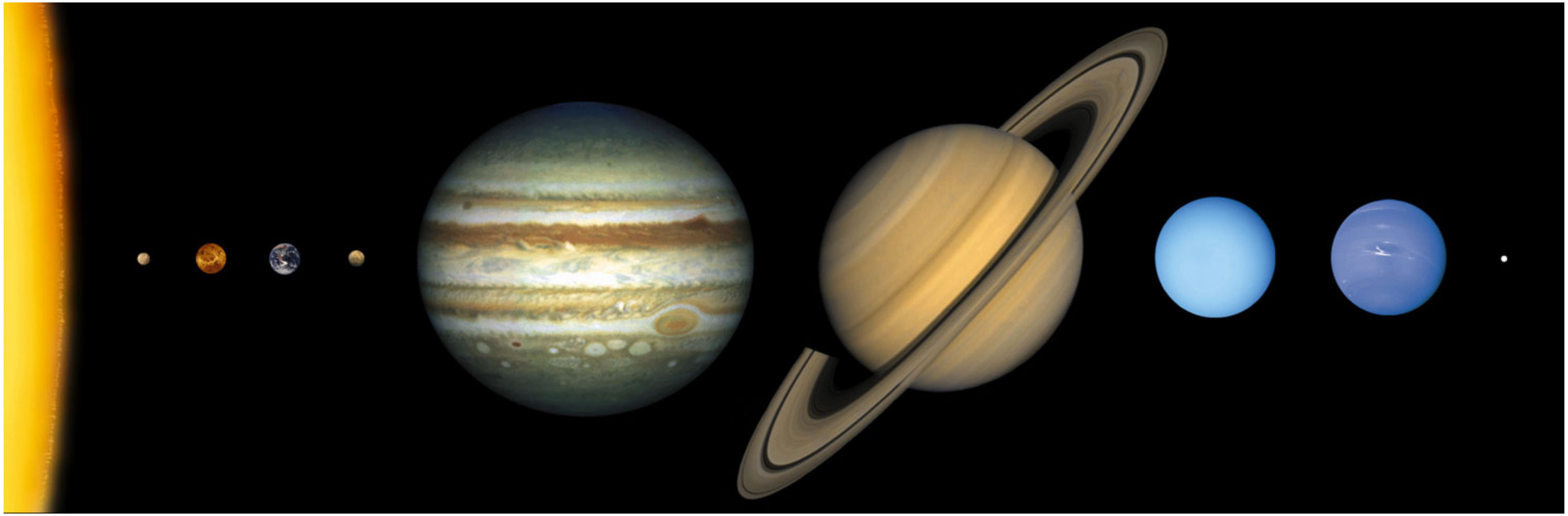
The Solar System



What is the solar system?

A grand tour of the solar system

What is the solar system?

Simply put: one star, eight planets (was nine…), a handful of "dwarf planets", ~150 moons, >10^5 asteroids/comets/Kuiper belt objects and ~10^{12} tonnes of interplanetary dust.

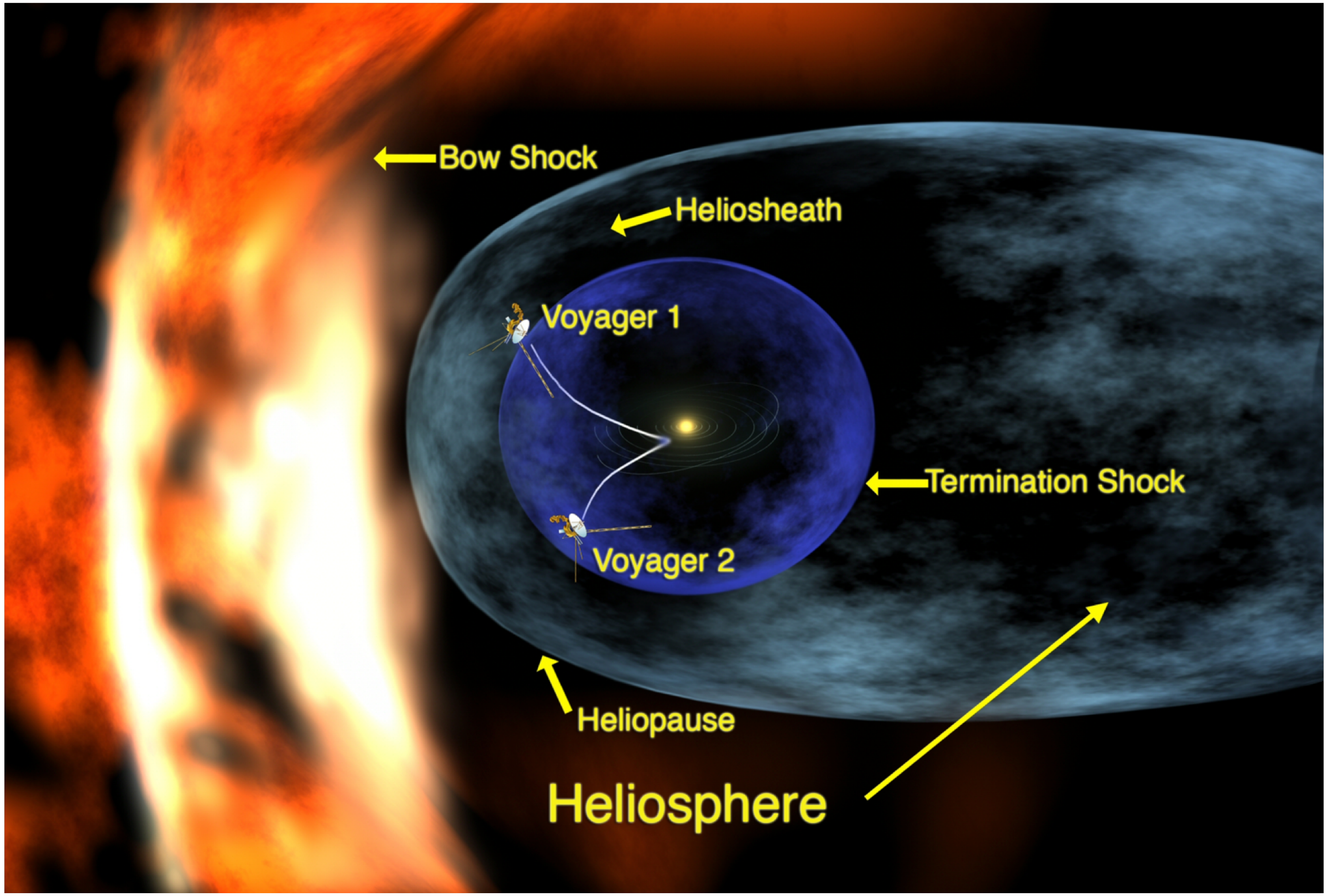
Everything within the solar system lies within the influence of the Sun (whether by gravity, magnetism or by the solar wind).

The Sun emits a "solar wind" of charged particles and the outer boundary of the solar system (known as the *heliopause*) is defined as the radius where the influence of this wind ends.

The distance to the heliopause is thought to be ~ 100-150 AU, but we haven't found out precisely yet…

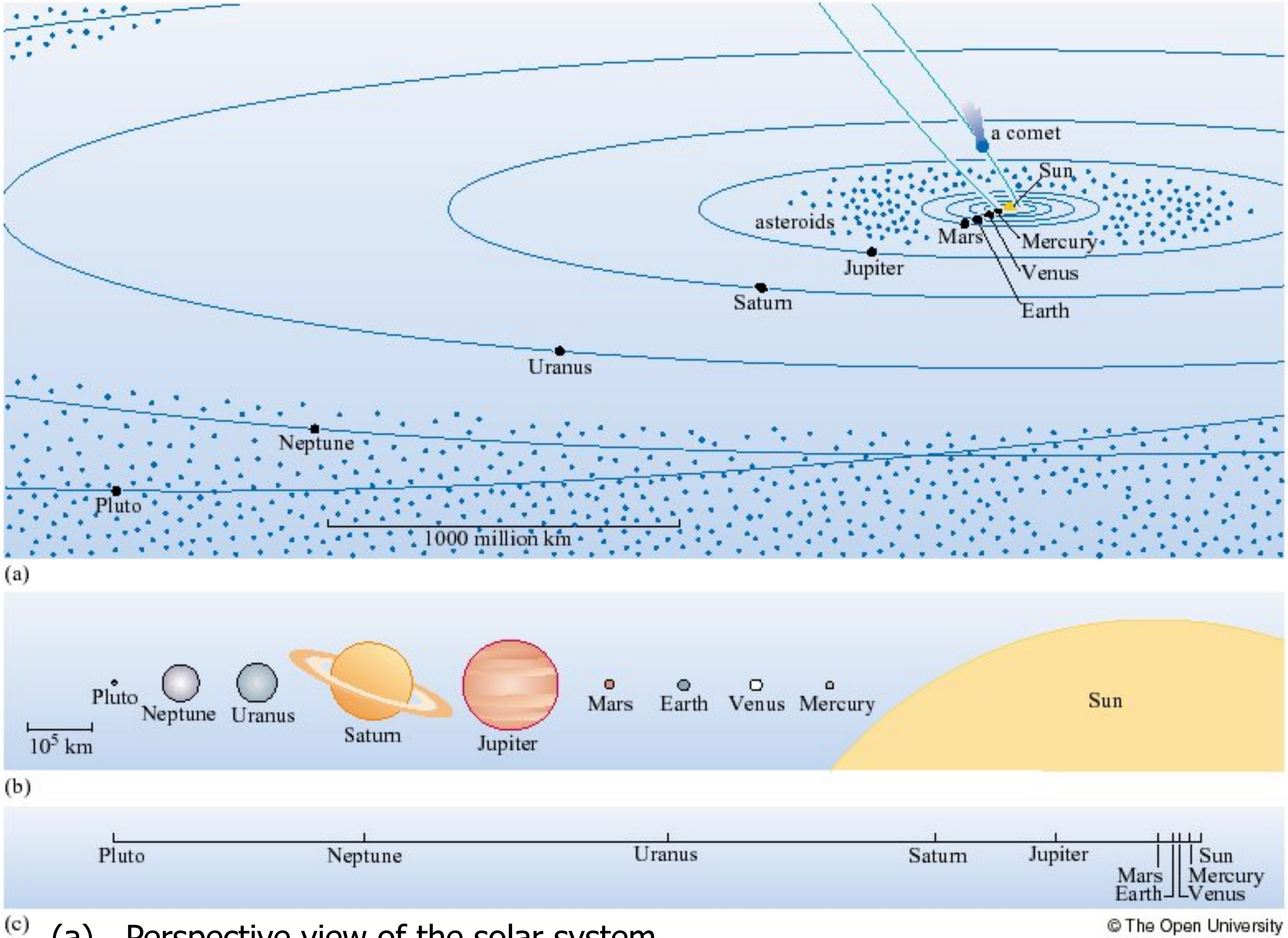
(AU = astronomical unit = the mean distance of the Earth from the Sun = 1.49598×10^8 km)

The edge of the solar system



After they finished their planetary exploration mission in 1989 the two Voyager space craft headed for the heliopause.

Voyager 1 crossed in 2004, Voyager 2 in 2007, at over 120 au from the Sun.



(a) Perspective view of the solar system

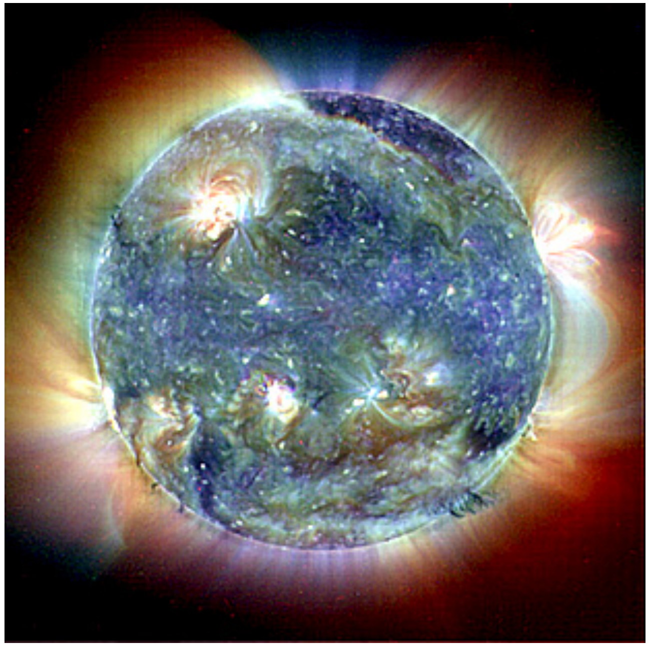
(b) Relative sizes of the Sun & planets

(c) Relative distances of the planets from the Sun

A grand tour of the solar system

To put the solar system in perspective we will briefly visit some of the planets.

The Sun dominates almost every measure in the Solar system: mass, luminosity, temperature – but not angular momentum



The sun in UV light (from the SOHO observatory, NASA)

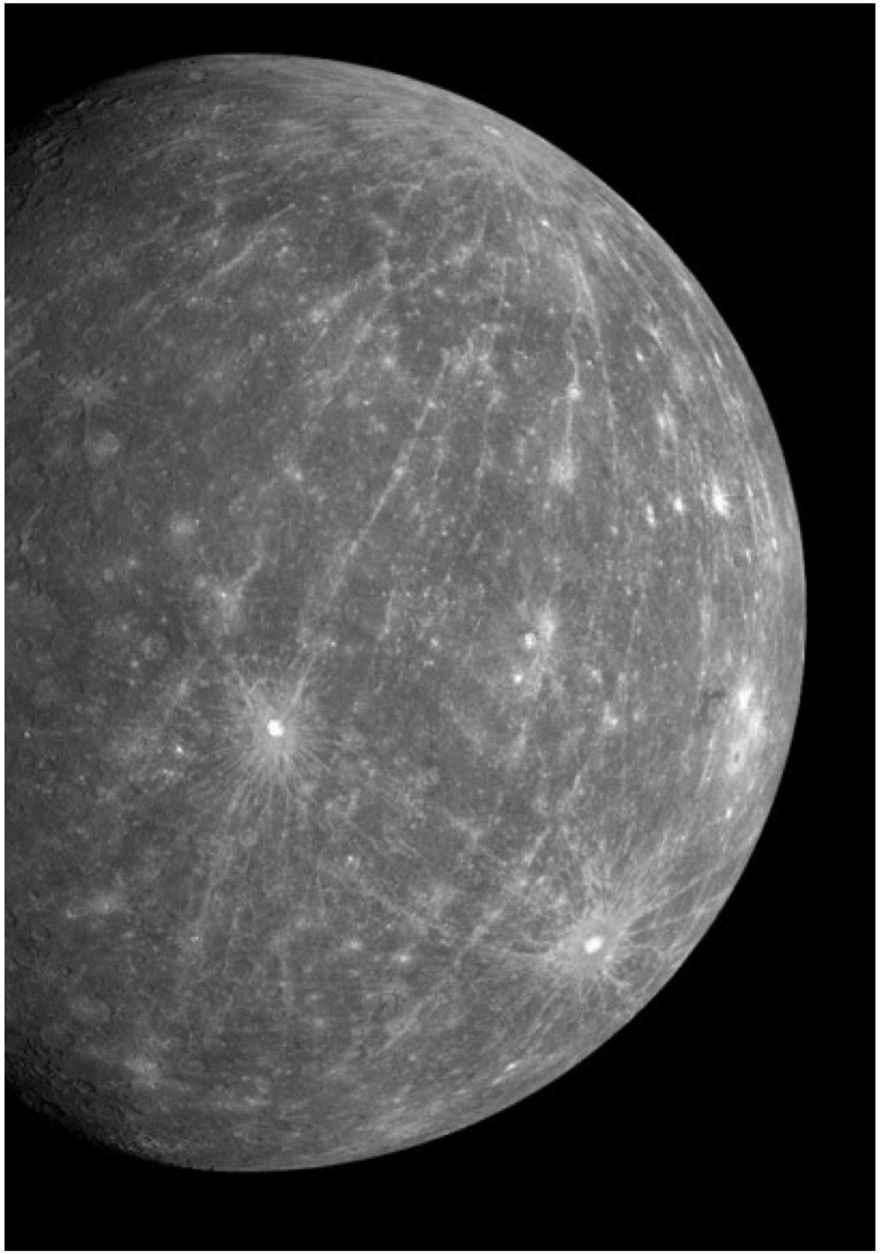
The Sun

Mass: 1.989×10^{30} kg

Radius: 6.96×10^{8} m

Density: 1410 kg m^{-3}

Surface temp: 5800 K



Composite image of Mercury from *Messenger*

Mercury

Mass: 3.3×10^{23} kg (0.055 M_E)

Radius: 2440 km (0.38 R_E)

Density: 5430 kg m^{-3}

Mean orbital radius: 0.39 AU

Mean surface temp: 443 K

A small, rocky planet with numerous craters and surface ridges

Craters are formed by impacts from asteroids or comets onto the surface.

Mercury has a tenuous atmosphere mainly of hydrogen & helium (from the solar wind)

Visited by the *Messenger* probe (2013-5).

Venus

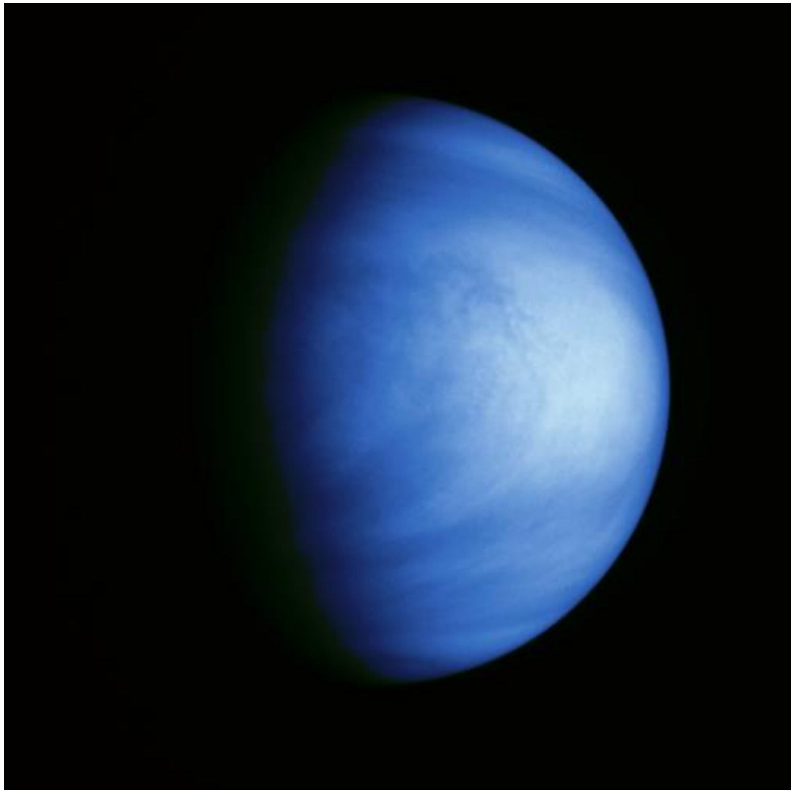
Mass: 4.87×10^{24} kg (0.815 M_E)

Radius: 6052 km (0.95 R_E)

Density: 5200 kg m^{-3}

Mean orbital radius: 0.72 AU

Mean surface temp: 733 K

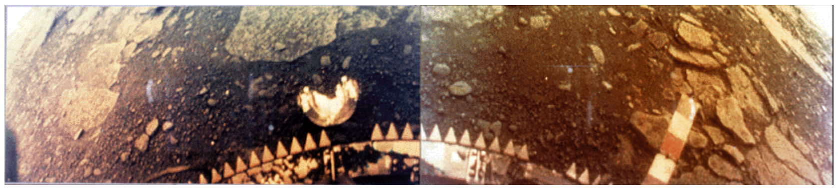


False colour image of Venus from the Galileo spacecraft

Venus has a thick CO_2 atmosphere (with 100× Earth pressure) with sulphuric acid clouds.

The surface temperature is extremely high and is caused by a strong (runaway?) greenhouse effect.

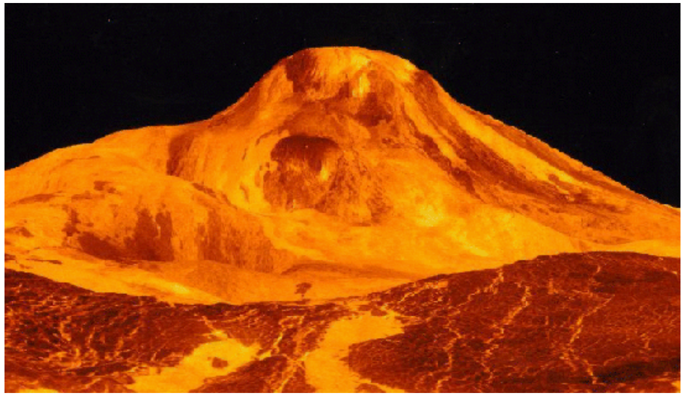
Venus has a slow rotation period (243 days) and weak magnetic field.



Ground view of Venus from Venera 13

Venus

Radar image of the surface of Venus from *Magellan*



Maat Mons, a venusian volcano

Even though Venus has a thick atmosphere, its surface still has some impact craters

But far fewer craters than Mercury ⇒ Venus' surface is *younger* than Mercury!

Most likely cause is volcanism – lava flows fill in craters or earthquakes destroy them

As Venus has few craters one theory is that there was a total volcanic resurfacing of Venus only ~ 500 million years ago

Planetary surfaces *evolve* over time. Impacts create craters – volcanos and erosion destroy them – we must understand both processes if we want to date the surfaces of the planets.

Earth

Image of Earth from Apollo 17

One of Earth's few surviving impact craters

Mass: 5.97×10^{24} kg (1.0 M_E)

Radius: 6371 km (1.0 R_E)

Density: 5510 kg m^{-3}

Mean orbital radius: 1.0 AU

Mean surface temp: 288 K

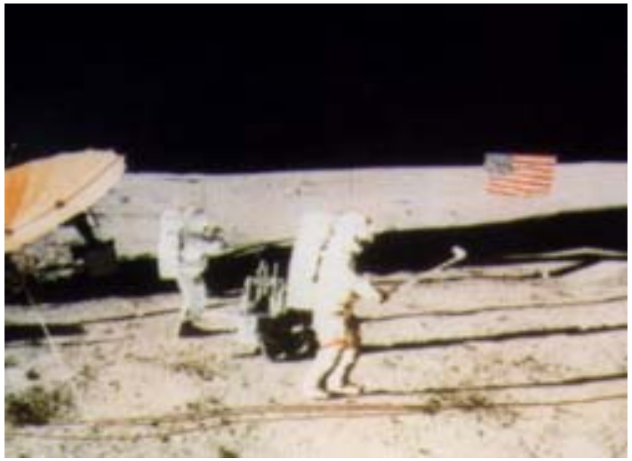
Earth has an oxygen/nitrogen atmosphere and is covered in oceans of water. It is the only planet in the solar system where we know there to be life.

Earth has few craters, which suggests that the surface is renewed frequently (by volcanos, erosion & plate tectonics)

Earth's strong magnetic field & high density imply it has a liquid metallic core

Earth's moon

Earth's moon



Anyone for tennis?

Mass: 7.40×10^{22} kg (0.012 M_E)

Radius: 1738 km (0.27 R_E)

Density: 3340 kg m^{-3}

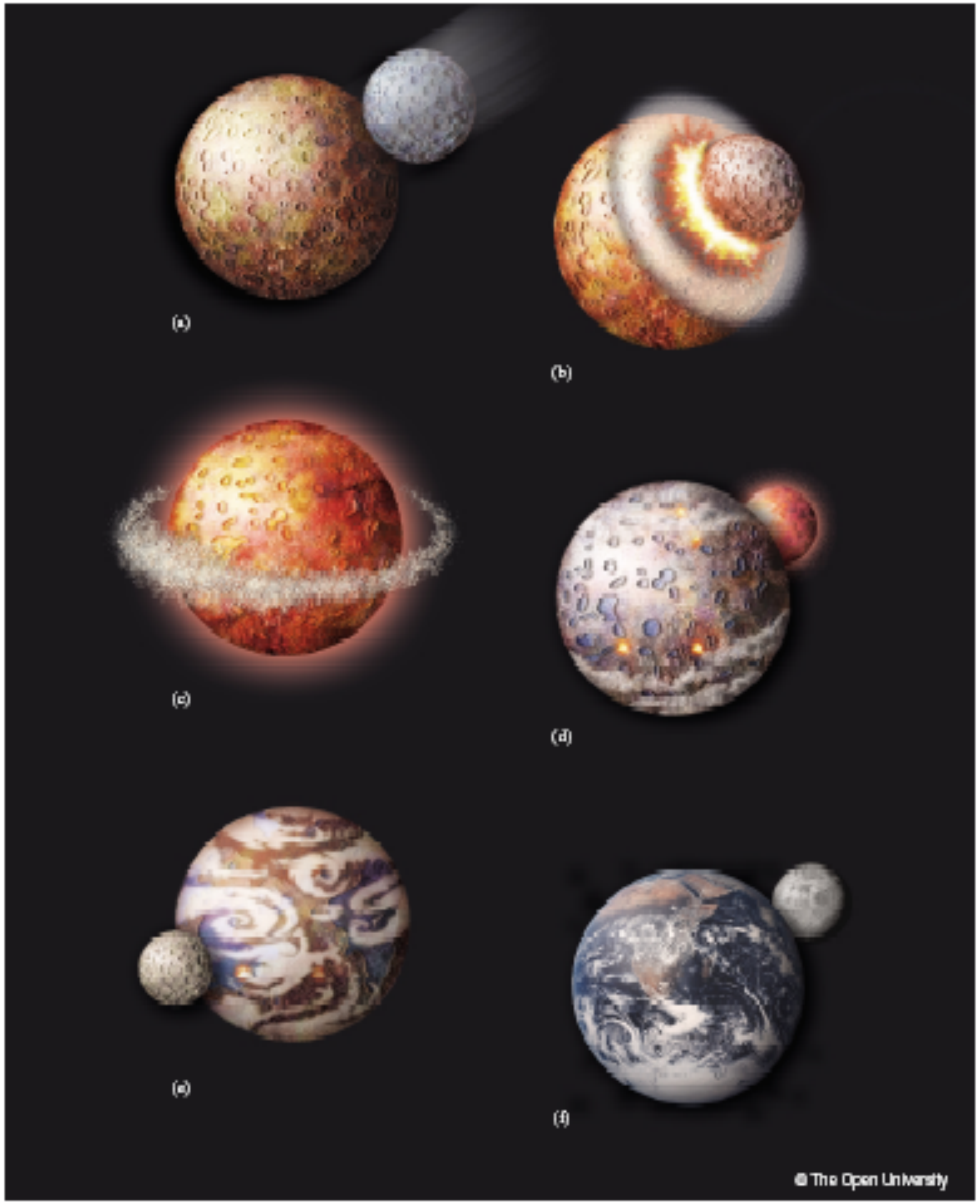
Mean orbital radius: 384×10^3 km (from Earth)

Mean surface temp: 250 K

The Moon is covered with impact craters and dark smooth areas known as *maria* (or seas)

The maria have few impact craters and are younger than the rest of the surface. They are thought to be lava flows, perhaps caused by large impacts or volcanos.

The Moon's rotation period is *synchronised* with its orbit: it shows us one face.



Earth's moon

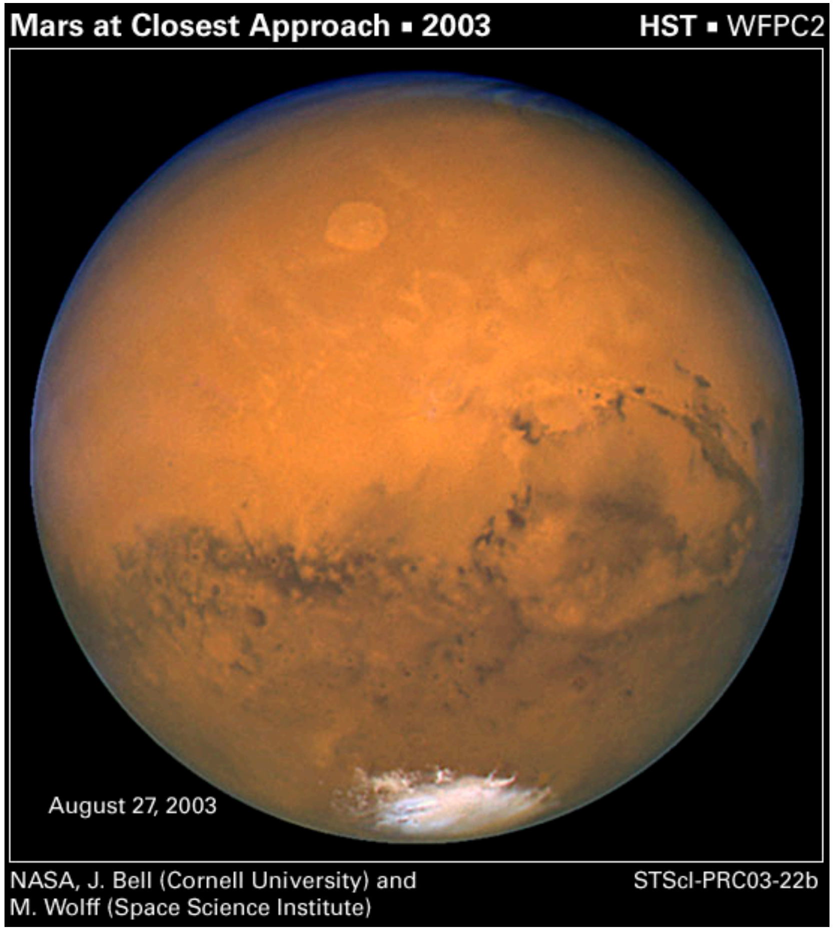
The chemical composition of the Moon is very similar to the Earth, so they must have formed from similar material.

But the Moon has a very small dense core and has a much lower density than the Earth. Plus, the Moon is depleted in volatile elements (such as K & Na) and enhanced in heavier ones (such as Sr & U).

So how did the Moon form?

The best theory so far is that a Mars-sized object impacted the Earth and formed a debris ring, from which the Moon condensed.

Mars



Mass: 6.42×10^{23} kg (0.107 M_E)

Radius: 3396 km (0.53 R_E)

Density: 3930 kg m^{-3}

Mean orbital radius: 1.52 AU

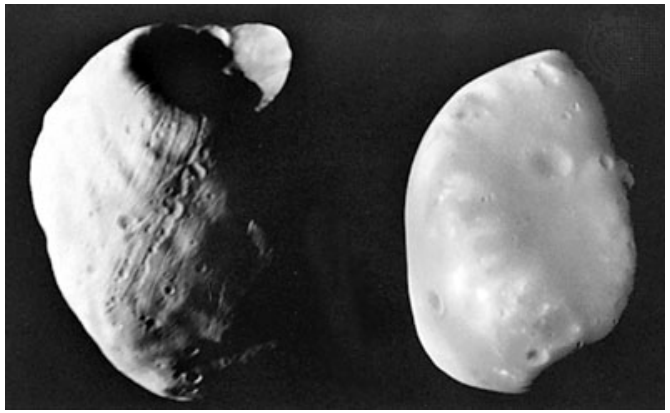
Mean surface temp: 223 K

Mars has a thin atmosphere of mainly CO_2, two polar icecaps (mixed H_2O & CO_2), but no oceans

However, there is evidence that Mars had liquid water on its surface in the past

Mars' surface is desert-like, littered with rocks and fine soil comprised of iron oxides (rust) and silicates

Planetwide dust storms are common

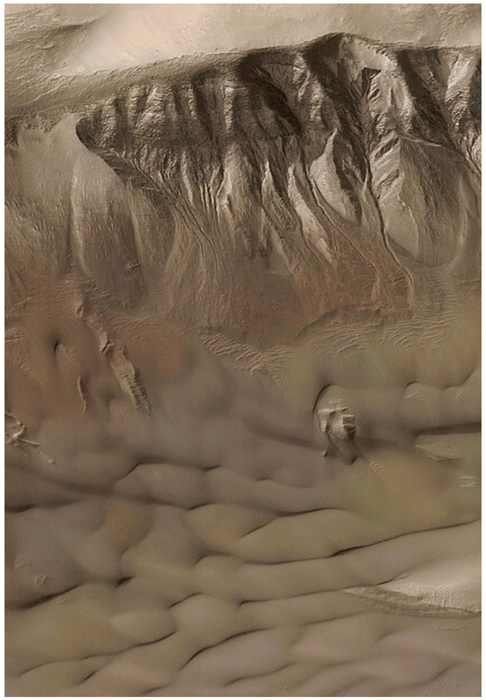


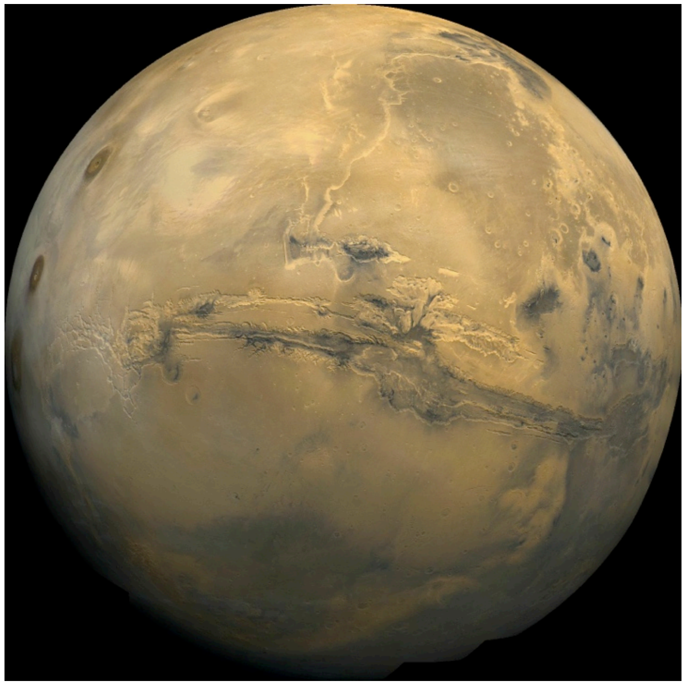
Mars' two moons Phobos & Deimos

Mars

Surface view of Mars from the Pathfinder mission, showing rocks and fine soil

Mars Global Surveyor reveals gullies & sand dunes





Mars has the largest canyon in the solar system – Valles Marineris

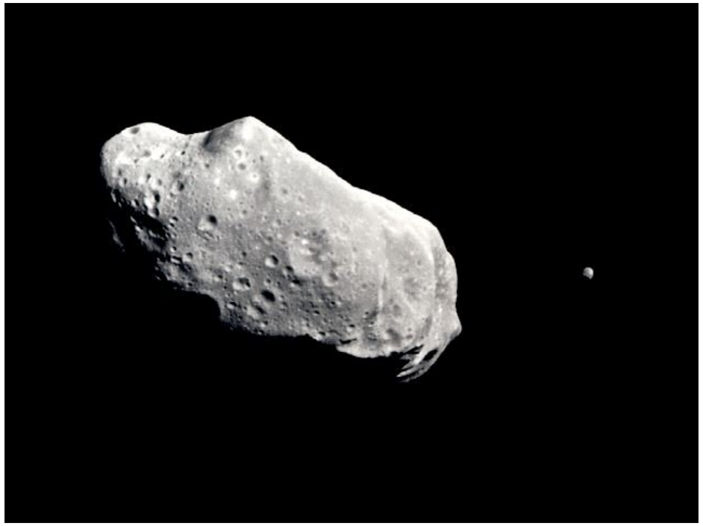
Asteroids

Mass: varies

Radius: from ~500 km to a few m or cm

Density: 1000-3000 kg m^{-3}

Mean orbital radius: 2-4 AU (but can vary)



Asteroids Gaspra & Ida – note that asteroids have craters too & that Ida has its own “moon” (Dactyl)

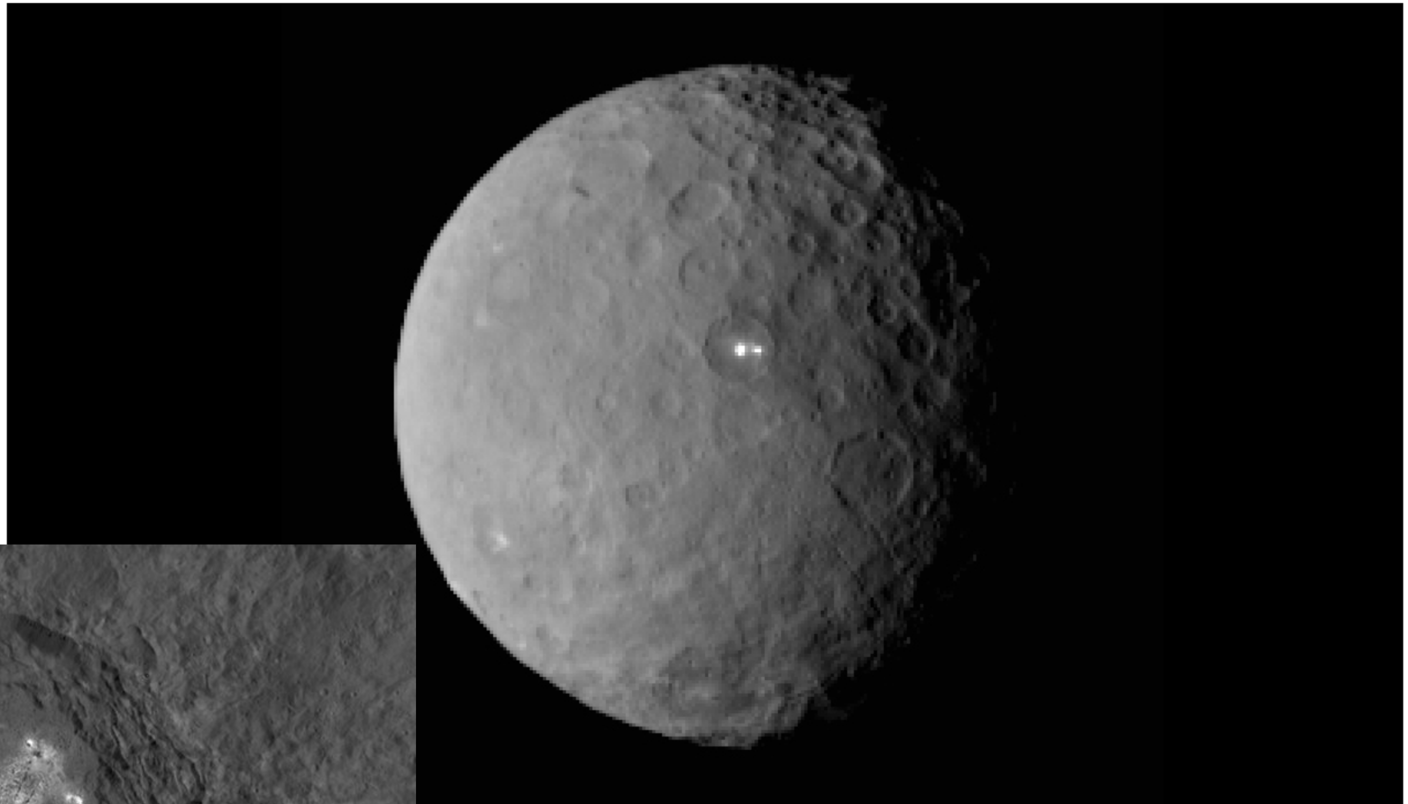
Asteroids are small rocky or metallic “boulders” in orbit around the Sun

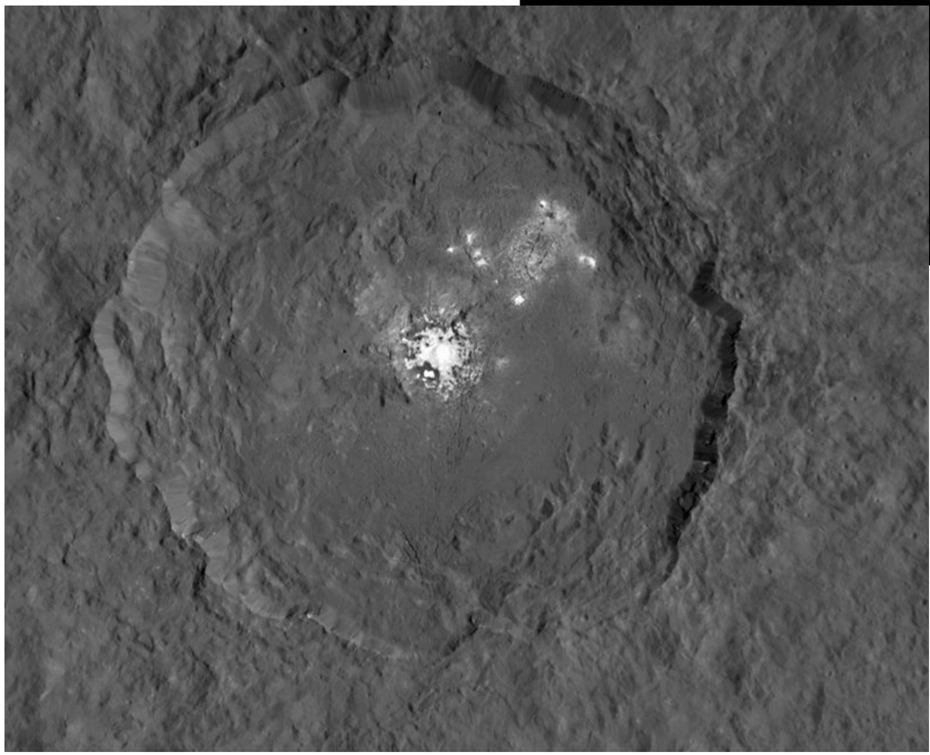
They are thought to be leftovers from the formation of the Solar System, which never accreted enough material to form a planet (due to Jupiter’s tidal forces)

They range in size from ~500 km (Ceres - a dwarf planet now…) to a few m or cm

Their densities suggest that they may be mainly made of rock but that they might not be solid objects (rubble piles)

Ceres





The biggest “asteroid” (dwarf planet)

Found to be surrounded by water vapour (2014)

Odd bright spots seen by Dawn spacecraft (2015) – ice volcanoes or salt deposits?

Comets

Nucleus of comet Halley from Giotto

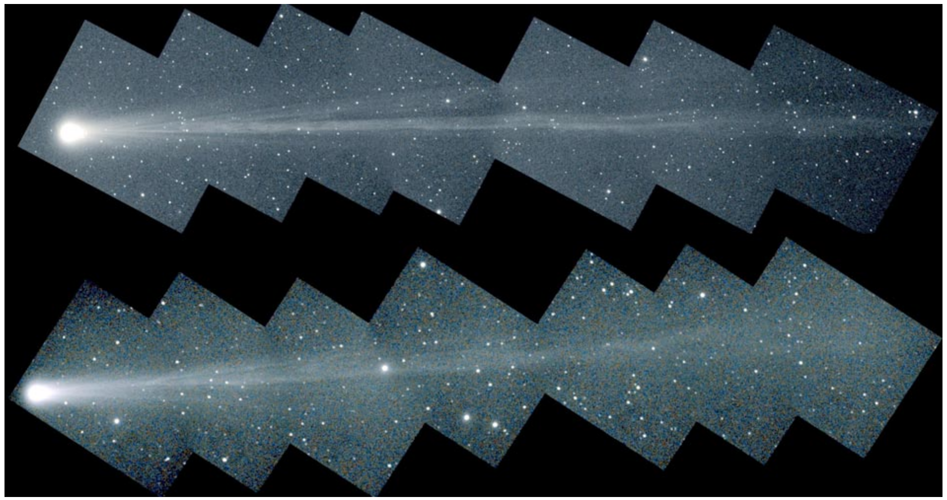
At the centre of the glowing coma lies the nucleus of the comet – a dirty icy body with a dark layer of dust or chemicals

Comets have low densities and so may be piles of rubble rather than solid bodies.

Comets are icy bodies on usually very eccentric orbits through the solar system.

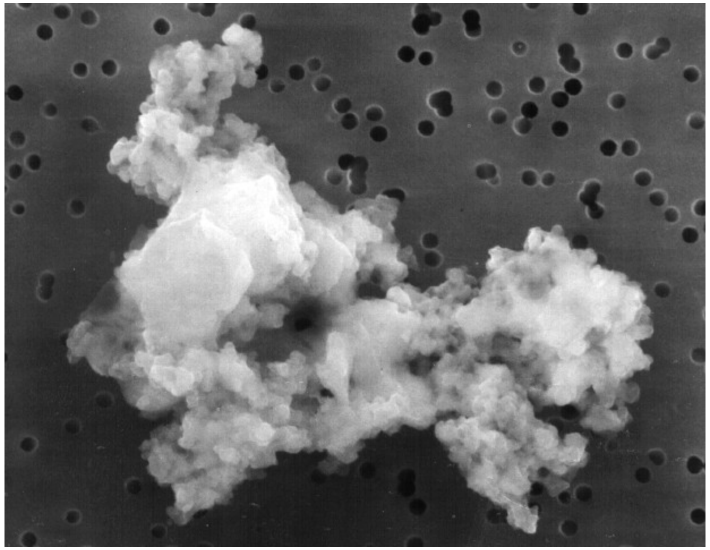
When comets approach the Sun, the increased solar radiation evaporates ice and/or other volatile chemicals to form a glowing "tail" stretching behind the comet

Two tails are often present: a dust tail (follows orbital path of the comet) and an ion tail (swept directly outwards from the sun by the solar wind).



Comet NEAT (C/2002 V1)

Interplanetary dust



Interplanetary dust captured by high-altitude experiment

The zodiacal light

Interplanetary dust has two main sources: the tails of comets and asteroid collisions. The dust is typically ~10μm in diameter.

The dust has a limited lifetime, radiation pressure from the Sun causes the dust to eventually spiral inwards (the Poynting-Robertson effect) and be destroyed.

We can see the dust in one of two ways: by its glow in the infrared (*zodiacal light*) or when it hits the Earth's atmosphere and burns up as a meteor.

Meteor showers are caused when the Earth passes through the dust tail left behind by a comet.

Jupiter

Mass: 1.90×10^{27} kg (318 M_E)

Radius: 69 910 km (10.97 R_E)

Density: 1330 kg m^{-3}

Mean orbital radius: 5.2 AU

Mean surface temp: 120 K (at cloud tops)

Jupiter & its moon Ganymede imaged by the HST

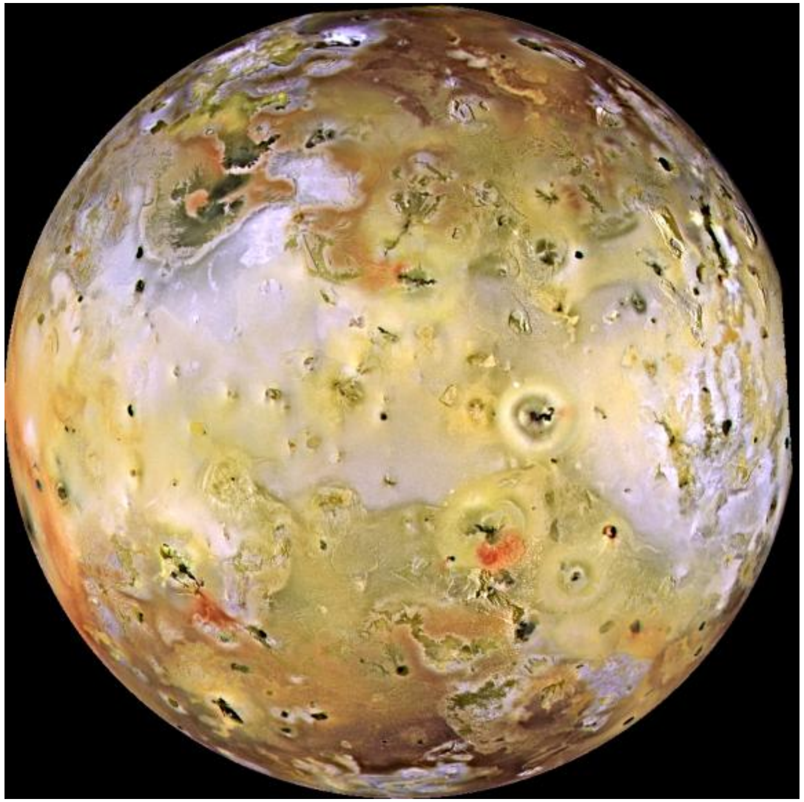
Jupiter has no discernible "surface" – the greater part of Jupiter is fluid hydrogen – all we can see are its clouds

Jupiter is the largest planet in the solar system with the largest family of moons (at least 67).

It is comprised mostly of hydrogen and helium in a thick atmosphere around a possible rocky or metallic core.

Jupiter's fast rotation period (9.9 hours) drives a complex weather system and flattens the planet at the poles.

Jupiter's moons: Io



False colour image of Io from the Galileo spacecraft

Jupiter has over 60 moons, but the four largest moons are the most well known and are known as the Galilean moons.

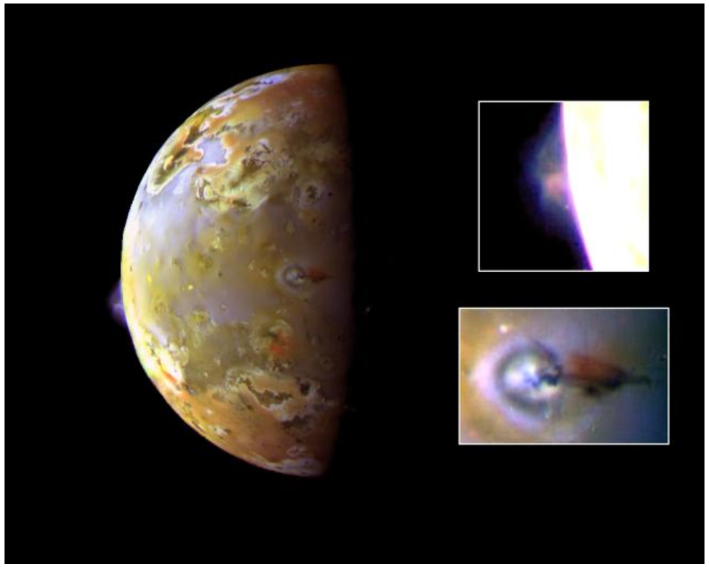
Io is the closest moon to Jupiter, orbiting at a distance of only 422,000 km from Jupiter.

Io is the most volcanic body in the Solar system. The tidal forces from Jupiter act to knead and heat Io, keeping its interior liquid.

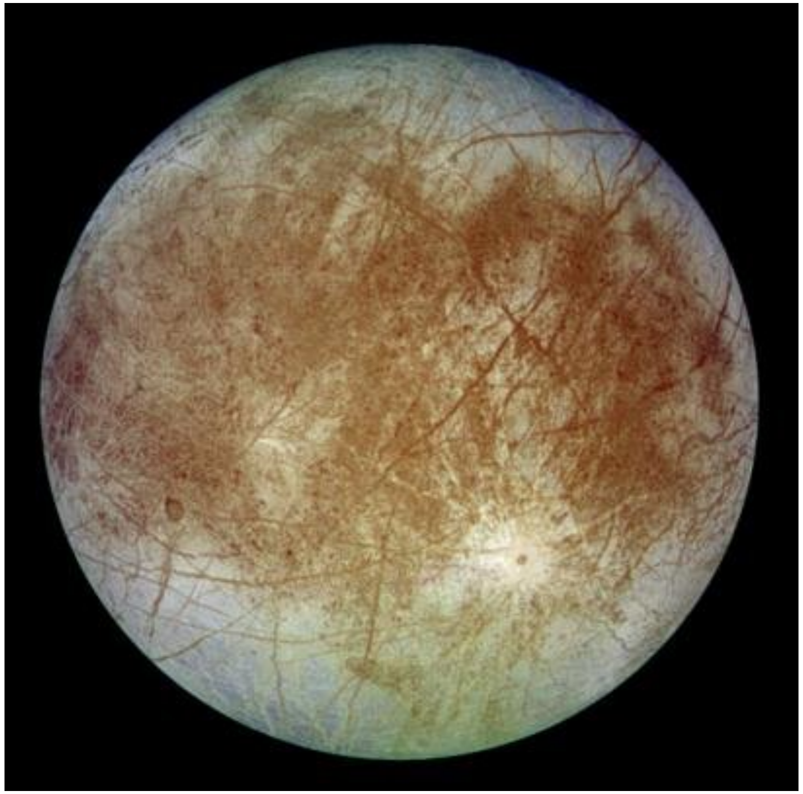
Because of Io's low gravity, the volcanic plumes can reach heights of ~ 300 km

Over 500 volcanoes have been identified on Io, though not all active

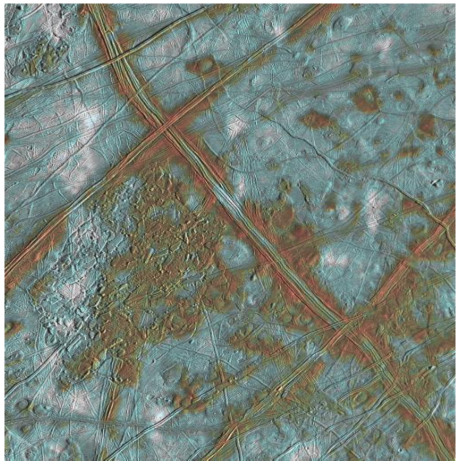
About 5% of Io's surface is covered in volcanoes.



Jupiter's moons: Europa



True colour image of Europa from the Galileo spacecraft



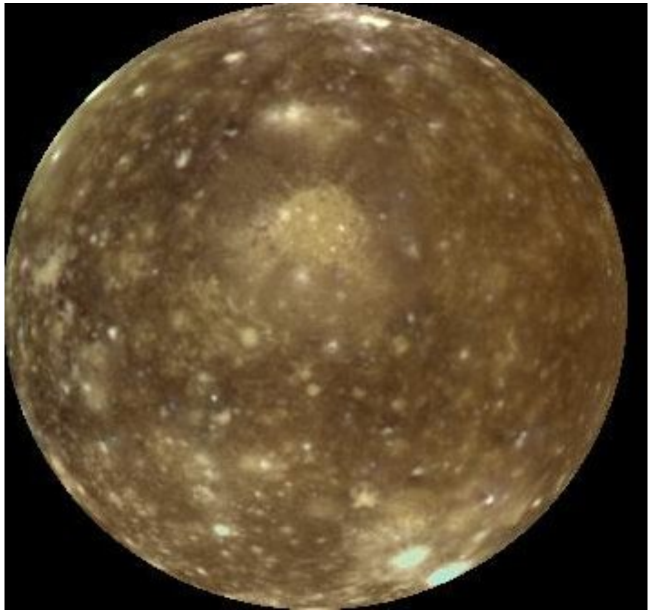
Ice "rafts" on the surface of Europa

Europa is the next moon out from Jupiter, orbiting at a distance of 671,000 km and with a mean radius of 1565 km.

Europa has a surface covered in "fracture" lines, with relatively few craters. As Europa has a low density (2990 kg m^{-3}), it is probably comprised of rock & ice – the fracture lines are pressure fractures in an icy crust.

The low number of craters can be explained by "cryovolcanism" – tidal heating from Jupiter can form ice-lava (or liquid water) which then re-freezes and fills in craters.

This tidal heating could also mean that Europa has a liquid ocean underneath its ice crust – could this liquid ocean support life?



Images of Ganymede & Callisto from the Galileo spacecraft

Jupiter's moons: Ganymede & Callisto

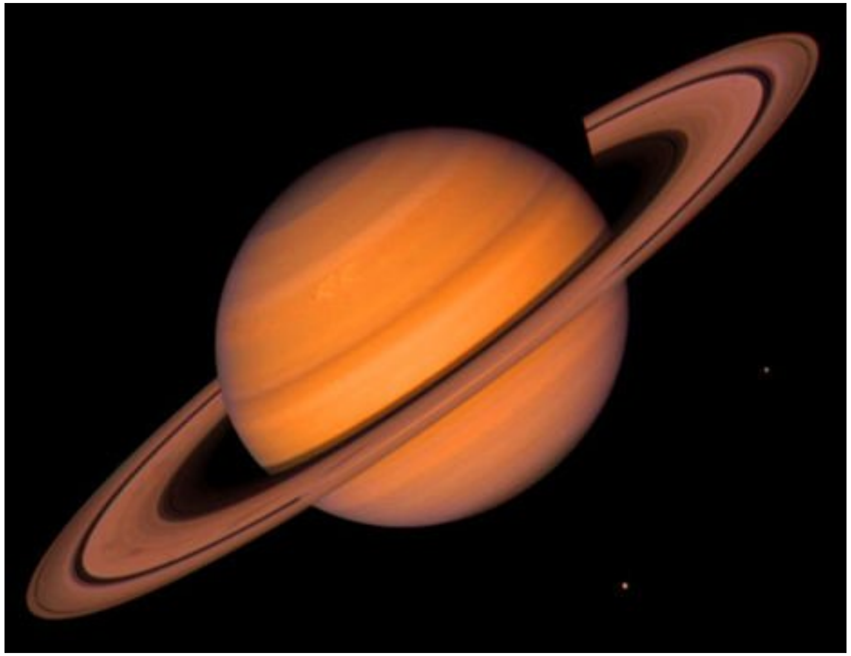
Ganymede & Callisto are similar moons to Europa, but with lower densities $\Rightarrow$ predominantly more ice .

Ganymede is the largest satellite in the solar system – its radius is larger than Mercury!

Ganymede & Callisto are more heavily cratered than Europa, which means their surfaces are older & cryovolcanism is not so widespread.

The dark areas on Ganymede could be "ice maria", as they have fewer craters than the lighter areas.

Saturn



Saturn & moons from Cassini

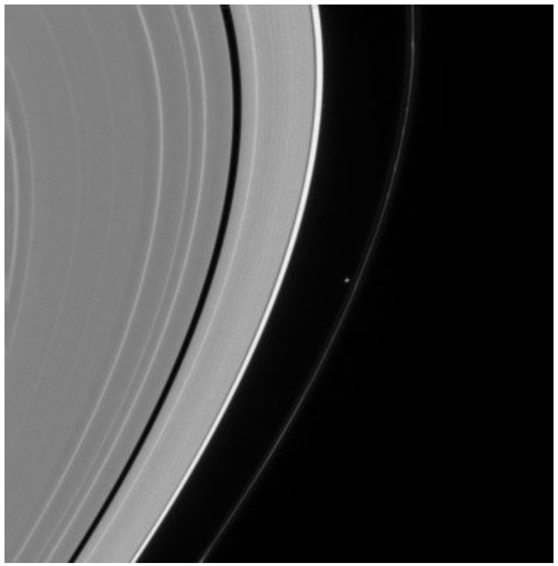
Mass: 5.69×10^{26} kg (95.2 M_E)

Radius: 58 230 km (9.13 R_E)

Density: 690 kg m^{-3}

Mean orbital radius: 9.54 AU

Mean surface temp: 89 K (at cloud tops)



Shepherd moon Prometheus

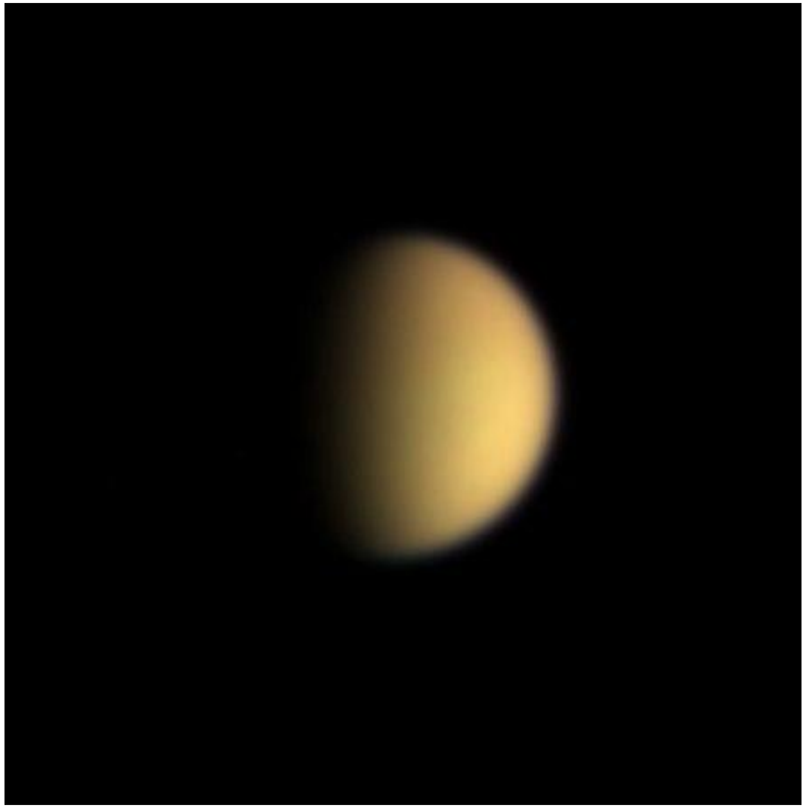
Saturn is the 2nd largest planet in the solar system, but is less dense than water!

It is comprised of mainly hydrogen and helium, perhaps with a central rocky core

Saturn has a spectacular ring system. The rings are made of particles of ice, ranging from 1 cm to a few m in diameter.

The gaps in the rings are kept clear by "shepherd moons"

Saturn's moons: Titan



True colour image of Titan taken from Cassini

Mass: 1.3×10^{23} kg (0.02 M_E)

Radius: 2575 km (0.4 R_E)

Density: 1880 kg m^{-3}

Titan is Saturn's largest moon, with a diameter almost half that of the Earth.

It is shrouded in a thick mainly nitrogen atmosphere, with minor methane and hydrocarbon components – thought to be close to the primordial Earth atmosphere

The temperature and pressure on Titan are close to the triple points of ethane and methane $\Rightarrow$ ethane/methane seas, rain & icebergs?

Titan was visited by the Huygens lander in January 2005

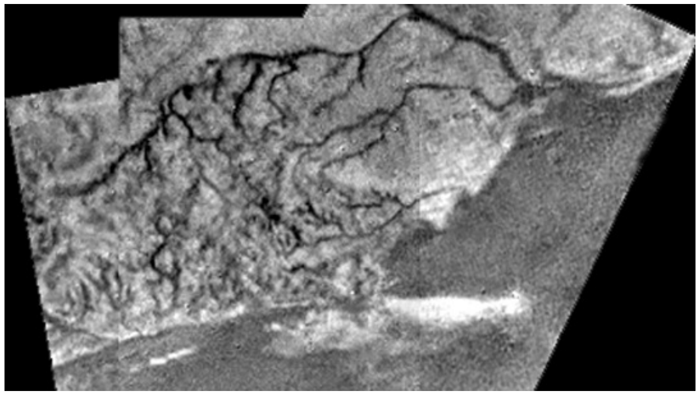
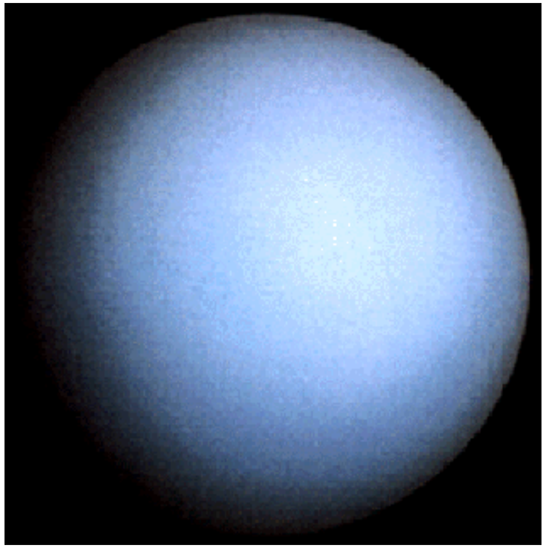
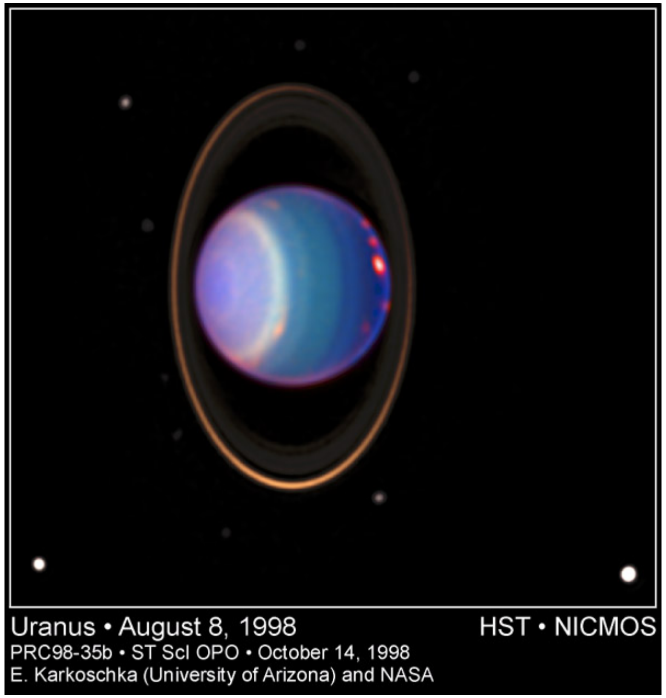


Image of Titan's surface from Huygens



Uranus from Voyager 2



Uranus from HST

Uranus

Mass: 8.68×10^{25} kg (14.4 M_E)

Radius: 25 360 km (4.0 R_E)

Density: 1.32 kg m^{-3}

Mean orbital radius: 19.19 AU

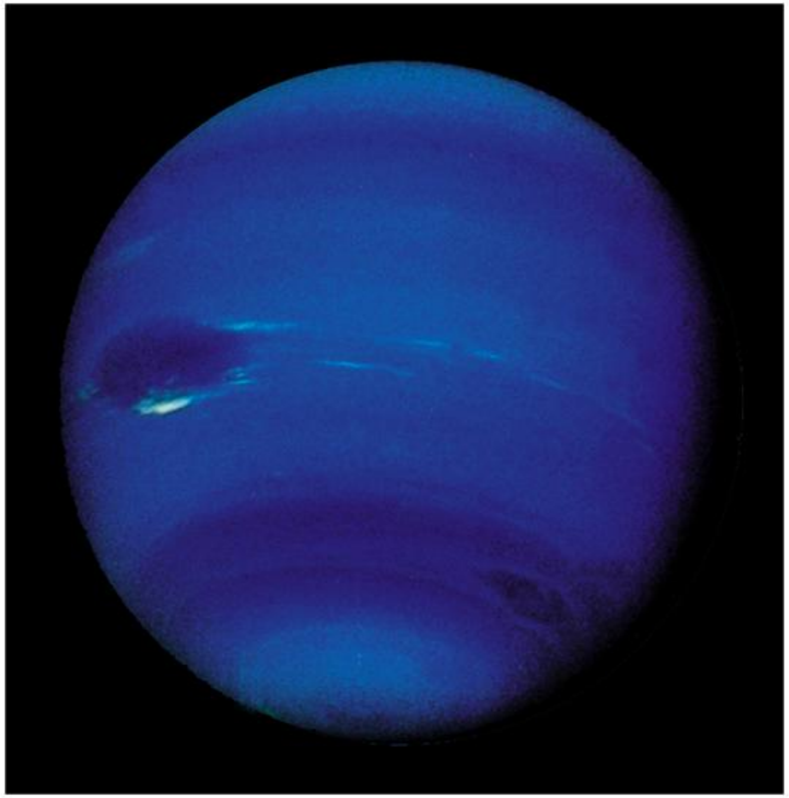
Mean surface temp: 53 K (at cloud tops)

Uranus was the first planet to be discovered in modern history (by Sir William Herschel in 1781)

The spin axis of Uranus is inclined at 98° to the ecliptic plane – most likely due to a huge impact event early in Uranus' history that knocked the planet "over on its side".

Uranus has a family of at least 20 moons and a narrow ring system.

Neptune



Neptune from Voyager 2

Mass: 1.02×10^{26} kg (17.1 M_E)

Radius: 24 620 km (3.9 R_E)

Density: 1.64 kg m^{-3}

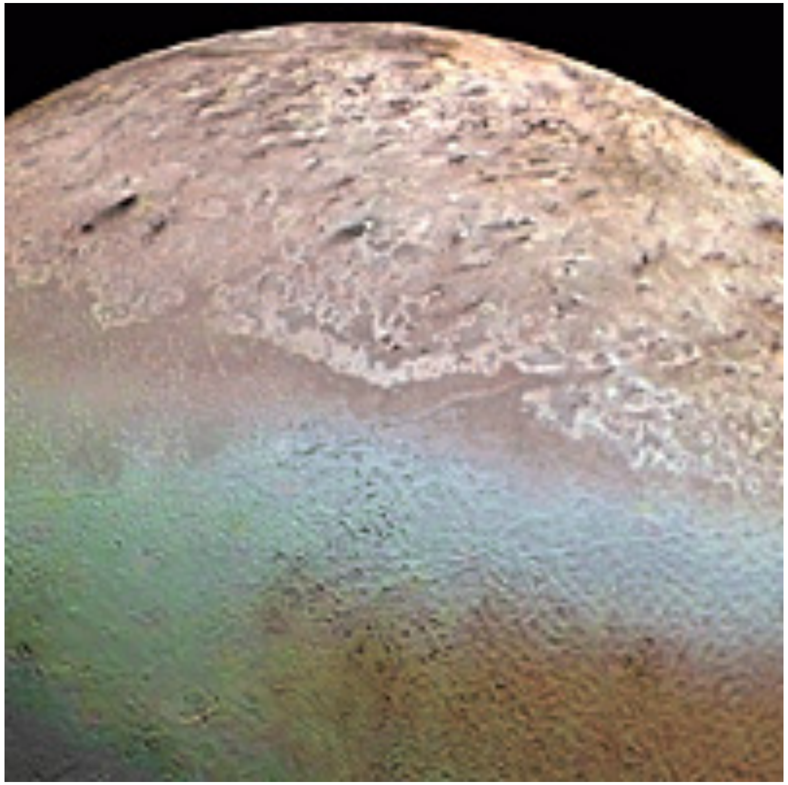
Mean orbital radius: 30.07 AU

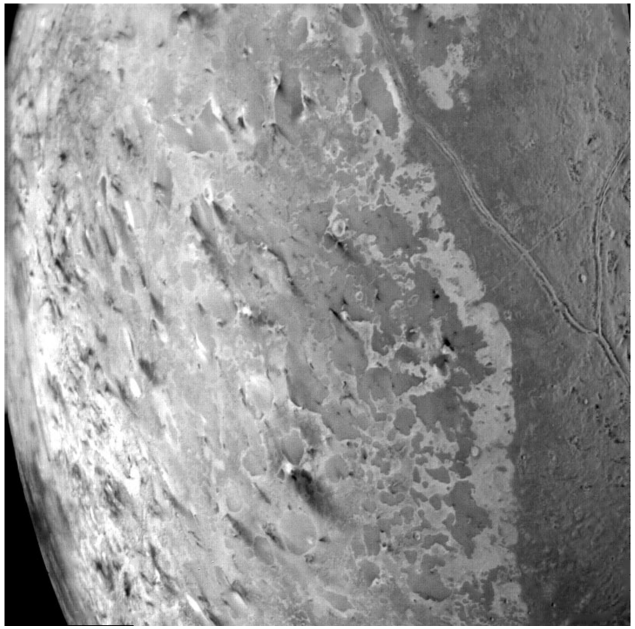
Mean surface temp: 54 K (at cloud tops)

Neptune was discovered in 1846 by Johann Galle and Heinrich D'Arrest. Its existence had been suspected for some time due to perturbations in the orbit of Uranus.

Neptune has at least 8 satellites, although only 3 are of any size.

The higher density of Neptune (& Uranus) compared to Jupiter & Saturn suggests a higher ratio of heavy elements





Neptune's moons: Triton

Triton is Neptune's largest moon (radius 1353 km).

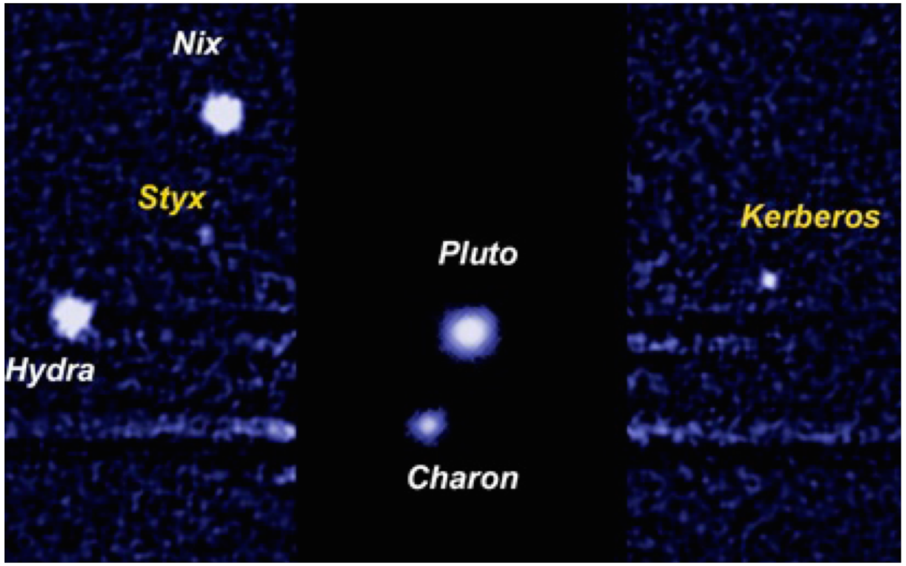
It is unusual in that it orbits around its planet in the opposite direction to all other moons in the solar system.

This could mean that Triton was captured by an encounter with Neptune rather than forming in orbit. Its relatively smooth surface could support this.

The dark streaks on Triton also show evidence for cryovolcanoes – about 50 volcanoes are known on Triton, making it perhaps the 2nd most volcanically active body in the Solar System.

Two views of Triton from Voyager 2

Pluto (& its moons)



Mass: 1.3×10^{22} kg (0.002 M_E)

Radius: 1137 km (0.18 R_E)

Density: 2100 kg m^{-3}

Mean orbital radius: 39.48 AU

Mean surface temp: ~ 40 K

Pluto has an extremely elliptical orbit, spending a large fraction of its "year" inside the orbit of Neptune. It is one of the largest bodies in the Kuiper belt.

Pluto has a large moon, Charon, which is ~1/2 the diameter & 1/7 of the mass of Pluto. Four more moons were discovered from 2005.

The New Horizons mission to Pluto flew past in July 2015.

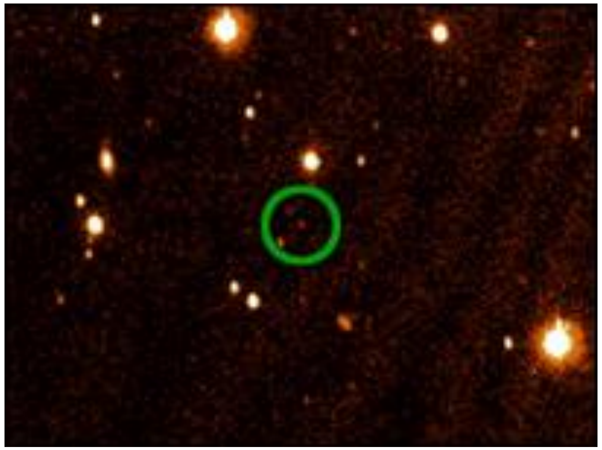
The Kuiper Belt

THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.



Discovery image of Sedna

Where do comets originate?

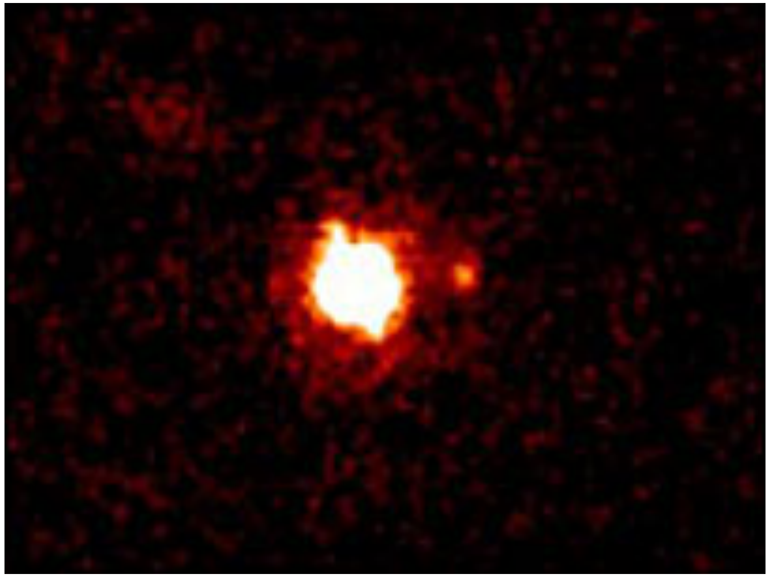
Comets are thought to originate from the Kuiper Belt (a belt of large icy bodies at roughly the same distance as Pluto) or the Oort Cloud (a cloud of icy bodies surrounding the solar system).

(animation on the left courtesy of the Minor Planet Center)

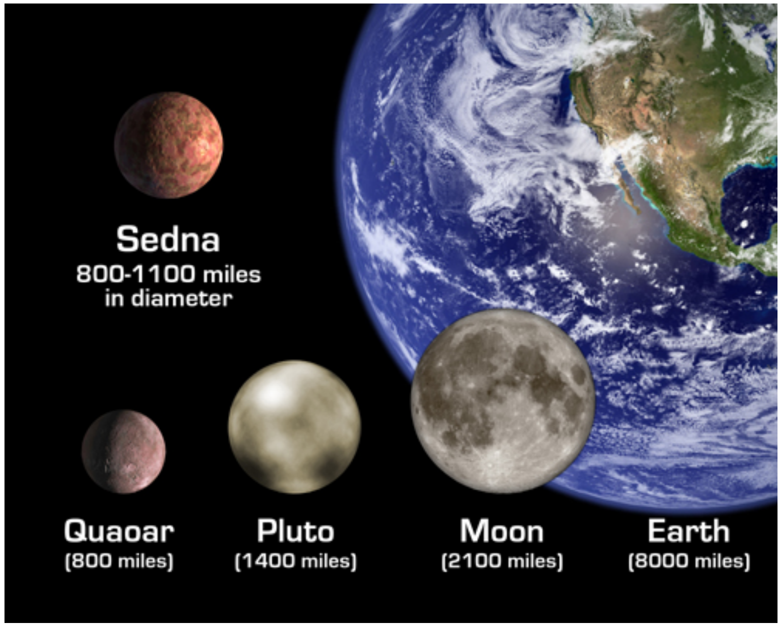
Gravitational perturbations (from nearby stars) or collisions between Kuiper Belt Objects (KBOs) alter their orbits, propelling them into the inner solar system where they become comets.

One recently discovered example of a KBO/Oort cloud object is Sedna, a 600 km radius object at a distance of 90 AU.

The KBO/planet controversy



Eris has a moon, Disnomia



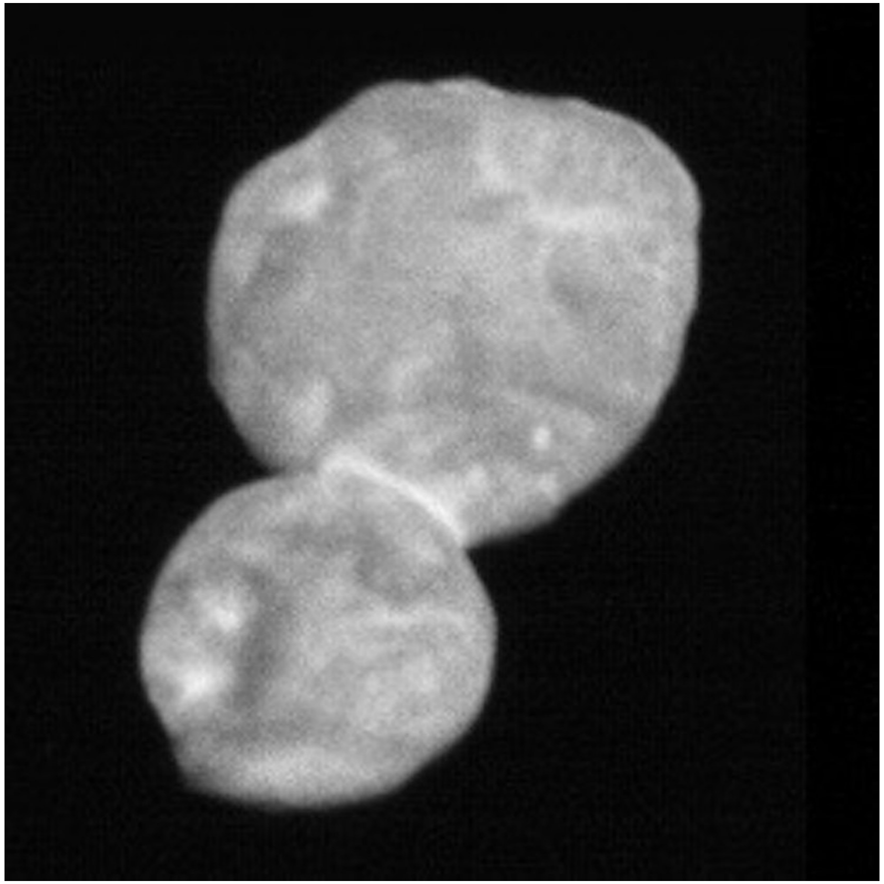
How big does an asteroid have to be before it is a planet?

Pluto & Charon are not much larger than many of the known KBOs - it's likely that Pluto, Charon & Neptune's moon Triton are just large KBOs rather than true moons or planets.

A KBO larger than Pluto was recently discovered (2003 UB313 or Eris), swiftly followed by two more ~ 3/4 the diameter of Pluto (2003 EL61 "Santa" & 2005 FY9 "Easterbunny").

The decision on the status of Eris was made by the IAU in 2006 - it is a *dwarf* planet (as are Pluto & Ceres).

Ultima Thule



Most recent update – New Horizons flew past Ultima Thule, a KBO, in December 2018.

The appearance is of two cratered bodies that collided gently and stuck together.

Gentle collisions are more likely for KBOs because they more relatively slowly in their orbits.