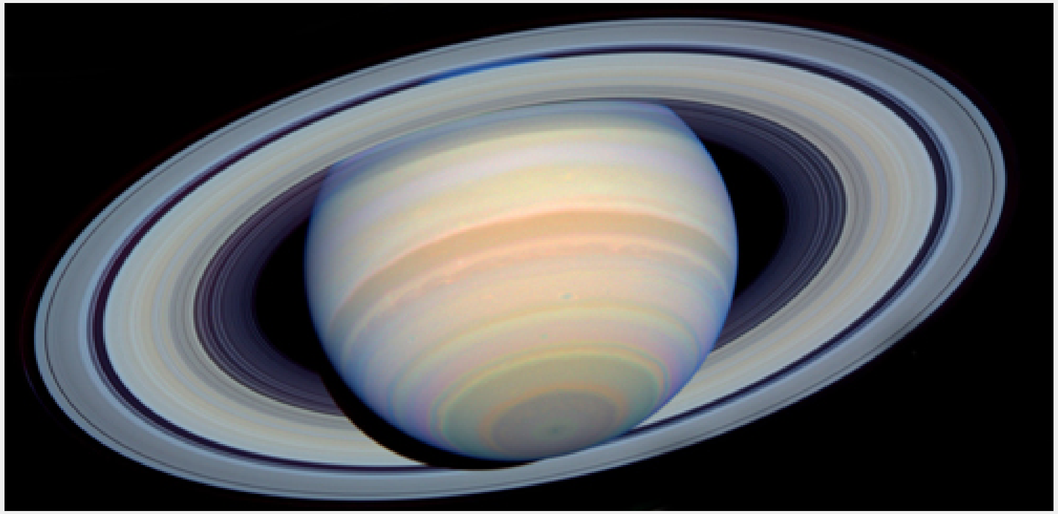
The Solar System: Terrestrials versus Jovians and Planetary Evolution



Saturn

Credit: NASA/HST

Summary

In this Activity we will be discussing:

- comparisons of the terrestrial planets Mercury, Venus, Earth and Mars and the Jovian planets;
- planetary evolution - in particular cratering and impacts, volcanism, and weathering.

Composition of the Solar System

Let's now discuss the major components of our Solar System: the Sun, eight planets, dozens of satellites and ring systems. The planets can be divided into two groups: the inner rocky **terrestrials** and the outer gaseous **Jovians**.

We will discuss their properties noting similarities and differences between the two groups, and then later in this Activity relate these to how the planets formed and evolved.

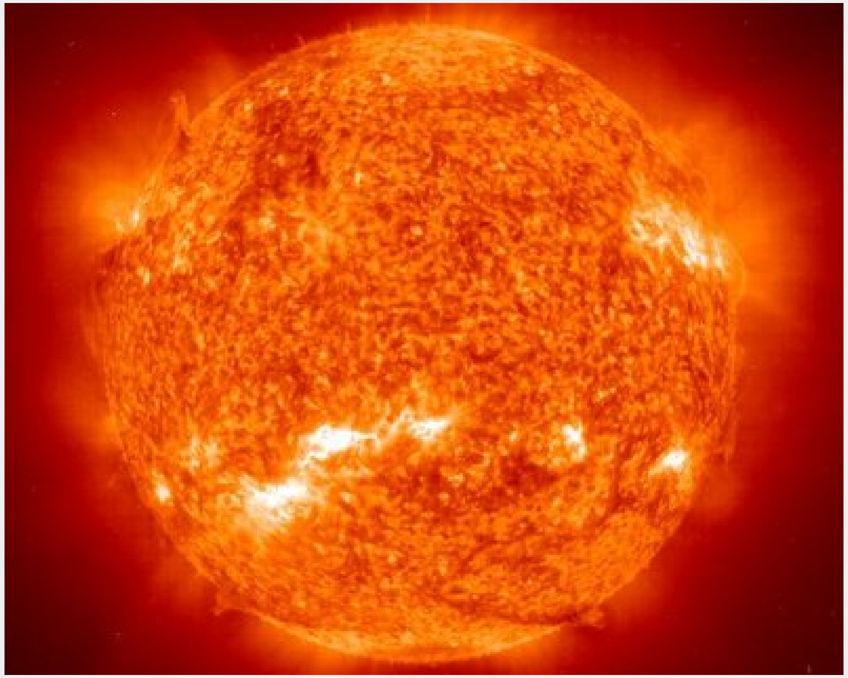
The eight planets

Credit: Courtesy NASA/JPL-Caltech.

The Sun

At the centre of the Solar System lies our majestic Sun, a star. The Sun contains about 99.8% of the total mass of the Solar System and its gravity governs the motion of almost all the other members.

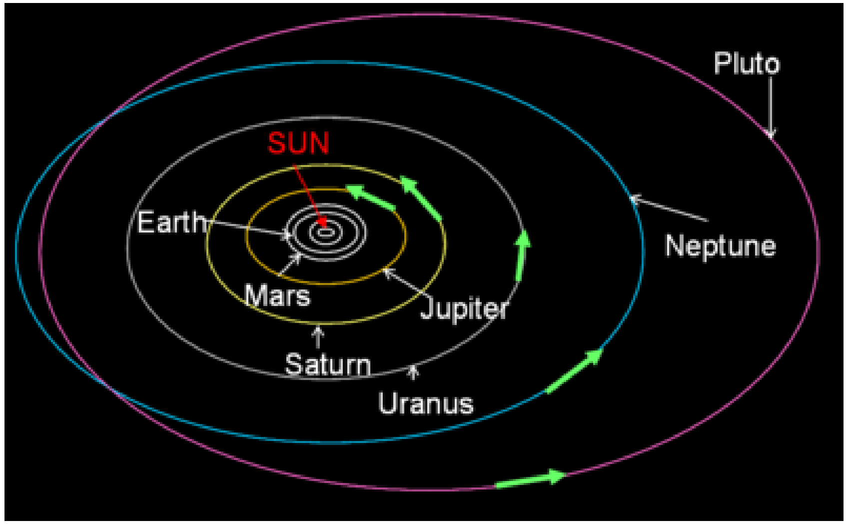
While it is extremely important to the planets within the Solar System, in the grander scheme the Sun is very much an ordinary, average star.



Credit: EIT - SOHO Consortium, ESA, NASA

The planets

All planets and the dwarf planet Pluto orbit around the Sun in the same direction (anti-clockwise viewed from above the Earth's north pole). All the planets lie in approximately the same plane. Pluto, however has an orbit inclined 17° to the ecliptic.



Terrestrials and Jovians

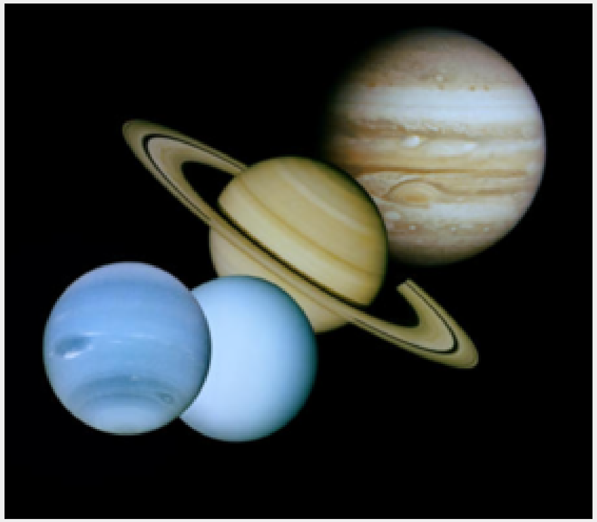
The planets make up only 0.18% of the total Solar System mass and Jupiter makes up 70% of that! In terms of mass, the planets are a very small part of the Solar System. The two planetary groups are:

- the inner rocky **terrestrials**: Mercury, Venus, Earth, Mars; and
- the outer gas giants, the **jovians**: Jupiter, Saturn, Uranus, Neptune.

We shall describe each in turn.

Terrestrials

Credit: NASA - JPL

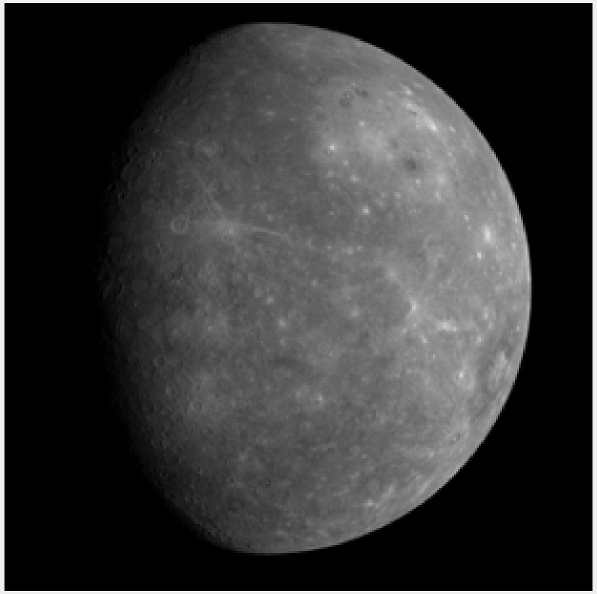


Jovians

Credit: NASA - JPL

Mercury

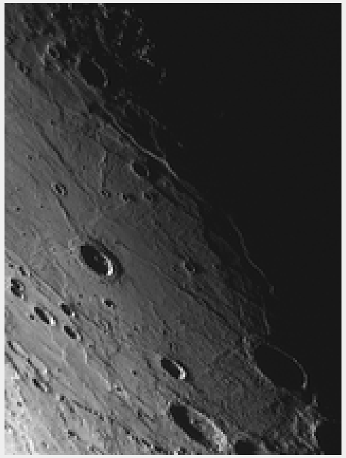
Mercury - the inner most planet to the Sun - follows a rather eccentric orbit (e = 0.2). It can be seen just after the Sun sets, or just before the Sun rises, and shows phases, like Venus and our Moon.



Mercury
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

Due to its eccentric orbit Mercury's distance from the Sun varies between 46 - 70 million km. Mercury's proximity to the Sun also leads to temperature extremes, as we will see.

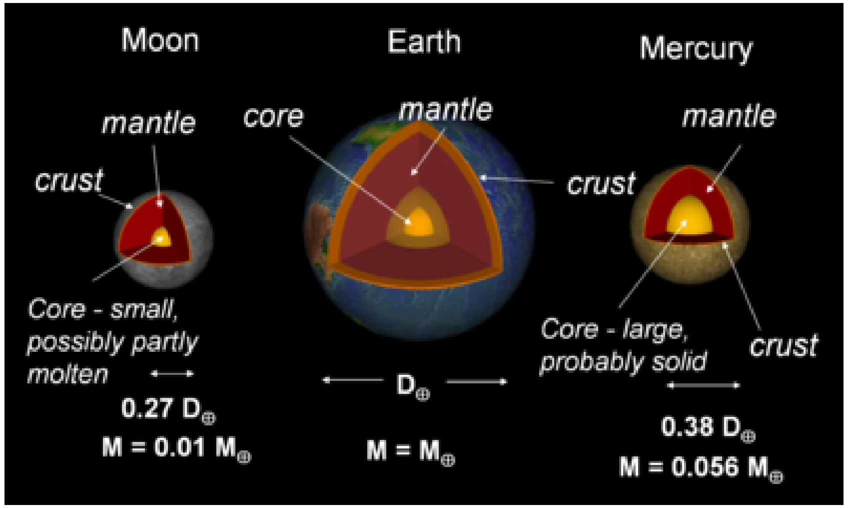
The combination of a small orbit and a high velocity makes its orbital period (its 'year') very short indeed (88 Earth days). A Mercury day (from Mercury noon until the next noon) takes 176 days - twice as long as its year! It is due to the competition between the planets rotation and its orbital motion. These have opposite effects - the rotation makes the Sun appear to move east to west - the orbital motion makes the Sun appear to move west to east - generally the rotation wins out.



Large Impact Basin on Mercury
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

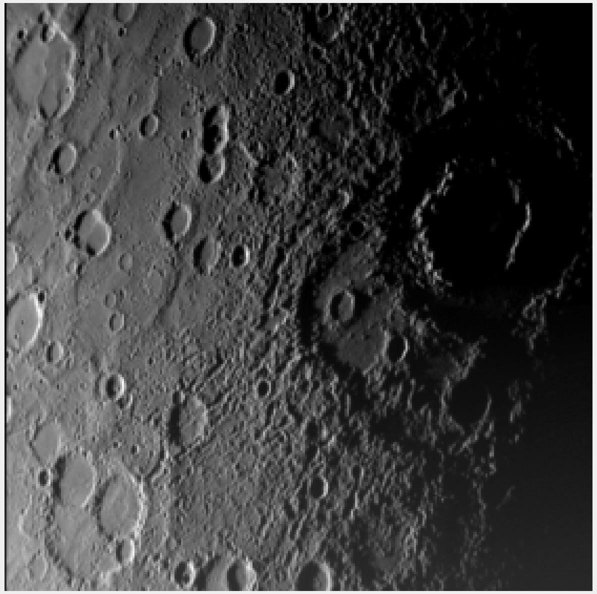
Mercury is about 40% bigger than our Moon so let's use the similar sized Moon as a comparison.

The acceleration due to gravity on the surface of Mercury however is about two times greater than that on the Moon. This is largely because Mercury is 60% denser than the Moon. Due to such a high density we conclude Mercury has a metal core much larger than our Moons core.



Like the Moon, Mercury has little atmosphere. With its proximity to the Sun and lack of an insulating atmosphere, Mercury's surface swings between extremes of temperature. In the long Mercury night, temperatures plummet to below -180 °C, which is cold enough for carbon dioxide to freeze!

In the long days temperatures reach about 430 °C, hot enough to melt lead. However the next planet we discuss has an even higher surface temperature than this!

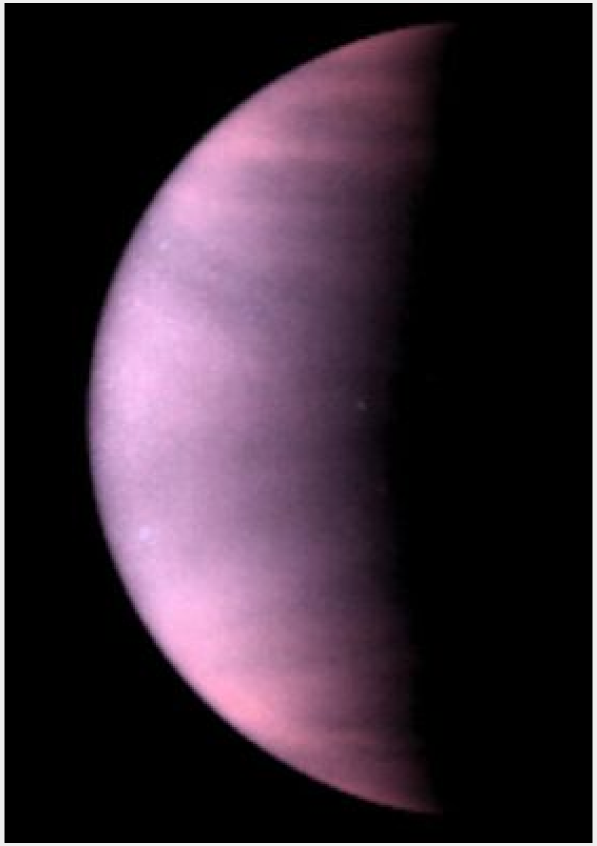


Mercury from an altitude of 18,000 km.

Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

Venus

Continuing with our theme of comparative planetology, let's look at the bulk properties of our nearest planetary neighbour, Venus, and compare them to Earth.



Venus cloud tops in Ultraviolet light

Credit: NSSDC/NASA - HST

A year on Venus takes about 7.5 Earth months. Years may be relatively short, but days are very long (117 Earth days!) and Venus rotates very slowly in the *opposite* direction to Earth and the other planets (except Uranus).

A large inclination (177°) of rotation axis to the orbital plane results from Venus' retrograde orbit. This can be thought of as a -3° tilt, which means Venus does not experience seasons.

Radar image of Venus

Credit: NASA/JPL/Magellan Team

Remote observing of Venus is difficult, due to its thick cover of highly reflective clouds.

Its high albedo (0.85 at a wavelength of 550 nm) due to the heavy cloud cover - compared to Earths 0.39 - makes Venus the brightest object in the sky after the Sun and the Moon.

The atmosphere consists almost entirely (96.5%) of carbon dioxide, CO_2. The surface temperature is a very hot 472 °C
.

Ultraviolet image of Venus clouds.

Credit: NSSDC Photo Gallery (NASA)

On Venus, the atmosphere dominates everything, including the evolution of the planetary surface.

Venus is permanently hidden by clouds at an altitude of 50 - 65 km which contain sulphuric acid and sulphur crystals though none of this corosive mixture makes it to the surface.

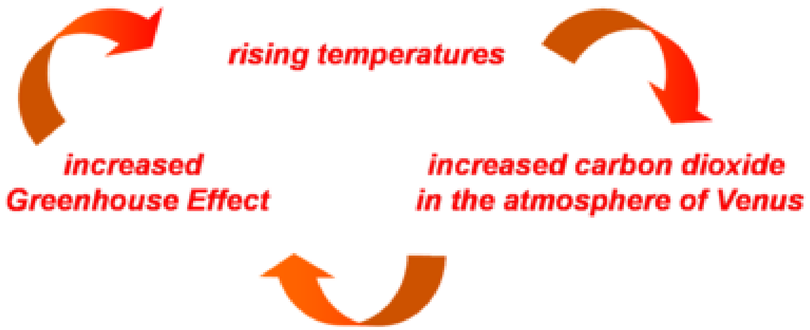
This false colour image, taken by the planetary mission Galileo in February, 1990, highlights structure in the swirling sulphuric acid clouds. The bright area is sunlight glinting off the upper cloud deck.

Credit: Courtesy NASA/JPL-Caltech

Runaway greenhouse effect

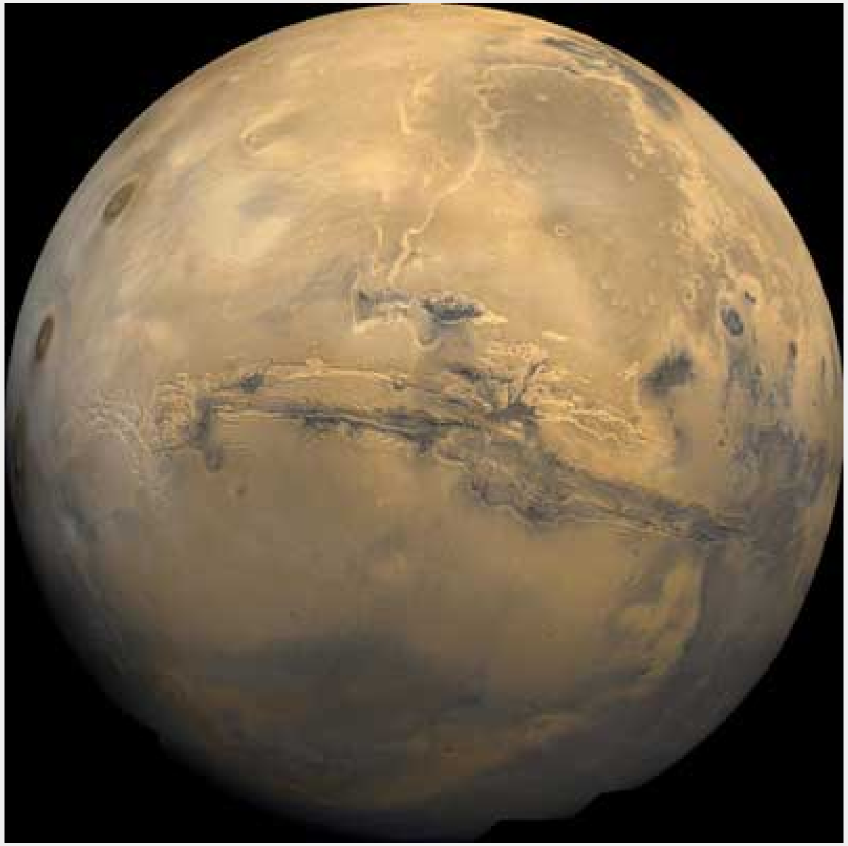
Why is the surface temperature (about 470 °C) so hot? Due to its extreme carbon dioxide atmosphere, Venus has undergone a *runaway greenhouse effect*. We were introduced to the greenhouse effect in the Activity *Earth and Moon* when we discussed the Earth's atmosphere.

Earth has only 0.035% of its atmosphere as CO_2, whilst Venus has it comprising 96.5% of it's total atmosphere. Venus therefore has a much greater ability to absorb infrared radiation and much less water to store CO_2 (as happens in the Earth's oceans). These effects conspire to form a vicious circle - increased $CO_2 \rightarrow$ increased greenhouse $\rightarrow$ increased temperatures $\rightarrow$ increased CO_2... and so on.



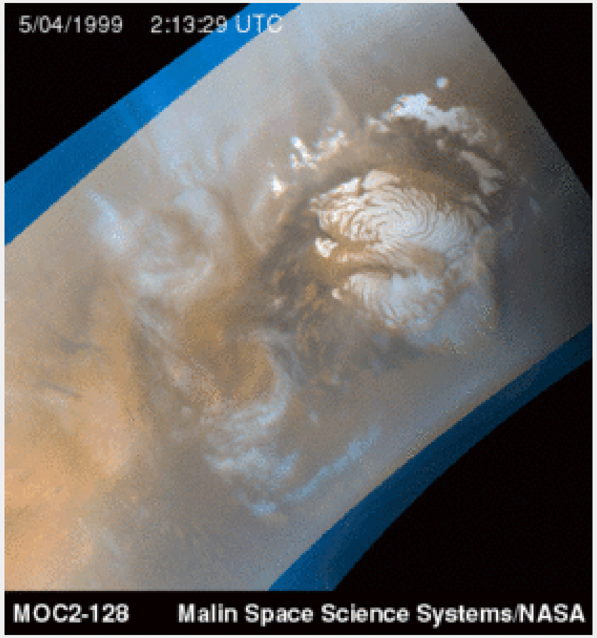
Mars

Now we'll look at the bulk properties of our other planetary neighbour, Mars, and compare them to those of Earth and Venus.



Credit: Courtesy NASA/JPL-Caltech

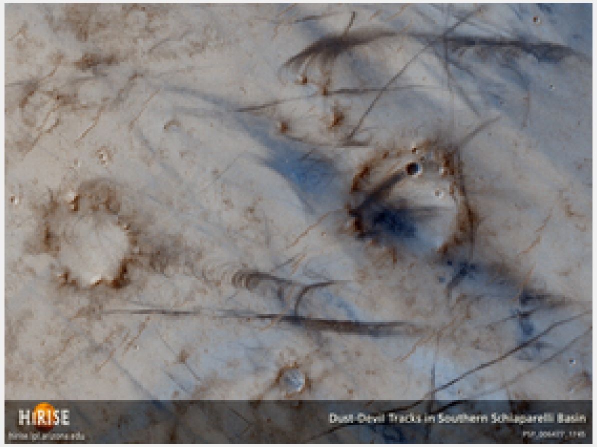
Mars is half as far again from the Sun as is Earth, which means that it receives less than half as much sunlight. A year on Mars takes almost twice as long (1.88 Earth years) as a year on Earth. Almost identical axis tilts give the Earth (23.5°) and Mars (25.2°) similar seasonal patterns.



Clouds in North Polar Region.

Credit: NASA/JPL/Malin Space Science Systems

Like Venus, Mars has an atmosphere composed mostly (95%) of carbon dioxide. Unlike Venus, the atmosphere that Mars has managed to retain is very thin. This challenges astronomers to decode why surface features probably caused by small twisters or 'dust-devils' are seen. Dust-devils do seem to exist though - see below.



Dust-devil tracks

Credit: NASA/JPL/University of Arizona

Dust-devil in motion

Credit: NASA/JPL-Caltech

Average temperatures on Mars are cooler than on Earth, as you would expect for a planet 50% further from the Sun. With almost no appreciable atmosphere to insulate it, the temperature range (-140°C to +20°C) is large - up to 100° between night and day at the equator.

Mars has been visited by numerous planetary missions since the 1960s. One of the latest (and continuing missions) is the Mars Exploration Rovers.

Sagan memorial station on Mars, 1997.

Credit: NASA/JPL-Caltech

Launched in 2003, the Mars Exploration Rovers - Spirit and Opportunity - successfully landed on opposite sides of Mars in January 2004.

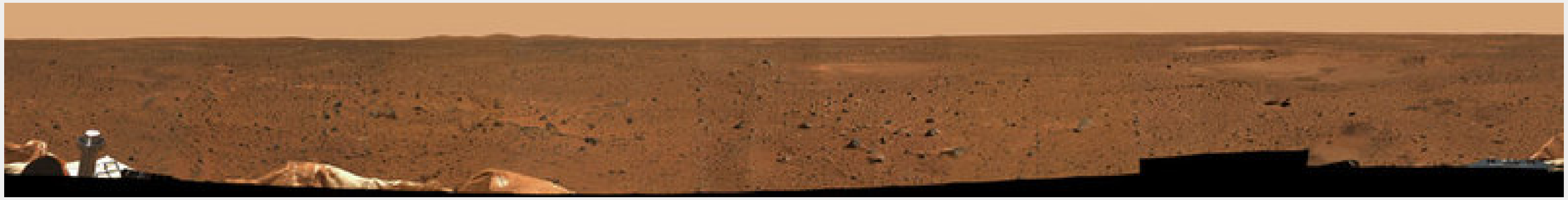
The rovers were designed to explore the surface of Mars for 90 days, and they are still going strong after more than 1400 days! (Although Spirit is now stationary.)

The rovers' mission focuses on determining whether there was liquid water on Mars in the past.

Artists impression of a Mars rover.

Credit: Courtesy NASA/JPL-Caltech

Spirit's landing site was at **Gusev Crater.** Columbia Hills complex can be seen on the horizon.



Gusev crater

Credit: NASA/JPL/Cornell

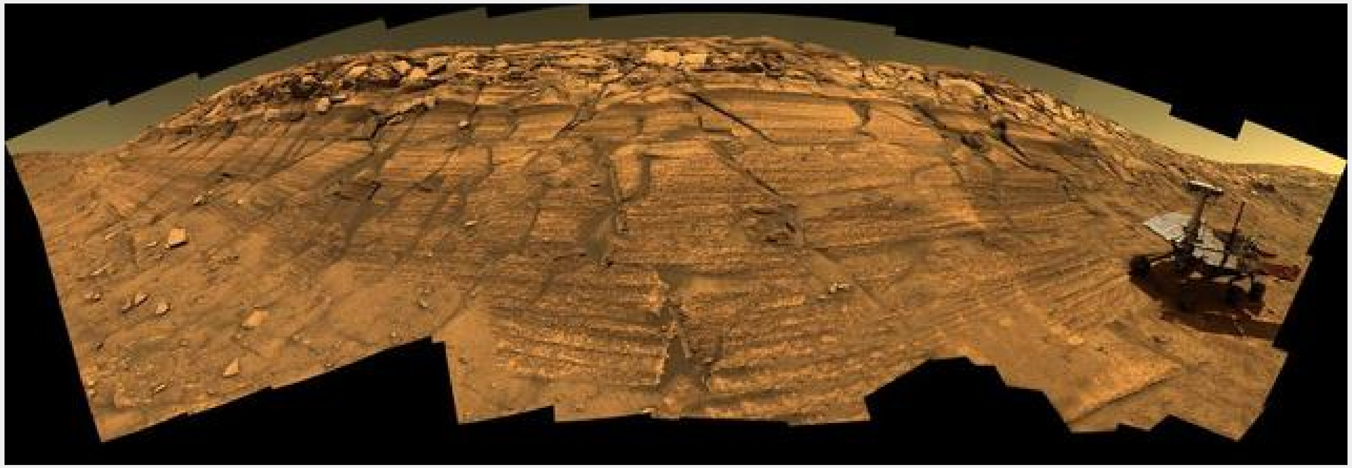
Opportunity's landing site was at **Meridiani Planum.**

Meridiani Planum

Credit: NASA/JPL/Cornell

While there is no evidence of liquid water on the surface of Mars today, the rovers have been looking for signs of water in the Martian past, such as geological components or features that form only in the presence of water.

The two rover landing sites were specifically chosen as potential sites of past water on Mars. Gusev Crater, a giant impact crater, may have been a lake at some point, and Meridiani contains a lot of the mineral hematite which usually requires water for its formation.



Rover Opportunity in Endurance Crater

Credit: NASA/JPL-Caltech/Cornell.

The rover Spirit has found a remarkably high concentration of silica in surface soil. The on board spectrometer suggested the samples contained 90% silica. In most cases water is required to make such a large amount of silica.

In April 2009, Spirit got stuck in sand and various maneuvers could not free it. Unfortunately engineers at NASA/JPL decided in Feb. 2010, after many months of trying to free Spirit, to convert it to a stationary science platform.

To find out more about Mars Exploration Rovers Mission, visit http://marsrovers.jpl.nasa.gov.

Excavation by Rover Spirit

Credit: NASA/JPL/Cornell

Jupiter

Let's now investigate Jupiter, the first and largest of the gas giant planets. In terms of the size of Earth it takes 10.5 Earths to cross Jupiter pole to pole and 11.2 Earths across the equator.

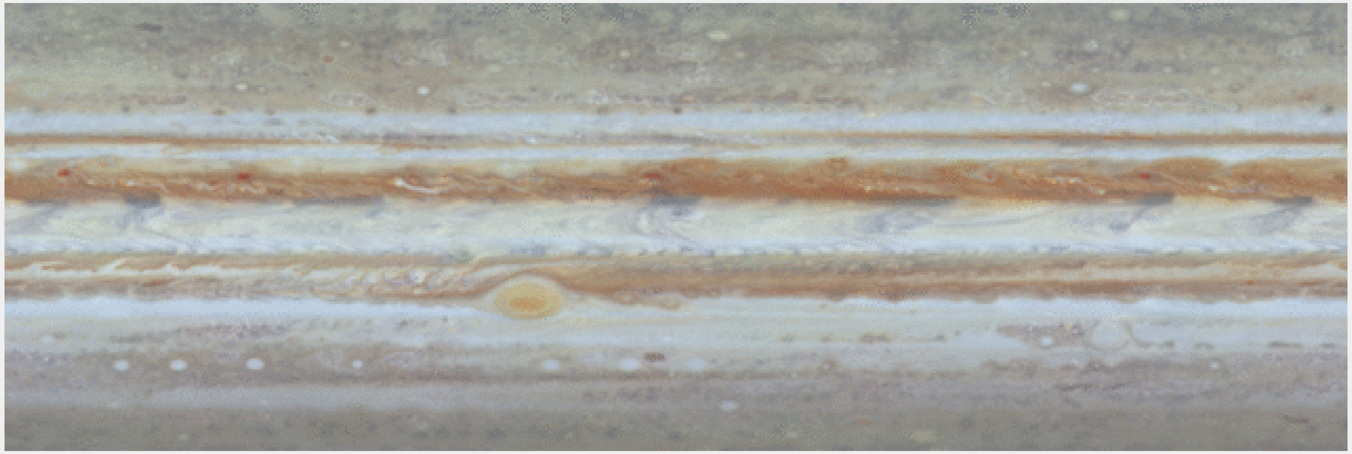
The *volume* of Jupiter would enclose more than 1000 Earths, yet its mass is 'only'(!) 318 Earths - suggesting it has a much lower density than Earth.

Jupiter

Credit: Cassini

A non-rotating planet might be expected to be spherical. Jupiter rotates in just 9 hours 50 minutes at its equator. It is the fastest rotation of any planet. Observations as far back as 1690 showed that the polar regions rotate slightly slower than the equatorial region. This *differential rotation* shows that Jupiter cannot be solid.

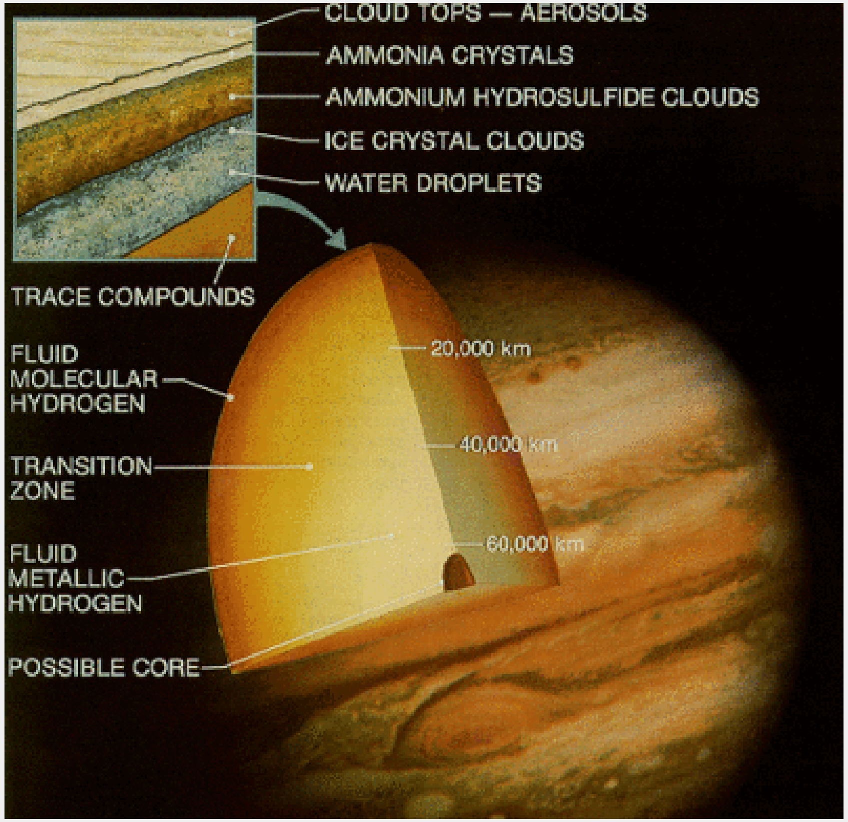
Its large equatorial bulge from the rapid rotation further suggests that Jupiter has a non-solid structure. (Along with the 'low' mass mentioned before.)



Jovian surface over 24 rotations

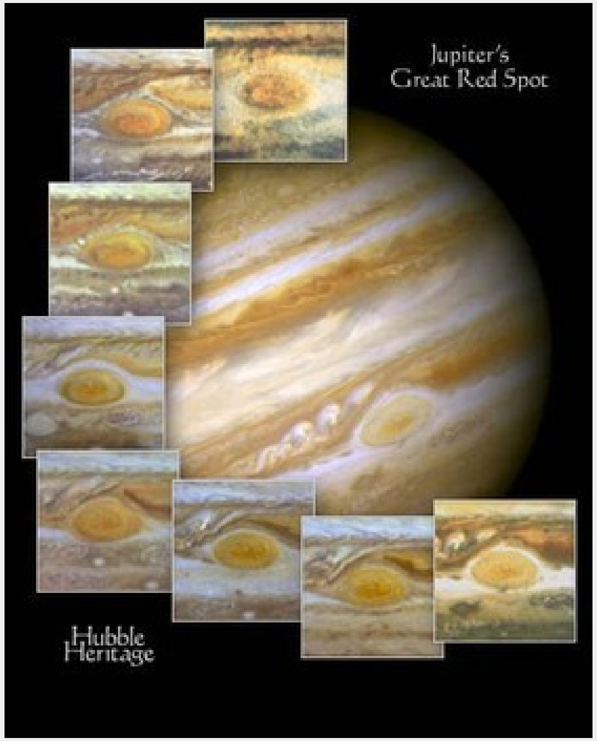
Credit: NASA/JPL/University of Arizona

Jupiter has a core - possibly rocky surrounded by helium and liquid metallic hydrogen, and finally surrounded by helium and molecular hydrogen. Overall, Jupiter appears to contain around 71% hydrogen, 24% helium and about 5% heavier elements by mass.

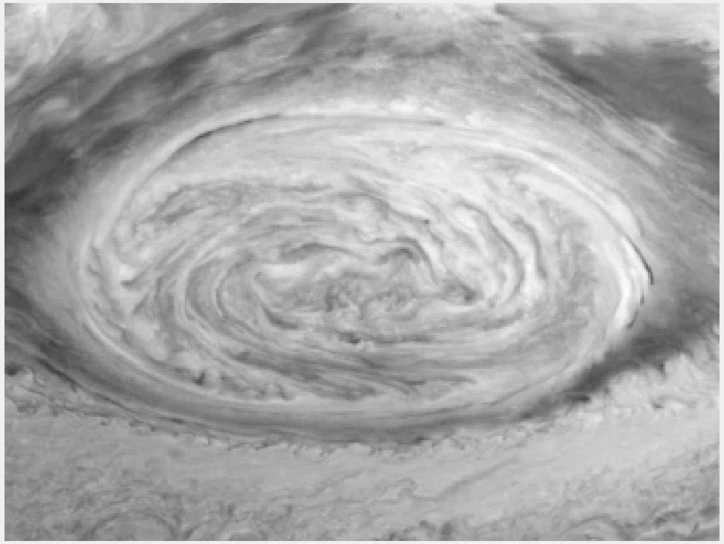


Credit: NASA/UCAR

The most famous example of Jupiter's markings is the Great Red Spot, which has persisted for over 400 years. It is an *anti-cyclonic storm* rotating in about 6 days. Its cooler, higher altitude clouds appear redder than surrounding regions. With wind speeds in excess of 600 km/hr, it is a turbulent region indeed.



Credit: NASA and The Hubble Heritage Team (STScI/AURA)

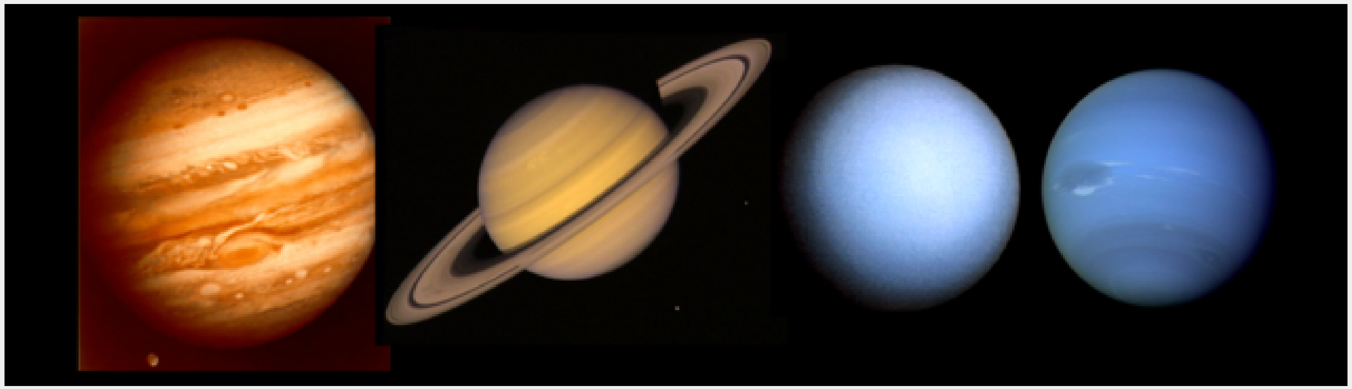


Credit: NASA/JPL/Project Galileo

The other Jovians

Let us now journey further outwards to explore the other Jovian planets. We list orbit durations and average distance from the Sun (relative to the Earth-Sun unit of 1 AU) for each:

Planet	Period	Semi-major Axis
Jupiter	11.8 years	5.2 AU
Saturn	29.5 years	9.5 AU
Uranus	84.1 years	19.2 AU
Neptune	164.8 years	30.1 AU

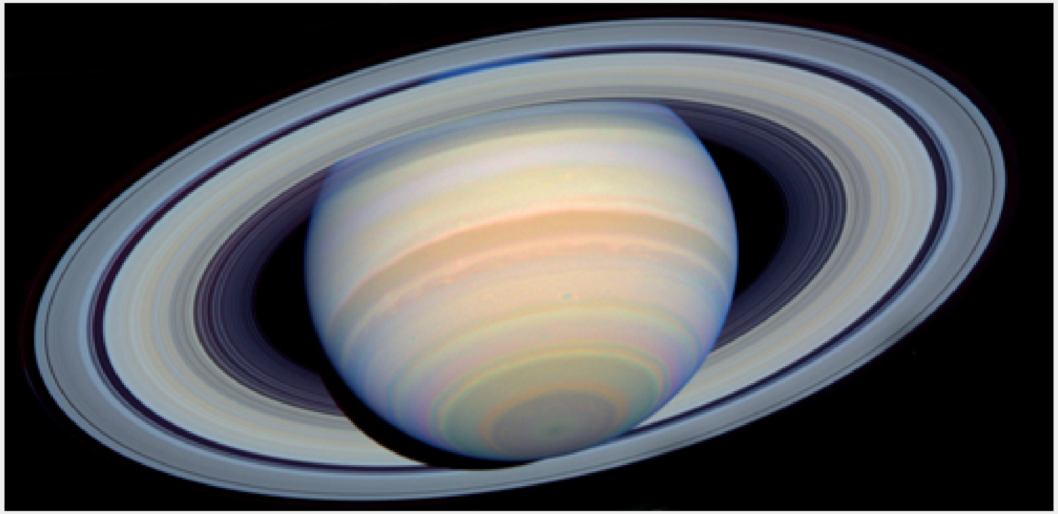


Jupiter, Saturn, Uranus and Neptune.

Credit: National Space Science Data Center Photo Gallery, NASA

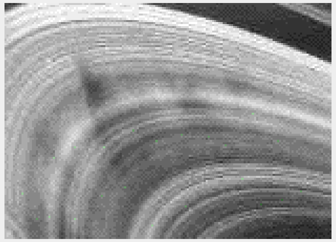
Rings of Saturn

The spectacular rings of Saturn are composed of hundreds of thousands of ringlets, with apparent gaps (e.g. the Cassini division). The rings are probably material from a satellite moon torn apart by tidal forces. The rings are composed of mm-cm sized ice crystals and are only about 10 km thick.



Credit: NASA/HST

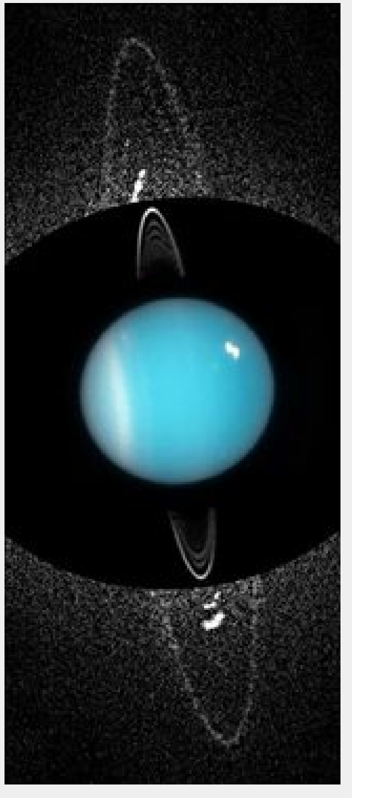
However the rings do not appear to be uniform. Voyager I images of the rings show amazing radial ‘spokes’. First images from the later mission of Cassini did not show spokes, but later images showed spokes emerging in the rings. It is thought that electrostatic repulsion between charged ring particles may play a role in their formation and evolution.



Credit: NASA/JPL/Voyager team

Other ring systems

Ring systems are common in all the Jovians. Jupiters rings were discovered in 1979 by Voyager I. In 1989 Voyager II discovered faint rings around Neptune. In 2005 Hubble Space Telescope found more rings around Uranus after the initial discovery in 1977 and subsequently by Voyager II in 1986. The rings are created by debris from meteoroid impacts on small nearby moons.



Uranus ring system.
Credit: NASA, ESA, and M. Showalter (SETI Institute)

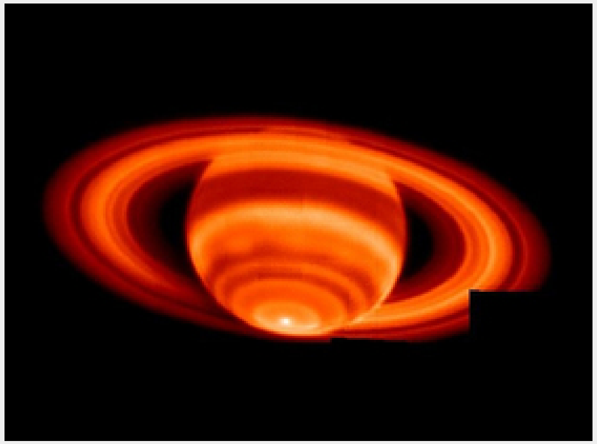
General descriptions

Jupiter:

The most massive planet, comprising 71% of all the planetary matter in our Solar System. With its high rotation rate, internal energy source, and impurities which colour its atmosphere at different depths, it exhibits a spectacularly detailed turbulent atmosphere with belts, storms, eddies and small ovals. It has a gravitational influence on objects such as comets and asteroids if they pass close enough.

Saturn:

With a slightly smaller size and rotation rate than Jupiter; and less than a third of its mass, but a stronger internal source of energy, Saturn exhibits more subtle variations of Jupiter's belts and storms in a similar three layered atmosphere.



Saturn at 17 microns

Credit: NASA/JPL

Jupiter and Saturn in 2001

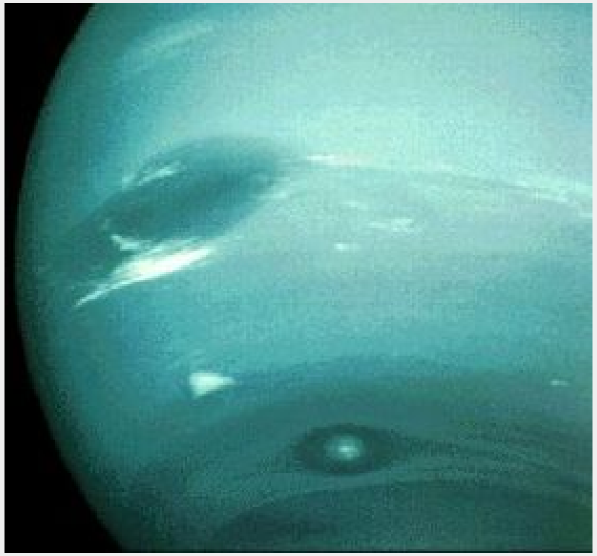
Credit: Steve Thompson (with permission) - SAO graduate

Uranus:

Less than half the diameter of Saturn and twice as distant from the Sun, Uranus is much colder and lacking a strong internal energy source. Though it has high speed winds its atmosphere is generally featureless. Traces of methane give it its blue-green tint. Uranus' unique feature is its 98° tilt to its orbit plane. That its ring system and most of its satellite orbits are circular and in its equatorial plane, suggests it was perturbed early in its formation.

Neptune:

Slightly smaller but more massive than Uranus and with an internal heat source driving a high-wind atmosphere with rotating storms seen as spots and clouds. The blue colour of the atmosphere is because of its methane content which, like Earth's air, scatters blue light more than red.



Neptune

Credit: Courtesy NASA/JPL-Caltech.

Planetary evolution

We will now discuss the various factors that influence the later evolution of the planets. These factors include tectonics, volcanism, weathering and we begin with impacts.

Phobos

Credit: Dr. Edwin V. Bell, II (NSSDC/Raytheon ITSS)

Impacts and craters

Evidence of cratering exists on all the terrestrial planets, and on all the satellites with ancient surfaces.

However we only see limited signs of cratering on Earth. This is because oceans cover much of the Earth's surface, and also because tectonic activity, weathering, extensive plant life, and human activities such as agriculture effectively erase the cratering record on Earth. Some spectacular examples of craters do remain however.

Meteoroids (and asteroids) generally travel with velocities in the range of 10 to 70 km/s with considerable energy. Upon impact, this energy is transferred to the surface of the target body. What results is an *impact crater*.

The diameter of craters formed when large meteorites strike the Earth are typically 10-20 times as large as the diameter of the meteorite which causes it.

Wolfe Creek, Western Australia

Credit: NASA/RST/Nicholas Short

Using this rule of thumb, the meteoroid which created the Barringer Crater (with a diameter of 1 km) in Arizona would have had a diameter between 50 and 100 metres.

Barringer crater, Arizona

Credit: D. Roddy (LPI)

Mass extinctions

One of the best studied large impacts occurred 65 million years ago, which separates the Cretaceous and Tertiary geologic periods on Earth. This boundary (*KT*), coincides with a mass extinction event. The KT boundary gets a lot of attention because the impact most likely wiped out the dinosaurs.

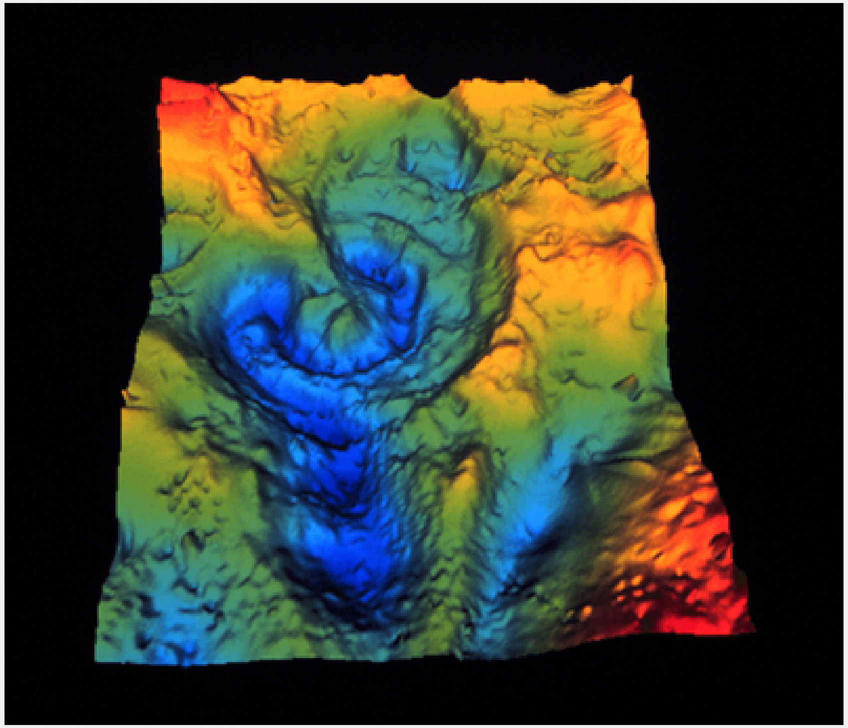
A worldwide layer of sediment rich in iridium (a mineral rare on Earth but common in meteoroids) was discovered in 1980 at depths associated with the KT boundary. It was suggested that the entire Earth was enshrouded in a dust cloud from a giant impact, which sent dust and ash (and iridium) into the atmosphere, turning day to night. This dark winter probably lasted several years. Plants and then animals died - leading to a mass extinction.

Artists impression of a large impact

Credit: Courtesy NASA/JPL-Caltech

The search for the giant impact crater began, and finally in 1990 the Chicxulub crater was found off Mexico's Yucatan Peninsula. The crater is buried under several kilometres of sediment, but geologic mapping shows the crater is about 180 km in diameter - making it the largest impact crater on Earth.

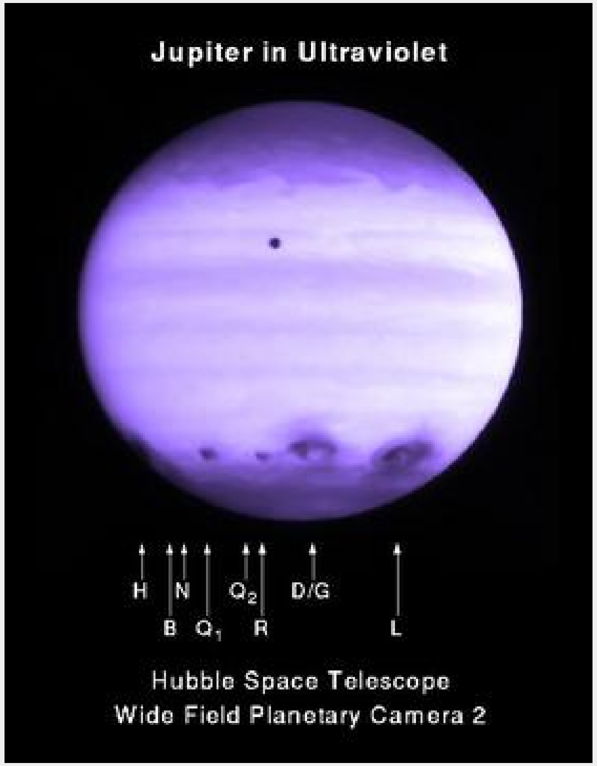
The impacting body must have been about 20 km in size. The impact itself would have created a massive earthquake, a 100 m tidal wave that raced across the Gulf of Mexico, and lifted about 100 trillion tons of dust into the atmosphere!



Credit: NASA/Solar System Exploration web site

In 1994 we saw dramatic evidence of an impact - on Jupiter. Between July 16 and 22, 1994 astronomers recorded many fragments, some estimated to be 3 km in diameter, of Comet P/Shoemaker-Levy 9 colliding with Jupiter.

The comet had been broken into fragments via a close passage with Jupiter in 1992. The impact highlighted several things. Jupiter is an effective 'sweeper' of such objects - clearing them from the inner Solar System. The impact released more energy into Jupiter's atmosphere than that in the total nuclear arsenal on Earth. Jupiter in the past could have saved Earth from similar such (catastrophic) events.



Comet Shoemaker-Levy impact sites.

Credit: Hubble Space Telescope Comet Team

Plate tectonics

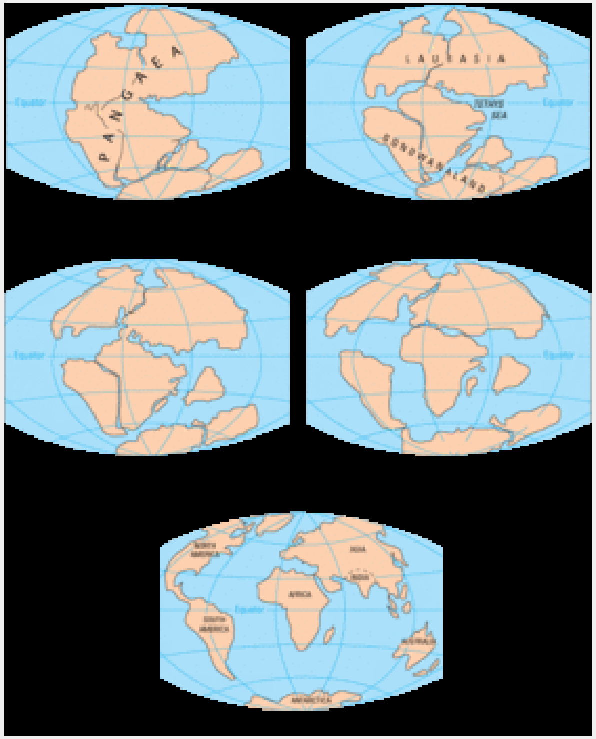
Underneath newly formed crusts the mantle may still be hot enough to undergo plastic flow - and, move in ***convective currents***.

If the planet's interior cools slowly the convection currents in the mantle can drag along regions of crust by a few cm per year. This is what we call *plate tectonics* on Earth which are still ongoing.

Himalayas.

Credit: NASA

The theory of *continental drift* initially advocated by Alfred Wegener proposed that about 220 million years ago all continents were joined in one supercontinent, Pangea. Pangea then fragmented via plate tectonic movement into the present day distribution of continents.



Continental drift.

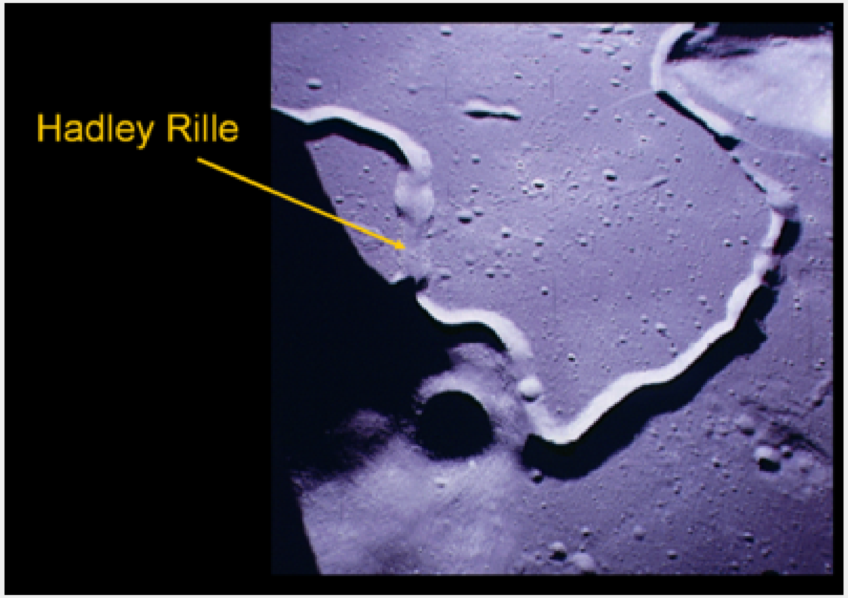
Credit: USGS

Volcanism

Lava flows are likely to occur if an impact cracks the planet's thin crust while the mantle is still molten.

As we have seen on Earth, when tectonic plates collide with each other, they crumple the crust to form mountain chains and force molten lava to the surface to erupt as volcanoes.

On the Moon Hadley Rille formed from a lava flow about 3.3 billion years ago. In total it is 120 km long, about 1.5 km wide and in places 300 m deep. It was near here that Apollo 15 landed.



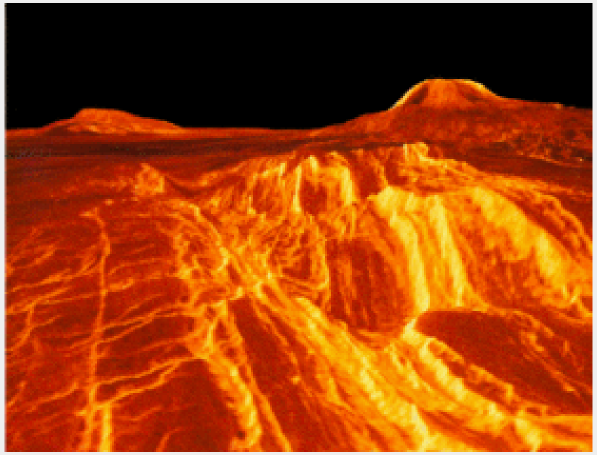
Hadley Rille

Credit: Courtesy NASA/JPL-Caltech

Where convection currents in the mantle do not exist (such as Mars and Venus), local **hot spots** in the mantle can still force molten lava up to the surface over millions of years, forming huge volcanoes, just like Olympus Mons on Mars and Gula Mons on Venus.

Olympus Mons - Mars

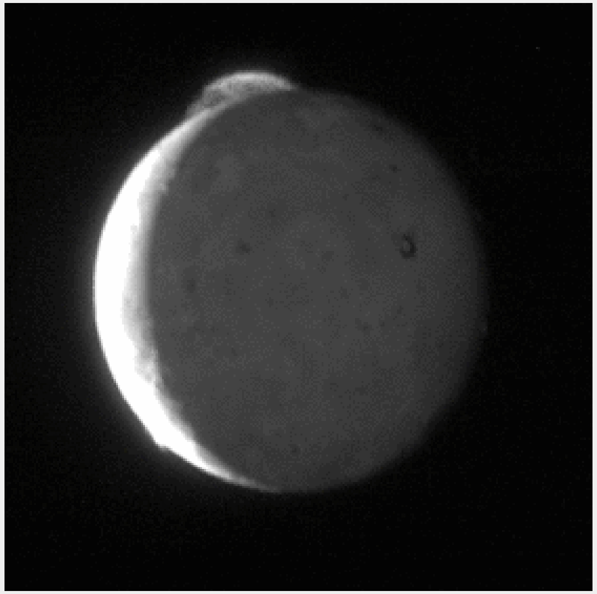
Credit: NASA - Viking 1



Gula Mons - Venus

Credit: NASA/JPL/Magellan Team

On Jupiters satellite moon Io, volcanism - with plumes as high as 500 km - is observed but is not generated by tectonic movement. The gravitational force on Io imparted by nearby Jupiter raises tidal bulges in the crust by 30 m! The continued 'flexing' heats the interior and causes the eruptions. The plumes contain sulphur that give the nearby surface a reddish colour.



Plume activity from Io volcano Tvashtar.
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

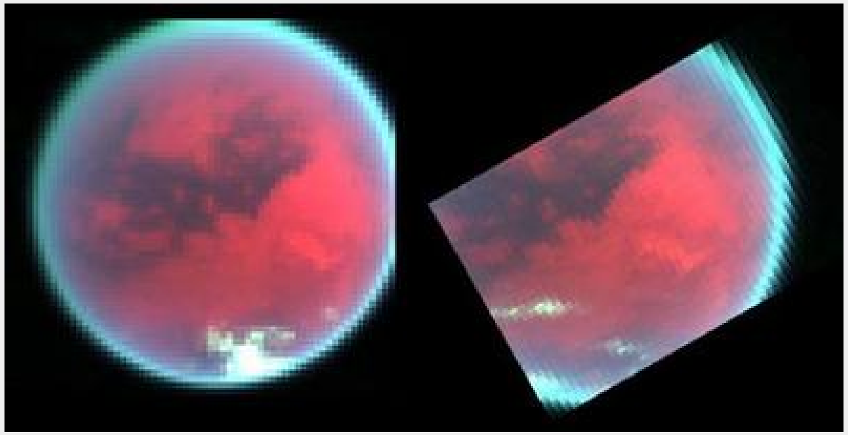
Plume from Io volcano Pillan Patera.
Credit: NASA/JPL/University of Arizona /LPL

Weathering

Once a planet's mantle cools enough to bring its volcanic activity largely to an end, planets with atmospheres will then largely settle down to a long period of gradual weathering, from one or more of:

- dust storms
- wind erosion
- water and ice erosion (if the planet supports liquid water and rain).

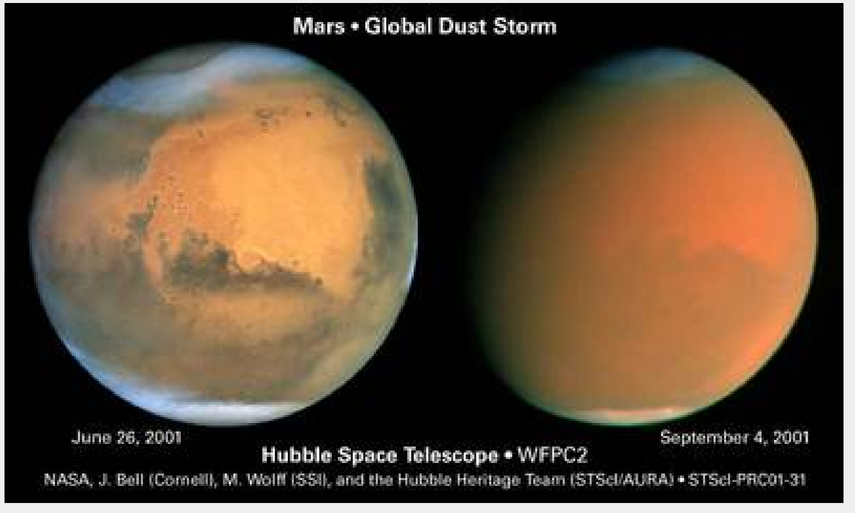
Which of these processes occur, the rate of occurrence and to what degree, depends on the atmospheric conditions and circulation patterns on the particular planet involved.



Changing cloud cover on Titan

Credit: NASA/JPL/University of Arizona

Localised dust storms on Mars have on occasion turned into global, planet-covering storms. About 10 global dust storms have been reported on Mars since 1877.

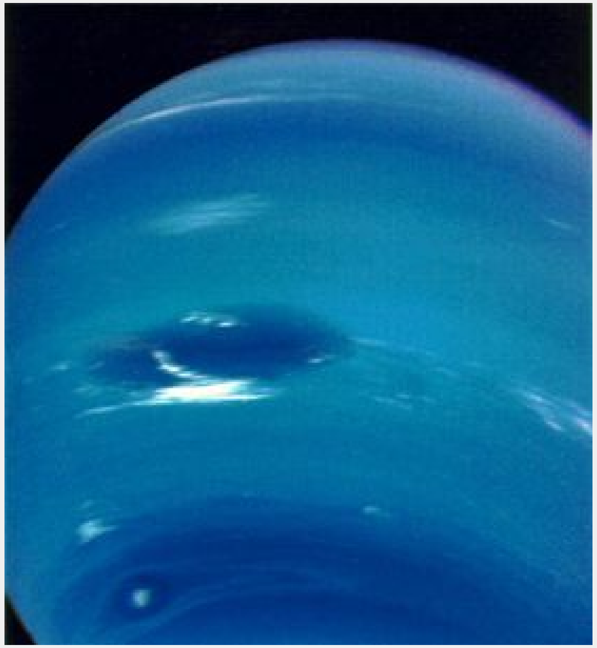


Dust storm on Mars in 2001.

Credit: NASA, James Bell (Cornell Univ.), Michael Wolff (Space Science Inst.), Hubble Heritage Team (STScI/AURA)

While not exactly weathering, the atmospheres of the Jovian planets evolve. The Great Dark Spot on Neptune was observed by Voyager II in 1989. It is similar to the anti-cyclone Great Red Spot system on Jupiter.

In 1996 images taken by Hubble Space Telescope showed that the Great Dark Spot had disappeared. These changes in the surface structure show the dynamic nature of the planet's atmosphere - yet are in stark comparison to the Great Red Spot on Jupiter that has existed for over 400 years.



Great Dark Spot on Neptune.

Credit: NASA/JPL/Voyager Team

Summary

Let's now review what we have covered in this Activity.

Mercury:

The innermost planet to the Sun. Its day is twice as long as its year.

Venus:

Nearest planet to Earth has a runaway greenhouse atmosphere, dominated by CO_2 with extreme surface temperatures (470 °C) and high atmospheric pressures.

Mars:

The most similar planet to Earth – has very small atmosphere, seasonal dust storms and mostly CO_2 polar caps. No current evidence of water, but geological evidence of past (from $\sim$1 billion years ago) subsurface water.

Jupiter:

The first of the gas giants with a rocky core surrounded by liquid metallic and metallic hydrogen. The largest planet. Rotates once every 10 hours. Visual appearance dominated by high velocity turbulent atmosphere providing red, brown, yellow hues in belts, zones and eddies. Great Red Spot is a cyclonic storm system in its upper atmosphere that has been seen for over 400 years.

Saturn:

Slightly smaller size and rotation rate than Jupiter and less than a third of its mass. Exhibits more subtle variations of Jupiter's belts and storms in a similar atmosphere. Visual appearance dominated by its magnificent ring system.

Uranus:

Twice as distant from the Sun than Saturn, Uranus is much colder and lacks a strong internal energy source. It has high speed winds yet its atmosphere is generally featureless. Uranus' unique feature is its 98° tilt to its orbit plane suggesting it was perturbed early in its formation.

Neptune:

Slightly smaller but more massive than Uranus and with an internal heat source driving a high-wind atmosphere with rotating storms seen as spots and clouds. The blue colour of the atmosphere is because of its methane content.

Planetary evolution:

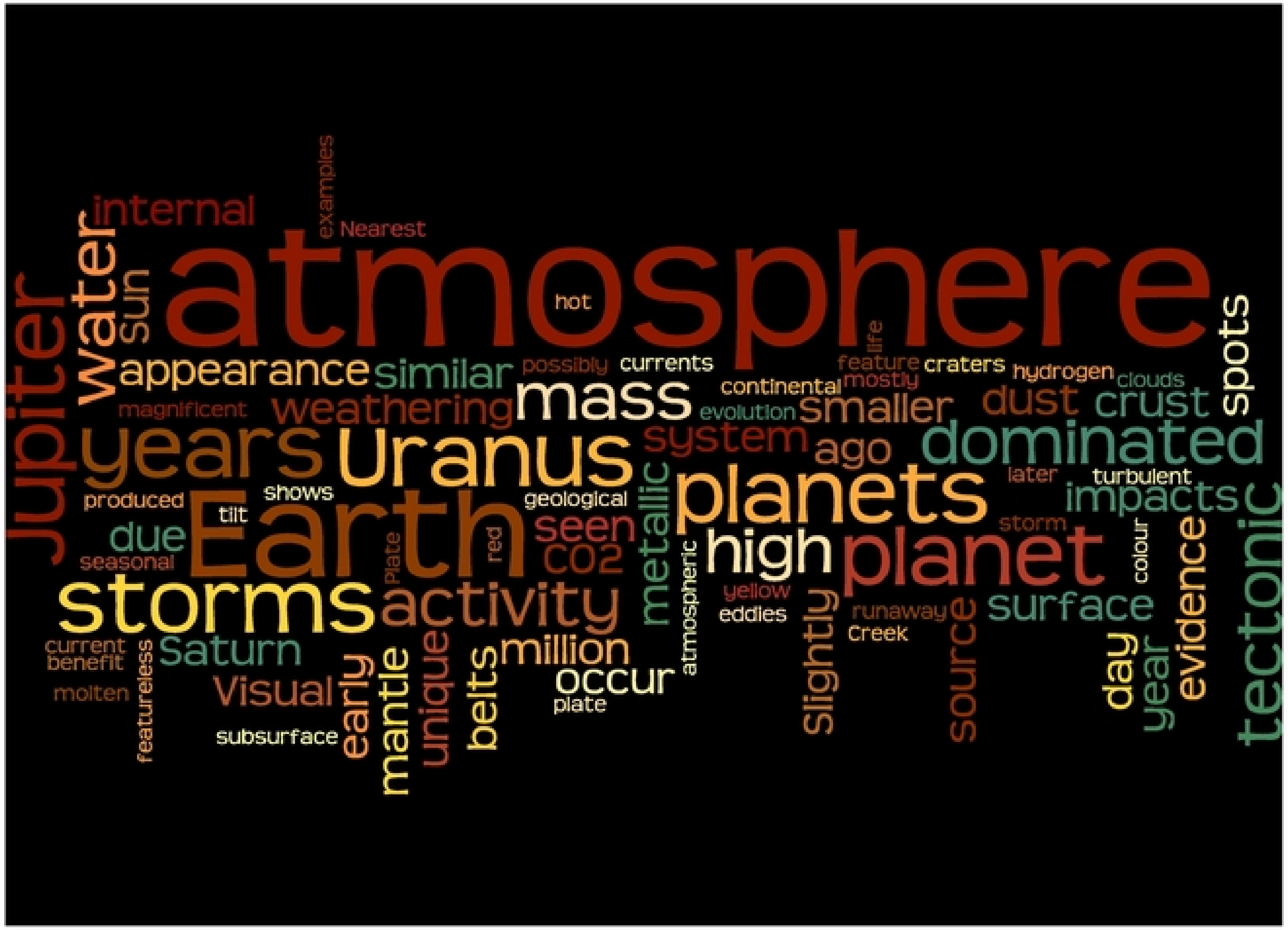
The terrestrial planets continue to evolve due to cratering, volcanism and weathering. Earth is unique in its ongoing tectonic plate activity.

Impact craters:
Formed as large bodies detonate as they hit a planets surface. Famous examples on Earth include Wolfe Creek and Barringer. Chicxulub (200 km crater) possibly caused the mass extinction at the KT boundary - 65 million years ago. Comet Shoemaker-Levy is a recent example of an impact with Jupiter. It is likely that Jupiter has attracted many such impacts - to the benefit of Earth and the inner planets.

Plate tectonics:
Convection currents in the mantle can drag the crust by a few cm a year. On Earth over the last 220 million years continental drift has produced the present day distribution of land mass.

Volcanism:
Can occur early in a planets life if impacts crack the thin crust whilst the mantle is still molten or later if tectonic activity makes plates collide. Local hot spots without tectonic activity can form volcanoes. Io shows that gravitational ‘flexing’ can also cause volcanic plumes.

Weathering:
Atmospheric weathering can occur due to dust storms, wind, water and ice erosion.



Module 2 activity 2 Learning Outcomes.

Additional resources

The Nine (Eight) Planets
click here.

Project CLEA
click here.

Solar System Live - by John Walker
click here.