Objects of the Solar System

8

Our solar system contains eights planets orbiting the Sun, dwarf planets, asteroids, comets and meteors, as well satellites orbiting planets and smaller ring particles. In this chapter the properties of these different object are discussed.

8.1 Mercury

Mercury is the innermost planet of the solar system. Its diameter is 4800 km. Mercury is always found in the vicinity of the Sun; its maximum elongation is only 28°. Observations are difficult because Mercury is always seen in a bright sky and close to the horizon. Mercury has phases like the Moon. When it is closest to the Earth in the inferior conjunction, the dark side of the planet is toward us. And when the whole illuminated hemisphere is towards the Earth Mercury is behind the Sun and farthest from us. A couple of times in a century Mercury transits the solar disk (Sect. 7.5). Observations during transits have shown that Mercury does not have an appreciable atmosphere.

The first maps of Mercury were drawn at the end of the 19th century but the reality of the details was not confirmed. As late as in the beginning of the 1960's, it was believed that Mercury always turns the same side toward the Sun. However, measurements of the thermal radio emission showed that the temperature of the night side is too high, about 100 K, instead of almost absolute zero. Finally, the rotation period was established by radar.

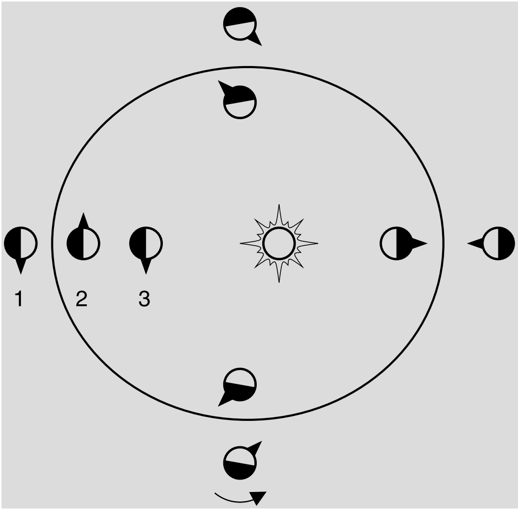

Fig. 8.1 Length of day in Mercury. The positions of Mercury during the first revolution are shown outside the ellipse. Upon returning to the aphelion, the planet has turned 540° ($1\frac{1}{2}$ revolutions). After two full cycles the planet has rotated three times around its axis and the same side points toward the Sun. The length of the day is 176 d, longer than on any other planet

One revolution around the Sun takes 88 days. The rotation period is two-thirds of this, 59 days. This means that every second time the planet is in, say, perihelion, the same hemisphere faces the Sun (Fig. 8.1). This kind of spin–orbit coupling can result from tidal forces exerted by a central body on an object moving in a fairly eccentric orbit.

Re-examination of old observations revealed why Mercury had been presumed to rotate synchronously. Owing to its geometry, Mercury is

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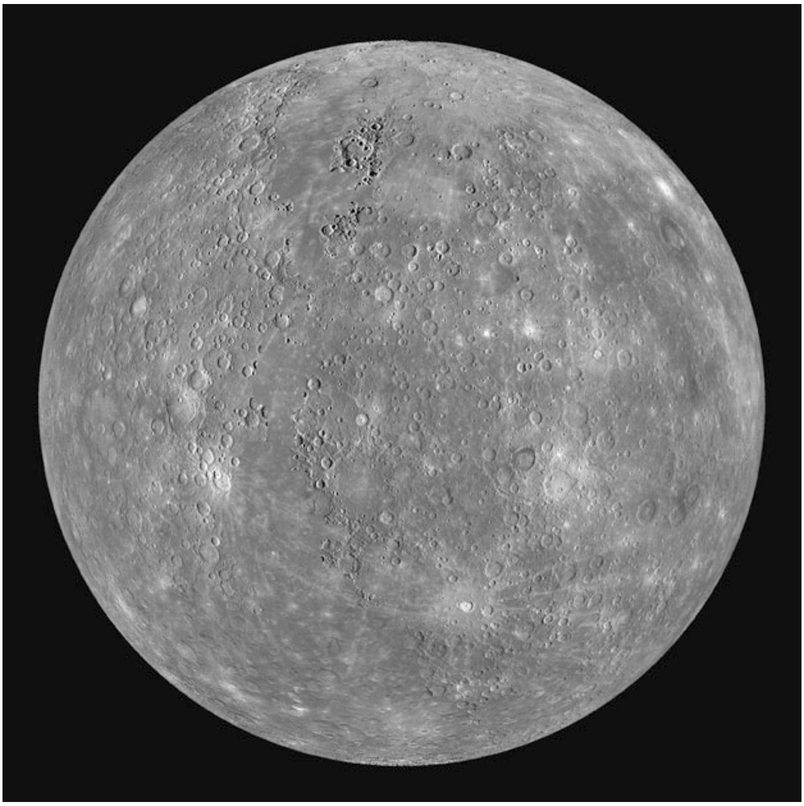


Fig. 8.2 Mercury imaged by the Messenger probe. The centre of *the upper mosaic image* is at the intersection of the equator and meridian of the planet. The ray crater Debussy is near the lower edge. The mosaic image *on the opposing page* shows the opposite hemisphere. *The circled area* is the over 1500 km wide Caloris basin. *Below* it a more easily distinguished 225 km wide circular depression is the Mozart basin. (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington). *Below*: A detail of the surface photographed by Mariner 10 during it's first encounter with Mercury in 1974. The scarp is about 350 kilometres long and transects two craters 35 and 55 kilometres in diameter. It is up to 2 km high in some places and it appears to be a fault produced by compression of the crust. (NASA/JPL/Northwestern University)

easiest to observe in spring and autumn. In six months, Mercury orbits twice around the Sun, rotating exactly three times around its own axis. Consequently, during observations, the same side was always facing the Sun! The details visible on the surface are very obscure and the few exceptional observations were interpreted as observational errors.

Since the rotation period of Mercury is $\tau_\star = 58.6$ d ans the orbital period $P = 87.97$ d, (2.43) shows that the length of day is $\tau = 176$ d, or two Mercury's years. The rotation axis is almost perpendicular to the orbital plane.

The mean distance from the Sun is 0.39 au. The eccentricity of the orbit is 0.21, which means that the distance varies between 0.31 and 0.47 au. Because of the high eccentricity, the surface temperature of the subsolar point varies substantially: at the perihelion, the temperature is about 700 K; at the aphelion, it is 100 K lower. Temperature variations on Mercury are the most extreme in the solar system because in the night side the temperature drops below 100 K.

The precession of the perihelion of Mercury is more than 0.15° per century. When the Newtonian perturbations are subtracted, there remains an excess of 43″. This is fully explained by the general theory of relativity. The explanation of the perihelion precession was one of the first tests of the general theory of relativity.

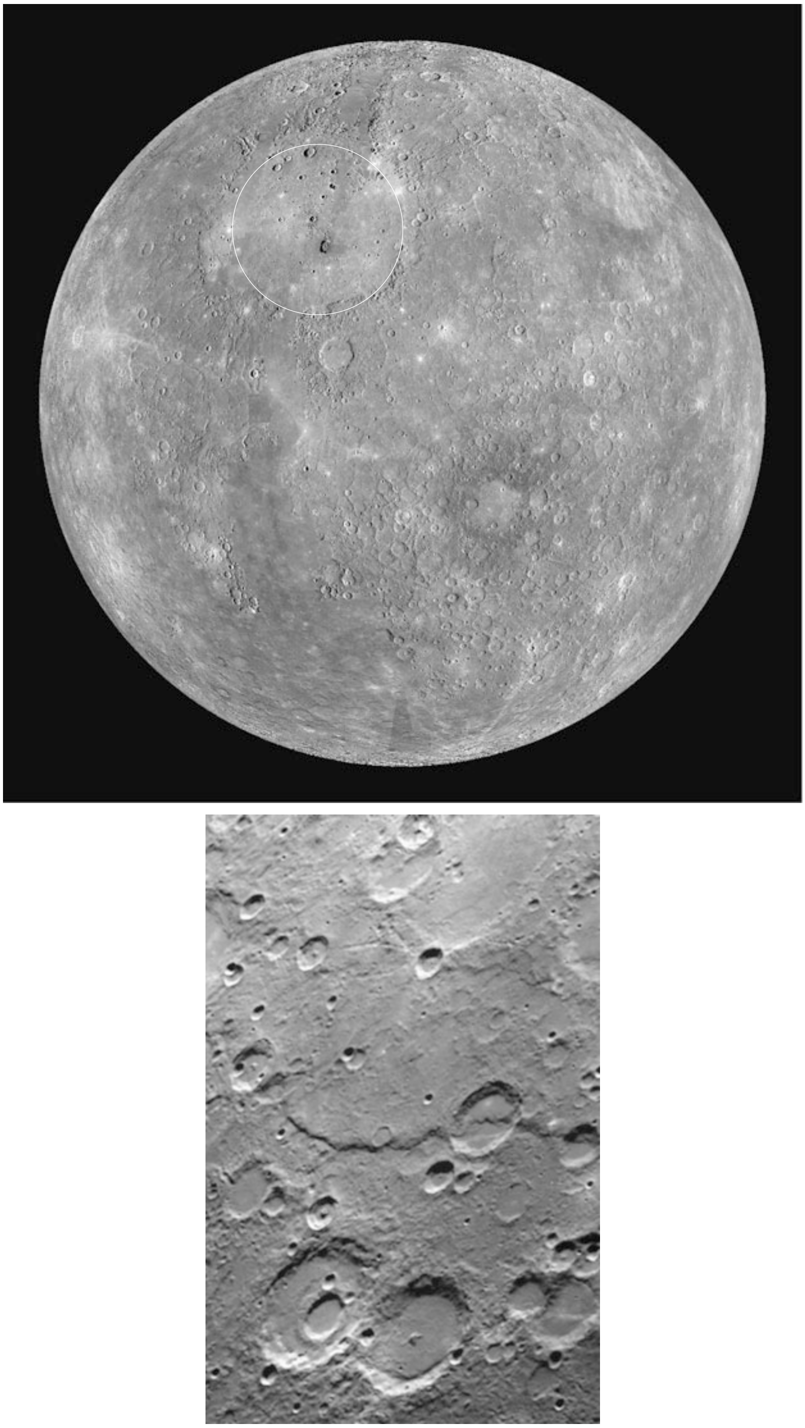


Fig. 8.2 (Continued)

The first spacecraft studying Mercury was the US *Mariner 10* that passed Mercury three times in 1974 and 1975. The orbital period of Mariner 10 around the Sun was exactly twice the period of Mercury. The two-thirds-factor meant that the same side of the planet was illuminated during every fly-by! The other side remained unknown. It was only in 2004 that the *Messenger* (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) mapped the whole surface of Mercury, first on three fly-bys in 2008–2009 and from an orbit around Mercury in 2011–2015. The next probe will be the *BepiColombo* built by the European Space Agency ESA. The launch is scheduled for 2017, and after several fly-bys it should settle on an orbit around Mercury in 2024.

Since Mercury has no satellites, precise values of its mass and density could be calculated only after Mariner's flight.

The Mariner 10 data revealed a moon-like landscape. Mercury's surface is covered by impact craters (Fig. 8.2), indicating that the surface is old and undisturbed by continental drift or volcanic eruptions. There are some signs of volcanic activity, but they are very old, possibly over a billion years.

There are also some circular formations resembling lunar maria, formed by impacts of larger object and filled by lava seeping from the interior of the planet. The largest circular area is the 1500 km wide *Caloris Basin*. The shock wave produced by the Caloris impact was focused to the antipodal point, breaking the crust into complex blocks in a large area, the diameter of which is hundreds of kilometers. This region is named the *Weird Terrain*.

There are also faults that were possibly produced by compression of the crust. The volume change probably was due to the cooling of the planet.

Mercury's relatively small size and proximity to the Sun, resulting in low gravity and high temperature, are the reasons for its lack of atmosphere. There is a layer made up of atoms blasted off the surface by the solar wind. The tenuous "atmosphere" is composed mainly of oxygen, nitrogen, and helium. The atoms quickly escape into space and are constantly replenished.

Due to the absence of an atmosphere, the temperature on Mercury drops very rapidly after sunset. The rotational axis is almost perpendicular to the orbital plane; therefore it is possible that, close to the poles, there are areas where the temperature is permanently below the freezing point. Radar echos from the surface of Mercury show several anomalously reflective and highly depolarised features at the north and south poles. Some of these areas can be addressed to the craters, the bottoms of which are permanently in shadow. One candidate of the radar-bright features is water ice that has survived in the permanent shadow.

Existence of ice was confirmed by the Messenger probe. At the bottoms of some craters the temperature never exceeds 100 K. The ice is covered by regolith that prevents the ice from sublimating and evaporating to space. It has been estimated that the total amount of ice could be even 1/1000 of the ice in the Antarctic.

It has been said that Mercury looks like the Moon from the outside but is terrestrial from the inside. According to theoretical models, the internal structure is similar to that of the Earth but the core is substantially larger. The density of the planet is about the same as that of the Earth, indicating that the size of the Fe–Ni core is roughly about 75 % of the planet's radius. The thickness of the mantle is only 500–700 km and that of the crust 100–300 km.

Due to the vicinity of the Sun, the temperature of the primeval nebula at the distance of Mercury was quite high during planetary formation. Thus the relative abundances of the volatile elements are smaller than on any other terrestrial planet.

The Sun creates strong tides on Mercury, with main periods of 44 and 88 days. Measuring the tidal variation is difficult due to its slowness, but it has bee calculated that the vertical motion near the equator could be a couple of meters. (The crust of the Earth moves about 30 cm due to the lunar tides.)

Mercury has a weak magnetic field, about 1 % as strong as that of the Earth. The presence of the magnetic field is unexpected because Mercury is much smaller than the Earth and it rotates slowly. According to the dynamo theory, a mag-

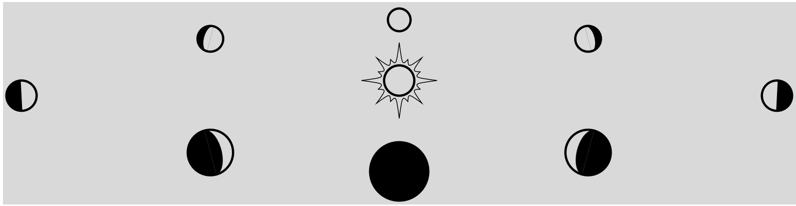


Fig. 8.3 The phases of Venus were discovered by Galileo Galilei in 1610. This drawing illustrates how the apparent size of Venus changes with phase. The planet is far behind the Sun when the illuminated side faces the Earth

netic field is generated by flows in a liquid, electrically conducting core. The magnetic field cannot be a remnant from ancient times, since the internal temperature of the planet must have exceeded the critical Curie point. Therefore, it must be assumed that a part of the core is molten. Possibly the deformations caused by tides and the friction releasing heat keep the core molten and maintain mass flows generating the magnetic field.

8.2 Venus

Venus is the brightest object in the sky, after the Sun and the Moon. Like Mercury, Venus can be seen only in the morning or in the evening sky. Sometimes it is possible to see Venus even if the Sun is above the horizon, if its exact position is known. In antiquity, Venus was thought to be two different planets, *Hesperos* and *Phosphorus*, evening star and morning star.

The maximum elongation of Venus is about 47°. Venus is a remarkable object when shining in the dark sky at its brightest, 35 days before or after the inferior conjunction, when one-third of the surface is seen lit (Fig. 8.3).

At the inferior conjunction, the Earth–Venus distance is only 42 million km. The diameter of Venus is about 12,000 km, which means that the apparent diameter can be as large as one arc minute. Under favourable conditions it is even possible to see the shape of the crescent Venus with binoculars. At the superior conjunction, the apparent diameter is only 10 arc seconds.

Venus is covered by clouds. Its surface is nowhere visible; only featureless yellowish cloud tops can be seen (Fig. 8.4). Therefore, even the rotation period was long unknown.

The chemical composition of the Venusian atmosphere was known prior to the space age. Spectroscopic observations revealed CO_2, but no oxygen. About 98 % of the atmosphere is carbon dioxide. Some clues about the cloud composition were obtained from polarimetric observations. The famous French planetary astronomer *Bernard Lyot* made polarimetric observations in the 1920's, but not until decades later was it realised that his observations could be explained by assuming that light was scattered by liquid spherical particles whose index of refraction is 1.44. This is significantly higher than the index of refraction of water, 1.33. Moreover, water is not liquid at that temperature. A good candidate was sulphuric acid H_2SO_4. Later, spacecraft confirmed this interpretation.

In 1962, radar measurements revealed that the rotation period is 243 days in a retrograde direction, i.e. opposite to the rotation of other planets. The axis of rotation is almost perpendicular to the orbital plane; the inclination is 177°. The reason for the strange rotation is not known.

The temperature at the cloud tops is about 250 K. Because the Bond albedo is as high as 75 %, the surface temperature was believed to be moderate, even suitable for life. Opinions changed dramatically when thermal radio emission was measured at the end of the 1950's. This emission originates on the surface of the planet and can penetrate the clouds. The surface temperature turned out to be 750 K, well above the melting point of lead. The reason for this is the greenhouse effect. The outgoing infrared radiation is blocked by atmospheric carbon dioxide. The pressure of the atmosphere at the surface is 90 atm.

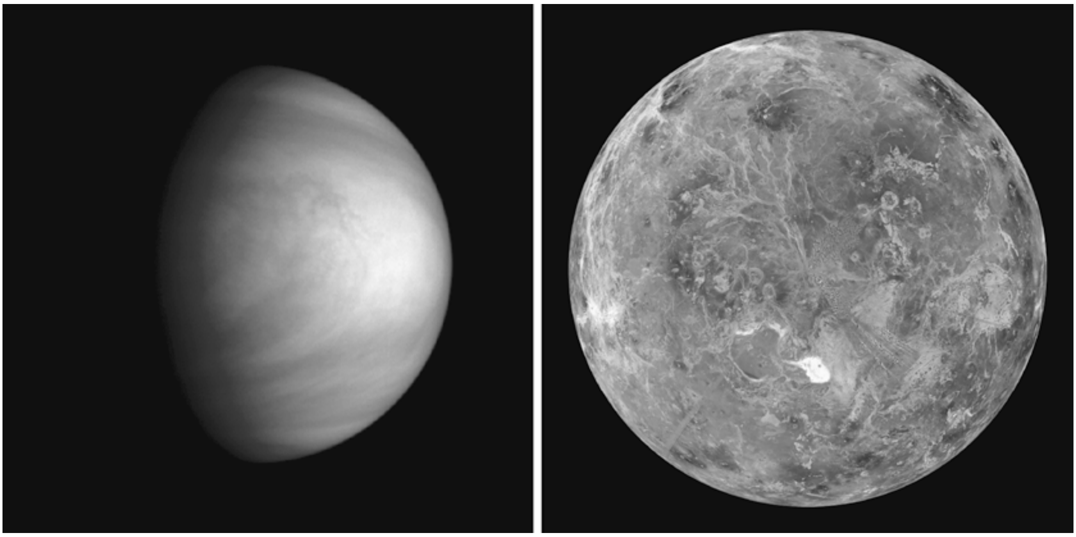


Fig. 8.4 *Left:* Venus in visible light imaged by the Galileo orbiter in February 1990. The cloud features are caused by winds that blow from east to west at about 100 m/s. *Right:* The northern hemisphere of Venus in a computer-generated picture of the radar observations. The north pole is at the centre of the image of the Magellan synthetic aperture radar mosaic. (NASA/JPL)

Mariner 2 (1962) was the first spacecraft to encounter the planet. Five years later, the Soviet Venera 4 sent the first data from below the clouds, and the first pictures of the surface were sent by Venera 9 and 10 in 1975. The first radar map was completed in 1980, after 18 months of mapping by the US Pioneer Venus 1. The best and the most complete maps (about 98 % of the planet's surface) were made using the synthetic aperture radar observations of the Magellan spacecraft in 1990–1994. The resolution of the maps is as high as 100 m and the elevation was measured with a resolution of 30 metres. The Venus Express launched by ESA studied Venus from an orbit during 2006–2014.

Radar mappings revealed canyons, mountains, craters, volcanoes and other volcanic formations (Fig. 8.5). The surface of Venus is covered by about 20 % of lowland plains, 70 % of gently rolling uplands and lava flows, and 10 % of highlands.

There are only few major highland areas. The largest continent, *Aphrodite Terra*, is close to the equator of Venus; its size is similar to South America. Another large continent at the latitude 70°N is called *Ishtar Terra*, where the highest mountain on Venus, the 12 km high *Maxwell Montes* is situated. (IAU has decided that the Venusian nomenclature has to be feminine. Maxwell Montes, after the famous physicist James Clerk Maxwell, is an exception.)

On Venus there are volcanic features all over the surface. There is no evidence of massive tectonic movement although local deformations can exist. Small volcanoes are evenly distributed but big ones are concentrated mainly on highlands. The origin of the latter may resemble that of the Hawaiian volcanoes: the volcanoes are located above a "hot spot" of the mantle. in a place where currents of the mantle move hot magma towards the surface.

Venus has more volcanoes than any other planet in the solar system. Over 1500 major volcanoes or volcanic features are known, and there may even be one million smaller ones. Most are shield volcanoes, but there are also many complex features. None are known to be active at present, although large variations of sulphur dioxide in the atmosphere may indicate that some volcanoes are active.

Almost all volcanism on Venus seems to involve fluid lava flows without any explosive erup-

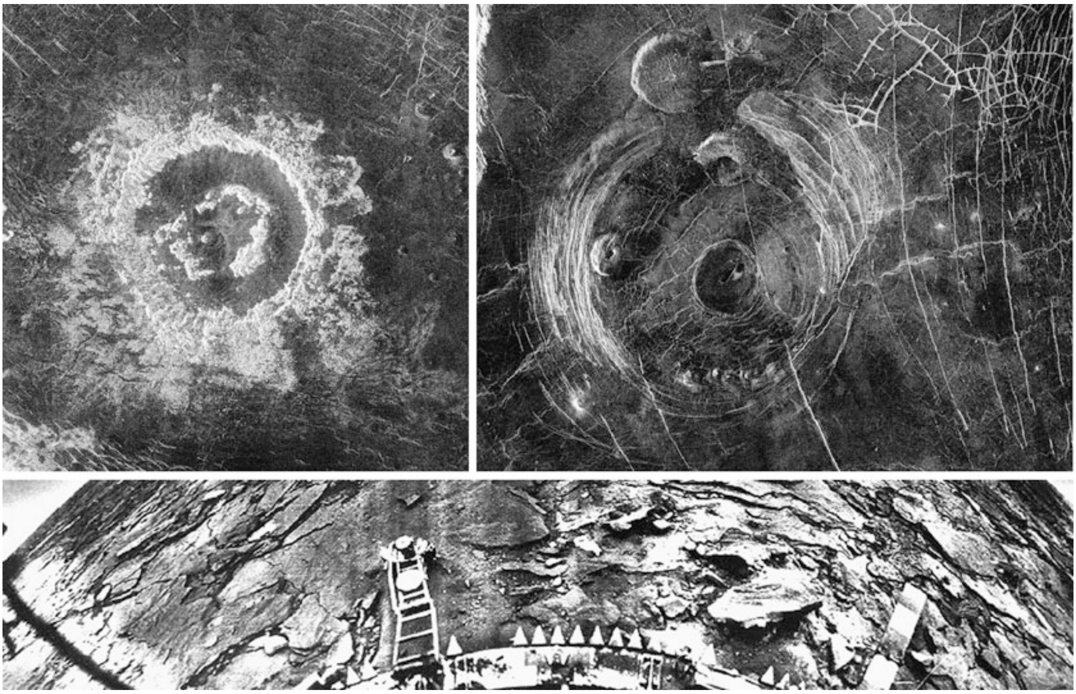


Fig. 8.5 Surface features of Venus. (*Top left*): A Magellan image of a 50 km peak-ring crater Barton at 27.4°N and 337.5°E. (*Top right*): A Magellan radar image of a region 300 km across, located in a vast plain to the south of Aphrodite Terra. The large circular structure near the centre of the image is a corona, approximately 200 km in diameter. North of the corona is a 35 km flat-topped volcanic construct known as a pancake dome. Complex fracture patterns like in the upper right of the image are often observed in association with coronas and various volcanic features. (NASA/JPL). (*Bottom*): The surface of Venus photographed by the Venera 14 lander in March 1982

tions. Due to the high air pressure, Venusian lavas need a much higher gas content than the Earth lavas to erupt explosively. The main gas driving lava explosions on the Earth is water vapour, which does not exist on Venus.

Flat-topped volcanic constructs known as *pancake domes* are probably formed by the eruption of an extremely viscous lava. A *corona* is a circular trench surrounding an elevated plain, the diameter of which can be as big as several hundreds of kilometres. They are possibly examples of local hot spots, mantle upwellings that have expanded and formed bulges. When the flow has stopped, the bulge has sunk and formed a set of ring mountains.

In other places fluid lava flows have produced long, sinuous channels extending for hundreds of kilometres.

Venus has no large scale tectonic activity. The reason may be the thinner and weaker crust and lack of water; therefore there are no large subduction zones between continents. Instead, the crust can consist of local zones only. Since the internal heat cannot flow out like on the Earth, the crust will warm up until at a critical temperature it will collapse and be renewed in hundred million years. The last time this happened was about 500 million years ago.

Most of the Venusian *impact craters* are undeformed. This indicates that the Venusian surface must be young because erosion, volcanism and tectonic forces should affect the craters, too. Resurfacing processes may frequently cover the old craters, and all craters visible are therefore young, presumably less than 500 million years. There are no impact crates smaller than a few kilometers because smaller meteoroids are burned in the thick atmosphere.

The Earth and Venus are almost equal in size, and their interiors are assumed to be similar.

Venus has an iron core about 3000 km in radius and a molten rocky mantle covering the majority of the planet. Probably due to its slow rotation, however, Venus has no magnetic field. The analyses made by the Venera landers have shown that the surface material of Venus is similar to terrestrial granite and basalt.

About 1 % of the incident light reaches the surface of Venus; this light is deep red after travelling through clouds and the thick atmosphere. Most of the incident light, about 75 %, is reflected back from the upper layers of clouds. The absorbed light is emitted back in infrared. The carbon dioxide atmosphere very effectively prevents the infrared radiation from escaping, and the temperature had not reached the equilibrium until at 750 K.

In spite of the thick layer of clouds, the visibility on the surface is several kilometres, and even in the clouds, a few hundred metres. Therefore, the clouds are relatively transparent. The densest clouds are at a height of 50 km, but their thickness is only 2–3 km. Above this, there are haze-like layers which form the visible "surface" of the planet. The uppermost clouds move rapidly; they rotate around the planet in about 4 days, pushed by strong winds powered by the Sun. The flow patterns of the clouds are best visible in ultraviolet light. The sulphuric acid droplets do not rain on the Venusian surface but they evaporate in the lower atmosphere before reaching the surface.

Venus' atmosphere is very dry: the amount of water vapour present is only 1/1,000,000 of that in the Earth's atmosphere. One possible explanation is that, due to solar UV radiation, the water has dissociated to hydrogen and oxygen in the upper layers of the atmosphere, the former escaping into interplanetary space.

Venus has no satellites.

8.3 The Earth and the Moon

The third planet from the Sun, the *Earth*, and its satellite, the *Moon*, form almost a double planet. The relative size of the Moon is larger than that of any other satellite, excluding the moon of the dwarf planet Pluto. Usually satellites are much smaller than their parent planets.

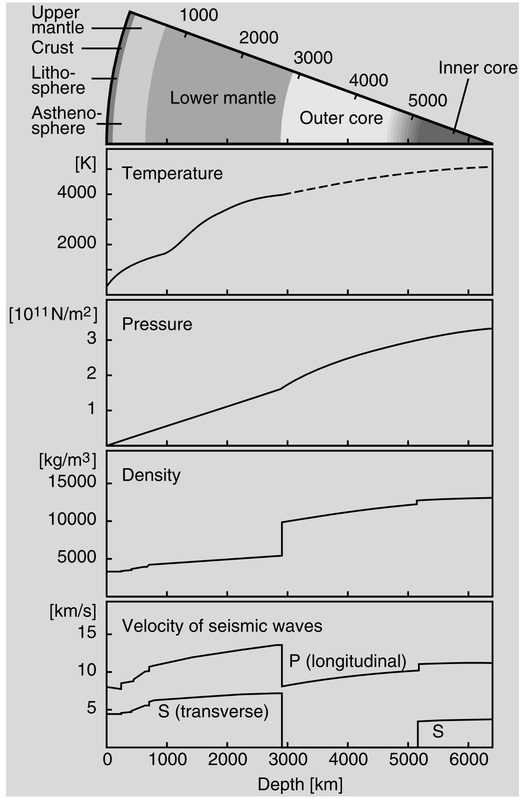


Fig. 8.6 Internal structure of the Earth. The speed of the seismic waves, density, pressure, and temperature are shown as a function of depth. The crust, lithosphere, lower mantle and inner core are solid, the outer mantle is molten and the asthenosphere is partly molten

The Earth is a unique body, since a considerable amount of free water is found on its surface. This is possible only because the temperature is above the freezing point and below the boiling point of water and the atmosphere is thick enough. The Earth is also the only planet where life is known to exist. (Whether it is intelligent or not is yet to be resolved...). The moderate temperature and the water are essential for terrestrial life, although some life forms can be found in extreme conditions.

The diameter of the Earth is 12,000 km. At the centre, there is an iron–nickel core where the temperature is 5000 K, the pressure 3×10^{11} N m^{-2} and the density 12,000 kg m^{-3} (Fig. 8.6).

The core is divided into two layers, *inner* and *outer core*. The inner core, below 5150 km comprises only of 1.7 % of the mass of the Earth. It is solid because of high pressure. The nonexistence of the seismic transverse S waves below a depth of 2890 km indicates that the outer core is molten. However, the speed of the longitudinal P waves change rapidly at a depth of 5150 km showing an obvious phase transition. It has been discovered that the solid inner core rotates with respect to the outer core and mantle.

The outer core comprises about 31 % of the mass of the Earth. It is a hot, electrically conducting layer of liquid Fe–Ni where the convective motions take place. There are strong currents in the conductive layer that are responsible for the magnetic field.

Between the outer core and the lower mantle there is a 200 km thick transition layer. Although this *D″ layer* is often included as a part of the lower mantle, seismic discontinuities suggest that it might differ chemically from the lower mantle.

A silicate *mantle* extends from 2890 km upward up to a depth of few tens of kilometres. The part below 650 km is often identified as the *lower mantle*. It contains about 49 % of the mass and is composed mainly of silicon, magnesium, and oxygen but some iron, calcium, and aluminium may also exist. The major minerals are olivine $(Mg,Fe)_2SiO_4$ and pyroxene $(Mg,Fe)SiO_3$. Under pressure the material behaves like a viscous liquid or an amorphous medium, resulting in slow vertical flows.

Between the lower and upper mantle there is a 250 km thick *transition region* or *mesosphere*. It is the source of basaltic magmas and is rich in calcium and aluminium. The upper mantle, between some tens of kilometres down to 400 km contains about 10 % of the mass. Part of the upper mantle, called the *asthenosphere*, might be partially molten.

A thin *crust* floats on the mantle. The thickness of the crust is only 10–65 km; it is thickest below high mountain ranges such as the Himalayas and thinnest below the mid-ocean basins. The seismic discontinuity showing the border between the crust and mantle was discovered in 1909 by the Croatian scientist *Andrija Mohorovičić*, and it is now known as the *Moho discontinuity*.

The basaltic *oceanic crust* is very young, mostly less than 100 million years and nowhere more than 200 Ma. It is made through tectonic activity at the *mid-ocean ridges*, where new material is spreading out.

The *continental crust* is mainly composed of crystalline rocks that are dominated by quartz (SiO_2) and feldspars (metal-poor silicates). Because the continental crust is lighter than the oceanic crust (average densities are about $2700\ \mathrm{kg\,m^{-3}}$ and $3000\ \mathrm{kg\,m^{-3}}$, respectively), the continents are floating on top of other layers, and currently they are neither created nor destroyed.

The *lithosphere* is the rigid outer part of the Earth (crust and the topmost part of the upper mantle). Below that is the partially molten asthenosphere where the damping of seismic waves is stronger than in the rigid lithosphere.

The lithosphere is not a single rigid and seamless layer; instead it is divided into more than 20 individual plates. The *plate tectonics* ("continental drift") is powered by the motion of the material in the mantle (Fig. 8.7). New material is flowing up at the mid-ocean ridges, pushing the tectonic plates apart. New oceanic crust is generated at the rate of 17 $\mathrm{km^3}$ per year. The Earth is the only planet that shows any large-scale tectonic activity. The history of the motion can be studied by using e.g. the paleomagnetic data of magnetic orientation of crystallised rocks.

At the end of the Precambrian era, about 700 million years ago, more than half of the continents were together forming the continent known as *Gondwana*, containing Africa, South America, Australia and Antarctica. About 350 million years ago Gondwana was on the South Pole but it moved toward the equator before the final breakup. Mutual collisions formed new mountains and finally in the beginning of the Mesozoic era, about 200 million years ago, all the continents were joined into one supercontinent, *Pangaea*.

Quite soon the flow pattern in the mantle changed and the Pangaea broke up. The Atlantic Ocean is still growing and new material is flowing up at the *mid-Atlantic ridge*. North America is drifting away from Europe at the rate of a few centimetres per year (your fingernails are growing at the same speed). At the same time, parts of the Pacific oceanic plate are disappearing below other plates. When an oceanic crust is pushed

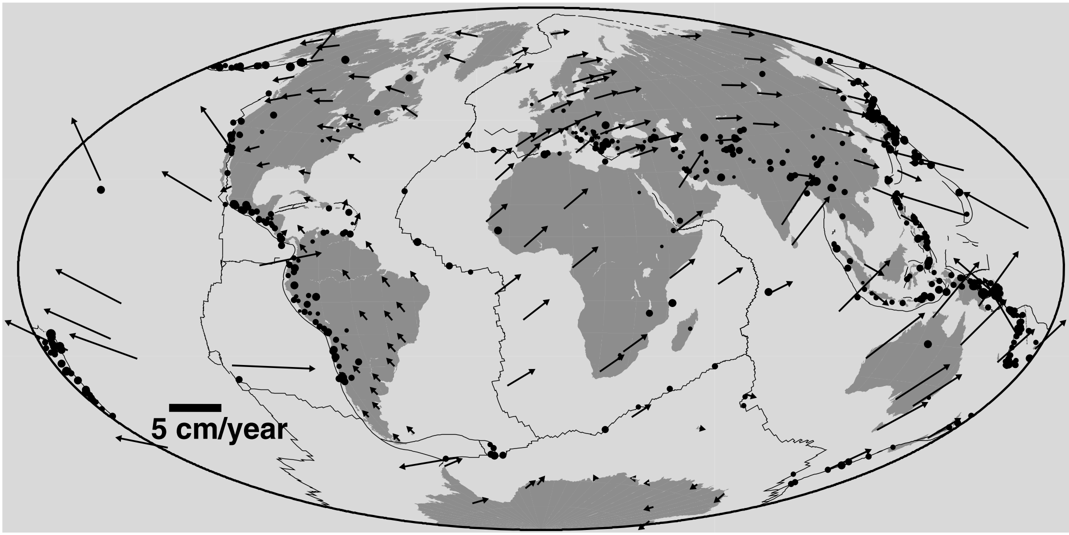


Fig. 8.7 The tectonic plates. The *dots* on the map indicate the location of earthquakes with magnitudes greater than 5 in the years 1980–1989. *Arrows* show the velocities observed with permanent GPS (Global Positioning System) tracking stations. The velocity scale is shown at *lower left*

below a continental crust, a zone of active volcanoes is created. The earthquakes in the *subduction zones* can even originate 600 km below the surface. In the mid-ocean ridges, the depth is only tens of kilometres.

Mountains are formed when two plates collide. The push of the African plate toward the Eurasian plate formed the Alps about 45 million years ago. The collision of the Indian plate created the Himalayas some 40 million years ago, and they are still growing. The plates can also move sideways. Earthquakes in such a fault usually occur in depths less than about 100 kilometres. An example is the San Andreas fault in California.

No other planet has such large scale tectonic activity. The interiors of Mars and Mercury are already too cold to maintain convection in their mantles. The structure of the crust of Venus is too weak to move large regions. Also, the free water of the Earth may be important in keeping up the plate tectonics.

The climate is an efficient factor reshaping the surface. The mountains created by collisions of tectonic plates are eroded already in a few hundred million years by temperature changes, rain, wind and ice. Impact crater disappear even faster, and many of the currently known craters have been found by local gravitational anomalies instead of geographical features.

Most of the Earth's surface is covered with water. The Earth is the only planet that currently has free running water. The water condensed from the water vapour released in volcanic eruptions. Depending on glaciation, the sea level ascends or descends by over 100 metres with respect to the solid ground. During the last ice age the sea level was 150 m below the current. Due to the melting of glaciers the sea level is rising by one millimetre per year, but the rate is increasing by the greenhouse effect.

Compared with the geological time scale the increase in the greenhouse effect caused by human activity is a very young phenomenon. Ice ages have come and gone in periods of a time scales of 100,000 years. The current warming of the climate is a temporary phenomenon, which, however, may have some effect on the beginning of the next ice age. Although the human activities have little effect from the geological point of view, they may have disastrous effects on the current biosphere.

The primordial atmosphere of the Earth was very different from the modern one; there was, for

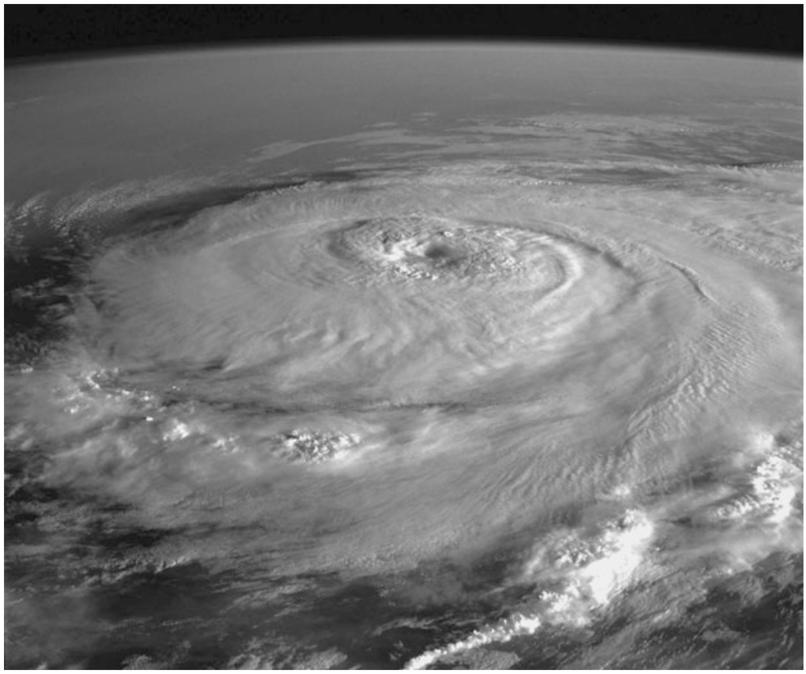


Fig. 8.8 Hurricane Elena in the Gulf of Mexico seen from the space shuttle Discovery in September 1, 1985. Wind speeds may exceed 170 km/h. Compare this to the Great Red Spot of Jupiter in Fig. 8.18. (NOAA)

example, no oxygen. Earlier it was assumed that the original atmosphere was reducing, but more recent studies seem to indicate that it was neutral. When organic chemical processes started in the oceans more than 2×10^9 years ago and reached the level of photosynthesis, the amount of oxygen rapidly increased (and was poison to the first forms of life!). The original carbon dioxide is now mainly concentrated in carbonate rocks, such as limestone, and the methane was dissociated by solar UV radiation. The current atmosphere has very little resemblance to the early atmosphere a couple of billion years ago.

The Earth's main atmospheric constituents are nitrogen (77 % by volume) and oxygen (21 %). Other gases, such as argon, carbon dioxide, and water vapour are present in minor amounts. The chemical composition is unchanged in the lower part of the atmosphere, called the *troposphere*. Most of the climatic phenomena occur in the troposphere, which reaches up to 8–10 km (Fig. 8.8). The height of the layer is variable, being lowest at the poles, and highest at the equator, where it can extend up to 18 km.

The layer above the troposphere is the *stratosphere*, extending up to 60 km. The boundary between the troposphere and the stratosphere is called the *tropopause*. In the troposphere, the temperature decreases 5–7 K/km, but in the stratosphere it begins to rise, due to the absorption of solar radiation by carbon dioxide, water vapour and ozone. The ozone layer, which shields the Earth from the solar UV radiation, is at a height of 20–25 km.

A total of 99 % of air is in the troposphere and stratosphere. The stratopause at a height of 50–60 km separates the stratosphere from the *mesosphere*.

The mesosphere extends up to 85 km. In this layer, the temperature decreases again, reaching the minimum of about −90 °C at the height of 80–90 km in the *mesopause*. Chemicals in the mesosphere are mostly in an excited state, as they absorb energy from the Sun.

Above the mesopause is the *thermosphere* that extends up to 500 kilometres. The temperatures increases with altitude and can be above 1200 °C at the height of 500 km. The gas is in the form of a fully ionised plasma. Therefore, the layer above the mesopause is also called the *ionosphere*.

The density of air below a height of 150 km is high enough to cause colliding meteoroids to

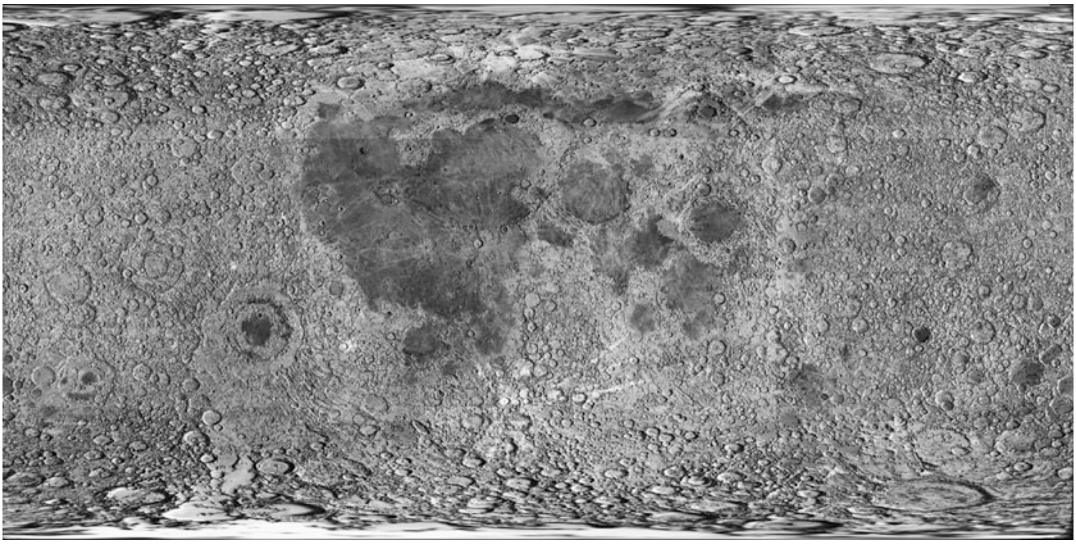


Fig. 8.9 A map of the Lunar surface, composed of images taken by the Clementine space probe in 1994. Note the large areas of maria in the Lunar near side, *at the centre* of the figure, as compared to the almost complete absence of the maria at the Lunar far side. (US Naval Observatory)

burn into ashes due to friction. It also plays an important role in radio communications, since radio waves are reflected by the ionosphere. Auroras are phenomena of the upper part of the ionosphere.

The thermosphere goes over into the *exosphere* at about 500 km. There the air pressure is much lower than in the best laboratory vacuums.

The magnetic field of the Earth is generated by flows in its core. The field is almost a dipole but there are considerable local and temporal variations. The mean field strength close to the equator is 3.1×10^{-5} Tesla (0.31 Gauss). The dipole is tilted 11° with respect to the Earth's axis, but the direction gradually changes with time. Currently the field is decreasing about 30 nT a year and moving counterclockwise; however, the angle between the magnetic axis and the rotation axis remains nearly constant. Moreover, the magnetic north and south poles have exchanged places several times during the past, once every 100,000–1,000,000 years. The last time this happened was about 780,000 years ago.

The Moon Our nearest neighbour in space is the *Moon* (Fig. 8.9). Its motion was described in Sect. 7.4. Dark and light areas are visible even with the naked eye. For historical reasons, the former are called seas or *maria* (from Latin, *mare*, sea, pl. maria). The lighter areas are uplands but the maria have nothing in common with terrestrial seas, since there is no water on the Moon. Numerous craters, all meteorite impacts, can be seen, even with binoculars or a small telescope. The lack of atmosphere, volcanism, and tectonic activity help to preserve these formations.

The Moon is the best-known body after the Earth. The first man landed on the Moon in 1969 during the *Apollo 11* flight. A total of over 2000 samples, weighing 382 kg, were collected during the six Apollo flights (Fig. 8.10). Moreover, the unmanned Soviet Luna spacecraft collected and returned about 310 grams of Lunar soil. Instruments placed on the Moon by the Apollo astronauts operated as long as eight years. These included seismometers, which detected moonquakes and meteorite impacts, and passive laser reflectors which made exact Earth–Moon distance measurements possible. The reflectors are still used for *Lunar laser ranging* (LLR) measurements.

Seismometric and gravimetric measurements have supplied basic information on the internal structure of the Moon. Moonquakes take place

Fig. 8.10 Apollo 17 astronaut Harrison Schmitt on the Moon in 1972. (NASA)

at a depth of 800–1000 km, considerably deeper than earthquakes, and they are also much weaker than on the Earth. Most of the quakes occur at the boundary of the solid mantle, the *lithosphere*, and the *asthenosphere* (Fig. 8.11). The transversal S waves cannot penetrate the asthenosphere, indicating that it is at least partially molten. Tidal forces may generate at least some of the moonquakes because most of them occur close to perigee or apogee.

Lunar orbiters have observed local mass concentrations, *mascons*, beneath the maria. These are large basaltic blocks, formed after the huge impacts which produced the maria. The craters were filled by lava flows during the next billion years or so in several phases. This can be seen, e.g. in the area of *Mare Imbrium*. Large maria were formed about 4×10^9 years ago when meteorite bombardment was much heavier than today. The last 3×10^9 years have been quite peaceful, without any major events.

The centre of mass is not at the geometric centre of the Moon but about 2.5 km away due to the 20–30 km thick basaltic plates below the large maria. Moreover, the thickness of the crust varies, being the thickest at the far side of the Moon, about 100 km. On the near side the thickness of the crust is about 60 km.

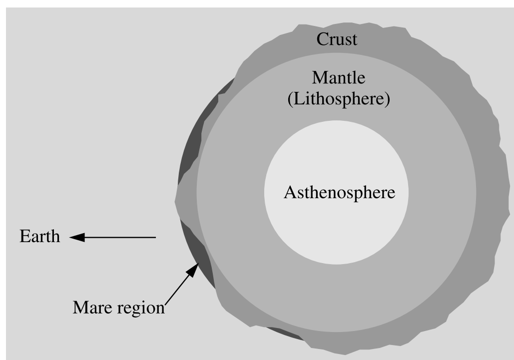


Fig. 8.11 Structure of the Moon. The height differences of the surface are strongly exaggerated

The mean density of the Moon is $3400\,\mathrm{kg\,m^{-3}}$, which is comparable to that of basaltic lavas on the Earth. The Moon is covered with a layer of soil with scattered rocks, *regolith*. It consists of the debris blasted out by meteorite impacts. The original surface is nowhere visible. The thickness of the regolith is estimated to be at least tens of metres. A special type of rock, *breccia*, which is a fragment of different rocks compacted and welded together by meteor impacts, is found everywhere on the Moon.

The maria are mostly composed of dark basalts, which form from rapid cooling of massive lava flows. The highlands are largely composed of *anorthosite*, an igneous rock that forms when lava cools more slowly than in the case of basalts. This implies that the rocks of the maria and highlands cooled at different rates from the molten state and were formed under different conditions.

Data returned by the *Lunar Prospector* and *Clementine* spacecraft indicated that water ice is present at both the north and south lunar poles. Data indicates that there may be nearly pure water ice buried beneath the dry regolith. The ice is concentrated at the bottoms of deep valleys and craters that are in a permanent shadow where the temperature is below 100 K.

The Moon has no global magnetic field. Some of the rocks have remanent magnetism indicating a possible global magnetic field early in the Moon's history. Without the atmosphere and magnetic field, the solar wind can reach the Moon's surface directly. The ions from the solar wind have embedded in the regolith. Thus samples returned by the Apollo missions proved valuable in studies of the solar wind.

The origin of the Moon is still uncertain; it has, however, not been torn off from the Earth at the Pacific Ocean, as is sometimes believed. The Pacific is less than 200 million years old and formed as a result of continental drift. Also, the chemical composition of the lunar soil is different from that of terrestrial material.

Recently it was suggested that the Moon was formed in the early stages of the formation of the Earth, when a lot of protoplanet embryos were orbiting the Sun. An off-axis collision of a Mars-size body resulted in ejection of a large amount of debris, a part of which then accreted to form the Moon. Differences in chemical compositions of the modern Earth and the Moon can be explained with the theory, as well as the orientation and evolution of the Moon's orbit and the Earth's relatively fast spin rate.

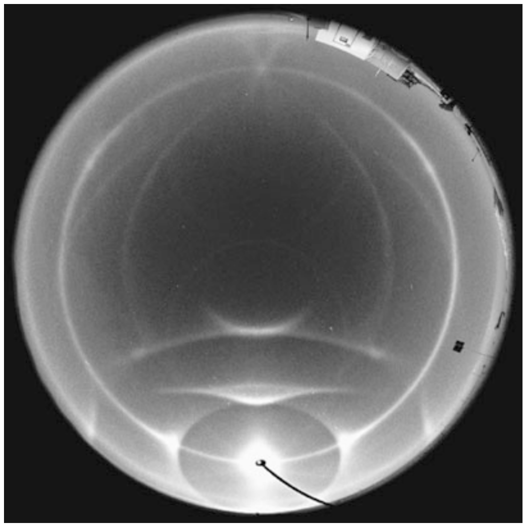
Box 8.1 (Atmospheric Phenomena) The best-known atmospheric phenomenon is the *rainbow*, which is due to the refraction of light from water droplets. The radius of the arc of the rainbow is about 41° and the width, 1.7°. The centre of the arc is opposite the Sun (or any other source of light). When the light is refracted inside a water droplet, it is divided into a spectrum, where the red colour is at the outer edge and blue, at the inner edge. Light can be reflected twice inside the droplet, resulting in a secondary rainbow outside the primary one. The colours of the secondary rainbow are in reversed order and its radius is 52°. A rainbow caused by the Moon is usually very weak and colourless, since the human eye is incapable of resolving colours of a dim object.

A *halo* results when the solar or lunar light is reflected from atmospheric ice crystals. The most common halo is a 22° arc or circle around the Sun or the Moon. Usually the halo is white, but occasionally even bright colours can be seen. Another common form is the side lobes which are at the same height as the Sun but at a distance of 22° from it. All other forms of halo are less common. The best "weather" for halos is when there are cirrostratus or cirrus clouds or an icy fog in the sky.

Noctilucent clouds are thin formations of cloud, at a height of approximately 80 km. The clouds contain particles, which are less than one micron in diameter, and become visible only when the Sun (which is below the horizon) illuminates the clouds. Most favourable conditions are at the northern latitudes during the summer nights when the Sun is only a few degrees below the horizon.

The night sky is never absolutely dark. One reason (in addition to light pollution) is the *airglow* or light emitted by excited atmospheric molecules. Most of the radiation is in the infrared domain, but e.g. the forbidden line of oxygen at 558 nm, has also been detected.

The same greenish oxygen line is clearly seen in *auroras*, which are formed at a height of 80–300 km. Auroras can be seen mainly from relatively high northern or southern lati-



Top: Halos are particularly common in Antarctic (photo Marko Riikonen).
Bottom: Auroras (photo Pekka Parviainen)

tudes because the Earth's magnetic field forces charged particles, coming from the Sun, close toward the magnetic poles. Alaska and northern Scandinavia are the best places to observe auroras. Occasionally, auroras can be seen as far south as 40°. They are usually greenish or yellow-green, but red auroras have been observed, too. They most commonly appear as arcs, which are often dim and motionless, or as belts, which are more active and may contain rapidly varying vertical rays.

Meteors (also called shooting stars although they have nothing to do with stars) are small grains of sand, a few micrograms or grams in weight, which hit the Earth's atmosphere. Due to friction, the body heats up and starts to glow at a height of 100 km. Some 20–40 km lower, the whole grain has burnt to ashes. The duration of a typical meteor is less than a second. The brightest meteors are called *bolides* (magnitude smaller than about −2). Even larger par-

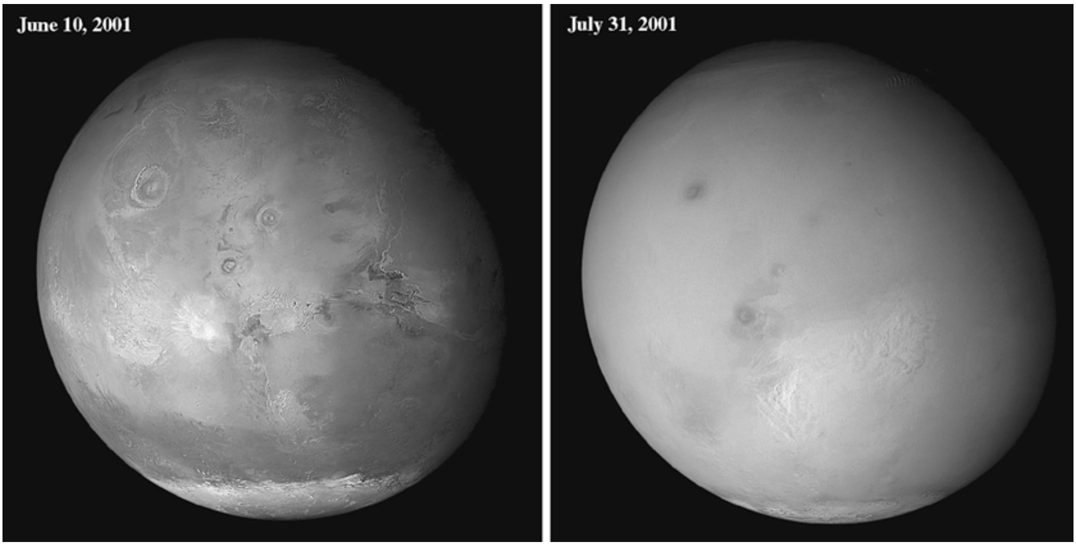


Fig. 8.12 Two pictures of Mars, taken by the Mars Global Surveyor in June and July 2001. The view from June (*left*) shows the Tharsis volcanic region, Valles Marineris and the late winter south polar cap. The view from July shows the same regions, but most of the details are hidden by dust storms and haze. (NASA/JPL/Malin Space Science Systems)

ticles may survive down to the Earth. Meteors are further discussed in Sect. 8.13.

8.4 Mars

Mars is the outermost of the terrestrial planets. Its diameter is only half of that of the Earth. Seen through a telescope, Mars seems to be a reddish disk with dark spots and white polar caps. The polar caps wax and wane with the Martian seasons, indicating that they are composed of ice. Darker areas were suspected to be vegetation. At the end of the 19th century, an Italian astronomer, *Giovanni Schiaparelli* claimed that there are canals on Mars.

In the United States, the famous planetary astronomer *Percival Lowell* studied the canals and even published books on the topic. Martians were also very popular in science fiction literature. Now the canals are known to be nonexistent, an optical illusion when the obscure details at the limit of visibility seem to form straight lines, canals. Finally, the first clear pictures by Mariner 4 in 1965 buried even the most optimistic hopes concerning life on Mars. Later spacecraft revealed more details of the planet.

Mars is a superior planet, which means that it is most easily observable when it is closest to the Earth, i.e. during opposition, when the planet is above the horizon all night long.

The rotation axis of Mars is tilted 25° to the ecliptic, about the same amount as the Earth's axis. A Martian day is only half an hour longer than a terrestrial day. Mars' orbit is significantly elliptical, resulting in temperature variations of about 30 °C at the subsolar point between the aphelion and perihelion. This has a major influence on the climate. Huge dust storms are occasionally seen on Mars (Fig. 8.12). Usually the storms begin when Mars is at the perihelion. Heating of the surface gives rise to large temperature differences that in turn cause strong winds. The wind-driven dust absorbs more heat and finally the whole planet is covered by a dust storm where the wind speeds exceed 100 m/s.

The atmosphere of Mars is mainly composed of carbon dioxide (95 %). It contains only 2 % nitrogen and 0.1–0.4 % oxygen. The atmosphere is very dry: if all the moisture were condensed on the surface, the water layer would be thinner than 0.1 mm. Even the minor amount of wa-

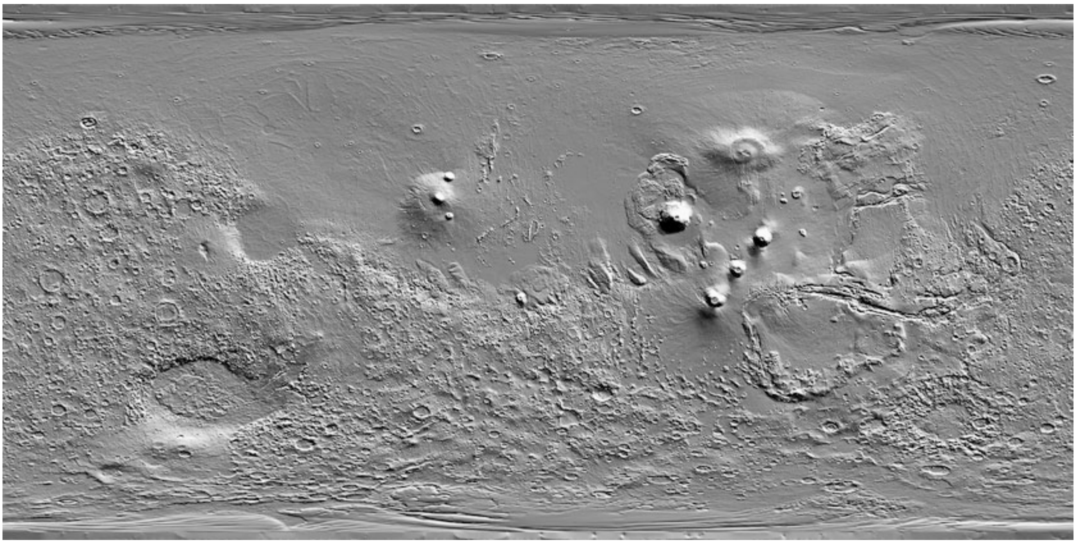


Fig. 8.13 A topographic shade map of Mars made from the Mars Global Surveyor data. The most prominent features are the large shield volcanoes in the northern hemisphere and the Valles Marineris canyon system that is more than 3000 km long and up to 8 km deep. (MOLA Science Team/NASA)

ter vapour is sufficient to occasionally form some thin clouds or haze.

The air pressure is only 5–8 mbar. A part of the atmosphere has escaped but it is probable that Mars never had a thick atmosphere. The primordial atmosphere of Mars was, however, somewhat similar to that of the Earth. Almost all of its carbon dioxide was used up to form carbonate rocks. Because there are no plate tectonics on Mars, the carbon dioxide was not recycled back into the atmosphere as on the Earth. Therefore, the greenhouse effect on Mars is significantly smaller than on the Earth.

Craters were already found in the first pictures. The southern hemisphere is especially marked by craters, indicating that the original surface is still visible there. The largest impacts, *Hellas* and *Argyre* are about 2000 km in diameter. On the other hand, the northern hemisphere has an abundance of large lava basins and volcanoes (Fig. 8.15). The surface is younger than in the southern hemisphere. The largest volcano, *Olympus Mons*, protrudes more than 20 km above the surrounding terrain. The diameter at the bottom is about 600 km.

There are no active volcanoes on Mars. The mare-like plains on Mars are of the same age as the Lunar maria, about 3×10^9 years old. Volcanism in the highland and mare-like plains stopped at that time, but the giant shield volcanoes are much younger, possibly $1–2 \times 10^9$ years. The youngest lava flows on Olympus Mons are possibly less than 100 million years old. Mars shows no sign of plate tectonics. It has no mountain chains, nor any global patterns of volcanism.

There are also several canyons, the largest of which is *Valles Marineris* (Fig. 8.13). Its length is 5000 km, width 200 km, and depth about 6 km. Compared with Valles Marineris, the Grand Canyon is merely a scratch on the surface.

Ancient riverbeds (Fig. 8.15), too small to be seen from the Earth, were also discovered by spacecraft. Rivers were probably formed soon after the formation of Mars itself, when there was a great deal of water and the atmospheric pressure and temperature were higher. At present, the temperature and air pressure on Mars are too low for free water to exist, although there have been speculations on warm weather cycles in the more recent history of the planet. The mean temperature is now below -50 °C and, on a warm summer day, the temperature can rise close to zero near the equator. Most of the water is contained in kilometres deep permafrost below the

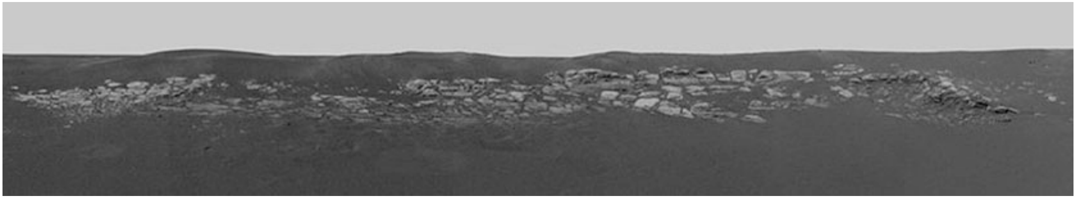


Fig. 8.14 The panorama taken by the Opportunity rover shows structures resembling terrestrial sediments that could have been caused by water. (NASA/JPL/Caltech)

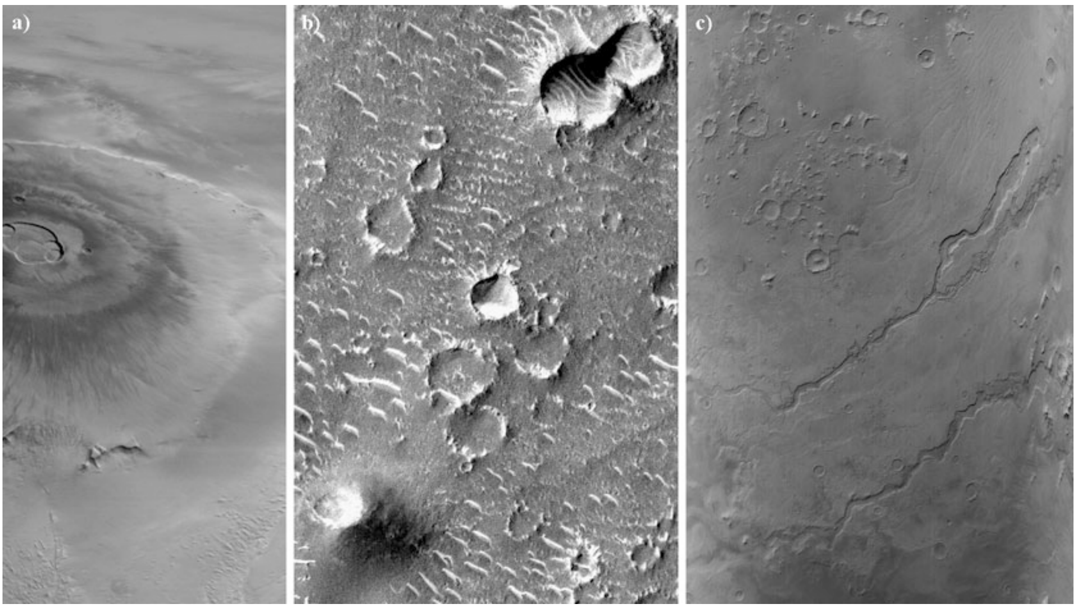


Fig. 8.15 Volcanoes, impact craters and rivers. (**a**) Mars Global Surveyor wide-angle view of Olympus Mons in April 1998. (**b**) Small impact craters and sand dunes with a resolution of 1.5 m per pixel. The picture covers a 1.5 km wide portion of Isidis Planitia. (**c**) Three major valley systems east of the Hellas plains. These valleys have probably been formed by large outbursts of liquid water but the age of the valleys is unknown. The valleys are all roughly 1 km deep and 10–40 km wide. The picture covers an area approximately 800 km across. (Mars Global Surveyor, 2000) (NASA/JPL/Malin Space Science Systems)

surface and in the polar caps. The theory was confirmed in 2002, when the Mars Odyssey spacecraft detected a large supply of subsurface water ice of a wide area near the south pole. The ice is mixed into the soil a meter below the surface. Two rovers, Spirit and Opportunity, operating on the Mars discovered in 2004 minerals like hematite and goethite which proved the existence of liquid water on the surface of Mars. The period when the liquid water existed is unknown.

The *polar caps* are composed both of water and carbon dioxide ice. The northern cap is almost season-independent, extending down to latitude 70°. On the other hand, the southern cap, which reaches to the latitude $-60°$ in the southern winter, disappears almost totally during the summer. The southern cap consists mostly of CO_2 ice. The permanent parts are of ordinary water ice, since the temperature, -73 °C, is too high for CO_2 ice. The water ice layers can be hundreds of metres thick.

The dark areas are not vegetation, but loose dust, moved around by strong winds. These winds raise the dust high into the atmosphere, colouring the Martian sky red. The Mars landers have re-

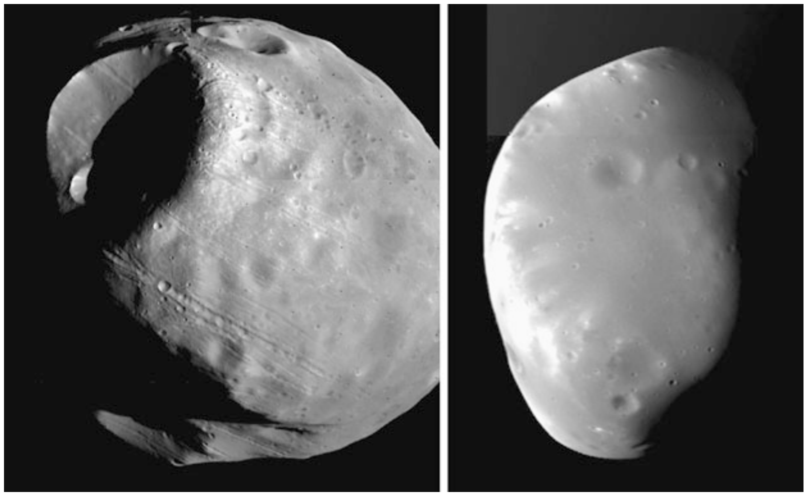


Fig. 8.16 Phobos (*left*) and Deimos, the two moons of Mars. They can be captured asteroids. (NASA)

vealed a reddish regolithic surface, scattered with boulders (Fig. 8.14). The red colour is caused mainly by iron oxide, rust; already in the 1950's, the existence of limonite ($2\,FeO_3\,3\,H_2O$) was deduced from polarisation measurements. The on-site analysis showed that the soil consists of 13 % iron and 21 % silicon. The abundance of sulphur was found to be ten times that found on the Earth.

The interior of Mars is not well known. Mars has probably a dense core approximately 1500 km in radius, a molten rocky mantle which is denser than the Earth's mantle and a thin crust. The crust is 80 km thick in the southern hemisphere but only about 35 km thick in the northern one. The low mean density compared with other terrestrial planets may indicate that in addition to iron the core contains a relatively large fraction of sulphur.

The Mars Global Surveyor confirmed in 1997 a weak magnetic field. It is probably a remnant of an earlier global field that has since disappeared. This has important implications for the structure of Mars' interior. There are no electric currents creating a magnetic field and therefore the core may be (at least partially) solid.

Three biological experiments of the Viking landers in 1976 searched for signs of life. No organic compounds were found—however, the biological tests did give some unexpected results. A closer look at the results indicated no life, but some uncommon chemical reactions.

Mars has two moons, *Phobos* and *Deimos* (Fig. 8.16). The size of Phobos is roughly 27 km × 21 km × 19 km, and the orbital period around Mars is only 7 h 39 min. In the Martian sky, Phobos rises in the west and sets in the east. Deimos is smaller. Its diameter is 15 km × 12 km × 11 km. The orbital period of Deimos is slightly over 30 hours, or just six hours longer than the rotation period of Mars. The synodic period of Deimos is nearly 5.5 days, and so it will stay over 2.5 days above the Martian horizon.

There are craters on both moons. Polarimetric and photometric results show that they are composed of material resembling carbonaceous chondrite meteorites.

8.5 Jupiter

The realm of terrestrial planets ends at the asteroid belt. Outside this, the relative abundance of volatile elements is higher and the original composition of the solar nebula is still preserved in the giant planets. The first and largest is *Jupiter*. Its mass is 2.5 times the total mass of all other planets, almost 1/1000 of the solar mass. The bulk of Jupiter is mainly hydrogen and helium. The relative abundance of these elements are approximately the same as in the Sun, and the density is of the same order of magnitude, namely $1330\ \mathrm{kg\,m^{-3}}$.

During oppositions, the angular diameter of Jupiter is as large as $50''$. The dark *belts* and

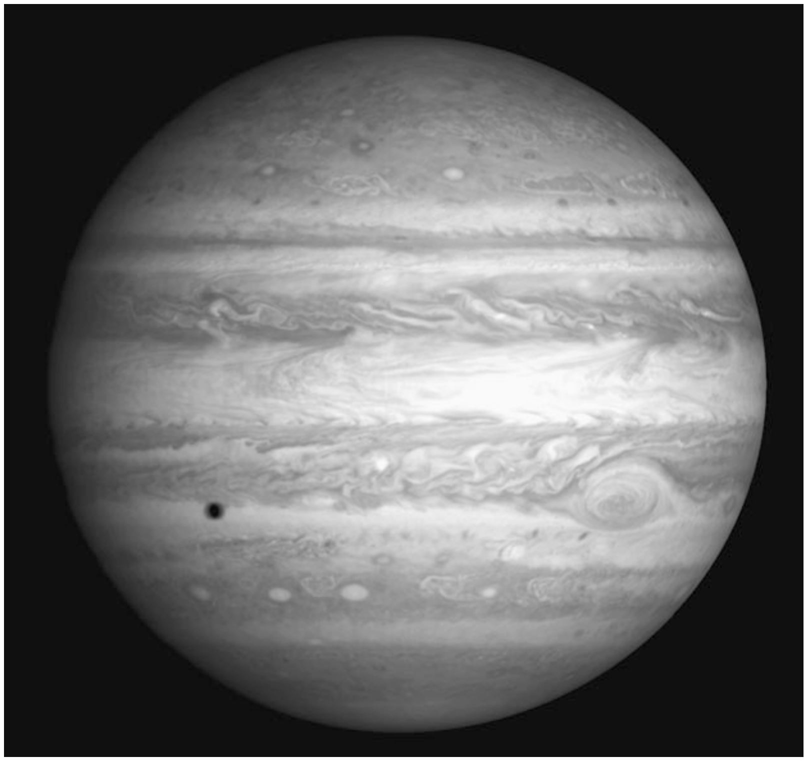


Fig. 8.17 A composed image of Jupiter taken by the Cassini spacecraft in December 2000. The resolution is 114 km/pixel. *The dark dot* is the shadow of the moon Europa. (NASA/JPL/University of Arizona)

lighter *zones* are visible even with a small telescope. These are cloud formations, parallel to the equator (Fig. 8.17). The most famous detail is the *Great Red Spot*, a huge cyclone, rotating counterclockwise once every six days. The spot was discovered by *Giovanni Cassini* in 1655; it has survived for centuries, but its true age is unknown (Fig. 8.18).

The rotation of Jupiter is rapid; one revolution takes 9 h 55 min 29.7 s. This is the period determined from the variation of the magnetic field, and it reflects the speed of Jupiter's interiors where the magnetic field is born. As might be expected, Jupiter does not behave like a rigid body. The rotation period of the clouds is about five minutes longer in the polar region than at the equator. Due to its rapid rotation, Jupiter is nonspherical; flattening is as large as $1/15$.

There is possibly an iron-nickel core in the centre of Jupiter. The mass of the core is probably equal to a few tens of Earth masses. The core is surrounded by a layer of metallic liquid hydrogen, where the temperature is over 10,000 K and the pressure, three million atm. Owing to this huge pressure, the hydrogen is dissociated into single atoms, a state unknown in ordinary laboratory environments. In this exotic state, hydrogen has many features typical of metals. This layer is electrically conductive, giving rise to a strong magnetic field. Closer to the surface where the pressure is lower, the hydrogen is present as normal molecular hydrogen, H_2. At the top there is a 1000 km thick atmosphere.

The atmospheric state and composition of Jupiter has been accurately measured by the spacecraft. *In situ* observations were obtained in 1995, when the probe of the Galileo spacecraft was dropped into Jupiter's atmosphere. It survived nearly an hour before crushing under the pressure, collecting the first direct measurements of Jupiter's atmosphere.

Belts and zones are stable cloud formations. Their width and colour may vary with time, but the semi-regular pattern can be seen up to the latitude 50°. The colour of the polar areas is close to that of the belts. The belts are reddish or brown-

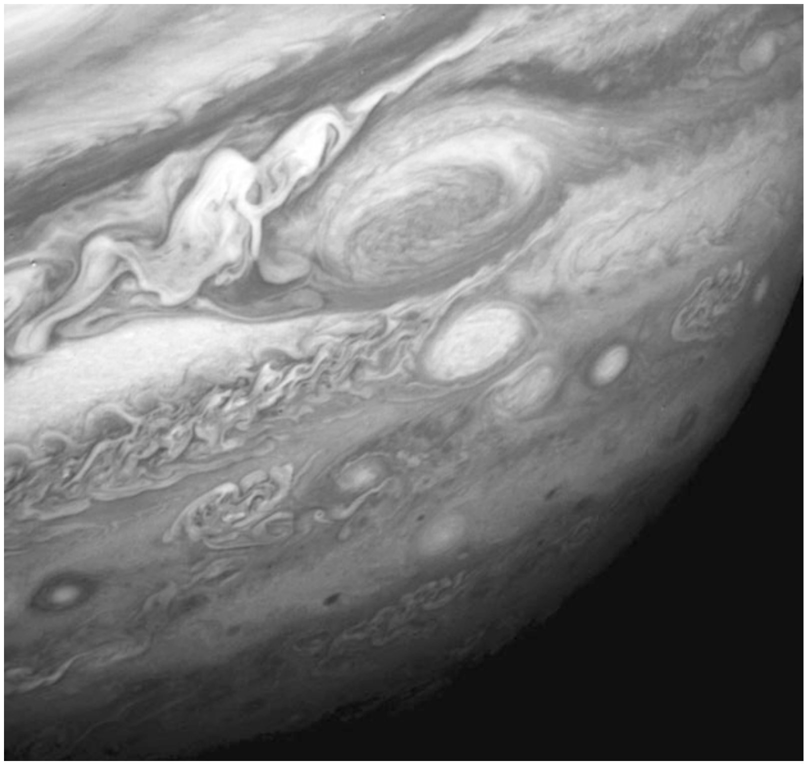


Fig. 8.18 Jupiter's Great Red Spot and its surroundings with several smaller ovals as seen by Voyager 1 in 1979. Cloud details of 160 kilometres are visible. (NASA)

ish, and the motion of the gas inside a belt is downward. The gas flows upward in the white zones. The clouds in the zones are slightly higher and have a lower temperature than those in the belts. Strong winds or jet streams blow along the zones and belts. The speed of the wind reaches 150 m/s at some places in the upper atmosphere. According to the measurements of the Galileo probe, the wind speeds in the lower cloud layers can reach up to 500 m/s. This indicates that the winds in deeper atmospheric layers are driven by the outflowing flux of the internal heat, not the solar heating.

The colour of the *Great Red Spot* (GRS) resembles the colour of the belts (Fig. 8.18). Sometimes it is almost colourless, but shows no signs of decrepitude. The GRS is 14,000 km wide and 30,000–40,000 km long. Some smaller red and white spots can also be observed on Jupiter, but their lifetime is generally much less than a few years.

The ratio of helium to hydrogen in the deep atmosphere is about the same as in the Sun. The results of the Galileo spacecraft gave considerably higher abundance than previous estimates. It means that there are no significant differentiation of helium, i.e. helium is not sinking to the interior of the planet as was expected according to the earlier results. Other compounds found in the atmosphere include methane, ethane and ammonia. The temperature in the cloud tops is about 130 K.

Jupiter radiates twice the amount of heat that it receives from the Sun. This heat is a remnant of the energy released in the gravitational contraction during the formation of the planet. Thus Jupiter is still gradually cooling. The internal heat is transferred outward by convection; this gives rise to flows in the metallic hydrogen, causing the strong magnetic field.

The ring of Jupiter (Fig. 8.19) was discovered in 1979. The innermost toroid-shaped halo is between 92,000–122,500 km from Jupiter's centre. It consists of dust falling from the main ring toward the planet. The main ring extends from the halo boundary out to about 128,940 km, just in-

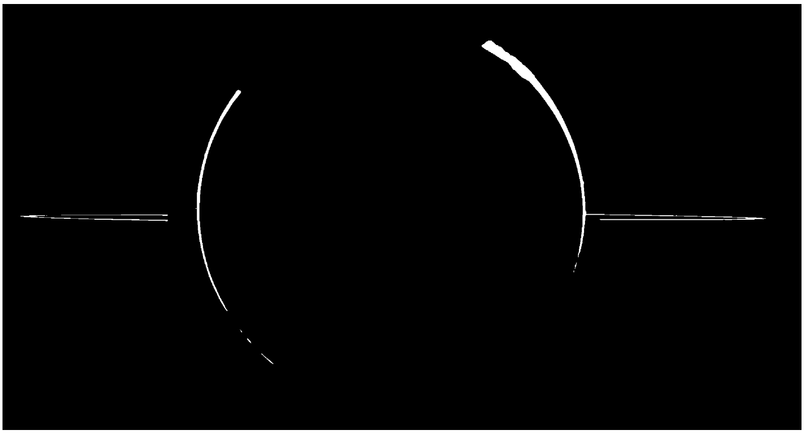


Fig. 8.19 Mosaic of Jupiter's ring system taken by the Galileo spacecraft when the spacecraft was in Jupiter's shadow looking back toward the Sun. Jupiter's ring system is composed of three parts: a thin outermost ring, a flat main ring, and an innermost doughnut-shaped halo. These rings are made up of dust-sized particles that originate from Io, or are blasted off from the nearby inner satellites by small impacts. (NASA/University of Arizona)

side the orbit of the moon Adrastea. The ring particles are small, a few microns only, and they scatter light forward much more effectively than backward. Therefore, they were not discovered prior the Voyager flyby. A ring consisting of such small particles cannot be stable, and new material must enter the ring continuously. Possible sources are the small moons Adrastea and Metis.

The two faint outermost rings are fairly uniform in nature. The inner of them extends from the orbit of Adrastea out to the orbit of Amalthea at 181,000 km. The fainter outermost ring extends out to Thebe's orbit at 221,000 km.

Jupiter's rings and moons exist within an intense radiation belt of Jupiter's magnetic field. The magnetosphere extends 3–7 million kilometres toward the Sun, depending on the strength of the solar wind. In the opposite direction it stretches to a distance of at least 750 million kilometres, behind Saturn's orbit.

Jupiter is an intense radio source. Its radio emission can be divided into three components, namely thermal millimetre and centimetre radiation, nonthermal decimetric radiation and burstal-decametric radiation. The nonthermal emission is most interesting; it is partly synchrotron radiation, generated by relativistic electrons in the Jovian magnetosphere. Its intensity varies in phase with Jupiter's rotation; thus the radio emission can be used for determining the exact rotation rate. The decametric bursts are related to the position of the innermost large moon, Io, and are possibly generated by the electric current of millions of Amperes observed between Jupiter and the plasma torus at the orbit of Io. Also auroras are common in Jupiter (Fig. 8.20).

In the beginning of year 2016 there were 67 known moons of Jupiter, but probably more small satellites will be found in the future. The four largest, *Io*, *Europa*, *Ganymede* and *Callisto* are called the *Galilean satellites* (Fig. 8.21), in honour of Galileo Galilei, who discovered them in 1610. The Galilean satellites can already be seen with ordinary binoculars. They are the size of the Moon or even planet Mercury. The other moons are small, most of them only a few kilometres in diameter.

Owing to tidal forces, the orbits of Io, Europa and Ganymede have been locked into a resonance, so that their longitudes λ strictly satisfy the equation

$$\lambda_{\mathrm{Io}} - 3\lambda_{\mathrm{Europa}} + 2\lambda_{\mathrm{Ganymede}} = 180^\circ . \qquad (8.1)$$

Hence the moons can never be in the same direction when seen from Jupiter.

Io is the innermost Galilean satellite. It is a little larger than the Moon. Its surface is spotted by numerous calderas, volcanoes without a mountain. The molten material is ejected up to a height of 250 km, and a part of the gas gets into Io's or-

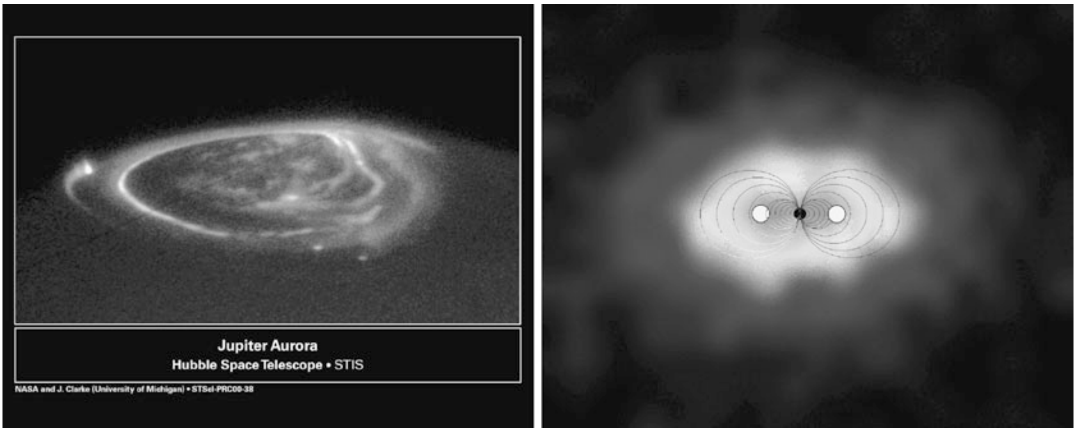


Fig. 8.20 *Left:* NASA Hubble Space Telescope close-up view of an aurora on Jupiter. The image shows the main oval of the aurora, centred over the magnetic north pole, and diffuse emissions inside the polar cap. (NASA, John Clarke/University of Michigan) *Right:* The image taken on January 2001 by NASA's Cassini spacecraft shows the bubble of charged particles trapped in the magnetosphere. The magnetic field and the torus of the ionised material from the volcanoes of Io are drawn over the image. (NASA/JPL/Johns Hopkins University)

bit. The volcanic activity on Io is much stronger than on the Earth. There is a 100 m bulk of the permanent tide raised by Jupiter. Due to the orbital perturbations caused by Europa and Ganymede the orbit of Io is slightly elliptical and therefore the orbital speed varies. The tidal bulk is forced to move with respect to the surface. This generates friction, which is transformed to heat. This heat keeps the sulphur compounds molten beneath the colourful surface of Io. No traces of impact craters are visible. The whole surface is new, being renewed continuously by eruptions. There is no water on Io.

Europa is the smallest of the Galilean satellites, a little smaller than the Moon. The surface is ice-covered and the geometric albedo is as high as 0.6. The surface is smooth with only a few features more than a hundred metres high. Most of the markings seem to be albedo features with very low relief. Only a few impact craters have been found indicating that the surface is young. The surface is renewed by fresh water, trickling from the internal ocean. Galileo spacecraft has found a very weak magnetic field. The field varies periodically as it passes through Jupiter's magnetic field. This shows that there is a conducting material beneath Europa's surface, most likely a salty ocean that could even be 100 km deep. At the centre, there is a solid silicate core.

Ganymede is the largest moon in the solar system. Its diameter is 5300 km; it is larger than the planet Mercury. The density of craters on the surface varies, indicating that there are areas of different ages. Ganymede's surface is partly very old, highly cratered dark regions, and somewhat younger but still ancient lighter regions marked with an extensive array of grooves and ridges. They have a tectonic origin, but the details of the formations are unknown. About 50 % of the mass of the moon is water or ice, the other half being silicates (rocks). Contrary to Callisto, Ganymede is differentiated: a small iron or iron/sulphur core surrounded by a rocky silicate mantle with an icy (or liquid water) shell on top. Ganymede has a weak magnetic field.

Callisto is the outermost of the large moons. It is dark; its geometric albedo is less than 0.2. Callisto seems to be undifferentiated, with only a slight increase of rock toward the centre. About 40 % of Callisto is ice and 60 % rock/iron. The ancient surface is peppered by meteorite craters; no signs of tectonic activity are visible. However, there have been some later processes, because small craters have mostly been obliterated and ancient craters have collapsed.

The currently known moons can be divided into four different groups: small moons inside the

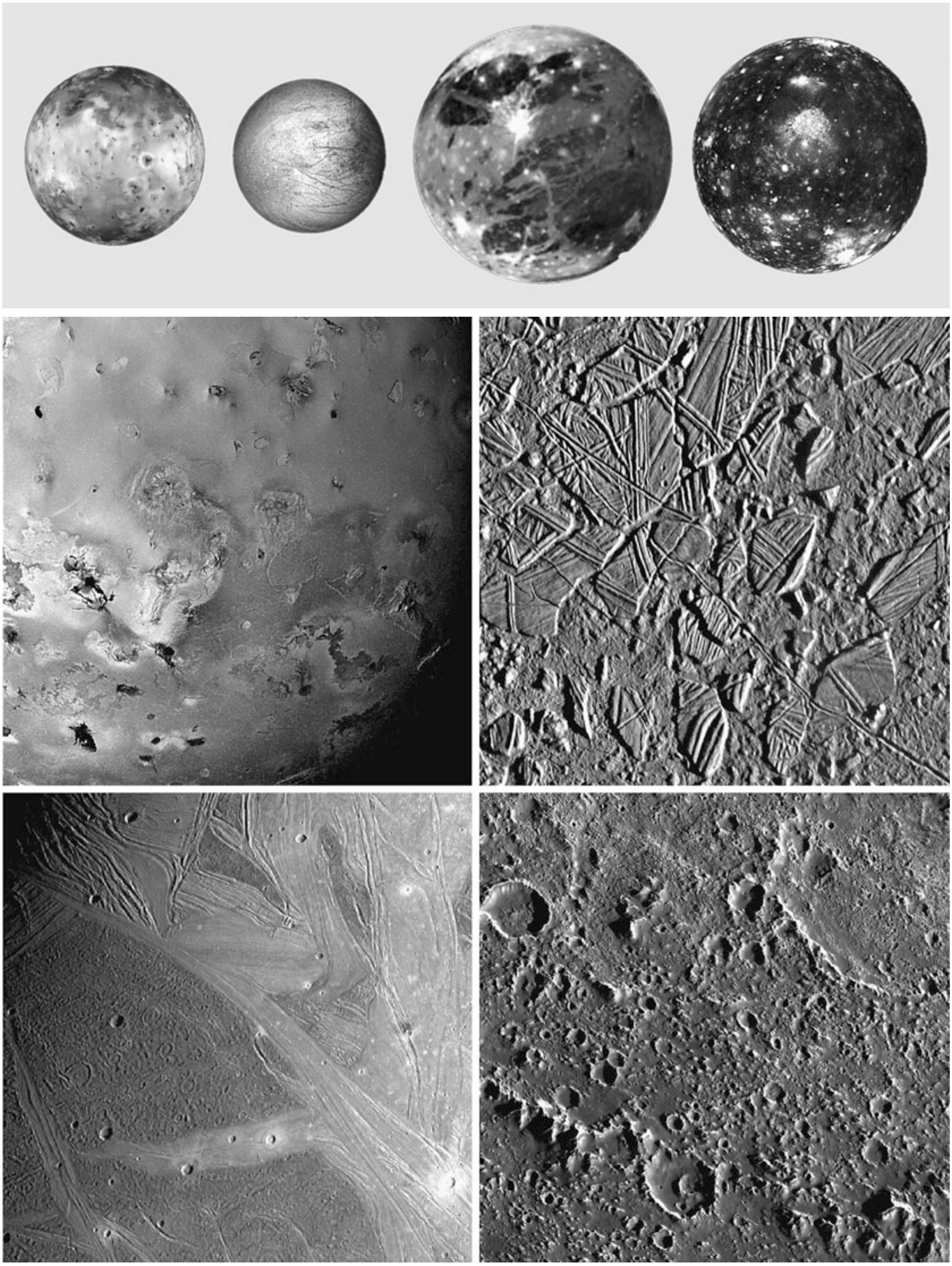


Fig. 8.21 (*Top*) The Galilean satellites of Jupiter. From *left* to *right*: Io, Europa, Ganymede, and Callisto (NASA/DLR). (*Right page top*) Surface details of Io and Europa. (*Right page bottom*) Surface details of Ganymede and Callisto. (NASA/Brown University, NASA/JPL)

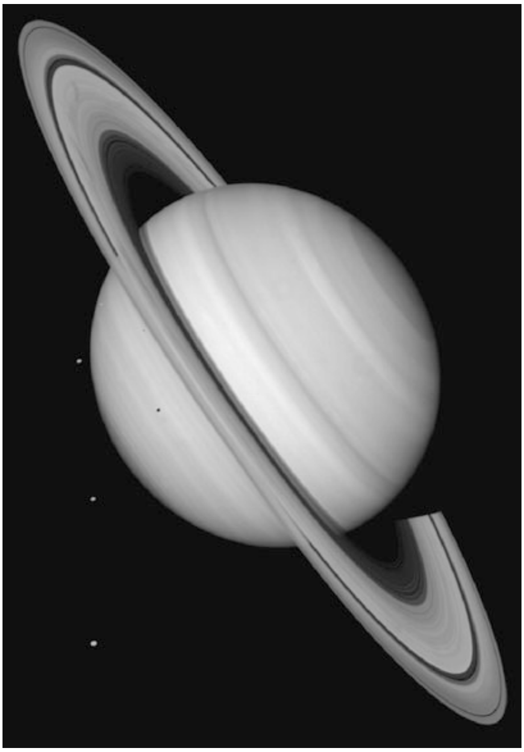


Fig. 8.22 Saturn and its rings. Three satellites (Tethys, Dione, and Rhea) are seen to the left of Saturn, and the shadows of Mimas and Tethys are visible on Saturn's cloud tops. (NASA/JPL)

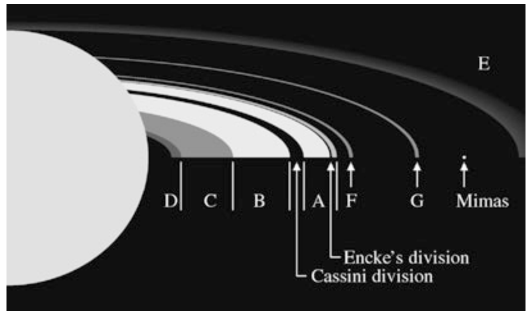


Fig. 8.23 A schematic drawing of the structure of the Saturnian rings. The brightest A and B rings can be seen even with a small telescope; the other ones are very faint

orbits of the Galilean satellites, the Galilean satellites, and two groups of irregular moons outside the orbit of the Galilean satellites. The moons of the inner distant group move on direct orbits, and the moons of the most distant group on retrograde orbits. It is possible that many of these are small asteroids captured by Jupiter.

8.6 Saturn

Saturn (Fig. 8.22) is the second largest planet. Its diameter is about 120,000 km, ten times the diameter of the Earth, and the mass, 95 Earth masses. The density is only 700 $\mathrm{kg\,m^{-3}}$, less than the density of water. The rotation axis is tilted about 27° with respect to the orbital plane, so every 15 years, the northern or the southern pole is well observable.

The rotation period is 10 h 39.4 min, determined from the periodic variation of the magnetic field by the Voyager spacecraft in 1981. However, Cassini spacecraft observed in 2004 the period of 10 h 45 min. The reason for the change is unknown. Due to the rapid rotation, Saturn is flattened; the flattening is $1/10$, which can be easily seen even with a small telescope.

The internal structure of Saturn resembles that of Jupiter. Due to its smaller size, the metallic hydrogen layer is not so thick as on Jupiter. The thermal radiation of Saturn is 2.8 times that of the incoming solar flux. The heat excess originates from the differentiation of helium. The helium atoms are gradually sinking inward and the released potential energy is radiated out as a thermal radiation. The abundance of helium in Saturn's atmosphere is only about half of that on Jupiter.

The winds, or jet streams, are similar to those of Jupiter but Saturn's appearance is less colourful. Viewed from the Earth, Saturn is a yellowish disk without any conspicuous details. The clouds have fewer features than those on Jupiter, because a haze, composed of hydrogen, ammonium and methane floats above the cloud tops. Furthermore, Saturn is farther from the Sun than Jupiter and thus has a different energy budget.

The temperature at the cloud tops is about 94 K. Close to the equator the wind speeds exceed 400 m/s and the zone in which the direction of the wind remains the same extends 40° from the equator. Such high speeds cannot be explained with external solar heat, but the reason for the winds is the internal flux of heat.

Saturn's most remarkable feature is a thin *ring system* (Figs. 8.23, 8.24), lying in the planet's equatorial plane. The Saturnian rings can be seen even with a small telescope. The rings were discovered by *Galileo Galilei* in 1610; only 45 years later did *Christian Huygens* establish that the formation observed was actually a ring, and not two oddly behaving bulbs, as they appeared to Galileo. In 1857 *James Clerk Maxwell* showed theoretically that the rings cannot be solid but must be composed of small particles.

The rings are made of normal water ice. The size of the ring particles ranges from microns to truck-size chunks. Most of the particles are in range of centimetres to metres. The width of the ring system is more than 60,000 km (about the radius of Saturn) and the thickness, at most 100 m, and possibly only a few metres. Cassini spacecraft discovered also molecular oxygen around the rings, probably as a product of the disintegration of water ice from the rings.

According to Earth-based observations, the rings are divided into three parts, called simply A, B, and C. The innermost C ring is 17,000 km wide and consists of very thin material. There is some material even inside this (referred to as the D ring), and a haze of particles may extend down to the clouds of Saturn.

The B ring is the brightest ring. Its total width is 26,000 km, but the ring is divided into thousands of narrow ringlets, seen only by the spacecraft. From the Earth, the ring seems more or less uniform. Between B and A, there is a 3000 km wide gap, the *Cassini division*. It is not totally void, as was previously believed; some material and even narrow ringlets have been found in the division by the Voyager space probes.

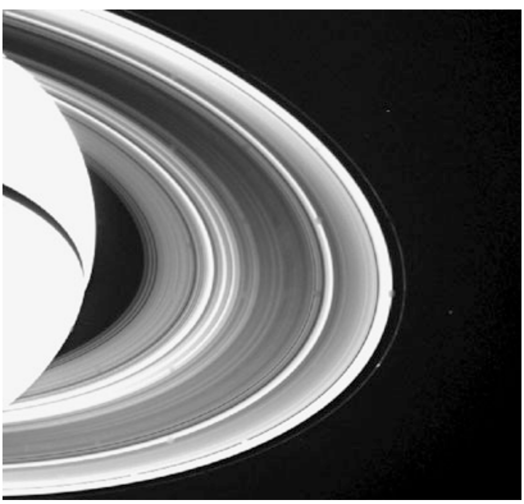


Fig. 8.24 At a close distance, the rings can be seen to be divided into thousands of narrow ringlets. (JPL/NASA)

The A ring is not divided into narrow ringlets as clearly as the B ring. There is one narrow but obvious gap, *Encke's division*, close to the outer edge of the ring. The outer edge is very sharp, due to the "shepherd" moon, some 800 km outside the ring. The moon prevents the ring particles from spreading out to larger orbits. It is possible that the appearance of B is due to yet-undiscovered moonlets inside the ring.

The F ring, discovered in 1979, is about 3000 km outside A. The ring is only a few hundred kilometres wide. On both sides there is a small moon; these shepherds prevent the ring from spreading. An interior moon passing a ring particle causes the particle to move to a larger orbit. Similarly, at the outer edge of the ring, a second moon forces the particles inward. The net result is that the ring is kept narrow.

Outside the F ring, there are some zones of very sparse material, sometimes referred to as the G and E rings. These are merely collections of small particles.

The Saturnian rings were possibly formed together with Saturn and are not debris from some cosmic catastrophe, like remnants of a broken moon. The total mass of the rings is 10^{-7} of the mass of Saturn. If all ring particles were collected together, they would form an ice ball, 600 km in diameter.

In 2009 a very sparse ring was observed at the distance of the moon Phoebe. It has the same inclination as Phoebe, nearly 30°. It has probably originated in material shattered from Phoebe by micrometeorites. The ring extends inward to the orbit of Iapetus. The hemispheres of Iapetus are quite different, one side is very dark. Since Iapetus always turns the same side towards Saturn, only one hemisphere is hit by ring particles. Eventually ice evaporates away leaving only the dark cinder.

A total of 62 moons (in 2016) of Saturn are known. Many of the large Saturnian moons (Fig. 8.25) were observed by Pioneer 11 and Voyager 1 and 2 spacecrafts. Some of the large moons

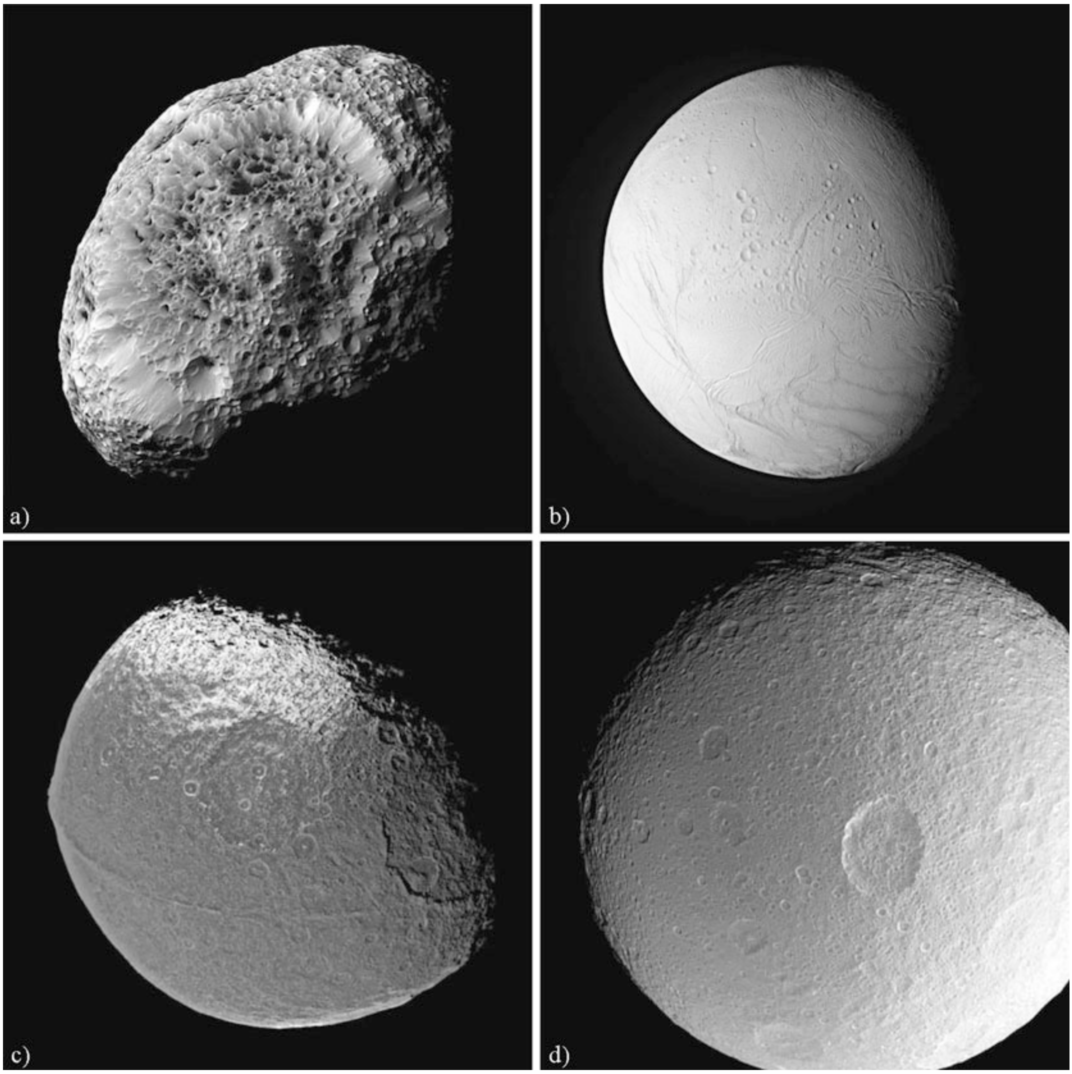


Fig. 8.25 Saturnian moons photographed by the Cassini spacecraft in 2005–2006 (**a**) Hyperion, (**b**) Enceladus, (**c**) Iapetus and (**d**) Tethys. (**e**) A radar picture of the northern latitudes of Titan, taken by Cassini in summer 2006. The black patches are probably methane lakes. The width of the picture is about 450 km. (Photo NASA)

like Enceladus and Tethys are composed mainly of ice. The temperature of the primeval nebula at the distance of Saturn was so low that bodies of pure ice could form and survive.

Some moons are dynamically interesting; some have an exotic geological past. Outside the F ring, there are two moonlets, *Epimetheus* and *Janus*, almost in the same orbit; the difference of the semimajor axes is about 50 km, less than the radii of the moons. The inner moon is gaining on the outer one. The moons will not collide, since the speed of the trailing moon increases and the moon moves outward. The speed of the leading moon decreases and it drops inward. The moons exchange their roles roughly every four years. There are also several shepherding satellites, like *Atlas*, *Prometheus* and *Pandora* that keep rings in their place. Their gravitational pull prevents ring particles from drifting away.

The innermost of the "old" moons is *Mimas*. There is a huge crater, named Herschel, on Mimas' surface with a diameter of 100 km and

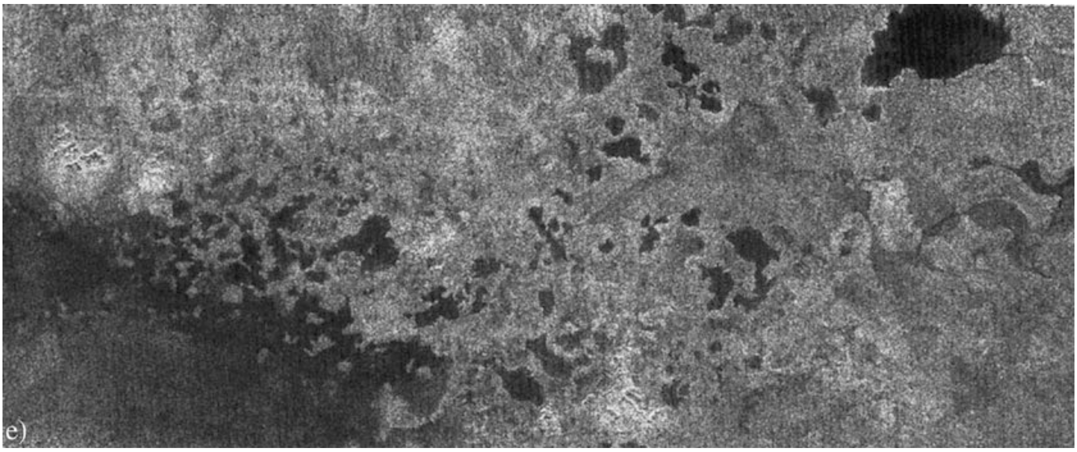


Fig. 8.25 (Continued)

a depth of 9 km (Fig. 8.25). Bigger craters exist in the solar system, but relative to the size of the parent body, this is almost the biggest crater there could be room for (otherwise the crater would be bigger than Mimas itself). On the opposite side, some grooves can be seen, possibly signifying that impact has almost torn the moon apart.

The surface of the next moon, *Enceladus*, consists of almost pure ice, and one side is nearly craterless. Craters and grooves can be found on the other hemisphere. Tidal forces result in volcanic activity where water (not lava or other "hot" material) is discharged to the surface.

Titan is the largest of the Saturnian moons. Its diameter is 5100 km, so it is only slightly smaller than Jupiter's moon Ganymede. Titan is the only moon with a dense atmosphere. The atmosphere is mainly nitrogen (99 %) and methane, and the pressure at the surface is 1.6 bar. The temperature is about 90 K. Reddish clouds form the visible surface some 200 km above the solid body. The *Huygens* lander made measurements and sent images of Titan in 2005. It detected lakes of methane as well as geysers ejecting methane, ammonia and water.

8.7 Uranus

The planets from Mercury to Saturn were already known in antiquity. The next planet, Uranus, cannot be seen with the naked eye.

The famous German-English amateur astronomer *William Herschel* discovered Uranus in 1781. Herschel himself first thought that the new object was a comet. However, the extremely slow motion revealed that the body was far beyond the orbit of Saturn. Based on the first observations, the Finnish astronomer *Anders Lexell* calculated a circular orbit. He was one of the first to propose that the newly discovered object was a planet. *Johann Bode* of the Berlin Observatory suggested the name Uranus but more than five decades passed before the name was unanimously accepted.

The mean distance of Uranus is 19 au, and the orbital period 84 years. The inclination of the rotation axis is 98°, which is totally different from the other planets. Due to this uncommon geometry, the poles are either lit or in darkness for decades. The rotation period, confirmed by the Voyager 2 magnetometric measurements in 1986, is 17.3 hours; the exact period had been uncertain prior to the fly-by.

Uranus is greenish, as viewed through a telescope. Its colour is due to the strong methane absorption bands in the near-infrared. A part of the red light is also absorbed, leaving the green and blue part of the spectrum untouched. Uranus is almost featureless (Fig. 8.26) because its clouds are below a thick haze or smog. The origin of the smog may be methane that solar radiation broke into radicals which then formed e.g. asethylene and ethane.

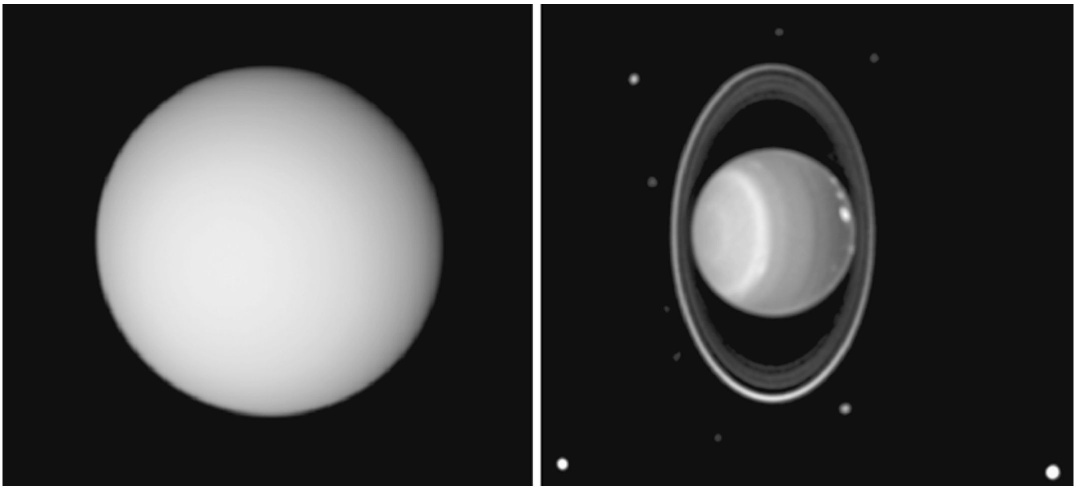


Fig. 8.26 Two views of Uranus. *The left picture* shows Uranus as it would appear to the naked eye. (NASA). At *the right* there is a Hubble Space Telescope view of Uranus surrounded by its rings. Also 10 satellites are visible in the original picture. (Seidelmann, U.S. Naval Observatory, and NASA)

Fig. 8.27 *Left:* The rings of Uranus are very narrow and composed of a dark material. Nine rings are visible in the picture of Voyager in 1986. *Right:* Rings seen in the light scattered forward when the Voyager spacecraft was in the shadow of the planet. (NASA)

The strong *limb darkening* caused by the smog makes the terrestrial determination of the Uranus' size difficult. Therefore, the radius was not accurately determined until 1977 during a stellar occultation caused by Uranus. The rings of Uranus were discovered at the same time.

The internal structure of Uranus is thought to be slightly different from that of other giant planets. Above the innermost rocky core, there is a layer of water, which, in turn, is surrounded by a mantle of hydrogen and helium. The mixture of water and ammonia and methane therein are dissociated to ions under the heavy pressure. This mixture behaves more like a molten salt than water. The convection flows in this electrically conductive "sea" give rise to the Uranian magnetic

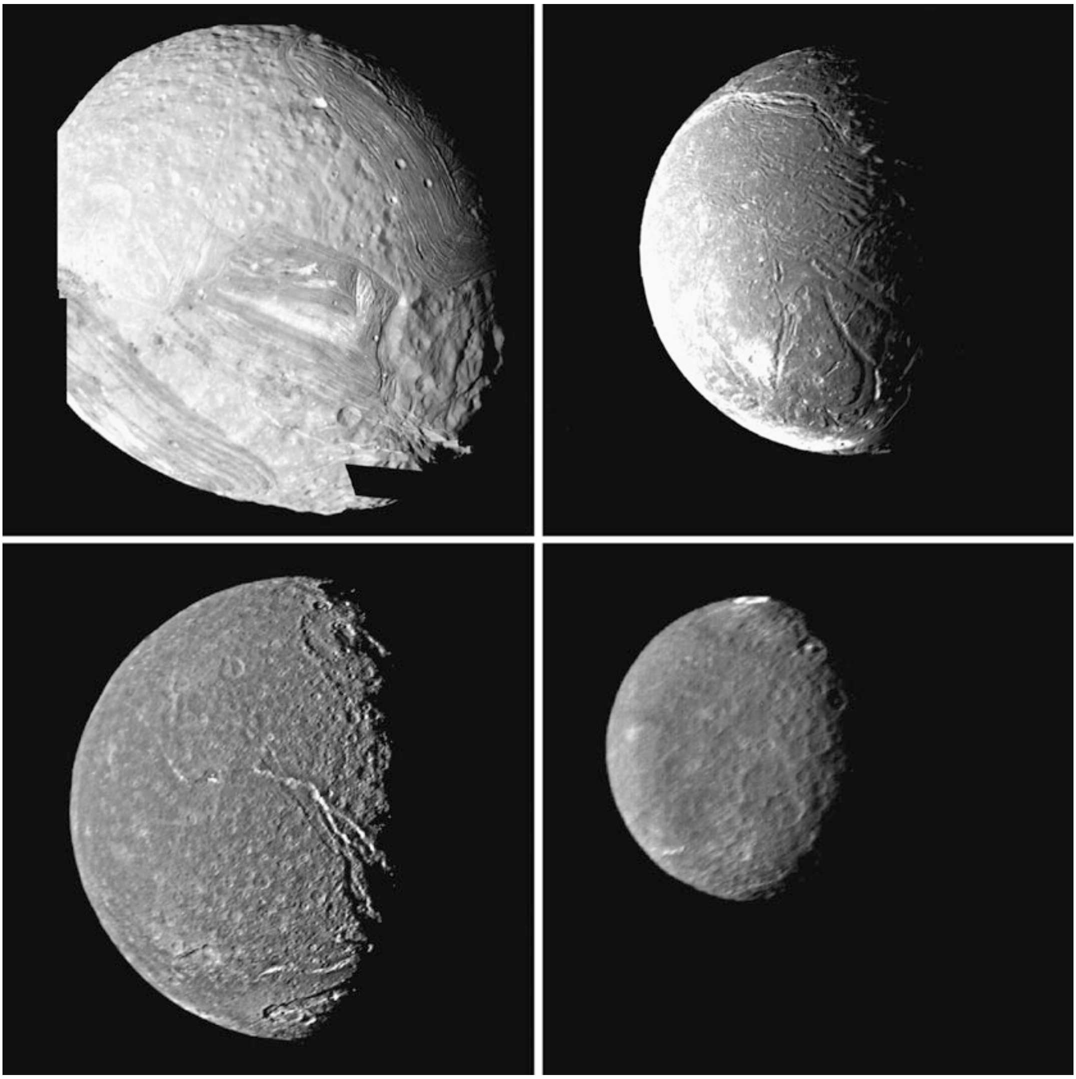


Fig. 8.28 Four Uranian moons (from *top left* to *lower right*): Miranda, Ariel, Titania and Umbriel. (NASA)

field. The strength of the magnetic field at the cloud tops is comparable to the terrestrial field. However, Uranus is much larger then the Earth, so the true strength of the field is 50 times greater than that of the Earth. The Uranian magnetic field is tilted 59° with respect to the rotation axis. No other planet has such a highly inclined magnetic field.

The Uranian rings (Fig. 8.27) were discovered in 1977, during a stellar occultation. Secondary occultations were observed before and after the main event. A total of 13 rings are known, nine of which were discovered in the occultation. The innermost ring is broad and diffuse. All other rings are dark and very narrow, only a few hundred metres or a few kilometres wide. The Voyager 2 results showed that the rings contain very little dust, unlike those of Jupiter and Saturn. The mean size of the ring particles is more than 1 metre. The ring particles are darker than practically any known material in the solar system; the cause of this dark colour is unknown.

There are 27 moons (2016 number) orbiting around Uranus, ten of which were discovered by

Voyager 2. The geological history of some moons is puzzling, and many features reminiscent of an active past can be found.

The innermost of the large moons, *Miranda*, is one of the most peculiar objects discovered (Fig. 8.28). It has several geological formations also found elsewhere (but here they are all mixed together), in addition to the quite unique V-shaped formations. It is possible that Miranda's present appearance is the result of a vast collision that broke the moon apart; some pieces may have later settled down, inside out. Another peculiar object is Umbriel. It belongs to the ever increasing family of unusual dark bodies (such as the Uranian rings, one side of Iapetus and Halley's comet). The dark surface of Umbriel is covered by craters without any traces of geological activity.

8.8 Neptune

The orbit of Uranus was already well known in the beginning of the 19th century. However, some unknown perturbations displaced Uranus from its predicted orbit. Based on these perturbations, *John Couch Adams*, of Cambridge, and *Urbain Jean-Joseph Le Verrier*, of Paris, independently predicted the position of the unknown perturbing planet.

The new planet was discovered in 1846 by *Johann Gottfried Galle* at the Berlin Observatory; Le Verrier's prediction was found to be only 1° off. The discovery gave rise to a heated controversy as to who should be given the honour of the discovery, since Adams' calculations were not published outside the Cambridge Observatory. When the quarrel was settled years later, both men were equally honoured. The discovery of Neptune was also a great triumph of the Newtonian theory of gravitation.

The semimajor axis of the orbit of Neptune is 30 au and the orbital period around the Sun 165 years. The internal rotation period, confirmed by Voyager 2 in 1989, is 16 hours 7 minutes and the rotation period of the outer layers of the clouds is about 17 hours. The obliquity of the rotation axis is 29° but the magnetic field is tilted some 47° with respect to the rotation axis. The magnetic field is tilted like in Uranus, but the field strength is much smaller.

The density of Neptune is 1638 $\mathrm{kg\,m^{-3}}$, and the diameter 49,500 km. Thus the density of Nep-

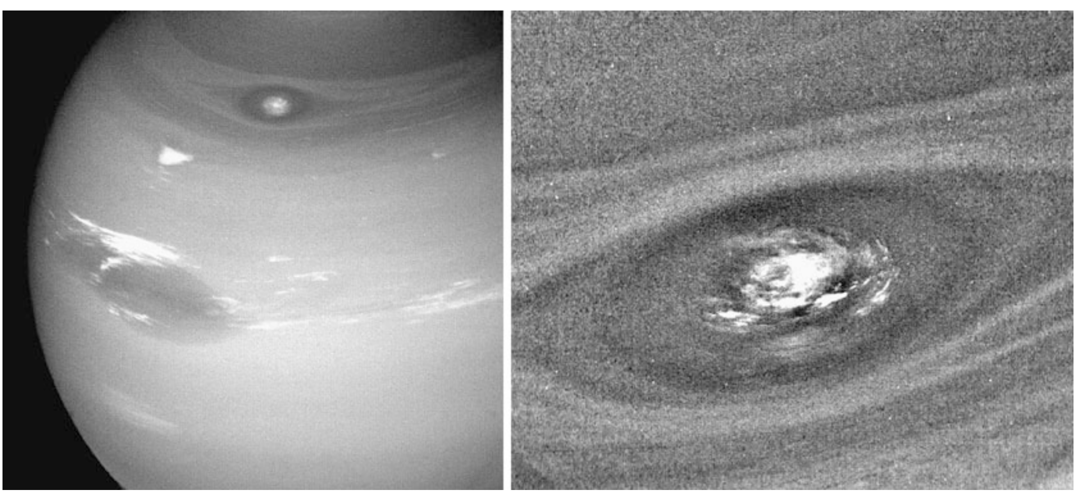


Fig. 8.29 (*Left*) Neptune shows more features than Uranus. In the picture of Voyager 2 the Great Dark Spot, accompanied by bright, white clouds is well visible. Their appearance is changing rapidly. To the south of the Great Dark Spot is a bright feature and still farther south is another dark spot. Each feature moves eastward at a different velocity. (*Right*) Details of the Southern Dark Spot. The V-shaped structure near the right edge of the bright area indicates that the spot rotates clockwise. Unlike the Great Red Spot on Jupiter, which rotates counterclockwise, the material in the Neptune's dark oval will be descending. (NASA/JPL)

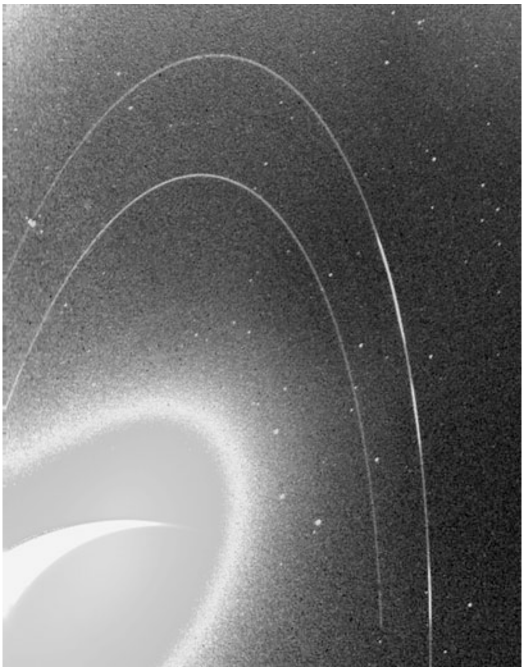


Fig. 8.30 The rings of Neptune. Ring particles are small and best visible in the forward scattered light. There are several brightenings in the outermost ring. One of the rings appears to have a twisted structure. Neptune at left is overexposed. (NASA/JPL)

tune is higher than that of other giant planets. The internal structure is quite simple: The core, composed of silicates (rocks) is about 16,000 km in diameter. This is surrounded by a layer of water and liquid methane and the outermost gaseous layer, atmosphere, is mainly composed of hydrogen and helium, methane and ethane being a minor components.

Cloud structures are more complicated than on Uranus, and some dark spots, like in Jupiter, were visible during the Voyager fly-by (Fig. 8.29). The speed of the winds are high, up to 400 m/s.

Like other giants, Neptune also has rings (Fig. 8.30). The rings were discovered by Voyager 2, although their existence was already expected prior the fly-by. Two relatively bright but very narrow rings are at a distance of 53,000 and 62,000 km from the centre of the planet. Moreover, there are some faint areas of fine dust.

There are 14 known moons, six of which were discovered by Voyager 2. Before the Voyager fly-by, only two of them, Triton and Nereid, were known.

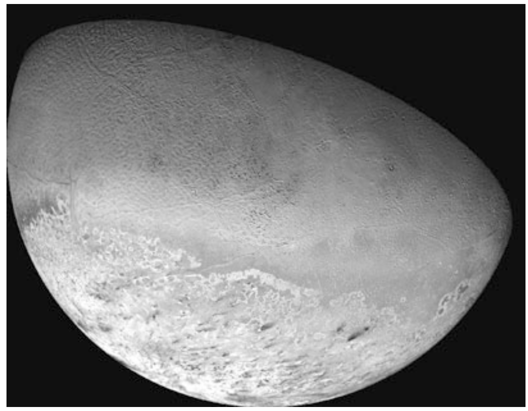


Fig. 8.31 The southern hemisphere of Triton, Neptune's largest satellite in a picture taken in 1989 by Voyager 2. The dark spots may indicate eruptions of "icy volcanoes". Voyager 2 images showed active geyser-like eruptions spewing nitrogen gas and dark dust particles several kilometres into the atmosphere. (NASA)

The largest of the moons, *Triton*, is 2700 km in diameter, and it has a thin atmosphere, mainly composed of nitrogen. The albedo is high: Triton reflects 60–80 % of the incident light. The surface is relatively young, without any considerable impact craters (Fig. 8.31). There are some active "geysers" of liquid nitrogen, which partly explains the high albedo and the lack of the craters. The low surface temperature of Triton, 37 K, means that the nitrogen is solid and covers the surface like snow. It is the lowest surface temperature known in the solar system.

8.9 Dwarf Planets

Besides actual planets there are some planet like objects that orbit the Sun and are nearly spherical but have not managed to clear the neighbourhood of their orbits. The upper and lower limits to the size and mass of dwarf planets are not strictly specified. The lower limit, however, is determined by the hydrostatic equilibrium shape, but the size at which this happens may vary according to the composition and history of the object. It is estimated that up to 40–50 dwarf planets will be discovered in coming years.

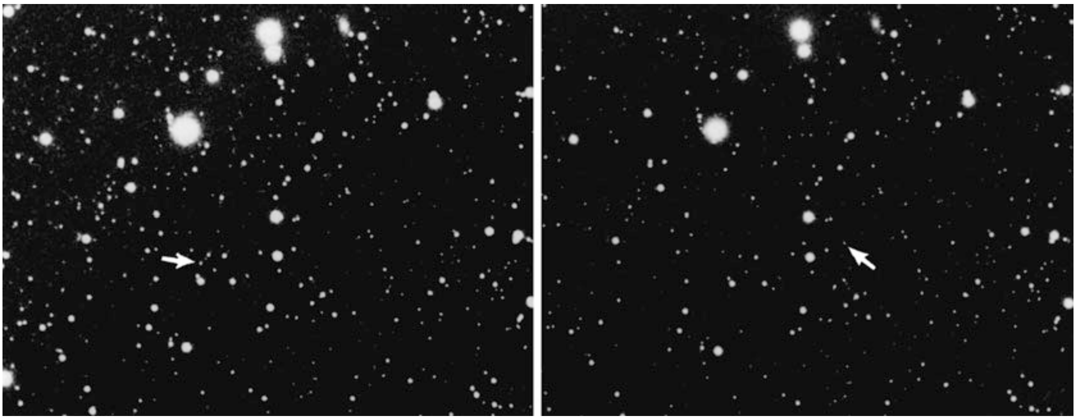


Fig. 8.32 A small portion of the pair of pictures where Pluto was discovered in 1930. The planet is marked with an *arrow*. (Lowell Observatory)

Currently, there are five dwarf planets in the Solar System, namely *Ceres*, *Pluto*, *Eris*, *Haumea*, and *Makemake*. Ceres was formerly counted as an asteroid, Pluto was a planet and Eris (2003 UB 313, known also by the nickname Xena) was the first Trans-Neptunian object which turned out to be larger than Pluto.

Pluto *Pluto* was discovered in 1930 at the Lowell Observatory, Arizona, after an extensive photographic search (Fig. 8.32). This search had already been initiated in the beginning of the century by *Percival Lowell*, on the basis of the perturbations observed in the orbits of Uranus and Neptune. Finally, *Clyde Tombaugh* discovered Pluto less than 6° off the predicted position. However, Pluto turned out to be far too small to cause any perturbations on Uranus or Neptune. Thus the discovery was purely accidental, and the perturbations observed were not real, but caused by minor errors of old observations.

The orbit of Pluto is different from planetary orbits. The eccentricity is 0.25 and the inclination is 17°. During its 250 year orbit, Pluto is closer to the Sun than Neptune for 20 years; one such period lasted from 1979 to 1999. There is no danger of Pluto and Neptune colliding, since Pluto is high above the ecliptic when at the distance of Neptune. Pluto's orbital period is in a 3:2 resonance with Neptune.

Pluto has no visible disk as seen with terrestrial telescopes; instead, it resembles a point, like a star. This fact gave an upper limit for the diameter of Pluto, which turned out to be about 3000 km. The exact mass was unknown until the discovery of the Plutonian moon, *Charon*, in 1978. The mass of Pluto is only 0.2 % of the mass of the Earth. The orbital period of Charon is 6.39 days, and this is also the period of rotation of both bodies. Pluto and Charon rotate synchronously, each turning the same side towards the other body. The rotation axis of Pluto is close to the orbital plane: the tilt is 122°.

Mutual occultations of Pluto and Charon in 1985–1987 gave accurate diameters of each body: The diameter of Pluto is 2300 km and that of Charon, 1200 km. The density of Pluto turned out to be about 2100 $\mathrm{kg\,m^{-3}}$. Thus Pluto is not a huge iceball but about 2/3 of its mass is composed of rocks. The relatively small abundance of ices is possibly due to the low temperature during the planetary accretion when most of the free oxygen was combined with carbon forming carbon monoxide. The computed lower limit for water ice is about 30 % which is fairly close to the value observed in Pluto.

Pluto has a thin methane atmosphere and there is possibly a thin haze over the surface. The surface pressure is 10^{-5}–10^{-6} atm. It has been speculated that when Pluto is far from perihelion, the whole atmosphere will become frozen and fall on the surface.

Pluto has five satellites. Two of them were discovered by the Hubble Space Telescope in 2005

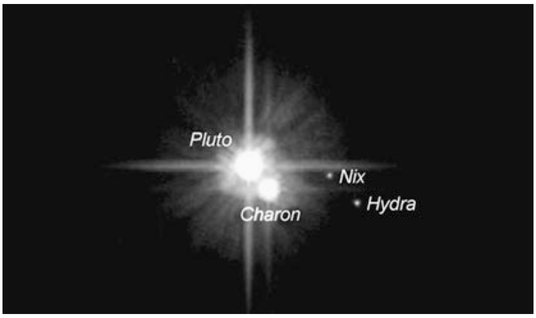


Fig. 8.33 The Hubble Space Telescope photographed Pluto and its three known moons in February 2006. The smaller moons were found in 2005, and were later named Nix and Hydra. Their diameter is estimated as 40–160 km. (M. Mutchler (STScI), A. Stern (SwRI), and the HST Pluto Companion Search Team, ESA, NASA)

Fig. 8.34 The only detailed images of Pluto were sent by the New Horizons probe in 2015. *The light heart shaped area* was named the Tombaugh region to honour the finder of Pluto. *The dark area to the left of* is called the Cthulhu region; Cthulhu is a mythical demon in H.P. Lovecraft's horror stories (NASA)

(Fig. 8.33). They orbit Pluto counterclockwise twice the distance of Charon. The New Horizons probe found two more moons.

Ceres *Ceres* was the first asteroid discovered in 1801 by *Giuseppe Piazzi*. It is also the largest of the main belt asteroids moving inside Jupiter's orbit. Its diameter is about 1000 km, thus exceeding the limit to be in the hydrostatic equilibrium. Thus it is no more an asteroid but a dwarf planet.

The average opposition magnitude of Ceres is 7.9. Thus it can be seen with binoculars but not with the naked eye.

Nearby images taken by a space probe show a few highly reflecting spots.

Eris In 2003 a Trans-Neptunian object was found, initially labelled as 2003 UB313. One of the initial nicknames was *Xena* according to the heiress of a tv series. When a moon orbiting Xena was found, it was obviously names as Gabrielle. However, these names never became official. The bigger object was given the name *Eris* and its companion *Dysnomia*.

The size of Eris is similar to that of Pluto. The size is, however, an estimate based on infrared radiation. Yet it was big enough to be classified as a planet if Pluto had retained its planetary status. Now Eris is a dwarf planet. The semimajor axis of the orbit is 97 au, orbital period 560 years and inclination 45°.

8.10 Minor Bodies

In addition to planets, moons orbiting the planets, dwarf planets and other biggish objects the solar system contains a lot of smaller objects that can be collectively called *minor bodies*.

The class of minor bodies includes *asteroids*, *comets*, *meteoroids*, and *interplanetary dust*. However, there is no clear distinction between the groups. Some asteroids are cometlike, some asteroids coming close to the Earth may have earlier been comets that have lost all of their volatile material. The classification is based more on the visual appearance and tradition than physical properties.

8.11 Asteroids

Asteroids form a large and scattered group of Sun-orbiting bodies. The oldest and best-known group form the main asteroid belt between Mars and Jupiter, with distances of 2.2–3.3 au from the Sun (Fig. 8.38). The most distant asteroids are far

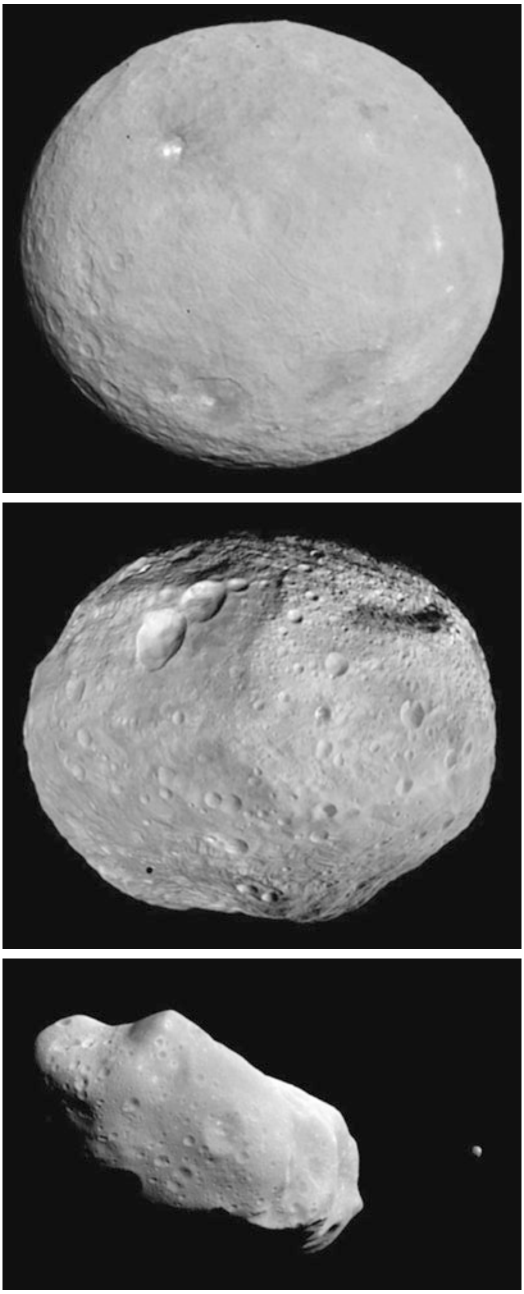


Fig. 8.35 *Top*: Ceres was the first detected asteroid. Spacecraft images shows its spherical shape, and so it became a dwarf planet. *Middle*: Vesta is clearly nonspherical and has remained as a minor body. It is the brightest asteroid: at opposition under ideal conditions it could be seen even with the naked eye. *Bottom*: The asteroid (243) Ida and a small moon Dactyl orbiting the asteroid. The irregular shape is typical for most asteroids. Ida is the first asteroid known to have a satellite

beyond the orbit of Pluto, called Trans-Neptunian objects. There are also a number of asteroids that come closer to the Sun than the Earth.

Earlier asteroids were called minor planets or even planetoids. These names were actually more natural than asteroid that only means that the object looks a starlike dot, although it has nothing to do with stars.

The first asteroid was found in 1801 (Ceres, now a dwarf planet), and at the beginning of 2016 there were more than 750,000 catalogued and 15,000 named asteroids. There were also a huge number of asteroids with an approximate orbit. The number of catalogued asteroids increases currently by thousands every month. It has been estimated that more than about half a million asteroids larger than 1 km exist in the Solar System. Diameters of asteroids vary from hundreds of meters to hundreds of kilometers. The largest asteroid Ceres is classified as a dwarf planet and the border between smallest asteroids and meteoroids is not specified.

An asteroid observer needs a telescope, since even the brightest asteroids are too faint to be seen with the naked eye. Asteroids are points of light like a star, even if seen through a large telescope; only their slow motion against the stellar background reveals that they are members of the solar system.

The rotation of an asteroid gives rise to a regular light variation. The amplitude of light variation is in most cases well below 1 magnitude and typical rotation periods range from 4 to 15 hours.

The characteristics of the main belt asteroids are best known. Total mass of the main belt asteroids is less than $1/1000$ of the mass of the Earth. The centre of the asteroid belt is at a distance of approximately 2.8 au, as predicted by the *Titius–Bode law* (Sect. 7.11). According to a formerly popular theory, asteroids were thought to be debris from the explosion of a planet. This theory, like catastrophe theories in general, has been abandoned.

The currently accepted theory assumes that asteroids were formed simultaneously with the major planets. The primeval asteroids were large chunks, most of them orbiting between the orbits of Mars and Jupiter. Due to mutual collisions and

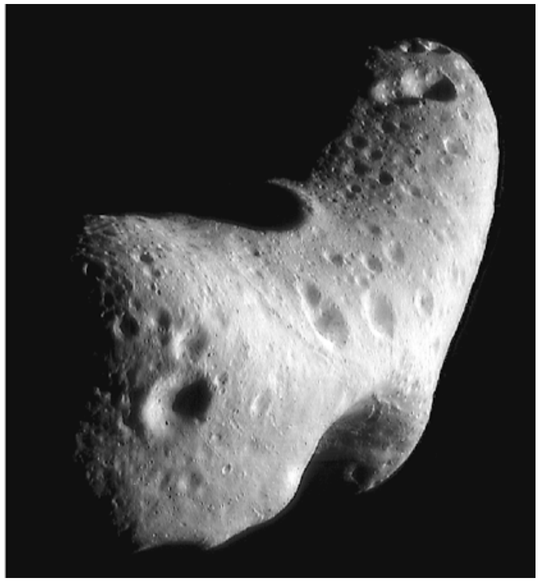


Fig. 8.36 *Left:* Asteroid (951) Gaspra was photographed by the Galileo spacecraft in October 1991. The illuminated part of the asteroid is about 16 × 12 km. The smallest craters in this view are about 300 m across. *Right:* A mosaic of asteroid (433) Eros was taken by the NEAR spacecraft from a distance of 200 km. The crater on top is about 5 km in diameter. The NEAR spacecraft orbited Eros for one year and finally landed on it in 2001. (JPL/NASA)

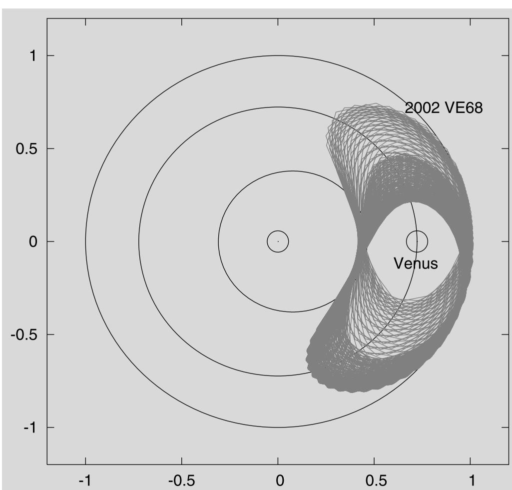


Fig. 8.37 Quasimoons or pseudomoons are asteroid moving on rather peculiar orbits. They are not real moons, since they orbit the Sun, but the orbital period is very close to that of some planet. Thus the asteroid seems to oscillate around the planet. A quasimoon moves on an eccentric orbit inside and outside the orbit of the planet. Eventually the asteroid will drift away from the planet but will return after a long time. Venus and Neptune each have one quasimoon and the Earth has several. The orbits of the quasimoons have been studied e.g. Seppo Mikkola in Finland and the Canadians Kimmo Innanen and Paul Wiegert

fragmentation, the present asteroids are debris of those primordial bodies which were never able to form a large planet. Some of the biggest asteroids may be those original bodies. The orbital elements of some asteroids are very similar. These are called the *Hirayama families*. They are probably remnants of a single, large body that was broken into a group of smaller asteroids. There are tens of identified Hirayama families, the largest ones including Hungarias, Floras, Eos, Themis, and Hildas (named after the main asteroid in the group).

The distribution of asteroids inside the asteroid belt is uneven (Fig. 8.38); they seem to avoid some areas known as the *Kirkwood gaps*. The most prominent void areas are at distances where the orbital period of an asteroid around the Sun (given by Kepler's third law) is in the ratio 1:3, 2:5, 3:7, or 1:2 to the orbital period of Jupiter. The motion of an asteroid orbiting in such a gap would be in resonance with Jupiter, and even small perturbations would tend to grow with time. The body would eventually be moved to another orbit. However, the resonance effects are not so simple: sometimes an orbit is "locked" to a reso-

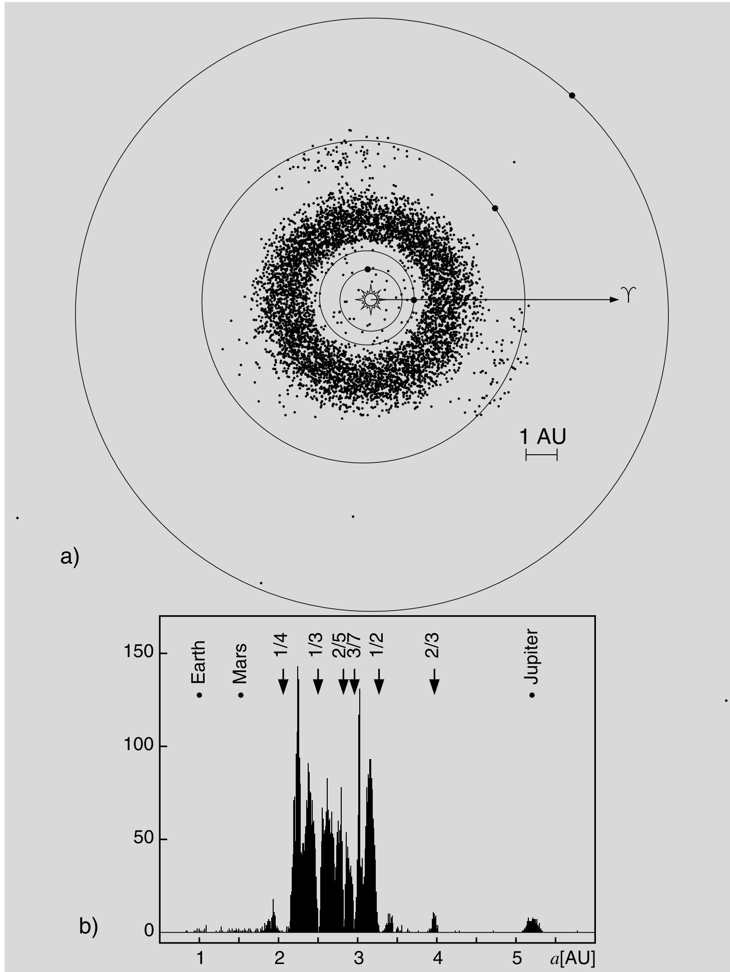


Fig. 8.38 (**a**) Most of the asteroids orbit the Sun in the asteroid belt between Mars and Jupiter. The figure shows the positions of about 96,000 catalogued asteroids on January 1, 2000, and the orbits and the positions of some major planets. The orbital elements of the asteroids are from the Lowell Observatory data base. (**b**) The total number of asteroids as a function of the distance from the Sun. Each bin corresponds to 0.1 AU. The empty areas, the Kirkwood gaps, are at those points, where the orbital period of an asteroid is in a simple ratio to the orbital period of Jupiter

nance, e.g. the *Trojans* move along the same orbit as Jupiter (1:1 resonance), and the *Hilda group* is in the 2:3 resonance.

Many groups of asteroids orbit the Sun outside the main belt. These include the above-mentioned Trojans, which orbit 60° behind and ahead of Jupiter. The Trojans, which are close to the special points L_4 and L_5 of the solution of the restricted three-body problem. At these Lagrangian points, a massless body can remain stationary with respect to the massive primaries (in this case, Jupiter and the Sun). In fact, the asteroids are oscillating around the stationary points, but the mean orbits can be shown to be stable against perturbations.

Another large family is the *Apollo-Amor asteroids*. The perihelia of Apollo and Amor are inside the Earth's orbit and between the orbits of the Earth and Mars, respectively. These asteroids are all small, less than 30 km in diameter. The most famous is 433 Eros (Fig. 8.36), which was used in the early 20th century for determining the length of the astronomical unit. When closest to the Earth, Eros is at a distance of only 20 million km and the distance can be directly measured using the trigonometric parallax. Some of the Apollo-Amor asteroids could be remnants of short-period comets that have lost all their volatile elements.

There is a marginal probability that some Earth-crossing asteroids will collide with the Earth. It has been estimated that, on the average, a collision of a large asteroid causing a global catastrophe may take place once in one million years. Collisions of smaller bodies, causing dam-

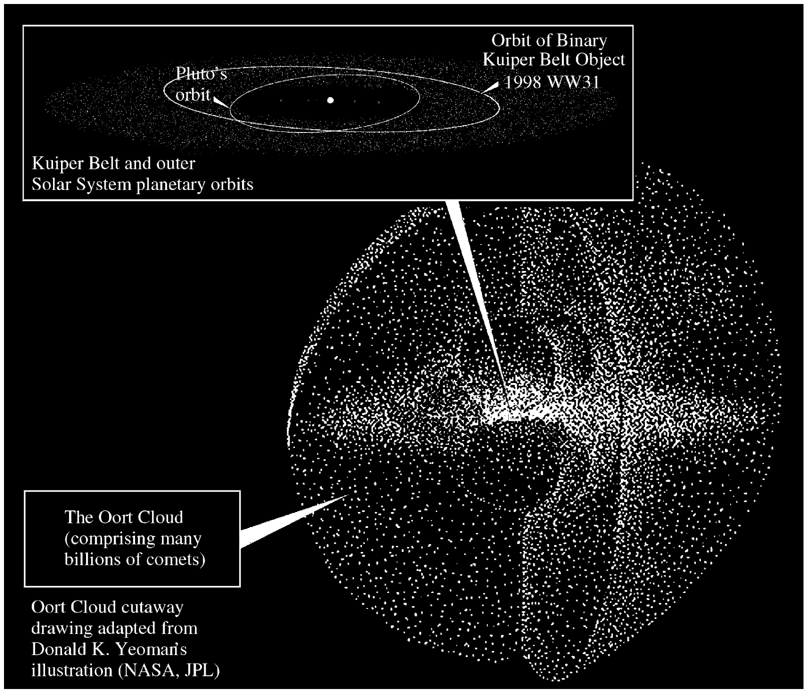


Fig. 8.39 The Kuiper Belt is a disk-shaped cloud of distant icy bodies inside the halo of the Oort cloud. The short-period comets originate in the Kuiper belt, whereas a huge amount of icy bodies that form a source of long period comets resides in the Oort cloud (see Sect. 8.12). (JPL/NASA)

age similar to a nuclear bomb, may happen once per century. It has been estimated that there are 500–1000 *near-Earth asteroids* larger than one kilometre in diameter but possibly tens of thousands smaller objects. Programs have been started to detect and catalogue all near-Earth asteroids and to predict the probabilities of hazardous collisions.

Distant asteroids form the third large group outside the main asteroid belt. The first asteroid belonging to this group (2060) Chiron, was discovered in 1977. Chiron's aphelion is close to the orbit of Uranus and the perihelion is slightly inside the orbit of Saturn. Distant asteroids are very faint and thus difficult to find.

Already in the 1950's *Gerard Kuiper* suggested that comet-like debris from the formation of the solar system can exist beyond the orbit of Neptune as an additional source of comets to the more distant Oort cloud. Later, computer simulations of the solar system's formation showed that a disk of debris should form at the outer edge of the solar system. The disk is now known as the *Kuiper belt* (Fig. 8.39).

The first Trans-Neptunian asteroid (1992 QB1) was discovered in 1992, and in the beginning of year 2006 there were about 1000 known members. The total number of Kuiper belt objects larger than 100 km in diameter is estimated to be over 70,000. Some of them may be even larger than Pluto. The Kuiper belt objects are remnants from the early accretion phases of the solar system. Several of the Trans-Neptunian objects are in or near a 3:2 orbital period resonance with Neptune, the same resonance as Pluto. Therefore they are called *plutinos*.

The exact sizes of asteroids were long unknown. *Edward E. Barnard* of the Lick Observatory determined visually the diameters of (1) Ceres, (2) Vesta, (3) Juno, and (4) Pallas in the 1890's (Fig. 8.39). Practically no other reliable results existed prior to the 1960's, when indirect methods applying photometry and spectroscopy were adopted. Moreover, several stellar occultations caused by asteroids have been observed since 1980's.

The first images of asteroids were obtained in the early 1990's. In 1991 the Galileo spacecraft passed asteroid (951) Gaspra, and in 1993 asteroid (243) Ida, on its long way to Jupiter (see Sect. 8.15). Finally, in 2001, the NEAR space-

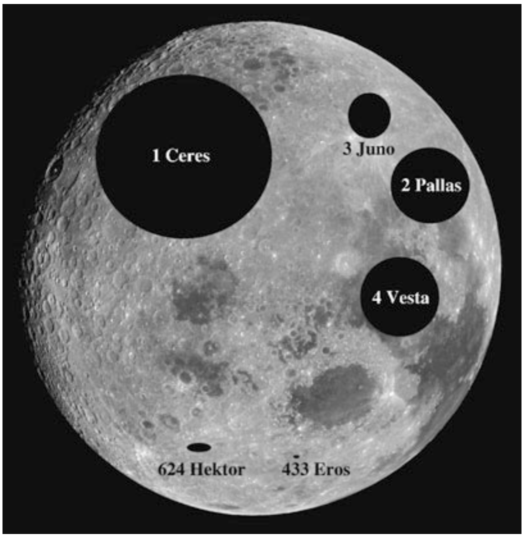


Fig. 8.40 Sizes of some asteroids compared with the Moon. (Moon image, NASA)

craft landed on asteroid (433) Eros after orbiting it for one year.

The images of asteroids (Fig. 8.35) show irregular, crater-filled bodies with regolith and pulverised rock on their surface. Some asteroids may once have been two separate objects that merged into one. In 1992 asteroid (4179) Toutatis passed the Earth only by 4 million kilometres. Radar images revealed a two-body system, where the components were touching each other. Double asteroids may be quite common, and there exist light curves of some asteroids which have been interpreted as results of twin bodies. Another example of a twin asteroid is 243 Ida that has a "moon", a smaller body gravitationally bound to it.

The composition of main belt asteroids is similar to that of iron, stone and iron-stone meteorites. Most asteroids can be divided into three groups, according to their photometric and polarimetric properties. 95 % of the classified asteroids belong to the types C and S types. Metal-rich M type asteroids are rarer.

About 75 percent of asteroids belong to the type C type. The *C asteroids* are dark due to radiation darkening (geometric albedo $p \approx 0.06$ or less), and they contain a considerable amount of carbon (mnemonic C for carbon). They resemble *stony meteorites*. The material is undifferentiated and thus they belong to the most primordial bodies of the solar system. The reflectivity of silicate-rich *S asteroids* is higher and their spectra are close to those of *stone-iron meteorites*. Their spectra show signs of silicates, such as olivine, e.g. fosterite Mg_2SiO_4 or fayalite Fe_2SiO_4. M type asteroids have more metals, mostly nickel and iron; they have undergone at least a partial differentiation.

The compositions and even sizes of the Trans-Neptunian objects are difficult to determine. They are dim, and due to their low temperature, the black-body radiation maximum is around 60 μm. This wavelength is almost impossible to observe on the Earth. Even the estimations of the albedos, and therefore the diameter are very uncertain.

Colours of TNOs range from blue-grey to red and the distribution appears to be uniform. However, population of the low-inclination objects seem to be red and high-inclination objects blue. The unperturbed orbits of the low-inclination objects suggest that they represent a relic of the original population of the Kuiper belt.

Interpretations of the spectra are ambiguous and spectra may not describe the composition of the whole object. The surface is altered by intense radiation, solar wind and micrometeorites and it can be quite different from the regolith and deeper layers underneath.

Small TNOs are probably mixtures of rock and ice with some organic surface material. The composition is similar to the comets. High density (2000–3000 $\mathrm{kg\,m^{-3}}$) of some large objects suggests a high non-ice content, similar to Pluto.

8.12 Comets

Comets are agglomerates of ice, snow, and dust; a typical diameter is of the order of 10 km or less. The nucleus contains icy chunks and frozen gases with embedded rock and dust. At its centre, there can be a small, rocky core.

Comets are the only celestial objects named after their finders. The letter P (periodic) preceding some names indicates that planetary perturbations have changed the orbit so that the comet has remained orbiting the Sun.

A comet is invisible when far from the Sun; when it gets closer than about 2 au, the heat of the Sun starts to melt the ice and snow. The outflowing gas and dust form an envelope, the *coma* around the nucleus. Radiation pressure and the solar wind push ionised gas and dust away from the Sun, resulting in the typical long-tailed shape of a comet (Fig. 8.42).

The tail is always pointing away from the Sun, a fact which was noticed in the 16th century. Usually, there are two tails, an *ion tail* (gas tail) and a *dust tail*. The partly ionised gas and very fine dust in the ion tail are driven by the solar wind. Some of the light is reflected solar light, but the brightness of the ion tail is mostly due to emission by the excited atoms. The dust tail is caused by the radiation pressure. Because the velocities of the particles of the dust tail are lower than the velocities in the ion tail, the dust tail is often more curved than the ion tail.

Fred Whipple introduced in 1950's a *"dirty snowball"* theory to describe the cometary structure. According to this model, cometary nuclei are composed of ice mixed with gravel and dust. The observations have revealed that the classical dirty snowball model is not quite accurate; at least the surface is more dirt than snow, also containing organic compounds. Several chemical compounds have been observed, including water ice, which probably makes up 75–80 % of the volatile material. Other common compounds are carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and formaldehyde (H_2CO).

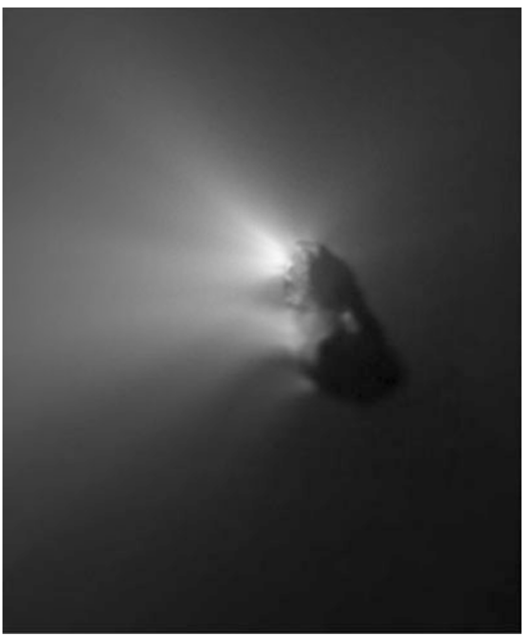


Fig. 8.41 *Lower right:* A composite image of the nucleus of comet P/Halley taken by ESA Giotto spacecraft in 1986. The size of the nucleus is approximately 13 × 7 km. Dust jets are originating from two regions on the nucleus. (ESA/Max Planck Institut für Aeronomie)

The most famous (and also best known) periodic comet is *Halley's comet* (Fig. 8.42). Its orbital period is about 76 years; it was last in perihelion in 1986. During the last apparition, the comet was also observed by spacecraft, revealing the solid cometary body itself for the first time. Halley is a 13 × 7 km, peanut-shaped chunk whose surface is covered by an extremely black layer of a possibly tar-like organic or other similar material. Violent outbursts of gas and dust make an exact prediction of its brightness impossible, as often noticed when cometary magnitudes have been predicted. Near the perihelion, several tons of gas and dust burst out every second.

Cometary material is very loose. Ablation of gas and dust, large temperature variations and tidal forces sometimes cause the whole comet to break apart. *Comet Shoemaker–Levy 9* which impacted into Jupiter in 1994 was torn apart two years earlier when it passed Jupiter at a distance of 21,000 km (Fig. 8.44). The impact of Shoemaker–Levy 9 showed that there can be density variation (and perhaps variation in composition, too) inside the original cometary body.

Comets are rather ephemeral things, surviving only a few thousand revolutions around the Sun or less. The *short-period comets* are all newcomers and can survive only a short time here, in the central part of the solar system.

Since comets in the central solar system are rapidly destroyed, there has to be some source of new short-period comets. In 1950 *Jan Oort* discovered a strong peak for aphelia of long period comets at a distance of about 50,000 au, and that there is no preferential direction from which comets come (Fig. 8.43). He proposed that there is a vast cloud of comets at the outer reaches of

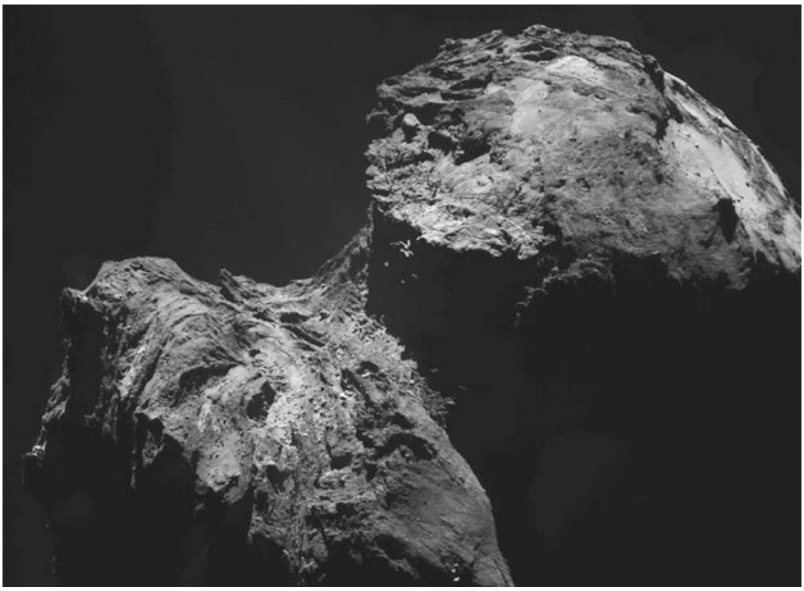


Fig. 8.42 *Top:* Comet Mrkos in 1957. The tail typical to comets is caused by the solar wind and radiation pressure when the comet approaches the Sun (Palomar Observatory). *Down*: The comet Churyumov–Gerasimenko is the first comet where a space probe has landed and sent detailed closeup images. (ESA)

the solar system, now know as the *Oort cloud* (Fig. 8.45). The total mass of the Oort cloud is estimated to be tens of Earth masses, containing more than 10^{12} comets.

A year later *Gerard Kuiper* showed that there is a separate population of comets. Many of the short period comets, with periods less than 200 years, have the orbital inclination less than 40°, and they orbit the Sun in the same direction as the Earth. The orbital inclination of long period comets are not peaked around the plane of the ecliptic but they are more random. Kuiper argued that the short period comets originate from a separate population of comets that resides in a disk-like cloud beyond the orbit of Neptune. The area is now known as the *Kuiper belt* (Fig. 8.39).

Occasionally perturbations from passing stars send some of the comets in the Oort cloud into orbits, which bring them into the central parts of the solar system, where they are seen as *long-period comets*. Around a dozen "new" comets are discovered each year. Most of these are visible only with a telescope, and only a couple of times per decade one can see a bright naked-eye comet.

Some of the long period comets are put into short period orbits by the perturbations of Jupiter and Saturn, whereas some others can be ejected from the solar system. However, there are no comets that have been proven to come from interstellar space, and the relative abundances of several isotopes in the cometary matter are the same as in other bodies of our solar system.

The origin of the Oort cloud and Kuiper belt is different. The Oort cloud objects were formed near the giant planets and have been ejected to the outer edge of the solar system by gravitational perturbations soon after the formation of the solar system. Small objects beyond the orbit of Neptune had no such interactions and they remained near the accretion disk.

In 2014 ESA's Rosetta probe settled on an orbit around the comet Churyumov-Gerasimenko and sent the Philae lander to its surface. The lander found several organic compounds and hard ice below a dust layer about 20 centimetres thick. The water vapour emanating from the comet was different from the terrestrial water: the ratio of deuterium to ordinary hydrogen was three times higher than on the Earth. This suggests that the source of water on the Earth is not comets, at least not of those like Churyumov-Gerasimenko.

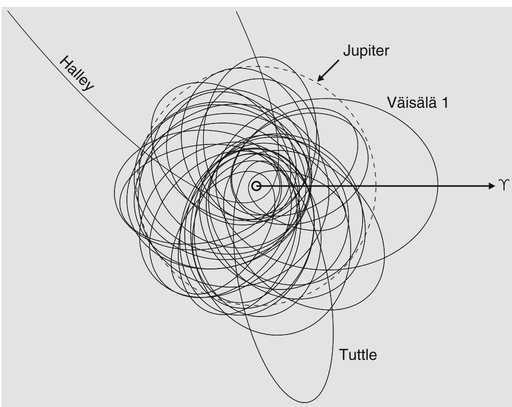


Fig. 8.43 Orbits of short period comets projected to the plane of the ecliptic

8.13 Meteoroids

Solid bodies smaller than asteroids are called meteoroids. The boundary between asteroids and meteoroids, however, is diffuse; it is a matter of taste whether a ten metre body is called an asteroid or a meteoroid. We could say that it is an asteroid if it has been observed so often that its orbital elements are known.

When a meteoroid hits the atmosphere, an optical phenomenon, called a *meteor* ("shooting star") is seen (Fig. 8.47). The smallest bodies causing meteors have a mass of about 1 gram; the (micro)meteoroids smaller than this do not result in optical phenomena. However, even these can be observed with radar which is able to detect the column of ionised air. Micrometeoroids can

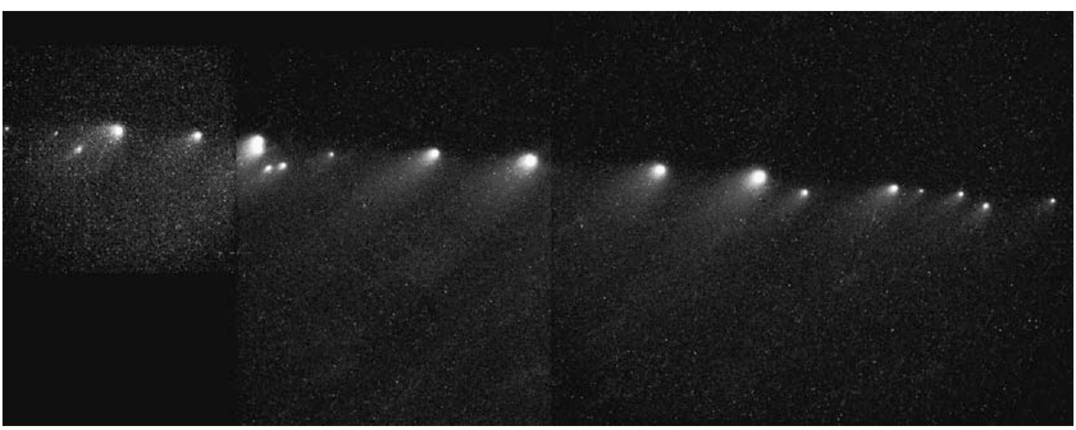


Fig. 8.44 Comet Shoemaker–Levy 9 five months before its collision to Jupiter as seen by the Hubble Space Telescope. (JPL/NASA)

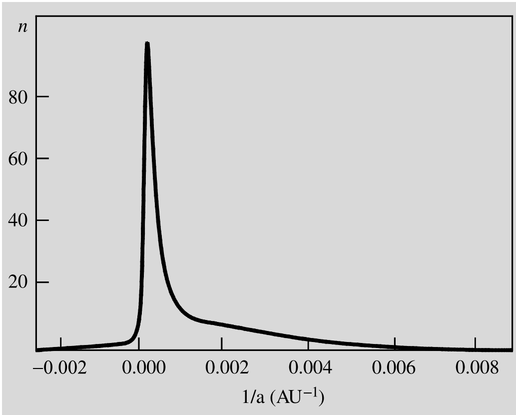


Fig. 8.45 A schematic diagram of the distribution of the semimajor axes of long-period comets. The abscissa is the inverse of the semimajor axis, $1/a$ [AU]$^{-1}$. The Oort cloud is visible as a strong peak at the very small positive values of $1/a$. The orbits shown here are the "original orbits", i.e. computed backward in time to remove all known perturbations

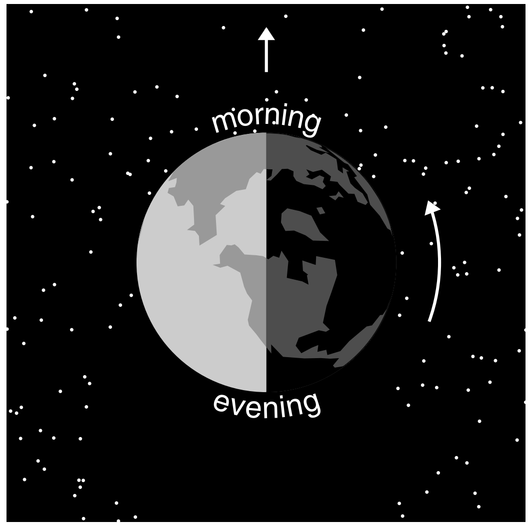


Fig. 8.46 When the Earth is moving on its orbit, the morning hemisphere is the leading one. Hence most of the meteoroids coming from random directions hit the morning hemisphere. Thus most meteors can be seen between midnight and sunrise

also be studied with particle detectors installed in satellites and space crafts. Bright meteors are called *bolides*.

The number of meteoroids increases rapidly as their size diminishes. It has been estimated that at least 10^5 kg of meteoritic material falls on the Earth each day. Most of this material is micrometeoroids and causes no visible phenomena.

Due to perspective, all meteors coming from the same direction seem to radiate from the same point. Such *meteor streams* (meteor showers) are, e.g. the *Perseids* in August and the *Geminides* in December; the names are given according to the constellation in which the radiation point seems to be. On the average, one can see a few sporadic meteors (Fig. 8.46) per hour. During a strong meteor shower one can see even tens of meteors per minute, although a normal rate is some tens per hour.

Most of the meteoroids are small and burn to ashes at a height of 100 km. However, larger bodies may come through and fall to the Earth. These are called *meteorites*. The relative speed of a typical meteoroid varies in the range 10–70 km/s. The speed of the largest bodies does not diminish in the atmosphere; thus, they hit the Earth at their cosmic speeds, resulting in large impact craters. Smaller bodies slow down and drop like stones

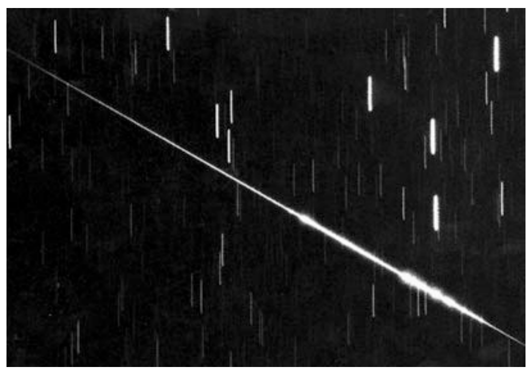


Fig. 8.47 Meteors are easy to capture on film: one just leaves a camera loaded with a sensitive film on a tripod with the shutter open for an hour or so. Stars make curved trails on the film. (L. Häkkinen)

but impacts of large bodies (diameter meters or more) may cause large-scale disaster.

Iron meteorites or irons, composed of almost pure nickel-iron, comprise about one quarter of all meteorites. Actually the irons are in a minority among meteoroids, but they survive their violent voyage through the atmosphere more easily than weaker bodies. Three-quarters are *stony meteorites*, or *stone-iron meteorites*.

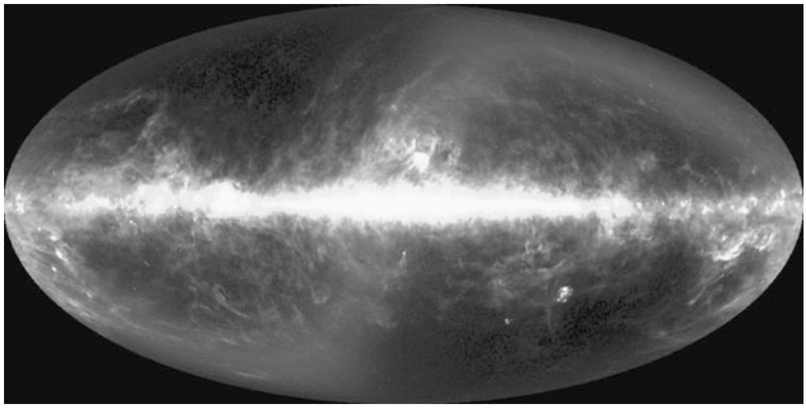


Fig. 8.48 A projection of the entire infrared sky created from observations of the COBE satellite. The bright horizontal band is the Milky Way. The dust of the solar system, visible on the Earth as zodiacal light is an S-shaped glow across the image. (G. Greaney and NASA)

Meteoroids themselves can be divided into three groups of roughly equal size. One-third is ordinary stones, *chondrites*. The second class contains weaker *carbonaceous chondrites* and the third class includes cometary material, loose bodies of ice and snow which are unable to survive down to the Earth.

Many meteor streams are in the same orbit as a known comet, so at least some meteoroids are of cometary origin. Near a perihelion passage, every second several tons of gravel is left on the orbit of a comet. There are several examples of meteorites that have their origin in the Moon or Mars. Debris of large impacts may have been ejected into space and finally ended up on the Earth. Some meteoroids are debris of asteroids.

8.14 Interplanetary Dust and Other Particles

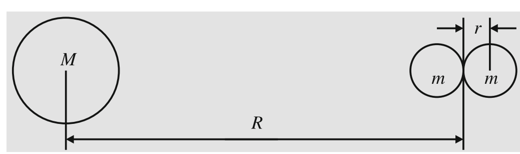
Two faint light phenomena, namely *zodiacal light* and *gegenschein* (counterglow) make it possible to observe interplanetary dust, small dust particles reflecting the light of the Sun. This weak glow can be seen above the rising or setting Sun (zodiacal light) or exactly opposite the Sun (gegenschein). The interplanetary dust is concentrated near the plane of the ecliptic. The typical sizes of the particles are in the range of 10–100 μm.

Solar Wind Elementary particles hitting the Earth originate both in the Sun and outside the solar system. Charged particles, mainly protons, electrons and alpha particles (helium nuclei) flow continuously out of the Sun. At the distance of the Earth, the average speed of this solar wind is about 500 km/s. The velocity and number of particles depend on eruptions and activity of the Sun (Sects. 13.3 and 13.4).

The charged particles interact with the solar magnetic field. The strength of the solar magnetic field at the Earth's distance is about $1/1000$ of that of the Earth. Particles coming from outside the solar system are called cosmic rays, which contain both elementary particles and heavier nuclei.

8.15 Examples

Example 8.1 (The Roche Limit) A French mathematician *Edouard Roche* computed in 1848 a limit where a moon will be torn apart due to the tidal forces if it approaches its parent planet. Roche proposed that the Saturnian rings were formed in that way.



We can compute the Roche limit for a body at a distance R of a planet the mass of which is M approximating the body with two small spheres of radius r and mass m. The difference of gravitation affecting the small spheres by the planet is

$$\Delta F = GMm\left[\frac{1}{(R-r)^2} - \frac{1}{(R+r)^2}\right]$$
$$\overset{R \gg r}{\approx} GMm\frac{4r}{R^3}.$$

The gravitational force between the small spheres is

$$F' = \frac{Gm^2}{4r^2}.$$

If $\Delta F > F'$, the small spheres will be pulled apart. The forces are equal at the Roche limit:

$$GMm\frac{4r}{R^3} = \frac{Gm^2}{4r^2}.$$

Thus the distance of the Roche limit R is

$$R = \sqrt[3]{\frac{16r^3M}{m}}.$$

Inserting the masses of the planet and the spheres in terms of the radii of the planet S and spheres r, and assuming that the densities ρ are equal, $m = \frac{4}{3}\pi r^3\rho$, $M = \frac{4}{3}\pi S^3\rho$, we obtain

$$R \approx 2.5 \times S.$$

Our result is valid only for a body without any internal strength. Smaller bodies with internal strength can survive inside the Roche limit. You, dear reader, act as an excellent example of this, because you read this example well inside the Roche limit of the Earth. A 100 km stony asteroid will survive even if it orbits the Earth just above the atmosphere but a sphere of water of the same size would break apart.

8.16 Exercises

Exercise 8.1 The interval between two oppositions of a planet was 398.9 d. The angular diameter of the planet at the opposition was 47.2″. Find the sidereal period, semimajor axis, and the true diameter (in kilometres) of the planet. Which planet was it?

Exercise 8.2 (a) Assume that three bodies move along circular orbits with angular velocities (mean motions) n_1, n_2 and n_3. Show that these bodies have a common synodic period if and only if there are nonzero integers k_1, k_2 and k_3 such that

$$k_1n_1 + k_2n_2 + k_3n_3 = 0, \quad k_1 + k_2 + k_3 = 0.$$

(b) The resonance of the Galilean satellites can be expressed in terms of their mean motions as

$$n_{\mathrm{Io}} - 3n_{\mathrm{Europa}} + 2n_{\mathrm{Ganymede}} = 0.$$

Find the synodic period of these three moons.

Exercise 8.3 The rotation period of Mars is 24.62 hours and the orbital period of Deimos 30.30 hours. How long is the time between two successive risings of Deimos and how much Deimos moves in one hour as seen from Mars?

Exercise 8.4 Find the distance of the Roche limit for all planets and see if any of their moons is orbiting the limit. And how are the rings of giant planets situated relative to the Roche limit?

Exercise 8.5 Assume that the hydrogen atom is a solid sphere with a radius of 5.3×10^{-11} m (the Bohr radius) and mass 1.67×10^{-27} kg. Use such balls to build a regular (infinite) grid where each ball is touching its six neighbours. What is the density of such matter? Compare with the density of Jupiter.