

UNIT 5

The Solar System

How a disc of gas and dust became eight planets, their moons, and a trillion comets

Image: NASA/JPL/Space Science Institute

By the end of this unit, I should be able to answer these questions:

- What does the solar system contain, and where do most of its mass and most of its angular momentum sit?
- Why did rocky planets form close to the Sun and giant planets farther out, and what part did the frost line play?
- How do I find the age of a rock or a meteorite from the numbers of parent and daughter atoms it contains?
- How warm should a planet be at its distance from the Sun, and why is the surface of Venus so much hotter than that?
- Why are rings found close to their planets, and how do I find where an asteroid or a moon is in resonance with a planet?
- How did the giant planets move after they formed, and which features of the solar system do the Nice model and the Grand Tack explain?

The solar system is the one planetary system we can visit. Spacecraft have photographed every planet from close up, landed on Venus, Mars, Titan, and a comet, and flown through a fountain of ocean water erupting from a small moon of Saturn. Everything we believe about how planets form in general is therefore tested first against this system. With the toolkit of Units 1 to 3, its history can be read from evidence of several kinds, such as the uranium and lead atoms in a meteorite, the temperatures of the planets, and the gaps that Jupiter has cleared in the asteroid belt.

1 Inventory and scale

The Sun holds 99.86% of the mass of the solar system. Jupiter has 71% of what is left, and the other seven planets, a few hundred moons, and more than a million catalogued asteroids and comets share the remainder. The angular momentum is distributed the other way round. The orbital motion of Jupiter alone carries about 60% of it, and the spin of the Sun carries less than 1%. A theory of how the system formed has to explain both distributions.

The planets come in two kinds (Table 1). Mercury, Venus, Earth, and Mars are small and dense, made of rock and iron. Jupiter and Saturn consist mostly of hydrogen and helium, and Uranus and Neptune consist mostly of water, ammonia, and methane under a hydrogen envelope. All eight move around the Sun in the same direction, on nearly circular orbits within a few degrees of a common plane (Unit 2).

Planet	Semi-Major Axis (au)	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density ($\mathrm{g\,cm^{-3}}$)
Mercury	0.387	0.0553	0.383	5.43
Venus	0.723	0.815	0.950	5.24
Earth	1.00	1.00	1.00	5.51
Mars	1.52	0.107	0.532	3.93
Jupiter	5.20	318	10.97	1.33
Saturn	9.58	95.2	9.14	0.687
Uranus	19.2	14.5	3.98	1.27
Neptune	30.1	17.1	3.86	1.64

Table 1. Semi-major axis, mass, mean radius, and mean density of the eight planets, with $M_\oplus = 5.97 \times 10^{24}\,\mathrm{kg}$ and $R_\oplus = 6371\,\mathrm{km}$. For comparison, water has a density of $1\,\mathrm{g\,cm^{-3}}$.

Beyond the planets, the solar system is filled with debris left over from its formation. The asteroid belt lies between 2.1 and 3.3 au, the Kuiper belt of icy bodies between 30 and 50 au, and the Oort cloud of comets reaches out to about 100 000 au, more than a third of the way to the nearest star (Figure 1). The solar wind blows a bubble into the interstellar gas, and Voyager 1 crossed its edge, the **heliopause**, in 2012 at 122 au. That spacecraft, launched in 1977, is about 172 au away in late 2026, and its radio signal needs almost a full day to reach us.

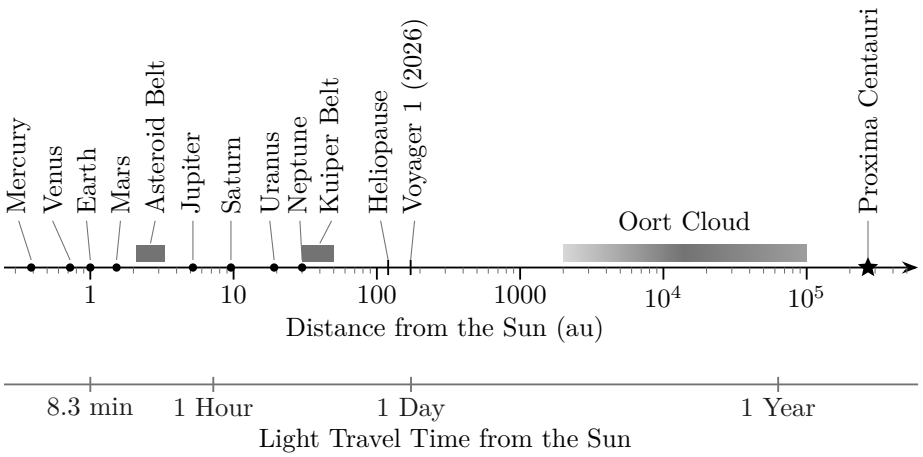
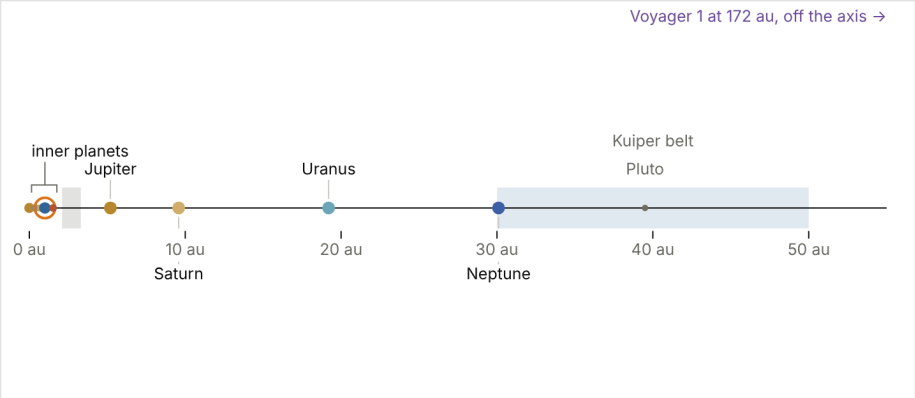


Figure 1. The solar system on a logarithmic distance scale. Each labelled tick is ten times farther from the Sun than the one before. The lower scale gives the time sunlight needs to get there.

INTERACTIVE **The solar system to scale**



Switch between distances and sizes, and click a planet to see how long sunlight needs to reach it. On the linear axis the four inner planets crowd together near the Sun, and on the logarithmic axis every factor of ten gets the same width.

Click the picture or this link to try it in the online version of this unit.

2 Formation from the solar nebula

The planets orbit in one plane and in one direction, which points to a rotating disc as their birthplace. Rock sits close to the Sun while ice and gas sit far out, so the disc was hot inside and cold outside. And the oldest solids in meteorites share a single age of 4.567 billion years, measured to within a few hundred thousand years.

2.1 Disc and frost line

About 4.57 billion years ago a dense core of a molecular cloud collapsed under its own gravity (Unit 7). Because angular momentum is conserved, the slowly rotating gas spun up as it fell inward, in the same way as a spinning skater turns faster when pulling in the arms. For a parcel of gas of mass m circling at speed v and distance r from the axis, the product mvr stays constant, so v grows as r shrinks. Angular momentum also has a direction, along the rotation axis, so it is a vector $\vec{L}$. Gas can fall freely along $\vec{L}$ but not across it, so the cloud flattened. The gas settled into a disc about 100 au in radius around the young Sun, perpendicular to $\vec{L}$, which is called the **solar nebula**. By mass it was 98.5% hydrogen and helium and 1.5% everything else, part of it in dust grains less than a micrometre across. Such discs are observed around young stars today (Unit 4 describes how ALMA images them), and they are short-lived. In star clusters older than about 5 million years only a small minority of stars still has one. Giant planets must collect their gas within that time.

Temperature decides what can exist as a solid. Close to the young Sun only metals and silicates existed as grains. Water stays vapour until the temperature falls below about 170 K, and the distance at which that happens is the **frost line**. A simple estimate uses the temperature of a black grain in full sunlight at distance a from the Sun, which Section 3 shows to be

$$T = 278\,\mathrm{K}\left(\frac{a}{1\,\mathrm{au}}\right)^{-1/2}.$$

Setting $T = 170\,\mathrm{K}$ and solving for the distance gives

$$a_{\mathrm{frost}} = \left(\frac{278\,\mathrm{K}}{170\,\mathrm{K}}\right)^{2}\,\mathrm{au} \approx 2.7\,\mathrm{au}.$$

Detailed disc models put the line anywhere between 2 and 5 au. The simple value lands in the middle of the asteroid belt, and that fits the record, because asteroids of the inner belt are dry rock while those of the outer belt contain up to 10% water. Beyond the frost line, water ice adds two to three times the mass available in rock and metal, and solid cores grow bigger.

2.2 Growth of solids into planets

Dust grains collide gently and stick, and within a few thousand years they grow into pebbles. There the growth stalls, for two reasons. Pebbles bounce off each other instead of sticking, and bodies around a metre in size feel a headwind, because the gas is partly supported by its own pressure and orbits slightly slower than a solid body does. A metre-sized rock at 1 au would spiral into the Sun in about a century. Current models get around the barrier collectively: drag concentrates pebbles into dense clumps, and the gravity of a clump pulls it together into a **planetesimal** some 100 km across. This can be seen in the Kuiper belt object Arrokoth, which the New Horizons probe passed in 2019. It looks like a product of this process, because it consists of two lobes, together 36 km long, that touched at walking speed and merged without damage.

The largest planetesimals have the longest gravitational reach and grow fastest. In under a million years the inner disc is dominated by a few dozen **planetary embryos** with masses between those of the Moon and Mars, which merge in giant collisions over the next tens of millions of years. Beyond the frost line the embryos were larger. A core of about $10\,M_\oplus$ holds on to hydrogen and helium, and once the envelope is as massive as the core the inflow runs away, which means the growing envelope's own gravity pulls in new gas ever faster. Jupiter and Saturn grew this way, by **core accretion**. Uranus and Neptune were slower, and they had collected only one or two Earth masses of gas when the disc dispersed.

EXCURSION *The impact that made the Moon*

The Moon has 1.2% of the mass of its planet, far more in proportion than any moon of the giant planets. Its density of $3.34\ \mathrm{g\,cm^{-3}}$ matches the Earth's rocky mantle, and its iron core holds less than 2% of its mass, against 32% for the Earth. The explanation proposed in the 1970s is a collision. A body about the size of Mars, later named Theia, hit the young Earth at a glancing angle after both had formed iron cores. The cores merged, and a spray of hot mantle rock went into orbit and collected into the Moon. Simulations reproduce the Moon's mass and its missing iron. They have more trouble with its oxygen isotopes, which are indistinguishable from the Earth's although most of the debris should come from Theia.

2.3 Radiometric ages

The ages in this unit come from radioactive decay. A radioactive parent nuclide decays into a stable daughter with a fixed **half-life** $t_{1/2}$, the time after which half of the parent atoms are left. Each atom decays at random, independently of the others, so the number of decays per second is proportional to the number of parent atoms still present.

LAW Law of radioactive decay

The number P of parent atoms falls at a rate proportional to P itself,

$$\frac{\mathrm{d}P}{\mathrm{d}t} = -\frac{\ln 2}{t_{1/2}}\,P,$$

and of N_0 parent atoms present at the time $t = 0$,

$$P = N_0\,2^{-t/t_{1/2}}$$

remain after a time t.

The second form is the solution of the first. Since $2^{-t/t_{1/2}} = e^{-t \ln 2/t_{1/2}}$, its slope is $-\ln 2/t_{1/2}$ times its own value, which is the defining property of the exponential function. Meanwhile $D = N_0 - P$ atoms have turned into daughters, and dividing the two numbers gives

$$\frac{D}{P} = 2^{t/t_{1/2}} - 1.$$

A logarithm (Unit 1) then solves for the time.

KEY EQUATION Radiometric age

$$t = t_{1/2} \frac{\ln(1 + D/P)}{\ln 2}$$

P and D are the numbers of parent and daughter atoms in the sample today, and $t_{1/2}$ is the half-life of the parent. The clock starts when the mineral solidifies and stops exchanging atoms with its surroundings, and D counts only daughters made by decay inside the sample.

WORKED EXAMPLE The oldest piece of the Earth

Zircon crystals take up uranium when they form and exclude lead. All ^{206}Pb in a zircon therefore comes from the decay of ^{238}U, which has a half-life of 4.468 billion years. The oldest zircon grains known, from the Jack Hills of Western Australia, contain about $D/P = 0.979$ atoms of ^{206}Pb per atom of ^{238}U. The key equation gives

$$t = 4.468\,\text{Gyr} \times \frac{\ln 1.979}{\ln 2} = 4.468\,\text{Gyr} \times \frac{0.6826}{0.6931} = 4.40\,\text{Gyr},$$

so the grains crystallized 4.40 billion years ago.

The oldest dated solids of all are calcium-aluminium-rich inclusions (CAIs), millimetre-sized grains in primitive meteorites that were the first minerals to condense from the hot gas. The two decay chains of uranium to lead give them an age of 4567.3 ± 0.2 million years, which defines the age of the solar system. By the zircon above, the Earth had a solid crust 170 million years later.

CHECK YOUR UNDERSTANDING Question 1

Zircon crystals grew in a magma that cooled into granite 300 million years ago. The magma came from older crust that had existed for 4 billion years before it melted. What age does the uranium-lead clock of these zircons give?

(A) About 300 million years
(B) About 4.0 billion years
(C) About 4.3 billion years
(D) About 4.57 billion years

The solution is at the end of the unit.

3 Terrestrial planets

3.1 Interiors and surfaces

The mean density of a planet is the first clue to its interior. It is the mass divided by the volume, which for a sphere of radius R is $\frac{4}{3}\pi R^3$:

$$\bar{\rho} = \frac{M}{\frac{4}{3}\pi R^3}.$$

Surface rock has a density of about 3 $\mathrm{g\,cm^{-3}}$ and iron reaches 7.9 $\mathrm{g\,cm^{-3}}$, so the Earth's mean value of 5.51 $\mathrm{g\,cm^{-3}}$ requires a large iron core. Seismic waves map that core. The Earth has a liquid outer core with a radius of 3480 km, which is 55% of the planet's radius, and a solid inner core at the centre. Iron separated from rock while the young planet was molten, a process called **differentiation**. Mercury is nearly as dense as the Earth although it is too small to be compressed much, so it must be mostly iron; its core spans about 83% of its radius. On Mars the seismometer of the InSight lander found a liquid core about half the planet's radius in size.

A planet's surface records its age in craters. An old surface has collected more impacts than a young one, and the Apollo samples, which were dated with the method of Section 2, calibrate the count. For example, the lunar highlands are more than 4 billion years old. Venus has about 940 craters spread evenly over the planet, with none of the crowded ancient terrain the Moon shows, so its entire surface must have been renewed by volcanism within roughly the last 500 million years. The Earth recycles its ocean floor by plate tectonics in less than 200 million years. Mars has old cratered highlands with dry river valleys, which were cut when liquid water flowed under a thicker atmosphere. Small planets cool fastest, and the Moon and Mercury have been geologically quiet for billions of years.

3.2 Equilibrium temperature and greenhouse effect

A planet absorbs sunlight and radiates infrared, and its temperature settles where the two balance. The balance depends on how much of the sunlight is actually absorbed. The fraction of the incoming sunlight that a planet reflects straight back to space is called its **albedo**,

$$A = \frac{\text{reflected power}}{\text{incoming power}}.$$

For example, fresh snow reflects about 80% of the incoming light ($A = 0.8$), while charcoal reflects only a few per cent.

DERIVATION Balance of absorbed and emitted power

A planet of radius R at distance a from the Sun presents a disc of area πR^2 to the solar flux $L_\odot/(4\pi a^2)$. A fraction A, the albedo, is reflected, and the rest is absorbed. If rotation or an atmosphere spreads the heat, the planet radiates as a black body of temperature T from its whole surface $4\pi R^2$ (Stefan-Boltzmann law with the constant σ, Unit 3):

$$P_{\mathrm{abs}} = (1-A)\,\pi R^2\,\frac{L_\odot}{4\pi a^2}, \qquad P_{\mathrm{emit}} = 4\pi R^2\,\sigma T^4.$$

Setting the two equal, the radius cancels and $T^4 = (1-A)\,L_\odot/(16\pi\sigma a^2)$. With $L_\odot = 4\pi R_\odot^2 \sigma T_\odot^4$ this becomes $T = T_\odot\sqrt{R_\odot/2a}\,(1-A)^{1/4}$. For $T_\odot = 5772\,\mathrm{K}$, $R_\odot = 6.957\times10^8$ m, and $a = 1\,\mathrm{au} = 1.496\times10^{11}$ m the factor in front is 278 K.

KEY EQUATION Equilibrium temperature

$$T_{\rm eq} = 278\,{\rm K}\,(1-A)^{1/4}\left(\frac{a}{1\,{\rm au}}\right)^{-1/2}$$

A rotating planet with albedo A at distance a from the Sun radiates as much power as it absorbs when its temperature is $T_{\rm eq}$. The size of the planet does not enter. For another star, multiply by $(L/L_\odot)^{1/4}$.

CHECK YOUR UNDERSTANDING Question 2

Two black planets that rotate quickly orbit the Sun at the same distance. One has ten times the radius of the other. How do their equilibrium temperatures compare?

(A) The larger one is about 3.2 times warmer

(B) The larger one is about 1.8 times warmer

(C) The smaller one is about 1.8 times warmer

(D) Both have the same temperature

The solution is at the end of the unit.

Figure 2 compares the formula with measurements. Mercury has no atmosphere and rotates slowly, so its day side reaches 700 K while the night side drops to 100 K. The giant planets are warmer than sunlight alone would make them (Section 4). And the surface of Venus is 510 K hotter than its equilibrium temperature, because of the **greenhouse effect**. An atmosphere lets most visible sunlight through to the ground. The ground radiates in the infrared, near a wavelength of 10 μm by Wien's law (Unit 3), and there molecules such as CO_2 and H_2O absorb strongly. The radiation that finally escapes to space comes from a high, cold layer of air, and it is this layer that sits at $T_{\rm eq}$. The ground beneath has to be warmer.

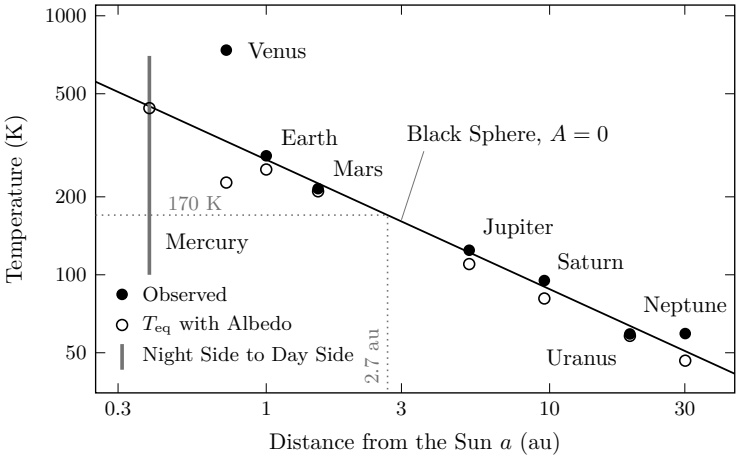
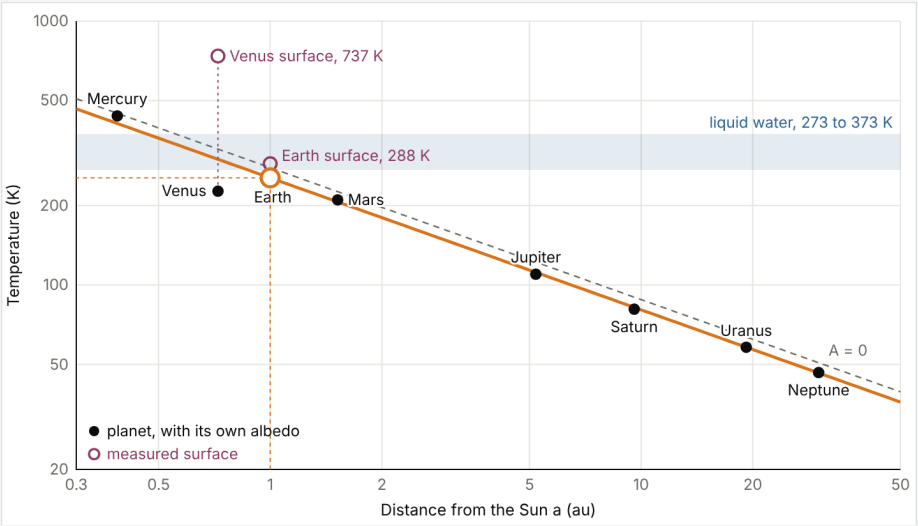


Figure 2. Temperatures in the solar system. The line is the equilibrium temperature of a black sphere; open circles include the measured albedo of each planet. Filled circles are observed values: the mean surface temperature for Venus, Earth, and Mars, and the effective radiating temperature for the giant planets. The grey bar spans the night and day sides of Mercury. The dotted lines mark 170 K, which the black sphere reaches at 2.7 au.

INTERACTIVE Equilibrium temperature of a planet



Move the planet with the distance slider and change its albedo to see where water would be liquid. The formula leaves out the greenhouse effect, which is why the measured surfaces of Venus and the Earth lie above their dots.

Click the picture or this link to try it in the online version of this unit.

WORKED EXAMPLE The greenhouse effect on the Earth

The Earth reflects 30% of the sunlight, so $T_{\rm eq} = 278\,\mathrm{K} \times 0.70^{1/4} = 255\,\mathrm{K}$. The measured mean surface temperature is 288 K, and water vapour and CO_2 supply the missing 33 K. A model with one layer shows how. Put a layer above the ground that is transparent to sunlight and absorbs all infrared. Seen from space, the layer must radiate $\sigma T_{\rm eq}^4$ per square metre, and it radiates the same amount downward. The ground receives the absorbed sunlight, also $\sigma T_{\rm eq}^4$, plus this back radiation, and has to emit the sum,

$$\sigma T_{\rm s}^4 = 2\,\sigma T_{\rm eq}^4 .$$

Its temperature is therefore $T_{\rm s} = 2^{1/4}\,T_{\rm eq}$, which gives a surface temperature of 303 K for the Earth. The real value is lower because air lets part of the infrared through.

WORKED EXAMPLE The greenhouse effect on Venus and Mars

For Venus, $A = 0.77$ and $a = 0.723\,\mathrm{au}$ give $T_{\rm eq} = 278\,\mathrm{K} \times 0.23^{1/4}/\sqrt{0.723} = 227\,\mathrm{K}$, colder than the Earth because of the bright clouds. The surface is at 737 K. With n absorbing layers the model gives $T_{\rm s} = (n+1)^{1/4}\,T_{\rm eq}$, and $(737/227)^4 = 111$, so Venus needs $n \approx 110$ layers, which its CO_2 atmosphere with a surface pressure of 92 bar can easily supply. Mars, with 0.006 bar of CO_2, gains about 5 K.

Liquid water made the difference between the two planets. Venus receives 1.9 times as much sunlight as the Earth, and an early ocean there would have evaporated. Without liquid water, CO_2 cannot be bound into carbonate rock, which is where the Earth keeps a comparable amount of the gas.

Whether a planet keeps a gas at all is decided by a contest between thermal motion and gravity. Molecules of mass m in a gas of temperature T move at a typical speed

$$v_{\rm th} = \sqrt{\frac{3kT}{m}},$$

where k is the Boltzmann constant. This is the root mean square speed; the most probable speed $\sqrt{2kT/m}$ used for line widths in Unit 3 is slightly smaller. A few molecules are always much faster than this typical value, and over billions of years their losses add up, so a planet holds a gas for the age of the solar system only if its escape velocity (Unit 2) is large enough:

$$v_{\rm esc} \gtrsim 6\, v_{\rm th}.$$

WORKED EXAMPLE Which gases the Earth keeps

In the Earth's upper atmosphere, at about 1000 K, hydrogen molecules move at $v_{\rm th} = 3.5\,{\rm km\,s^{-1}}$ and nitrogen molecules at $0.94\,{\rm km\,s^{-1}}$, so six times the thermal speed is $21\,{\rm km\,s^{-1}}$ for hydrogen and $5.7\,{\rm km\,s^{-1}}$ for nitrogen. The Earth's escape velocity of $11.2\,{\rm km\,s^{-1}}$ falls between the two values, so the Earth has lost its free hydrogen and kept its nitrogen. The Moon, whose escape velocity is only $2.4\,{\rm km\,s^{-1}}$, keeps no gas at all, and Jupiter, with $60\,{\rm km\,s^{-1}}$, keeps everything, including hydrogen.

4 Giant planets, rings, and moons

4.1 Gas giants and ice giants

Jupiter has 318 Earth masses, nearly the composition of the Sun, and no surface. Below the clouds the hydrogen gets steadily denser and turns into a liquid without a sharp boundary. Above a pressure of about a million bar, reached some 15% of the way to the centre, the electrons move freely and the fluid becomes **metallic hydrogen**. Convection in this conductor drives a magnetic field more than ten times stronger than the Earth's. Gravity measurements by the Juno orbiter show that the planet contains 10 to 25 $M_\oplus$ of elements heavier than helium, and that they are spread through the inner half of the radius rather than packed into a compact core with a sharp edge.

Jupiter's effective temperature, measured from its infrared emission, is 124 K, while the equilibrium formula predicts 110 K. Power goes as T^4, so the planet emits $(124/110)^4 \approx 1.6$ times what it absorbs. The surplus is heat left from formation, released as the planet slowly cools and contracts.

Uranus and Neptune are a different kind of planet. Their densities require interiors made mostly of water, ammonia, and methane, with hydrogen and helium limited to an envelope of at most 20% of the mass. These compounds arrived frozen in planetesimals, hence the name **ice giants**, although inside the planets they now form a hot, dense fluid.

4.2 Rings and the Roche limit

Saturn's main rings extend between 74 500 and 136 800 km from the centre of the planet and are in most places about 10 m thick. A sheet of paper as thin in proportion to its width as the rings are to their full diameter of about 274 000 km would be nearly 3 km wide. The rings consist of lumps of water ice, mostly between a centimetre and a few metres in size, each on its own Kepler orbit. Their age is disputed: the clean ice suggests a few hundred million years, since infalling dust should have darkened it, yet some models let the rings shed the dust and last since Saturn formed. Rings lie close to their planets while large moons orbit farther out, and the reason for this arrangement is tides.

DERIVATION Tidal disruption of a moon

A moon of mass m, radius r, and density ρ_m orbits a planet of mass M, radius R, and density ρ_M at distance d. The planet pulls on the near side of the moon more strongly than on its centre. For a small

rock lying on the near side the difference is

$$\Delta g = \frac{GM}{(d-r)^2} - \frac{GM}{d^2}.$$

Because r is small compared with d, this difference is the slope of the function $g(d) = GM/d^2$ multiplied by the small step r, and the slope is the derivative $\mathrm{d}g/\mathrm{d}d = -2GM/d^3$:

$$\Delta g \approx \left|\frac{\mathrm{d}g}{\mathrm{d}d}\right| r = \frac{2GMr}{d^3}.$$

The same result follows from the approximation $(1-x)^{-2} \approx 1 + 2x$ for the small number $x = r/d$. This tidal acceleration tries to lift the rock off, and the moon's own gravity, Gm/r^2, holds it down. The rock leaves when $2GMr/d^3 > Gm/r^2$. With $M = \frac{4}{3}\pi R^3 \rho_M$ and $m = \frac{4}{3}\pi r^3 \rho_m$ this condition reads

$$d < R\left(\frac{2\rho_M}{\rho_m}\right)^{1/3} = 1.26\,R\left(\frac{\rho_M}{\rho_m}\right)^{1/3}.$$

The estimate treats the moon as a rigid sphere. Édouard Roche (1820-1883) did the calculation in 1848 for a fluid moon, which the tide stretches into an egg shape and which is therefore easier to pull apart. The form of the result stays the same and the numerical factor becomes 2.44.

KEY EQUATION Roche limit

$$d_\mathrm{R} = 2.44\,R\left(\frac{\rho_M}{\rho_m}\right)^{1/3}$$

A moon of density ρ_m that is held together only by its own gravity is torn apart by tides if it orbits closer than d_R to the centre of a planet of radius R and density ρ_M.

WORKED EXAMPLE The edge of Saturn's rings

For Saturn ($R = 60\,268$ km, $\rho_M = 0.687\,\mathrm{g\,cm^{-3}}$) and lumps of solid ice ($\rho_m = 0.9\,\mathrm{g\,cm^{-3}}$) the formula gives

$$d_\mathrm{R} = 2.44 \times 60\,268\,\mathrm{km} \times \left(\frac{0.687}{0.9}\right)^{1/3} = 134\,000\,\mathrm{km}.$$

The Roche limit for ice therefore lies 134 000 km from the centre of Saturn. The outer edge of the A ring lies at 136 800 km (Figure 3). Inside this distance the ice cannot assemble into a moon, and outside it can; Mimas, the innermost of Saturn's classical moons, orbits at 185 500 km.

The limit applies only to bodies held together by gravity alone. Satellites and astronauts orbit far inside the Earth's Roche limit and stay in one piece, because chemical bonds hold them together. A loose pile of rubble has no such protection. For example, comet Shoemaker-Levy 9 passed Jupiter at 1.3 planetary radii in 1992 and broke into 21 pieces, which hit the planet two years later.

CHECK YOUR UNDERSTANDING Question 3

The Roche limit of Saturn for lumps of ice ($0.9\,\mathrm{g/cm^3}$) lies at 134 000 km. Where does it lie for loose clumps of rock with a density of $3.0\,\mathrm{g/cm^3}$?

(A) About 40 000 km
(B) About 90 000 km
(C) About 200 000 km
(D) About 450 000 km

The solution is at the end of the unit.

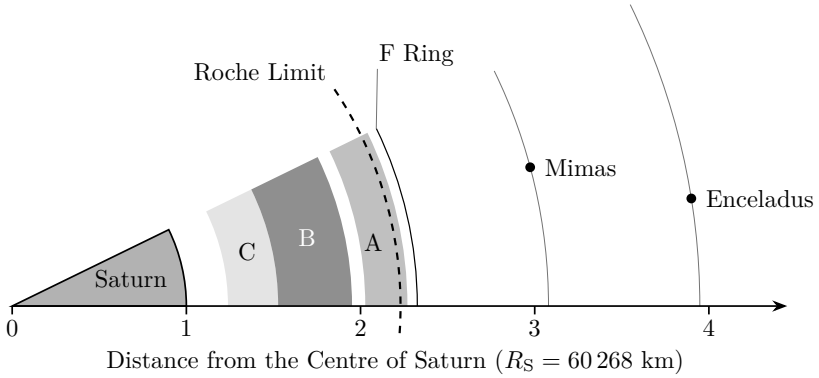


Figure 3. A sector of the Saturn system seen from above, to scale. The C, B, and A rings lie inside the Roche limit for solid ice (dashed). The narrow F ring follows just outside, and moons such as Mimas and Enceladus orbit farther out.

4.3 Moons with oceans

Tidal forces can also heat a moon from inside. This can be seen in the large moons of Jupiter. Io, the innermost of them, completes four orbits while Europa completes two and Ganymede completes one. This chain of periods, called the Laplace resonance after Pierre-Simon Laplace (1749-1827), who explained its stability, keeps Io's orbit slightly eccentric, so the tidal bulge that Jupiter raises on Io rises and falls during every 1.77-day orbit, and the constant flexing feeds over 400 active volcanoes. Europa receives a smaller dose of the same heating, and it is enough to keep water liquid. Under an ice shell some 20 km thick lies a salty ocean that holds roughly twice as much water as all the Earth's oceans together. The evidence for the ocean is magnetic. Jupiter's tilted field sweeps past Europa every 11 hours, and the Galileo orbiter measured an induced field in response, which requires a layer of electrically conducting material, such as salty water, close to the surface.

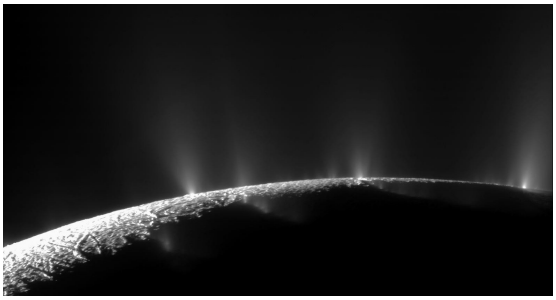


Figure 4. Jets of water vapour and ice grains rise from fractures near the south pole of Enceladus, photographed by Cassini in 2009. Credit: NASA/JPL/Space Science Institute.

Saturn's moon Enceladus, only 504 km across, should be frozen solid. In 2005 Cassini found jets of water vapour and ice grains shooting out of fractures near its south pole (Figure 4). The spacecraft flew through the plume and detected salts and organic molecules, along with silica and molecular hydrogen, which form where hot water meets rock. A slight wobble in the moon's rotation shows that the ice shell floats on a global ocean. The heating again comes from tides, maintained in this case by a 2:1 resonance with the larger moon Dione. These moons offer liquid water and an energy source far outside the zone where sunlight keeps water liquid, and NASA's Europa Clipper, launched in 2024, arrives at Jupiter in 2030 to take a closer look.

5 Small bodies and resonances

5.1 Asteroids and the Kirkwood gaps

The asteroid belt contains surprisingly little material. All its bodies together hold about 3% of the mass of the Moon, and more than a third of that sits in Ceres alone, which is 940 km across. Asteroids of the inner belt are mostly stony (S-type), while those of the outer belt are dark and rich in carbon (C-type). Meteorites deliver free samples of both to the ground, and the OSIRIS-REx mission collected its sample at the source. In 2023 it returned 121.6 g of the C-type asteroid Bennu, and the grains contain clay minerals, salts left behind by evaporated brine, and 14 of the 20 amino acids used in proteins.

A histogram of asteroid orbits (Figure 5) shows gaps, which Daniel Kirkwood (1814-1895) found in 1866. They lie where the orbital period would be a simple fraction of Jupiter's period. Kepler's third law (Unit 2) converts a ratio of periods into a ratio of semi-major axes, because for two bodies that orbit the same central body

$$\left(\frac{P_{\mathrm{res}}}{P_{\mathrm{pl}}}\right)^{2} = \left(\frac{a_{\mathrm{res}}}{a_{\mathrm{pl}}}\right)^{3}.$$

KEY EQUATION Location of an orbital resonance

$$a_{\mathrm{res}} = a_{\mathrm{pl}} \left(\frac{q}{p}\right)^{2/3}$$

A small body that completes p orbits while a planet with semi-major axis a_{pl} completes q orbits is in the $p:q$ resonance with that planet and has the semi-major axis a_{res}. The same formula holds for moons and ring particles around a planet. By convention a resonance is named after the ratio of the two orbital periods, longer period first, so Pluto, which completes two orbits while Neptune completes three, is said to be in the 3:2 resonance with Neptune.

WORKED EXAMPLE The Kirkwood gaps

An asteroid in the 3:1 resonance orbits three times while Jupiter ($a_{\mathrm{pl}} = 5.20\,\mathrm{au}$) orbits once, so $p = 3$, $q = 1$, and

$$a_{\mathrm{res}} = 5.20\,\mathrm{au} \times \left(\frac{1}{3}\right)^{2/3} = 5.20\,\mathrm{au} \times 0.481 = 2.50\,\mathrm{au}.$$

The 3:1 gap therefore lies at 2.50 au. The same calculation puts the 5:2, 7:3, and 2:1 resonances at 2.82, 2.96, and 3.28 au. These are the gaps in Figure 5.

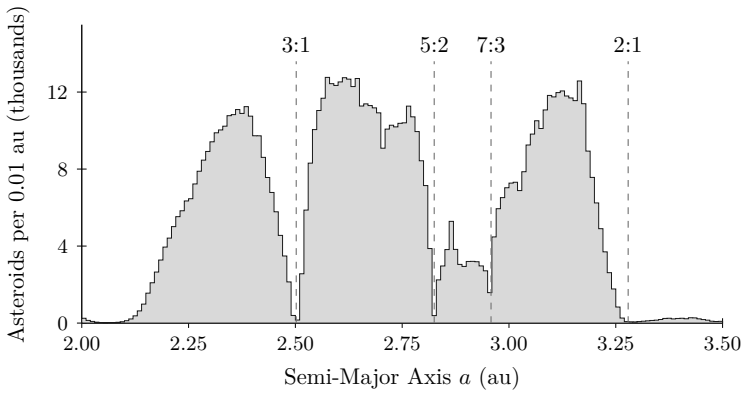


Figure 5. The Kirkwood gaps. The histogram counts the 857 000 numbered asteroids with semi-major axes between 2.0 and 3.5 au in the JPL Small-Body Database (October 2026). Dashed lines mark resonances with Jupiter computed from the key equation.

A resonance empties an orbit because the encounters repeat. An asteroid at 2.50 au meets Jupiter at the same points of its orbit again and again, so the small tugs add up, while elsewhere in the belt they average out. The asteroid's eccentricity grows erratically until, after a million years or so, its orbit crosses that of Mars or the Earth and a close encounter removes it. A resonance can also protect an orbit instead of clearing it. For example, Pluto completes two orbits while Neptune ($a_{\mathrm{pl}} = 30.1\,\mathrm{au}$) completes three, and the key equation with $q/p = 3/2$ gives $a_{\mathrm{res}} = 30.1\,\mathrm{au} \times 1.5^{2/3} = 39.4\,\mathrm{au}$, close to Pluto's measured semi-major axis of 39.5 au. Pluto is closer to the Sun than Neptune for 20 years of each 248-year orbit, and the 3:2 timing guarantees that Neptune is far away whenever Pluto crosses.

CHECK YOUR UNDERSTANDING Question 4

Few asteroids have a semi-major axis of 2.50 au, where one orbit takes exactly a third of Jupiter's period. Why is this orbit emptied?

(A) Jupiter comes closest to the belt there and pulls hardest

(B) Collisions between asteroids are most frequent there

(C) Jupiter's small tugs repeat at the same points and add up

(D) The disc of the young Sun held no material at that distance

The solution is at the end of the unit.

5.2 Comets, the Kuiper belt, and the Oort cloud

Beyond Neptune lies the **Kuiper belt**, a disc of icy bodies between 30 and about 50 au. Pluto, found in 1930, was its first known member, and several thousand are catalogued now. When Eris was discovered in 2005, as large as Pluto and 27% more massive, the International Astronomical Union had to choose between admitting many more planets and adopting a definition that excludes Pluto. It chose the definition, which demands that a planet has cleared the neighbourhood of its orbit, and Pluto became the prototype of the **dwarf planets**. The whole belt today contains about 2% of an Earth mass, while models that grow bodies as large as Pluto need 20 to 30 $M_\oplus$ of material. More than 99% of the original belt has been lost, and Section 6 says where it went.

A **comet** is an icy body on an orbit that brings it close to the Sun. The nucleus is small, dark, and porous. Comet 67P/Churyumov-Gerasimenko, which the Rosetta spacecraft accompanied for two years (Figure 6), is 4 km long, reflects 6% of the light that hits it, and has a density of $0.53\,\mathrm{g\,cm^{-3}}$, about half that of water. Inside about 3 au its water ice turns to vapour, and the escaping gas drags dust along and wraps the nucleus in a glowing cloud called the **coma**. Two tails stream away from the coma: a

straight tail of ions carried outward by the solar wind, and a curved tail of dust pushed by sunlight. A comet is used up after roughly a thousand such passages, so the comets we see must be recent arrivals from cold regions far from the Sun, where they were kept frozen.

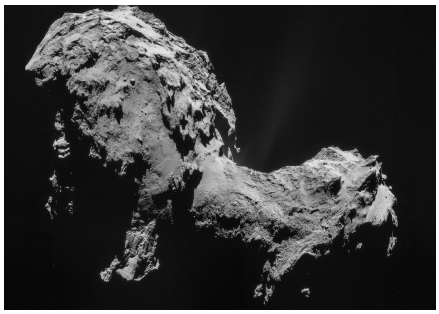


Figure 6. The nucleus of comet 67P/Churyumov-Gerasimenko, seen by the navigation camera of Rosetta from 28.6 km on 19 September 2014. Credit: ESA/Rosetta/NAVCAM, CC BY-SA IGO 3.0.

The comets we see come from two stores. Short-period comets orbit in the plane and direction of the planets and leak inward from the Kuiper belt. Long-period comets arrive from all directions on orbits with semi-major axes of tens of thousands of au. Jan Oort (1900-1992) concluded in 1950 that a spherical cloud of some 10^{11} to 10^{12} comet nuclei surrounds the Sun out to about 100 000 au. Nobody has seen an object inside the **Oort cloud**; the evidence for it is the orbits of the comets that fall out of it. Since 2017 three visitors on unbound orbits, 1I/'Oumuamua, 2I/Borisov, and 3I/ATLAS, have also been caught passing through the planetary region; they are small bodies thrown out by other planetary systems.

6 Planetary migration

The belts carry the marks of planets that moved. Pluto and hundreds of other bodies sit in Neptune's resonances on eccentric, inclined orbits, and bodies do not form on such orbits. Renu Malhotra showed in a paper published in 1993 that the pattern follows if Neptune migrated outward by at least 5 au, because its resonances moved with it, swept up bodies like a snowplough, and pumped up their eccentricities.

Planets can migrate in two ways. While the gas disc exists, the gravity of a planet raises spiral waves in the gas, and the pull of these waves changes the planet's orbit, usually inward, within about 100 000 years. After the gas is gone, planets move by scattering leftover planetesimals. Each small body thrown outward takes angular momentum from the planet, and each one thrown inward gives some back. Neptune, Uranus, and Saturn passed most of their planetesimals inward to Jupiter, which is massive enough to eject them from the solar system. Jupiter paid with a small inward shift, and the other three moved outward.

The **Nice model**, published in 2005 in three papers in the journal *Nature* by Rodney Gomes, Harold Levison, Alessandro Morbidelli, and Kleomenis Tsiganis, who worked together in Nice, turns this scattering into the central event of solar system history. The four giant planets start close together, between 5.5 and about 17 au, with a disc of planetesimals of $35\,M_\oplus$ outside them. Slow migration eventually carries Jupiter and Saturn across their mutual 2:1 resonance. Their orbits become eccentric, Uranus and Neptune are flung outward into the disc, and within a few million years the planetesimals are scattered in all directions. This one instability accounts for several observations at once:

- the present orbits of the four giant planets,
- the capture of Jupiter's Trojan asteroids, the bodies that share Jupiter's orbit at points 60° ahead of it and behind it,

- the resonant and scattered populations of the Kuiper belt, and
- the loss of more than 99% of the belt's original mass, part of which became the Oort cloud.

The authors first tied the instability to a spike of impacts on the Moon 3.9 billion years ago, inferred from Apollo samples. That spike is now in doubt, and later versions place the instability within the first 100 million years of the solar system, often with a fifth giant planet that Jupiter ejected.

Migration in the gas phase may have shaped the inner solar system as well. Models that grow the terrestrial planets from a smooth disc of embryos reproduce Venus and the Earth well, but they produce a Mars five to ten times more massive than the real one. The outcome comes out right only if the building material ended near 1 au, and the research spotlight below presents the best known proposal for why it did.

RESEARCH SPOTLIGHT

Alessandro Morbidelli *Collège de France and Observatoire de la Côte d'Azur*

Jupiter's inward and outward migration explains the small mass of Mars

Alessandro Morbidelli is one of the four authors of the Nice model. In 2011 he and Kevin Walsh, Sean Raymond, David O'Brien, and Avi Mandell simulated the inner solar system while the gas-driven migration of Section 6 moved the giant planets. Jupiter starts at 3.5 au and drifts inward to 1.5 au in about 10^5 years. Saturn, once massive enough, migrates faster, catches up, and is caught in the 3:2 resonance with Jupiter (Section 5). Such a locked pair reverses direction, and both planets move outward until the gas is gone, with Jupiter near 5.4 au. Sailors call a change of course like this a tack, and the scenario became known as the Grand Tack.

Jupiter's passage cuts off the disc of planetesimals at 1 au. Venus and the Earth grow inside the edge within 30 to 50 million years, and Mars forms from the little material scattered beyond it. The asteroid belt is emptied and then refilled from two sources, S-type bodies that formed between 1 and 3 au and C-type bodies from between and beyond the giant planets. Some C-type bodies end on orbits that cross the Earth's, enough to supply its water several times over.

Read the paper: Walsh, Morbidelli, Raymond, O'Brien and Mandell (2011), A low mass for Mars from Jupiter's early gas-driven migration, Nature 475, 206

The Grand Tack is a hypothesis under test. Competing models leave Jupiter where it formed and let planetesimals form only in narrow rings, one of them near 1 au. In every version the giant planets move by several au, and the many giant planets found very close to other stars suggest that such migration is common.

KEY POINTS

- The planets formed in a disc of gas and dust 4.567 billion years ago, a date read from radioactive decay in meteorites. Beyond the frost line near 2.7 au, ice-rich cores of about $10\,M_\oplus$ captured gas before the disc dispersed.
- The equilibrium temperature of a planet is $278\,\mathrm{K}\,(1-A)^{1/4}(a/1\,\mathrm{au})^{-1/2}$. The greenhouse effect raises the surface temperature above it, by 33 K on the Earth and by 510 K on Venus.
- Inside the Roche limit, $2.44\,R\,(\rho_M/\rho_m)^{1/3}$, tides prevent loose material from forming a moon, so rings lie close to their planets. Tidal flexing keeps oceans liquid inside Europa and Enceladus.
- Orbital resonances, located at $a_{\mathrm{pl}}(q/p)^{2/3}$, clear the Kirkwood gaps in the asteroid belt and protect Pluto from Neptune.
- The giant planets migrated. The Nice model and the Grand Tack use this to explain the structure of the Kuiper belt and the small mass of Mars.

Solutions to the questions in the text: 1-A, 2-D, 3-B, 4-C. The online version of this unit explains each answer.