$ (equivalently $f_e \div N$)	203 ÷ 48 = 4.2 mm

Quantity	Formula	Example
Highest useful magnification	$\approx 2 \times D$ (in mm), but rarely above ~300× because of seeing	2 × 203 = 406×
Lowest useful magnification	$\approx D \div 7$ (exit pupil of 7 mm)	203 ÷ 7 = 29×
Resolution (Dawes' limit)	$116 \div D$ arcseconds	116 ÷ 203 = 0.57″
Resolution (Rayleigh criterion, green light)	$138 \div D$ arcseconds	138 ÷ 203 = 0.68″
Light grasp compared with the eye	$(D \div 7)^2$	$(203 \div 7)^2 = 841\times$
Faintest stars visible (approximate)	$7.5 + 5 \times \log_{10}(D \text{ in cm})$	$7.5 + 5 \times \log_{10}(20.3)$ = magnitude 14.0
Camera image scale	$206.265 \times \text{pixel size (µm)} \div F$ arcseconds per pixel	206.265 × 2.9 ÷ 200 = 3.0″ per pixel
Camera field of view	$57.3 \times \text{sensor width (mm)} \div F$ degrees	57.3 × 5.57 ÷ 200 = 1.6° (and 0.9° high)
Relative exposure time for extended objects	$(N_1 \div N_2)^2$	f/10 vs f/4: $(10 \div 4)^2 \approx 6$ times longer

Where the constants come from: there are 206,265 arcseconds in a radian, which becomes 206.265 when the pixel size is in micrometres and the focal length in millimetres; 57.3 is the number of degrees in a radian. Dawes' 116 was found by experiment with pairs of equal stars; Rayleigh's 138 comes from the size of the diffraction pattern, 1.22 × wavelength ÷ aperture, for 550 nm light. The limiting-magnitude formula is a rule of thumb that assumes a dark sky and an experienced observer.

Matching the telescope to the target

No single telescope is best for everything. What matters most depends on what you want to see.

Target	What matters most	Good choices	Focal ratio	Typical magnification
Moon and planets	Resolution, contrast and steady air; plenty of light already	Long focal length: refractors, Maksutovs, Schmidt–Cassegrains, larger Dobsonians	Slow, f/8–f/15; f/20 or more with a Barlow lens for planetary imaging	100–300×, as the seeing allows
Double stars	Resolution — aperture sets the closest pair you can split	Any well-collimated telescope; refractors excel	Any; slower ratios (f/8 and up) are more forgiving of eyepiece quality	100–300×
Faint galaxies and small nebulae	Aperture above all, and a dark sky	Large Dobsonians for viewing; for imaging, a fast focal ratio and long total exposure	Viewing: any — aperture matters more. Imaging: fast, f/2–f/5	Low to medium, 50–150×
Large nebulae, star clusters, the Milky Way	Wide field of view	Short focal length: binoculars, small refractors, smart telescopes; narrowband filters for emission nebulae	Fast, f/4–f/6	Low, 15–50×, with a large exit pupil
The Sun	A certified solar filter — always	White-light filter on any telescope; dedicated hydrogen-alpha telescope for prominences	Any; hydrogen-alpha telescopes typically f/7–f/10	Low to medium
Comets	Wide field, with enough aperture for faint ones	Binoculars, rich-field refractors and reflectors	Fast, f/4–f/6	Low

Two things matter as much as the telescope. The first is the **sky**. Light pollution washes out faint galaxies and nebulae far more than it affects the Moon, planets and bright stars. The Bortle scale rates sky darkness from 1, a pristine desert sky, to 9, an inner-city sky; most suburban sites, including the one where the photographs in this book were taken, fall around 5 to 7. Narrowband filters and stacking many short exposures help a great deal from such skies. The second is the **observer**. Eyes take 20–30 minutes in the dark to adapt fully, and a single glance at a white light undoes it, which is why astronomers use red torches. And faint detail often appears only with patience: looking slightly to one side of an object, a trick called averted vision, uses the more sensitive outer parts of the retina.

AFTERWORD

About this book

A printable edition of the AstroStudious Astronomy Primer website.

This book collects the text, diagrams and photographs of the AstroStudious Astronomy Primer, a simple educational website about astronomy, at **astrostudious.com**. It tries to convey some basic astronomy concepts, with more detail in a few select areas, in the hope of answering some questions and encouraging further investigation of the wonders of the heavens.

The site was developed with the assistance of AI. Under direction, it was used to enhance content in order to help clarify important astronomical concepts. Comments, corrections and suggestions for new content are welcome through the website.

Illustrations

The diagrams were drawn for the website; those showing the sky, the orbits of the planets and the H–R diagram were computed from published astronomical data. The deep-sky photographs were taken from a Bortle 6 site in New Jersey with a Vaonis Vespera Classic smart telescope.

The other photographs and charts come from NASA, ESA, ESO, the IAU, observatories and individual photographers, and are used under public-domain and Creative Commons terms. Each is credited beneath the image, and all are listed by chapter, with links to their sources, in the Image credits at the back of the book. Creative Commons images are reproduced under the licence named in their credit (CC BY or CC BY-SA, with version); the licence texts are at creativecommons.org/licenses. Most images are cropped or resized to fit the page. Credits do not imply endorsement by any of these organisations.

Glossary

A glossary of the main terms, each with the chapter and page where it is explained, follows the image credits.

The website's Gallery holds more of the author's Messier, NGC and IC photographs, along with an interactive catalog and observing planner; the Observing page has an interactive telescope calculator.

Edition of October 2026.

BACK MATTER

Image credits

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Introduction: A sense of scale

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2. The Sun

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- Lagoon Nebula (M8), M78 and Trifid Nebula (M20) — photographed by the site author from a Bortle 6 site in New Jersey with a Vaonis Vespera Classic smart telescope.

4. Galaxies and the universe

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5. Celestial coordinates and the moving sky

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6. The constellations, the zodiac and the seasons

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- Diagrams — drawn for this site; Sun dates are computed from the official IAU constellation boundaries.
- Seasonal deep-sky photographs — taken by the site author with a Vaonis Vespera Classic smart telescope.

7. Observational astronomy

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BACK MATTER

Glossary

Short definitions of 125 terms used in this book, with the chapter and page where each is explained.

Terms are listed alphabetically. Words with a dotted underline have their own entries in this glossary. The gold reference after each definition points to the section where the idea is covered in full.

A

Absolute magnitude How bright a star would look if it sat at a standard distance of 10 parsecs. Taking distance out of the picture lets astronomers compare the true power of stars directly. The Sun's absolute magnitude is about +4.8. Compare apparent magnitude.

Ch. 3 · Sorting the stars, p. 47

Accretion disk A flattened, spinning disk of gas and dust spiralling inward onto a central object: a young star, a white dwarf, a neutron star or a black hole. Friction heats the inner disk, sometimes to millions of degrees, so it shines in X-rays.

Ch. 3 · Black holes, p. 60

Active galactic nucleus The brilliant core of a galaxy whose central supermassive black hole is actively swallowing gas. The surrounding accretion disk can outshine every star in the galaxy put together. The most luminous examples are called quasars.

Ch. 4 · How galaxies change, p. 75

Altitude The angle of an object above the horizon, from 0° at the horizon to 90° at the zenith. Together with azimuth it gives an object's position as seen from one particular place at one particular moment.

Ch. 5 · Altitude and azimuth: the sky from where you stand, p. 87

Aperture The diameter of a telescope's main lens or mirror. It is the most important number on any telescope: a larger aperture collects more light, so fainter objects show, and it gives finer resolution.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Apparent magnitude How bright an object looks from Earth. The scale runs backwards (smaller numbers are brighter) and is logarithmic: a difference of 5 magnitudes is a factor of exactly 100 in brightness, so one magnitude is about 2.5 times. Sirius is −1.5; the faintest naked-eye stars under a dark sky are around +6.

Ch. 3 · Sorting the stars, p. 47

Arcminute and arcsecond Small units of angle. A degree divides into 60 arcminutes (′), and each arcminute into 60 arcseconds (″). The full Moon spans about 30′; the resolution of a backyard telescope is around 1″.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Asterism A recognisable star pattern that is not one of the 88 official constellations. The Big Dipper (part of Ursa Major) and the Summer Triangle are asterisms.

Ch. 6 · What a constellation is, p. 99

Asteroid A small rocky or metallic body orbiting the Sun, left over from the formation of the planets. Most orbit in the asteroid belt; they range from boulders to Vesta, about 525 km across.

Ch. 1 · The asteroid belt, p. 9

Asteroid belt The ring of asteroids between the orbits of Mars and Jupiter, roughly 2.2 to 3.2 AU from the Sun. Jupiter's gravity kept the material from gathering into a planet. Despite the pictures, it is mostly empty space.

Ch. 1 · The asteroid belt, p. 9

Astronomical unit (AU) The average distance between Earth and the Sun, about 150 million km. Sunlight takes 8 minutes 20 seconds to cross it. It is the convenient yardstick for distances inside the Solar System.

Ch. 1 · How far apart everything is, p. 22

Axial tilt The angle between a planet's spin axis and the perpendicular to its orbit. Earth's is about 23.4°, and it is the cause of the seasons, not changes in our distance from the Sun. Uranus is tipped over at 98°.

Ch. 6 · What causes the seasons, p. 111

Azimuth The compass direction of an object, measured in degrees around the horizon from north (0°) through east (90°), south (180°) and west (270°). Used with altitude.

Ch. 5 · Altitude and azimuth: the sky from where you stand, p. 87

B

Big Bang The hot, dense early state from which the universe has been expanding for about 13.8 billion years. It was not an explosion at a point in space; space itself has been stretching everywhere at once. The cosmic microwave background is its afterglow.

Ch. 4 · The expanding universe, p. 81

Black hole A region where gravity is so strong that nothing, not even light, can escape from inside its event horizon. Stellar black holes are left when the cores of the most massive stars collapse; supermassive ones sit at the centres of galaxies.

Ch. 3 · Black holes, p. 60

Bortle scale A nine-step scale of sky darkness devised by John Bortle in 2001. Class 1 is a pristine dark site where the Milky Way casts shadows; class 9 is an inner-city sky. Suburban skies, like the one the Gallery images were taken from, are around class 5–6.

Ch. 7 · Matching the telescope to the target, p. 129

Brown dwarf An object between a large planet and a small star, roughly 13 to 80 times the mass of Jupiter. It is too light to fuse ordinary hydrogen steadily, so it glows dimly from the heat of its formation and slowly cools.

Ch. 3 · Evolution by mass, p. 51

C

Catadioptric telescope A telescope that uses both mirrors and a corrector lens, such as a Schmidt–Cassegrain or Maksutov. Folding the light path makes a long focal length fit in a short, portable tube. Compare refractor and reflector.

Ch. 7 · Optical telescopes, p. 117

Celestial equator Earth's equator projected outward onto the sky. It is the zero line for declination and divides the sky into northern and southern halves.

Ch. 5 · Right ascension and declination: addresses on the sky, p. 88

Celestial poles The two points on the sky directly above Earth's North and South Poles, around which the whole sky appears to turn each night. Polaris lies less than a degree from the north celestial pole today, though precession slowly moves the pole among the stars.

Ch. 5 · The celestial sphere, p. 86

Celestial sphere The imaginary globe of sky surrounding Earth, on which stars appear to be fixed. It is not real, since the stars lie at very different distances, but it is a useful way to give every object a position.

Ch. 5 · The celestial sphere, p. 86

Cepheid variable A pulsating yellow supergiant star that brightens and fades on a regular cycle of days to weeks. Henrietta Leavitt found that brighter Cepheids pulse more slowly (the Leavitt law), making them 'standard candles' for measuring distances to other galaxies.

Ch. 4 · Cepheid variables and the cosmic distance ladder, p. 79

Chandrasekhar limit The greatest mass, about 1.4 solar masses, that a white dwarf can have and still hold itself up by degeneracy pressure. Push past it and the star either collapses or explodes as a Type Ia supernova.

Ch. 3 · White dwarfs, p. 56

Chromosphere The thin layer of the Sun's atmosphere just above the photosphere. It shines a deep red in hydrogen-alpha light and is where plage, filaments and spicules are seen through solar telescopes.

Ch. 2 · The layers of the Sun, p. 27

Circumpolar Describes a star or constellation close enough to the celestial pole that it never sets from a given latitude. From New Jersey, the Big Dipper, Cassiopeia and Cepheus are circumpolar.

Ch. 6 · Circumpolar constellations, and the ones we never see, p. 109

CNO cycle A chain of nuclear reactions in which carbon, nitrogen and oxygen act as catalysts to fuse hydrogen into helium. It dominates in stars more massive than about 1.3 Suns; lighter stars like the Sun use the proton–proton chain instead.

Ch. 3 · Nucleosynthesis: how stars make the elements, p. 65

Comet A small icy body from the outer Solar System. As it nears the Sun the ice vaporises, forming a glowing head (the coma) and tails of gas and dust that can stretch millions of kilometres. Short-period comets come from the Kuiper belt; long-period ones from the Oort cloud.

Ch. 1 · Beyond the planets: the Kuiper belt and the Oort cloud, p. 18

Constellation One of 88 officially defined regions of the sky, set by the International Astronomical Union in the 1920s and 1930s. Every point on the sky belongs to exactly one. In everyday use the word also means the traditional star figure within that region.

Ch. 6 · What a constellation is, p. 99

Corona The Sun's outermost atmosphere, a tenuous gas heated to more than a million degrees, far hotter than the surface below it. It is seen as a pearly halo during a total solar eclipse and streams outward as the solar wind.

Ch. 2 · The layers of the Sun, p. 27

Coronal mass ejection (CME) A huge cloud of magnetised gas blasted from the Sun's corona into space, carrying billions of tonnes of material. When one hits Earth it can trigger a geomagnetic storm and auroras far from the poles.

Ch. 2 · Coronal mass ejections (CMEs), p. 39

Cosmic microwave background The faint glow of radiation filling the whole sky, released about 380,000 years after the Big Bang when the universe first became transparent. Stretched by expansion, it now corresponds to a temperature of just 2.7 degrees above absolute zero.

Ch. 4 · The expanding universe, p. 81

Cosmic web The largest-scale pattern in the universe: galaxies gathered into filaments and walls surrounding vast, nearly empty voids. It grew from tiny density ripples in the early universe, pulled together by gravity and dark matter.

Ch. 4 · Large-scale structure: the cosmic web, p. 82

D

Dark energy The unknown cause of the accelerating expansion of the universe, discovered in 1998 from distant Type Ia supernovae. It makes up roughly 68% of the universe's total energy content.

Ch. 4 · The expanding universe, p. 81

Dark matter Matter that has gravity but gives off no light and does not interact with ordinary matter in any way yet detected. Its pull is seen in how galaxies rotate and how clusters bend light. It outweighs ordinary matter about five to one.

Ch. 3 · Dark matter, p. 62

Dark nebula A cloud of cold gas and dust dense enough to block the light of stars or glowing gas behind it, appearing as a dark patch. The Horsehead Nebula is the classic example.

Ch. 3 · Glowing clouds: emission, reflection and dark nebulae, p. 45

Declination The sky's equivalent of latitude: an object's angle north (+) or south (−) of the celestial equator, from +90° at the north celestial pole to −90° at the south. Used with right ascension.

Ch. 5 · Right ascension and declination: addresses on the sky, p. 88

Deep-sky object Any object beyond the Solar System other than a single star: star clusters, nebulae and galaxies. The Messier, NGC and IC catalogs list the best-known ones.

Ch. 7 · Matching the telescope to the target, p. 129

Degeneracy pressure A quantum effect that resists squeezing matter beyond a certain density: no two electrons (or neutrons) can occupy the same state. Electron degeneracy holds up white dwarfs; neutron degeneracy holds up neutron stars. It does not depend on heat, so it never runs out.

Ch. 3 · White dwarfs, p. 56

Dwarf planet A body orbiting the Sun that is massive enough to have pulled itself round, but has not cleared other objects from its orbital path. The IAU recognises five: Ceres, Pluto, Eris, Haumea and Makemake.

Ch. 1 · Dwarf planets and the lesser worlds, p. 16

E

Ecliptic The path the Sun appears to follow across the sky over a year; equivalently, the plane of Earth's orbit. The planets and Moon always stay close to it. It is tilted 23.4° to the celestial equator, and the zodiac constellations lie along it.

Ch. 6 · The zodiac: the constellations behind the Sun, p. 102

Electromagnetic spectrum The full range of light, from radio waves through microwaves, infrared, visible light and ultraviolet to X-rays and gamma rays. All travel at the speed of light and differ only in wavelength. Different wavelengths reveal different things, so astronomers observe across the whole range.

Ch. 7 · The electromagnetic spectrum, p. 114

Elliptical galaxy A smooth, featureless galaxy shaped like a ball or an egg, made mostly of old reddish stars with little gas or new star formation. The largest galaxies known are giant ellipticals, often built up by mergers.

Ch. 4 · Kinds of galaxy, p. 69

Emission nebula A cloud of gas made to glow by ultraviolet light from hot young stars inside it. Hydrogen gives most of them their characteristic red-pink colour. The Orion Nebula (M42) is the brightest example.

Ch. 3 · Glowing clouds: emission, reflection and dark nebulae, p. 45

Epoch (J2000) The date to which a set of sky coordinates refers. Because precession slowly shifts the grid, catalogs give positions for a standard moment; most today use J2000.0, noon on 1 January 2000.

Ch. 5 · Precession: the wobbling axis, p. 92

Equinox The two moments each year, around 20 March and 22 September, when the Sun crosses the celestial equator and day and night are nearly equal everywhere. The March equinox is the zero point of right ascension.

Ch. 6 · What causes the seasons, p. 111

Event horizon The boundary around a black hole from inside which nothing can escape, because the escape velocity exceeds the speed of light. Its radius is about 3 km for every solar mass.

Ch. 3 · Black holes, p. 60

Exit pupil The width of the beam of light leaving the eyepiece: the aperture divided by the magnification. Around 2–7 mm suits the human eye; larger than the eye's own pupil, and some light is wasted.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

F

Field of view How much sky a telescope, eyepiece or camera shows at once, usually given in degrees or arcminutes. Lower magnification and shorter focal length give a wider field.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Filament (solar) A long, dark thread seen against the face of the Sun: a cloud of cooler, denser gas held up by magnetic fields. Seen on the Sun's edge against dark space, the same structure appears bright and is called a prominence.

Ch. 2 · Filaments, p. 33

Flare A sudden, intense flash of radiation from the Sun when tangled magnetic fields snap and reconnect, releasing in minutes the energy of millions of hydrogen bombs. Flares are rated A, B, C, M and X, each class ten times stronger than the last.

Ch. 2 · Flares, p. 36

Focal length The distance from a telescope's main lens or mirror to the point where it brings light to a focus. Longer focal lengths give a larger image and higher magnification with a given eyepiece.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Focal ratio The focal length divided by the aperture, written f/5, f/10 and so on. A 'fast' (low) focal ratio gives a wider field and shorter exposures for photography; a 'slow' (high) one suits planets and double stars.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Fusion (nuclear) The joining of light atomic nuclei into heavier ones, releasing energy. Fusion of hydrogen into helium powers every star on the main sequence, and later stages build carbon, oxygen and heavier elements. See nucleosynthesis.

Ch. 3 · Nucleosynthesis: how stars make the elements, p. 65

G

Galactic coordinates A sky coordinate system based on the plane of the Milky Way. Galactic longitude is measured from the direction of the galaxy's centre in Sagittarius, and galactic latitude above or below the galactic plane.

Ch. 5 · Two more systems: ecliptic and galactic, p. 91

Galaxy A vast system of stars, gas, dust and dark matter held together by its own gravity. Galaxies range from dwarfs with a few million stars to giants with trillions. The Milky Way is our own.

Ch. 4 · What a galaxy is, p. 68

Galaxy cluster A group of hundreds to thousands of galaxies bound together by gravity, filled with hot X-ray-emitting gas and dominated by dark matter. Clusters sit at the knots of the cosmic web. Smaller collections are called groups, like our own Local Group.

Ch. 4 · Large-scale structure: the cosmic web, p. 82

Gas giant A large planet made mostly of hydrogen and helium with no solid surface, such as Jupiter and Saturn. Uranus and Neptune, made largely of water, ammonia and methane 'ices', are often called ice giants.

Ch. 1 · The giant planets, p. 10

Geomagnetic storm A disturbance of Earth's magnetic field caused by a CME or a fast stream of solar wind. Strong storms bring auroras to low latitudes and can disrupt satellites, radio and power grids.

Ch. 2 · Coronal mass ejections (CMEs), p. 39

Globular cluster A dense, spherical swarm of hundreds of thousands of very old stars. About 150 orbit the Milky Way in its halo; many are over 12 billion years old. M13 in Hercules is the best known in northern skies.

Ch. 4 · The Milky Way, p. 78

Granulation The mottled pattern covering the Sun's photosphere, made by the tops of rising columns of hot gas. Each granule is about the size of Texas and lasts around ten minutes.

Ch. 2 · The layers of the Sun, p. 27

H

Halo (galactic) The roughly spherical region surrounding a galaxy's disk, containing scattered old stars, globular clusters and most of the galaxy's dark matter.

Ch. 4 · The Milky Way, p. 78

Helium flash The runaway ignition of helium fusion in the core of a red giant of roughly the Sun's mass. It happens within minutes, deep inside the star, and is almost invisible from outside.

Ch. 3 · Evolution by mass, p. 51

Hertzsprung–Russell diagram A chart plotting stars' luminosity against their surface temperature (or colour). Most stars fall along the main sequence, with giants above and white dwarfs below. It is the single most useful picture in stellar astronomy.

Ch. 3 · The Hertzsprung–Russell diagram, p. 49

Hubble constant The present rate of expansion of the universe: how fast galaxies recede for each unit of distance. Measurements disagree, about 73 km/s per megaparsec from the Cepheid distance ladder against about 67 from the cosmic microwave background; the 'Hubble tension' is unresolved.

Ch. 4 · The expanding universe, p. 81

Hubble–Lemaître law The finding that the farther away a galaxy is, the faster it is moving away from us, with speed in proportion to distance. Published by Georges Lemaître in 1927 and Edwin Hubble in 1929, it was the first evidence that the universe is expanding.

Ch. 4 · The expanding universe, p. 81

Hydrogen-alpha (H-alpha) A deep red wavelength of light (656.3 nm) given off by hydrogen. It is the colour of emission nebulae, and solar telescopes tuned to it show the Sun's chromosphere and prominences.

Ch. 7 · Solar telescopes, p. 122

I

Interferometry Combining signals from several separated telescopes so that together they achieve the resolution of one telescope as wide as the distance between them. The Event Horizon Telescope linked dishes across the globe this way to image a black hole's shadow.

Ch. 7 · Radio telescopes, p. 120

Interstellar medium The thin gas and dust between the stars. It is enriched over time by material that dying stars shed, and its densest, coldest pockets, the molecular clouds, are where new stars form.

Ch. 3 · Stellar nurseries, p. 42

Irregular galaxy A galaxy with no clear spiral or elliptical shape, often disturbed by gravitational encounters. The Large and Small Magellanic Clouds, companions of the Milky Way, are examples.

Ch. 4 · Kinds of galaxy, p. 69

K

Kuiper belt A broad ring of icy bodies beyond Neptune, about 30 to 50 AU from the Sun. Pluto is one of its largest members, and it is the source of many short-period comets.

Ch. 1 · The Kuiper belt, p. 19

L

Leavitt law The relationship, found by Henrietta Swan Leavitt in 1908–1912, that a Cepheid's pulsation period reveals its true luminosity. Comparing that with its apparent brightness gives its distance. Also called the period–luminosity relation.

Ch. 4 · Cepheid variables and the cosmic distance ladder, p. 79

Light-year The distance light travels in one year, about 9.46 trillion km. It is a measure of distance, not time. The nearest star beyond the Sun is about 4.2 light-years away.

Ch. 1 · How far apart everything is, p. 22

Local Group The small group of galaxies that includes the Milky Way, the Andromeda Galaxy (M31), the Triangulum Galaxy (M33) and dozens of dwarf galaxies, spread across about 10 million light-years.

Ch. 4 · How galaxies move, p. 74

Luminosity The total energy a star gives off each second: its true power, independent of distance. It is usually expressed in multiples of the Sun's luminosity. Compare apparent magnitude, which is how bright it looks from here.

Ch. 3 · Sorting the stars, p. 47

M

Magnification How much larger a telescope makes an object appear: the telescope's focal length divided by the eyepiece's. Useful magnification is limited by aperture and seeing; roughly twice the aperture in millimetres is a practical maximum.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Main sequence The long, diagonal band on the Hertzsprung–Russell diagram where stars spend most of their lives, steadily fusing hydrogen into helium in their cores. Its hot, bright end holds massive stars; its cool, dim end holds red dwarfs. The Sun is about halfway through its main-sequence life.

Ch. 3 · The Hertzsprung–Russell diagram, p. 49

Meridian The imaginary line across the sky from due north through the zenith to due south. An object is highest in the sky, and usually best placed for viewing, when it crosses the meridian.

Ch. 5 · Altitude and azimuth: the sky from where you stand, p. 87

Messier catalog A list of 110 nebulae, clusters and galaxies compiled by the French comet-hunter Charles Messier in the 18th century, so he would not mistake them for comets. Its entries, M1 to M110, include many of the finest deep-sky objects for northern observers.

See the Gallery at astrostudious.com

Molecular cloud A cold, dense cloud of gas, mostly hydrogen molecules, and dust, often hundreds of light-years across. Pockets within it collapse under gravity to form new stars, making these clouds the nurseries of the galaxy.

Ch. 3 · Stellar nurseries, p. 42

Mount (alt-azimuth and equatorial) The support that holds and points a telescope. An alt-azimuth mount moves up-down and left-right; an equatorial mount has one axis aligned with Earth's axis, so a single motion follows the stars. Long-exposure photography needs smooth, accurate tracking.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

N

Nebula A cloud of gas and dust in space. Some glow (emission nebulae), some shine by scattered starlight (reflection nebulae), and some block light (dark nebulae). Plural: nebulae.

Ch. 3 · Glowing clouds: emission, reflection and dark nebulae, p. 45

Neutrino A nearly massless, uncharged particle produced in vast numbers by nuclear reactions in stars and supernovae. Neutrinos pass through almost anything, including the whole Earth, so they carry news straight from the Sun's core.

Ch. 7 · Beyond light, p. 125

Neutron star The collapsed core left by a massive star's supernova: more mass than the Sun packed into a ball about 20 km across, made almost entirely of neutrons. A teaspoon of it would weigh about a billion tonnes.

Ch. 3 · Supernovae and neutron stars, p. 57

New General Catalogue (NGC) A catalog of 7,840 nebulae, clusters and galaxies published by J. L. E. Dreyer in 1888, with two supplements, the Index Catalogues (IC), adding about 5,400 more. NGC and IC numbers are still the standard names for most deep-sky objects.

See the Gallery at astrostudious.com

Nucleosynthesis The creation of chemical elements by nuclear reactions. Hydrogen, helium and a little lithium date from the Big Bang; elements up to iron are forged by fusion inside stars; heavier ones come from supernovae, neutron-star mergers and late-life giant stars.

Ch. 3 · Nucleosynthesis: how stars make the elements, p. 65

Nutation A small nodding of Earth's axis, caused mainly by the Moon's pull, superimposed on the slow circle of precession. The main term repeats every 18.6 years and shifts star positions by up to about 9 arcseconds.

Ch. 5 · Nutation: a nod on top of the wobble, p. 94

O

Oort cloud A vast, roughly spherical cloud of icy bodies thought to surround the Solar System, reaching perhaps 1 to 1.5 light-years from the Sun. It has never been seen directly; its existence is inferred from long-period comets.

Ch. 1 · The Oort cloud, p. 20

Open cluster A loose group of tens to a few thousand young stars that formed together from the same cloud. Over time they drift apart. The Pleiades (M45) is the best-known example.

Ch. 3 · Stellar nurseries, p. 42

P

Parallax The small apparent shift of a nearby star against more distant ones as Earth moves around the Sun. The smaller the shift, the farther the star. It is the first, most direct rung of the cosmic distance ladder.

Ch. 4 · Cepheid variables and the cosmic distance ladder, p. 79

Parsec The distance at which a star would show a parallax of one arcsecond: about 3.26 light-years. Astronomers often use kiloparsecs (thousands) and megaparsecs (millions).

Ch. 4 · Cepheid variables and the cosmic distance ladder, p. 79

Photosphere The visible surface of the Sun, the layer from which most of its light escapes, at a temperature of about 5,500 °C. Sunspots and granulation are features of the photosphere.

Ch. 2 · The layers of the Sun, p. 27

Plage Bright patches in the Sun's chromosphere around active regions, where concentrated magnetic fields heat the gas. They usually surround sunspots and are best seen in hydrogen-alpha or calcium light.

Ch. 2 · Plage, p. 32

Planetary nebula A glowing shell of gas thrown off by a Sun-like star at the end of its life, lit up by the hot exposed core that will become a white dwarf. Despite the name it has nothing to do with planets; early observers thought they looked like planetary disks. The Ring Nebula (M57) is one.

Ch. 3 · Planetary nebulae, p. 54

Precession The slow circling of Earth's spin axis, like a wobbling top, taking about 25,800 years to complete. It gradually moves the celestial poles and the equinoxes among the stars, so star coordinates must be given for a particular epoch.

Ch. 5 · Precession: the wobbling axis, p. 92

Prominence A large loop or sheet of cooler, dense gas suspended above the Sun's surface by magnetic fields, seen bright against dark space at the Sun's edge. Against the Sun's face, the same thing appears as a dark filament.

Ch. 2 · Prominences, p. 35

Proper motion A star's slow apparent movement across the sky caused by its own motion through space. It is tiny, usually a fraction of an arcsecond a year; the record holder, Barnard's Star, moves about 10 arcseconds a year.

Ch. 5 · Proper motion: the stars are not fixed, p. 95

Protostar A young star still gathering mass from its parent cloud, glowing from the heat of contraction before fusion begins in its core. Protostars are usually hidden in dust and best seen in infrared light.

Ch. 3 · Stellar nurseries, p. 42

Pulsar A rapidly spinning neutron star that sweeps beams of radio waves (and sometimes light or X-rays) across space like a lighthouse, so it appears to pulse. Some spin hundreds of times a second.

Ch. 3 · Supernovae and neutron stars, p. 57

R

Red giant A star in a late stage of life that has used up the hydrogen in its core and swollen to enormous size, with a cool, reddish surface. The Sun will become one in about 5 billion years, growing large enough to engulf Mercury and Venus.

Ch. 3 · Red giants, p. 53

Redshift The stretching of light to longer, redder wavelengths. For distant galaxies it is caused by the expansion of space while the light travels, so a galaxy's redshift reveals its distance and how far back in time we are seeing it.

Ch. 4 · The expanding universe, p. 81

Reflection nebula A cloud of dust that shines by scattering the light of nearby stars. Because blue light scatters more easily, reflection nebulae usually look blue, like the haze around the Pleiades.

Ch. 3 · Glowing clouds: emission, reflection and dark nebulae, p. 45

Reflector A telescope that gathers light with a curved mirror rather than a lens. Mirrors are cheaper to make in large sizes, so reflectors give the most aperture for the money; every large research telescope is a reflector.

Ch. 7 · Optical telescopes, p. 117

Refractor A telescope that gathers light with a lens at the front of a sealed tube. Refractors give sharp, high-contrast views and need little maintenance, but large lenses are expensive.

Ch. 7 · Optical telescopes, p. 117

Resolution The finest detail a telescope can show, set by its aperture. Dawes' limit gives roughly 116 ÷ aperture (mm) arcseconds. In practice, seeing usually limits detail before the optics do.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Right ascension The sky's equivalent of longitude, measured eastward along the celestial equator from the March equinox. It is given in hours, minutes and seconds (0 to 24 h) because the sky turns once a day. Used with declination.

Ch. 5 · Right ascension and declination: addresses on the sky, p. 88

S

Seeing The blurring and twinkling of star images caused by turbulence in Earth's atmosphere. Good seeing means a steady atmosphere and sharp detail; it varies from night to night and often hour to hour.

Ch. 7 · Optics in practice: what the numbers mean, p. 126

Sidereal day The time Earth takes to turn once relative to the stars: 23 hours 56 minutes 4 seconds, about four minutes shorter than the 24-hour solar day. That is why each star rises four minutes earlier every night.

Ch. 5 · The revolving Earth and sidereal time, p. 90

Smart telescope A compact, all-in-one telescope with a built-in camera, computerised mount and software, controlled from a phone or tablet. It finds targets by recognising star patterns and stacks many short exposures into a live image. The Gallery images were taken with one.

Ch. 7 · Optical telescopes, p. 117

Solar mass ($M_\odot$) The mass of the Sun, about 2×10^{30} kg, or 333,000 Earths. It is the standard unit for the masses of stars, black holes and galaxies.

Ch. 3 · Evolution by mass, p. 51

Solar wind The constant stream of charged particles flowing outward from the Sun's corona at hundreds of kilometres per second. It shapes comet tails, fills the Solar System, and, with CMEs, drives auroras.

Ch. 2 · The layers of the Sun, p. 27

Solstice The two moments each year, around 21 June and 21 December, when the Sun reaches its farthest north or south of the celestial equator, giving the longest and shortest days.

Ch. 6 · What causes the seasons, p. 111

Spectral class A star's classification by the features in its spectrum, which mainly reflect surface temperature. The sequence from hottest to coolest is O, B, A, F, G, K, M. The Sun is a G2 star.

Ch. 3 · Sorting the stars, p. 47

Spectroscopy Spreading light into its component colours (a spectrum) to study it. Dark and bright lines in a spectrum reveal an object's chemical makeup, temperature, motion toward or away from us, and much more. Most of what we know about stars comes from it.

Ch. 7 · Reading starlight: spectra and spectroscopy, p. 116

Spiral galaxy A galaxy with a flat, rotating disk in which bright arms of young stars and gas wind out from a central bulge. In barred spirals, like the Milky Way, the arms begin at the ends of a bar of stars across the centre.

Ch. 4 · Kinds of galaxy, p. 69

Stacking Combining many separate exposures of the same target into a single image. Random noise averages out while the faint signal builds up, revealing detail no single frame could show. Smart telescopes stack automatically as they observe.

Ch. 7 · Cameras and other instruments, p. 119

Stellar nursery A region inside a molecular cloud where new stars are forming, often lit up as an emission nebula by the hot young stars it has already produced. The Orion Nebula and the Eagle Nebula's 'Pillars of Creation' are famous examples.

Ch. 3 · Stellar nurseries, p. 42

Sunspot A dark, cooler region on the Sun's photosphere where intense magnetic fields block the flow of heat from below. Sunspots come and go over an 11-year cycle of solar activity.

Ch. 2 · Sunspots, p. 30

Supermassive black hole A black hole of millions to billions of solar masses, found at the centre of most large galaxies. The Milky Way's, Sagittarius A*, is about 4 million solar masses.

Ch. 3 · Black holes, p. 60

Supernova The explosion of a star, briefly outshining an entire galaxy. Core-collapse supernovae end the lives of massive stars, leaving a neutron star or black hole; Type Ia supernovae are white dwarfs pushed past the Chandrasekhar limit. Plural: supernovae.

Ch. 3 · Supernovae and neutron stars, p. 57

T

Terrestrial planet A planet made mainly of rock and metal with a solid surface: Mercury, Venus, Earth and Mars. Compare gas giant.

Ch. 1 · The rocky planets, p. 7

Trans-Neptunian object Any Solar System body orbiting beyond Neptune, including the Kuiper belt objects, Pluto, Eris and other dwarf planets, and the scattered disk.

Ch. 1 · Beyond the planets: the Kuiper belt and the Oort cloud, p. 18

V

Variable star A star whose brightness changes over time, either because it pulsates (like a Cepheid variable), erupts, or is regularly eclipsed by a companion.

Ch. 4 · Cepheid variables and the cosmic distance ladder, p. 79

W

White dwarf The hot, dense core left behind when a Sun-like star dies: roughly the Sun's mass packed into a sphere the size of Earth, held up by degeneracy pressure. It no longer fuses anything and slowly cools over billions of years.

Ch. 3 · White dwarfs, p. 56

Z

Zenith The point in the sky directly overhead, at an altitude of 90°. Objects near the zenith are seen through the least atmosphere, so they look sharpest.

Ch. 5 · Altitude and azimuth: the sky from where you stand, p. 87

Zodiac The band of constellations along the ecliptic through which the Sun, Moon and planets appear to move. Because of precession, the astrological signs no longer line up with the constellations they were named for.

Ch. 6 · The zodiac: the constellations behind the Sun, p. 102