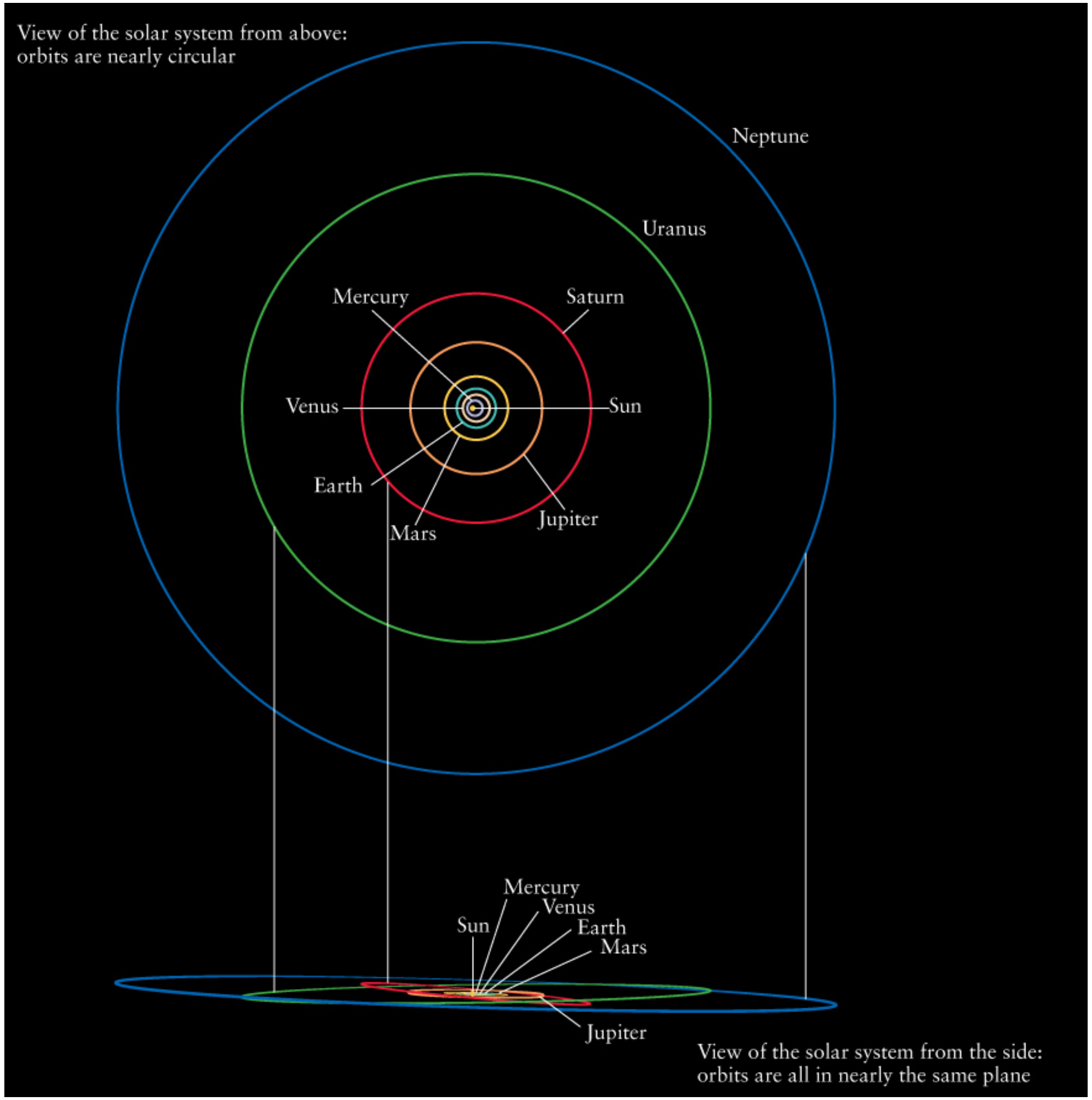
Our Solar System – an overview

The solar system consists of the Sun around which orbit 8 planets, 5 dwarf planets, and many 100's of thousands of minor bodies (asteroids, kuiper-belt objects, comets).



6 of the planets have one or more orbiting satellites. Dwarf planets, asteroids and kuiper belt objects may also have satellites.

Except for Mercury the planets have orbits that are nearly circular – their orbits are elliptical as described by Kepler's law, but the eccentricities are small ($e < 0.1$). The orbits also almost lie in the same plane - inclinations relative to Earth's orbit plane are small, typically < 4^{o}, except for Mercury.

Definitions:

A planet

The definition of a *planet* set in 2006 by the International Astronomical Union (IAU) states that, in the Solar System, a planet is a celestial body which:

1). is in orbit around the Sun,

2). has sufficient mass to assume hydrostatic equilibrium (a nearly round shape), and

3). has "cleared the neighbourhood" around its orbit.

A dwarf planet

A non-satellite body fulfilling only the first two of these criteria is classified as a "dwarf planet". According to the IAU, "planets and dwarf planets are two distinct classes of objects”

Although controversial, these definitions can be understood more clearly by noting that the 5 dwarf planets of the solar system are members of either the asteroid or kuiper-belt, so their gravitational influence has clearly been unable to clear their neighbourhood of other bodies. The planets, on the other hand, occupy orbits that are distinct from other bodies, except for co-orbital trojan asteroids which are trapped in special orbits by Jupiter and Neptune.

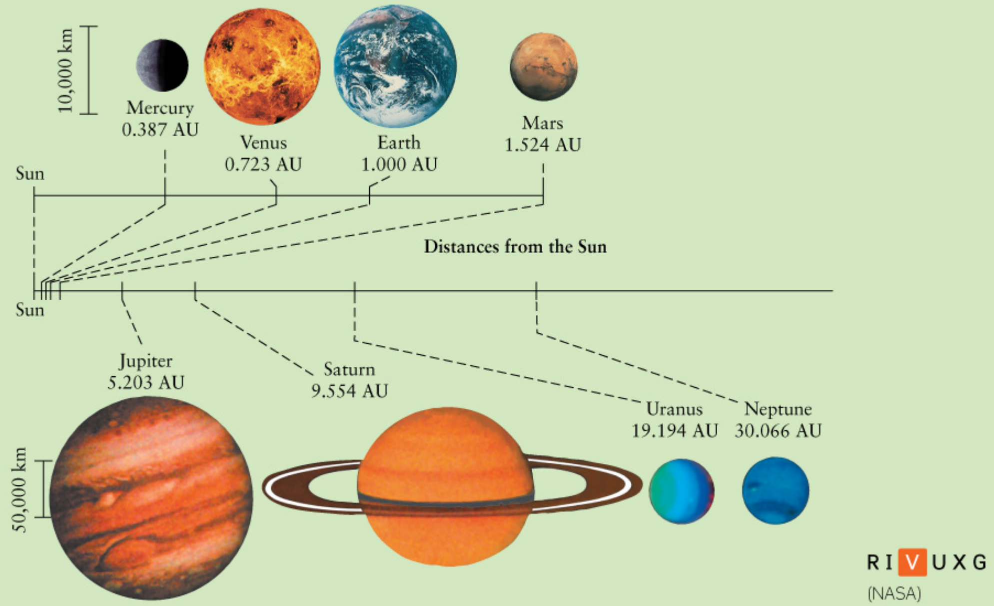
Orbital characteristics

Comparing the sizes of orbits, we note that the planets can be divided into bodies orbiting close to the Sun with compact orbits – the 4 inner planets, and bodies with more distant orbits that are more widely separated – the 4 outer planets.

We note that Mercury has the most eccentric orbit with e = 0.206 and the most inclined orbit with i=7^o from the Earth's orbit plane (the ecliptic).

Table 7-1 Characteristics of the Planets

	The Inner (Terrestrial) Planets			
	Mercury	Venus	Earth	Mars
Average distance from the Sun (10^6 km)	57.9	108.2	149.6	227.9
Average distance from the Sun (AU)	0.387	0.723	1.000	1.524
Orbital period (years)	0.241	0.615	1.000	1.88
Orbital eccentricity	0.206	0.007	0.017	0.093
Inclination of orbit to the ecliptic	7.00°	3.39°	0.00°	1.85°
Equatorial diameter (km)	4880	12,104	12,756	6794
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (kg)	3.302×10^{23}	4.868×10^{24}	5.974×10^{24}	6.418×10^{23}
Mass (Earth = 1)	0.0553	0.8149	1.0000	0.1074
Average density (kg/m^3)	5430	5243	5515	3934



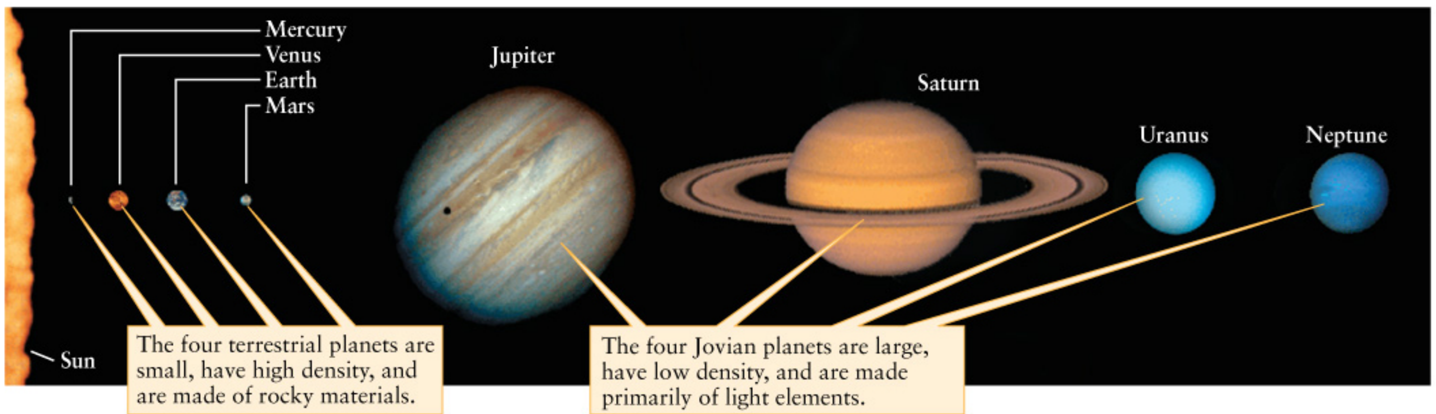
	The Outer (Jovian) Planets			
	Jupiter	Saturn	Uranus	Neptune
Average distance from the Sun (10^6 km)	778.3	1429	2871	4498
Average distance from the Sun (AU)	5.203	9.554	19.194	30.066
Orbital period (years)	11.86	29.46	84.10	164.86
Orbital eccentricity	0.048	0.053	0.043	0.010
Inclination of orbit to the ecliptic	1.30°	2.48°	0.77°	1.77°
Equatorial diameter (km)	142,984	120,536	51,118	49,528
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883
Mass (kg)	1.899×10^{27}	5.685×10^{26}	8.682×10^{25}	1.024×10^{26}
Mass (Earth = 1)	317.8	95.16	14.53	17.15
Average density (kg/m^3)	1326	687	1318	1638

Physical properties:

Comparing the physical properties of the planets, we see that they again fall into two natural categories – four small inner bodies, and four large outer ones. The inner planets are called terrestrial planets because they resemble the Earth (*terra* means Earth in Latin). Mercury, Venus, Earth and Mars are largely made of rock and metal with thin or non existent atmospheres. Their mean densities are in the range $3934 \leq \rho_{mean} \leq 5515$ kg m^{-3}. The density of rock on the surface of the Earth is approximately 3000 kg m^{-3}.

The four outer planets are called Jovian planets because they resemble Jupiter (Jove was another name for the Roman god Jupiter). These planets each have thick gaseous atmospheres and generally show distinct cloud features. Their mean densities are in the range $687 \leq \rho_{mean} \leq 1638$ kg m^{-3}, indicating that their bulk compositions are very different from the terrestrial planets.

The sizes and masses of the Jovian planets are much larger than the terrestrials. Jupiter is 318 times more massive than Earth. Uranus is 14.5 times more massive.



The mean densities of the planets are related to their chemical compositions.
Rocks on the surface of the Earth have a density of 3000 kg m^{-3}. If the Earth was made of pure rock then its mean density would be larger than 3000 kg m^{-3} because the weight of the outer layers of the Earth lying on the deeper lying layers causes them to become compressed – this is called gravitational compression. Nonetheless, the mean density of the Earth would be lower than the measured value of 5515 kg m^{-3}.

This indicates that the Earth contains a substantial fraction of material that is denser than rock – metals such as iron and nickel that make up the Earth's core.
Why do these metals lie at the Earth's centre rather than being distributed throughout its body ?

The low densities of the Jovian planets indicates that they are largely composed of lower density material than rock. Jupiter and Saturn are composed largely of hydrogen and helium, with a rock and ice core located at their centres. Hence they are often referred to as "gas giants". Uranus and Neptune also have rocky cores, on top of which lie a layer of compressed water and ammonia liquid mixtures. This liquid mantle is surrounded by a thick hydrogen and helium atmosphere. The original source of water and ammonia is believed to have been accumulation of icy bodies in the cold outer regions of the solar system. Hence these planets are often referred to as "ice giants".

Satellites

All the planets expect Mercury and Venus have satellites. Earth has one, Mars has two, Jupiter and Saturn more than 60 each, Uranus at least 27 and Neptune at least 13.

Seven of these satellites are substantially more massive than the rest, and some are of similar size and mass to the planet Mercury. Titan is the only satellite to have an atmosphere. Io shows active volcanism, and Triton shows active “cryovolcanism” - ice-volcanoes driven by the tidal heating of Triton by Neptune..

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Table 7-2 The Seven Giant Satellites

	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	7.35×10^{22}	8.93×10^{22}	4.80×10^{22}	1.48×10^{23}	1.08×10^{23}	1.34×10^{23}	2.15×10^{22}
Average density (kg/m^3)	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No

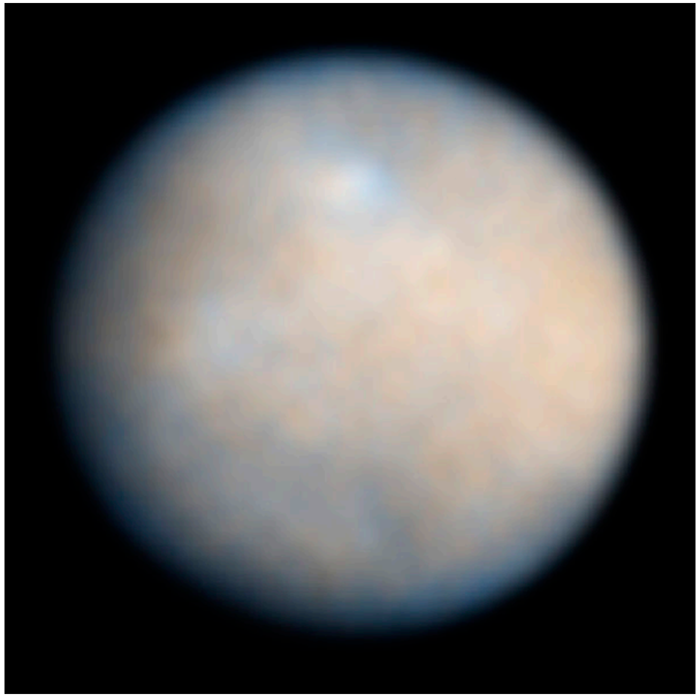
R I V U X G

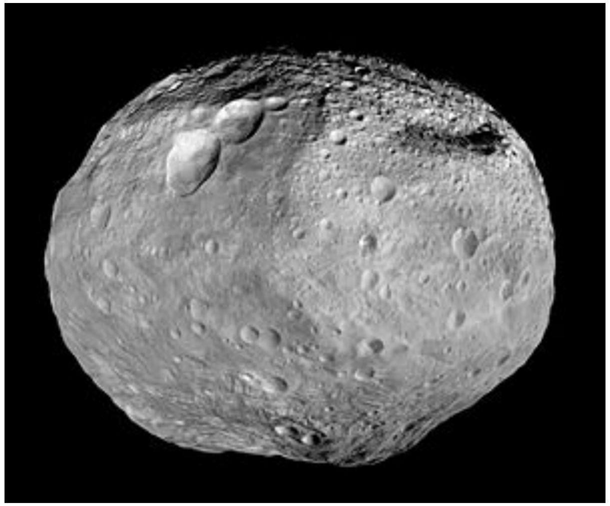
(NASA/JPL/Space Science Institute)

Asteroids and Kuiper belt objects

In addition to planets and satellites, the solar system contains relatively small bodies composed of rock or rock + ice.

Between the orbits of Mars and Jupiter at semi-major axes 2 – 3.5 AU there orbit 100's of thousands of asteroids. The largest asteroid, Ceres, has a radius ~ 500 km. This body is the only dwarf planet in the asteroid belt. Pallas and Vesta have radii ~ 250 km. The distribution of sizes is continuous, ranging from objects the size of boulders (i.e. 10's of metres) all the way up to Ceres. Small objects are more numerous than large ones.





Beyond the orbit of Neptune we have the Kuiper belt – a region stretching approximately from 39 – 70 AU containing a large number of icy bodies referred to as “Kuiper-belt” or “trans-Neptunian” objects. The Pluto-Charon system is a member of this population, and is caught in a 3:2 mean motion resonance with Neptune – Neptune orbits the Sun 3 times for every 2 orbits of Pluto. There are numerous other bodies in the 3:2 resonance, and additional resonances such as the 2:1 are also populated.

The kuiper belt hosts 4 confirmed dwarf planets (masses in Earth masses are shown in brackets): Pluto (2.2×10^{-3}), Eris (2.8×10^{-3}), Haumea (6.7×10^{-4}) and Makemake (6.7×10^{-4}).

For an icy body to be spherical its radius > 200 km.

Many kuiper belt objects are thought to have radii larger than this, but are not confirmed dwarf planets. There are probably ~ 200 dwarf planets in the solar system.

Table 7-4 Seven Large Trans-Neptunian Objects

	Quaoar	Haumea	Sedna	Makemake	Pluto	Charon (satellite of Pluto)	Eris
Average distance from the Sun (AU)	43.54	43.34	489	45.71	39.54	39.54	67.67
Orbital period (years)	287	285	10,800	309	248.6	248.6	557
Orbital eccentricity	0.035	0.189	0.844	0.155	0.250	0.250	0.442
Inclination of orbit to the ecliptic	8.0°	28.2°	11.9°	29.0°	17.15°	17.15°	44.2°
Approximate diameter (km)	1250	1500	1600	1800	2274	1190	2900

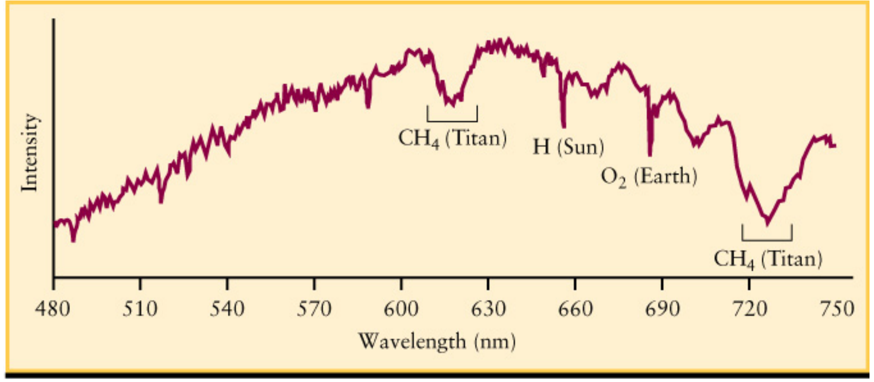
(Note: To date astronomers have been able to make images of the surfaces of Pluto and Charon only.)

R I V U X G

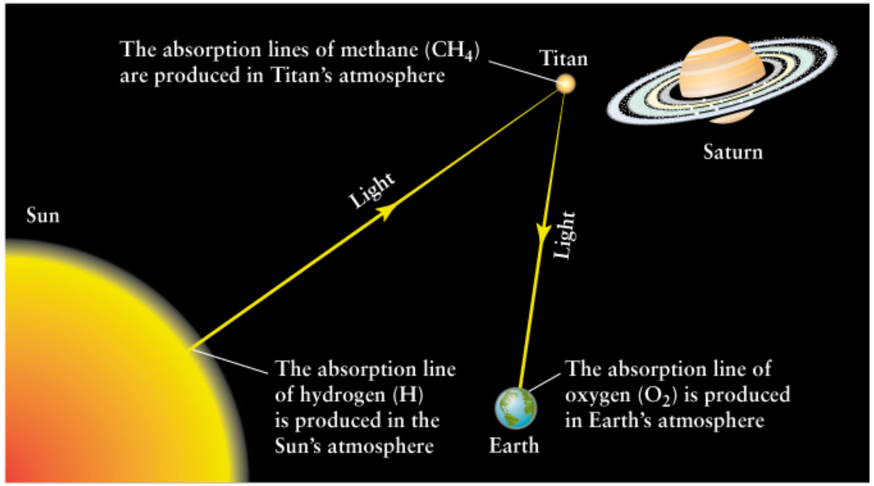
(Images of Pluto and Charon: Alan Stern, Southwest Research Institute; Marc Buie, Lowell Observatory; NASA; and ESA)

Spectroscopy – determination of chemical composition

Measurement of mean densities provides information about chemical composition, but direct measurement of the composition of remote bodies is most accurately provided by spectroscopy.



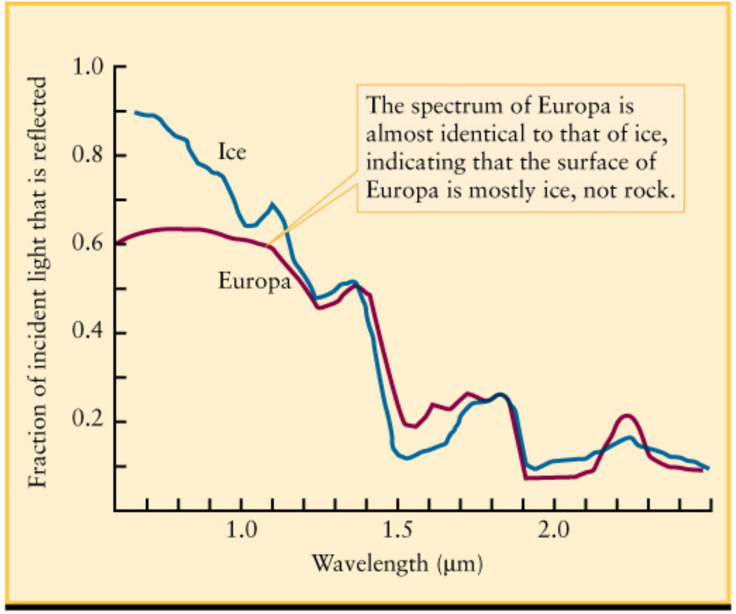
(b) The spectrum of sunlight reflected from Titan



(c) Interpreting Titan's spectrum

When sunlight reflects off a planetary atmosphere some of the sunlight is absorbed at specific wavelengths by chemical compounds within the atmosphere, giving rise to an absorption spectrum. Comparing this absorption spectrum with spectra measured in the laboratory allows determination of the composition of the atmosphere. For example, the atmospheres of Jupiter and Saturn are known to consist largely of hydrogen and helium because of spectroscopic measurements. Similarly, spectra obtained for Saturn's moon Titan show the existence of methane absorption features, demonstrating the existence of methane in its atmosphere. Spectral features in the UV show that N_2 is the main constituent of Titan's atmosphere, and spectral lines in the IR show the existence of complex organic molecules.

Spectroscopy can also be used to determine the chemical composition of the solid surfaces of planets, satellites, and minor bodies such as asteroids and kuiper-belt objects. Sunlight shining on a solid surface results in some wavelengths being reflected and others being absorbed. Spectral features from solid surfaces do not appear as single discrete lines, but rather as bands of absorption over a range of wavelengths. Comparison between the observed spectra and those measured in the laboratory allow identification of the chemical composition of solar system bodies. One example is Jupiter's moon Europa, which has an infrared spectrum very similar to that of water ice measured in the laboratory. Clearly this is a moon whose surface is composed mainly of ice. The young surface of Europa (indicated by the relatively few craters) indicates that the icy surface covers a liquid interior that is capable of resurfacing locations on the moon that become fractured by impacts. The mean density of Europa, however, indicates that its primary constituents are a mixture of rock and ice.



(b) The spectum of light reflected from Europa

Atmospheric composition and temperature

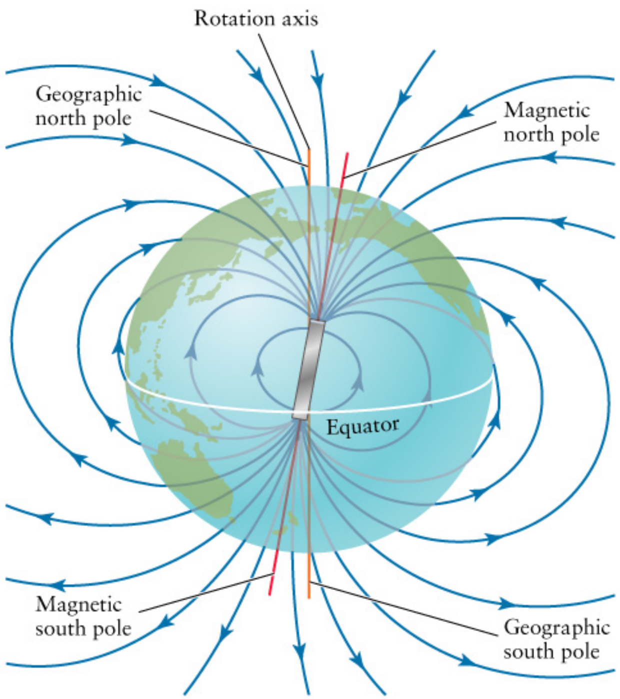
The atmospheres of the Jovian planets are primarily composed of hydrogen and helium, but the atmospheres of the terrestrial planets are almost devoid of these elements and are composed primarily of the molecules N_2, O_2 and/or CO_2. Why is this ?

The temperature of a gas is directly related to the speeds of its molecules. At a given temperature lighter molecules move faster than heavier molecules because they each have the same kinetic energy on average. Molecular hydrogen and helium are thus able to move at the escape velocity from warmer terrestrial planets because of their relatively weak gravity. See the supplementary on-line notes for a demonstration of this. The approximate calculation presented in the supplementary notes ignores the fact that atoms/molecules at a given temperature have a range of velocities given by the Maxwell-Boltzmann distribution. Even though the mean velocity of atoms may be below the escape speed from a planet, there will be a fraction of them that have velocity above the escape velocity. As a rule of thumb, atmospheric escape is unimportant only if the mean velocity is $\leq 1/6$ of the escape velocity, so that only a very small fraction of atoms move at the escape velocity.

Magnetic fields

Solar system bodies that possess significant magnetic fields include the Sun, Mercury, Earth, Jupiter, Saturn, Uranus and Neptune. Each of these bodies possess a global dipole magnetic field – similar in structure to a bar magnet.

The presence of a magnetic field indicates that the interior of the body contains regions where the material is an electrically conducting fluid. For the Earth and Mercury a molten iron core generates the magnetic field. In Jupiter and Saturn the deep interior contains highly conducting "metallic" hydrogen.



(b)

The magnetic fields of these bodies are continuously generated by a dynamo.

For a dynamo to operate the following are required:

i) An electrically conducting fluid

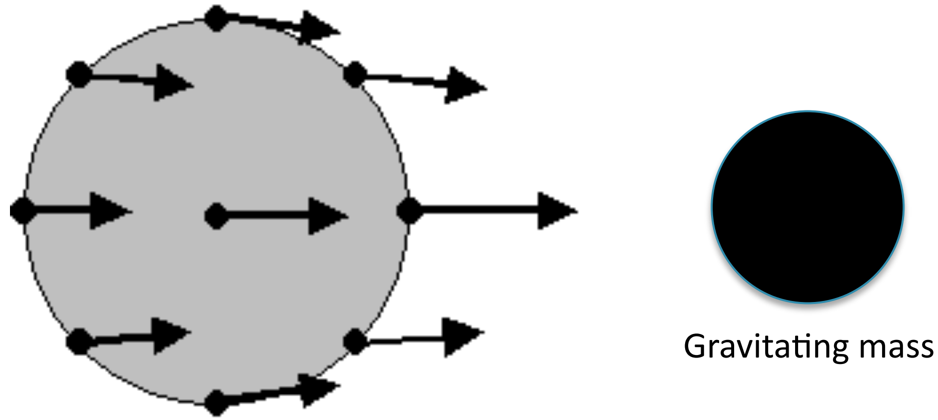
ii) Rotation

iii) Convective motions

Being a small planet, Mars has cooled sufficiently for the core to be solid. Mercury's interior remains molten because of its eccentric orbit and tidal interaction with the Sun. Venus lacks plate tectonics, preventing the interior from cooling efficiently through the surface, and therefore switching off the necessary convective motions that require the existence of a strong temperature gradient to operate.

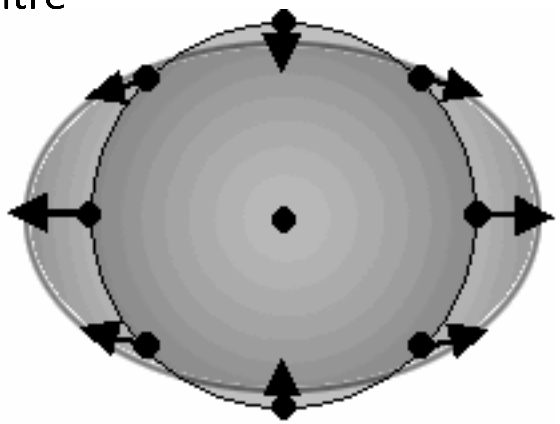
Tidal interactions

A body of finite size sitting in the gravitational field of an external mass experiences tidal forces. These result from the variation of the gravitational acceleration over the surface of the body. This variation arises because the gravitational acceleration depends on the distance to the gravitating mass.



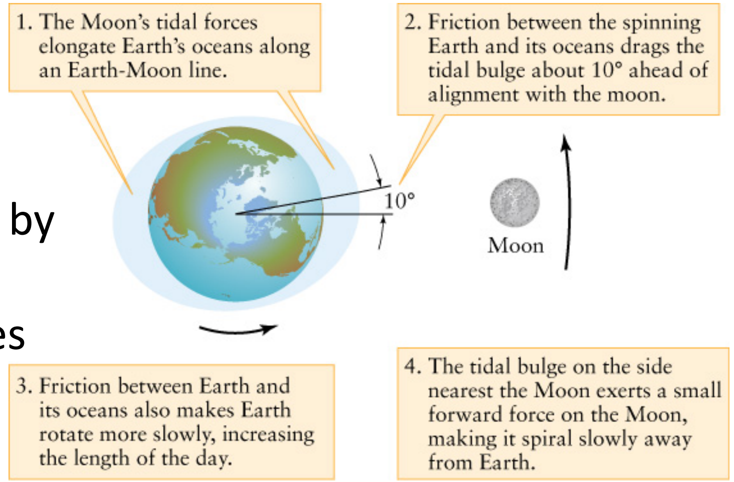
Forces relative to the Sun (or primary body)

The diagrams to the right show the forces acting on a body due to a gravitating mass. Subtracting the centre of mass acceleration (which just corresponds to the body as a whole being accelerated toward the gravitating mass), we see the tidal forces that act to distort the surface. For the Earth-Moon system, the distortion of the Earth is manifest as the raising and lowering of ocean tides.



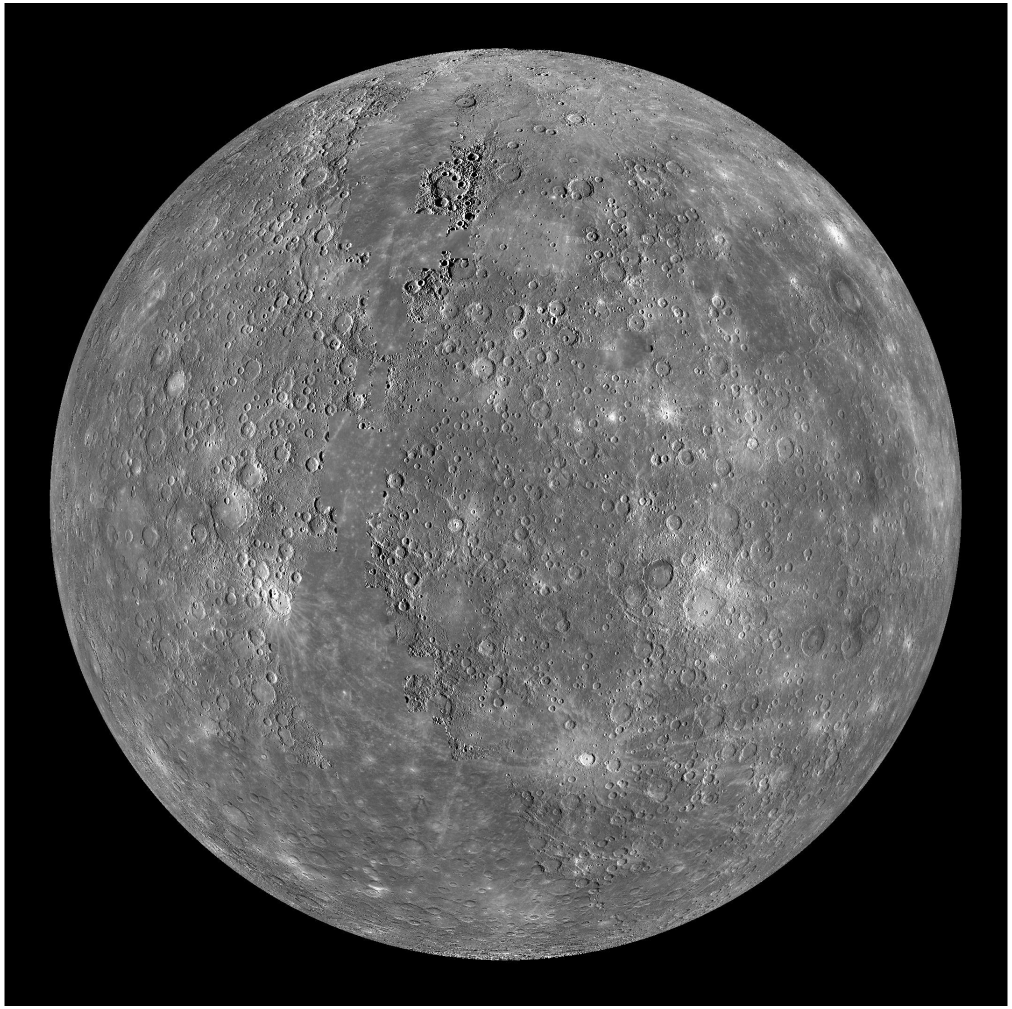
Forces relative to the center of the Earth

Derivation of tidal acceleration is given in the on-line supplementary lecture notes, where we also demonstrate that if tidal forces are large enough an object can be tidally disrupted – literally pulled apart by tidal forces. We also demonstrate how to estimate the height of the tidal distortion. All gravitating bodies induce tidal forces in nearby objects. In the case of the Earth-Moon system, tidal distortion of the Earth by the Moon, combined with the Earth's spin and Moon's orbital motion lead to an exchange of angular momentum between the two objects. As demonstrated in the figure, the fact that the Earth spins faster than the Moon orbits (the Earth spins once in 24 hours, the Moon orbits the Earth in 27.3 days) causes the Earth's tidal bulge to always be slightly ahead of the Moon. This creates a torque that pulls the Moon forward long its orbit, giving it a positive torque. The orbital angular momentum of the Moon is thus constantly increasing, causing it to move away from the Earth. Conservation of angular momentum implies that the Earth's spin rate must be constantly decreasing. So the months are getting longer because the Moon's orbital period increases as it moves away from the Earth. And the days are getting longer because the spin period of the Earth is increasing. This process will stop when the spin period of the Earth equals the orbital period of the Moon. At the present time the Moon is moving away from the Earth at a rate of 3.8 cm per year. Tides explain why the Moon shows the same face to Earth. The Moon was originally spinning faster than the current rate of once per 27.3 days, but its tidal distortion by the Earth has caused it to slow down to the point where it has achieved spin-orbit synchronism.



Mercury – key facts

Mercury is a barren, heavily cratered world devoid of an atmosphere and plate tectonics to renew its surface. The impact craters were mainly formed during the first ~ 800 Myr after formation of the Solar System.



Low-lying plains were formed by lava flows generated by giant impacts puncturing the young crust.

High mean density suggests Mercury has a large iron core filling ~ 75% of its radius.

Mercury maintains a magnetic field with strength ~ 1% of Earth's - suggests part of Mercury's iron core remains molten.

Mercury is in a 3:2 spin-orbit resonance, in which the planet spins on its axis 3 times for every two orbital periods – unlike the Moon's 1:1 spin-orbit resonance.
This is caused by Mercury's eccentric orbit, for which the orbital angular velocity varies continuously round its orbit, and the fact that tidal forces depend on the separation between Mercury and the Sun.

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Table 11-1 Mercury Data

Average distance from the Sun:	0.387 AU = 5.79×10^7 km
Maximum distance from the Sun:	0.467 AU = 6.98×10^7 km
Minimum distance from the Sun:	0.307 AU = 4.60×10^7 km
Eccentricity of orbit:	0.206
Average orbital speed:	47.9 km/s
Orbital period:	87.969 days
Rotation period:	58.646 days
Inclination of equator to orbit:	0.5°
Inclination of orbit to ecliptic:	7° 00′ 16″
Diameter (equatorial):	4880 km = 0.383 Earth diameter
Mass:	3.302×10^{23} kg = 0.0553 Earth mass
Average density:	5430 kg/m^3
Escape speed:	4.3 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.12
Average surface temperatures:	Day: 350°C = 662°F = 623 K Night: −170°C = − 274°F = 103 K
Atmosphere:	Essentially none

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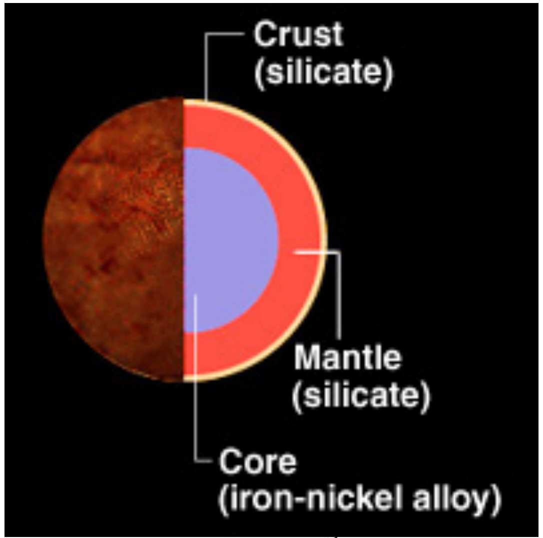
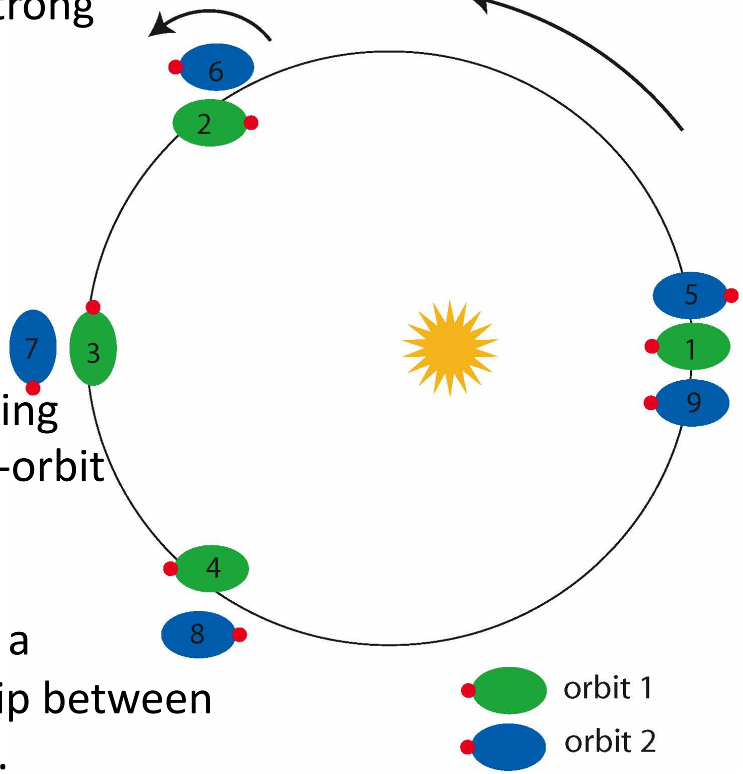
This is caused by Mercury's eccentric orbit, for which the orbital angular velocity varies continuously round its orbit, and the fact that tidal forces depend on the separation between Mercury and the Sun.

The top diagram shows Mercury's internal structure

The lower diagram demonstrates Mercury's 3:2 spin-orbit resonance. Mercury's spin period was deduced in 1965 from radar measurements that showed spreading of the frequency of the returning radar signal due to the Doppler shift induced by the rotating planet.



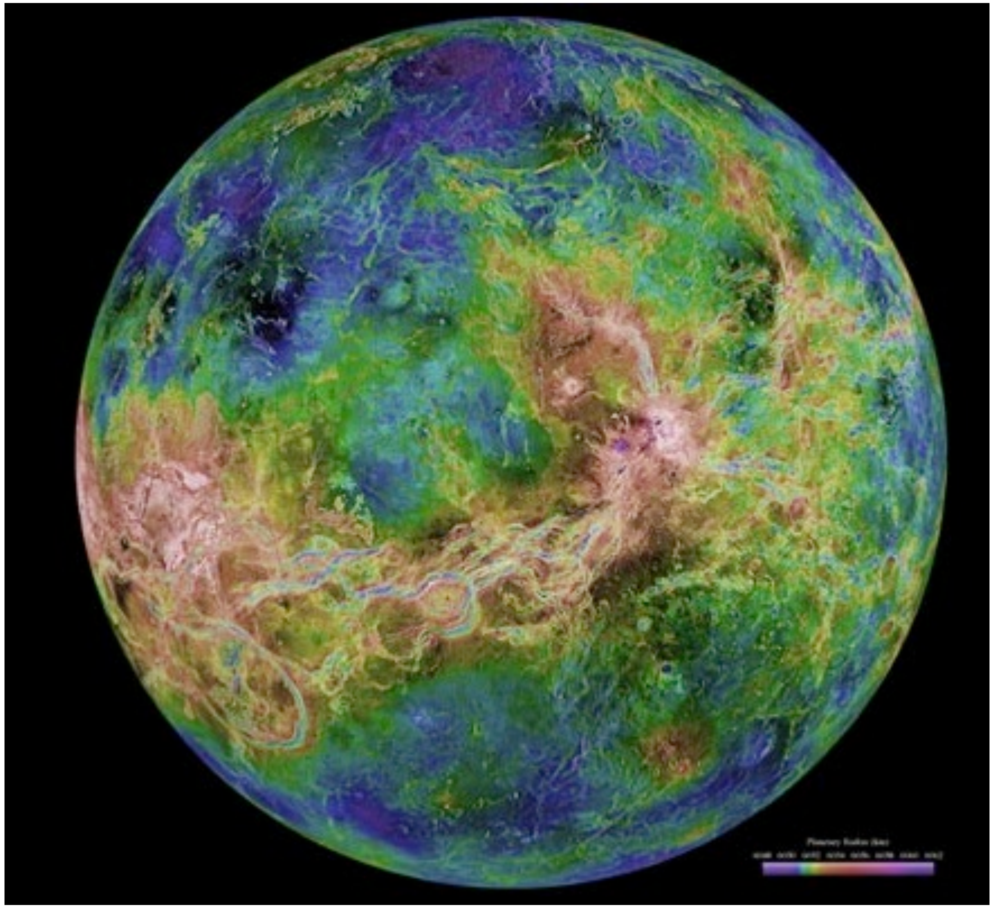
Mercury's eccentric orbit means that the tidal acceleration is strongest at perihelion – note the strong dependence of tidal acceleration on the distance between two bodies (here the Sun and Mercury). Hence tides try to force Mercury to spin with an angular velocity that is close to its orbit angular velocity at perihelion (position labeled 1,5,9). Tides also try to ensure that the axis of the tidal bulge points toward the Sun at perihelion. Combining these requirements leads to the observed 3:2 spin-orbit resonance.



Note that the term resonance is used to described a situation when there is a simple integer relationship between orbital periods, or orbital periods and spin periods.

Venus – key facts

Venus is shrouded in a dense CO_2 atmosphere, giving rise to a strong greenhouse effect leading to the highest surface temperature for any planet in the Solar System. Atmospheric pressure is 92 times larger than on the Earth at sea level.



Venus spins in a retrograde direction - caused by a combination of solar tides, that slow the rotation toward spin-orbit synchronism, and strong atmospheric winds caused by solar heating that reverse the rotation through friction between atmosphere and planetary surface.

Radar mapping of Venus’ surface indicates extensive low lying plains, interspersed with highland regions. Venus appears to be volcanically active but does not have plate tectonics - it is a one-plate planet that experiences localised crust deformation.

Venus does not have a detectable magnetic field generated by an internal dynamo, possibly because of its slow rotation or because of a lack of convection in the iron core.

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Table 11-2 Venus Data

Average distance from the Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from the Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from the Sun:	0.718 AU = 1.075×10^8 km
Eccentricity of orbit:	0.0068
Average orbital speed:	35.0 km/s
Orbital period:	224.70 days
Rotation period:	243.01 days (retrograde)
Inclination of equator to orbit:	177.4°
Inclination of orbit to ecliptic:	3.39°
Diameter (equatorial):	12,104 km = 0.949 Earth diameter
Mass:	4.868×10^{24} kg = 0.815 Earth mass
Average density:	5243 kg/m^3
Escape speed:	10.4 km/s
Surface gravity (Earth = 1):	0.91
Albedo:	0.59
Average surface temperature:	460°C = 860°F = 733 K
Atmospheric composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5% nitrogen (N_2) 0.003% water vapor (H_2O)

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Runaway greenhouse effect

It is believe that Venus originally had liquid water on its surface when it was young, and a less dense atmosphere. Being nearer the Sun than the Earth, a significant amount of this water would have vaporised into the atmosphere, providing a highly effective greenhouse gas. At an early stage in the planet's history liquid oceans would still have coexisted with this humid atmosphere. The temperature may have been above 100^{o}C, but because the atmospheric pressure was higher than on Earth the oceans would be below their boiling point. This state of affairs will have lasted 100's of millions of years, but during this time the luminosity of the Sun increased, raising the surface temperature of Venus, causing more water to evaporate and increasing the concentration of greenhouse gases in the atmosphere. Eventually the temperature would have risen above 647 K (374^{o}C), which is the critical point of water. Above this temperature, no matter how large the atmospheric pressure, Venus' oceans would have evaporated, increasing the greenhouse effect further. This is the runaway greenhouse effect.

In the absence of liquid water, CO_2 was unable to dissolve in the oceans, so its concentration in the atmosphere increased due to volcanic activity, raising temperatures even higher, until high enough to "bake" the CO_2 out of carbonate rocks such limestone. This is how Venus' thick CO_2 atmosphere was formed.

The water in the atmosphere was slowly photodissociated by UV from the Sun into H and O, and the H atoms escaped, explaining why Venus atmosphere contains no traces of water today. With the water removed, and all the CO_2 liberated from the rocks and in the atmosphere, Venus temperature would have leveled off to equal today's value.

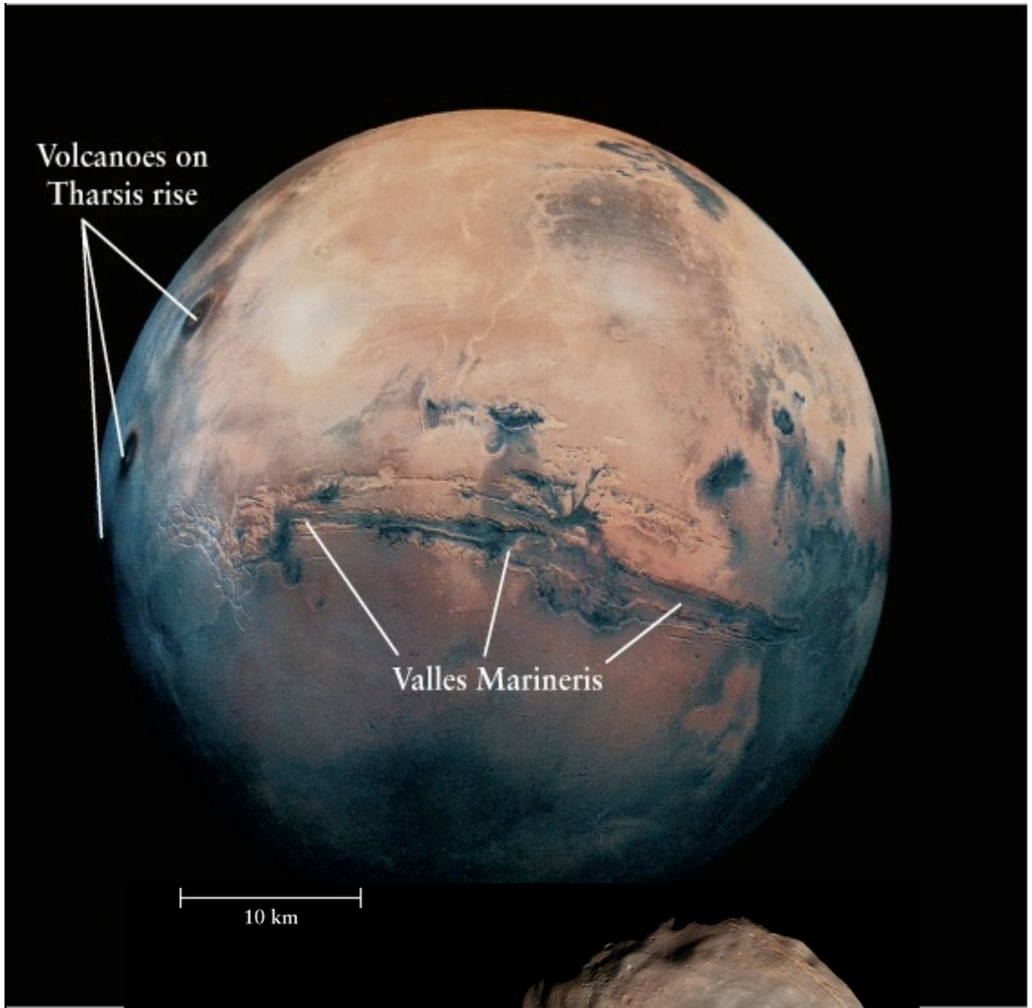
Mars – key facts

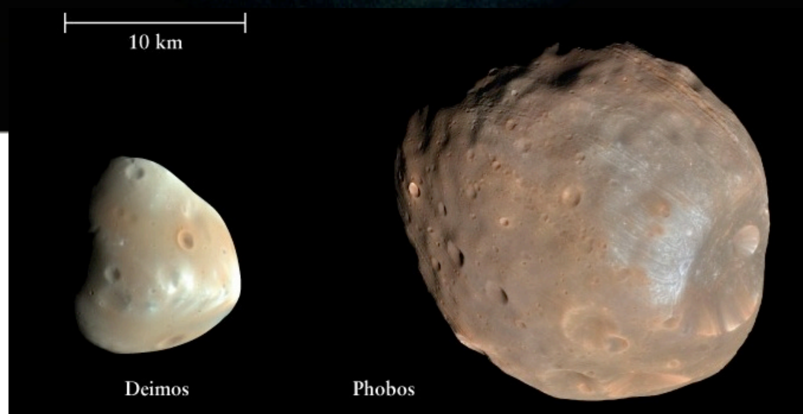
Mars is a dry, wind-blown planet and hosts the largest volcano in the Solar System (Olympus Mons – 24 km high) and two moons (Phobos & Deimos)

It has a thin CO_2 atmosphere with pressure at surface ~ 0.6% of Earth's. Water can only exist in either solid or vapour state at this low pressure.

The spin axis is tilted 25^o giving rise to strong seasonal variations. Polar caps consisting of H_2O and frozen CO_2 form. Freezing of the CO_2 atmosphere causes large changes is atmospheric pressure, driving seasonal winds and dust storms

The surface is highly cratered, including previously volcanically active regions, indicating an ancient surface and long-extinct volcanism.





Images from orbiting space-craft and in-situ rovers indicate presence of river valleys and sedimentary rocks. Mars had a warmer, denser atmosphere in the past and running water on its surface. Radar has detected water at the poles and as sub-surface permafrost.

Mars – key facts

Mars is a dry, wind-blown planet and hosts the largest volcano in the Solar System (Olympus Mons – 24 km high) and two moons (Phobos & Deimos)

It has a thin CO_2 atmosphere with pressure at surface ~ 0.6% of Earth's. Water can only exist in either solid or vapour state at this low pressure.

The spin axis is tilted 25° giving rise to strong seasonal variations. Polar caps consisting of H_2O and frozen CO_2 form. Freezing of the CO_2 atmosphere causes large changes is atmospheric pressure, driving seasonal winds and dust storms

The surface is highly cratered, including previously volcanically active regions, indicating an ancient surface and long-extinct volcanism.

Table 11-3 Mars Data

Average distance from the Sun:	1.524 AU = 2.279×10^8 km
Maximum distance from the Sun:	1.666 AU = 2.492×10^8 km
Minimum distance from the Sun:	1.381 AU = 2.067×10^8 km
Eccentricity of orbit:	0.093
Average orbital speed:	24.1 km/s
Orbital period:	686.98 days = 1.88 years
Rotation period:	$24^h\ 37^m\ 22^s$
Inclination of equator to orbit:	25.19°
Inclination of orbit to ecliptic:	1.85°
Diameter (equatorial):	6794 km = 0.533 Earth diameter
Mass:	6.418×10^{23} kg = 0.107 Earth mass
Average density:	3934 kg/m^3
Escape speed:	5.0 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.15
Surface temperatures:	Maximum: 20°C = 70°F = 293 K Mean: −23°C = −10°F = 250 K Minimum: −140°C = −220°F = 133 K
Atmospheric composition (by number of molecules):	95.3% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 0.03% water vapor (H_2O) 2% other gases

Images from orbiting space-craft and in-situ rovers indicate presence of river valleys and sedimentary rocks. Mars had a warmer, denser atmosphere in the past and running water on its surface. Radar has detected water at the poles and as sub-surface permafrost.

Mars' atmospheric evolution – runaway ice-house effect

Evidence for running water on Mars points to an earlier period when the atmosphere was substantially warmer and denser.

The carbon cycle maintains an equilibrium in atmospheric CO_2 abundance.

Precipitation (rain) washes CO_2 out of the atmosphere, where it forms carbonate rocks on the surface. Volcanic activity releases CO_2 into the atmosphere.

The small size of Mars caused it to cool relatively quickly, allowing a deep crust to form that switches off volcanic activity. Continued precipitation reduced the concentration of CO_2 from the atmosphere, reducing the the greenhouse effect. The consequent reduction in temperature led to increased precipitation (cold air precipitates a greater amount of water vapour), increasing the rate of loss of CO_2 and H_2O from the atmosphere. This cycle reinforces itself leading to a reduction in the atmospheric density and surface temperature.

A reduced atmospheric density also allows greater penetration of UV photons from the Sun. These dissociate molecules such as $N_{2,}$ CO_2, and H_2O. Dissociation combined with the energy input from the penetrating UV photons leads to atmospheric escape and further reduction of the atmospheric density.

Atmospheric loss of H atoms left behind oxygen that reacted with iron bearing compounds on the surface leading to the formation of haematite