Chapter 2
Space and Planetary Environment

The environments in which exploration and exploitation robots operate can be roughly subdivided into four types

- Low Earth orbit
- Deep space
- Interstellar medium
- Planets and small celestial bodies

The latter can be further subdivided in

- Moon
- Rocky planets
- Giant planets
- Satellites of giant planets
- Small bodies

2.1 Low Earth Orbit Environment

Usually Low Earth Orbits (LEO) are orbits with a height lower than 1,000 km. However, the environment encountered in LEO is roughly the same encountered in orbits up to the Van Allen belts (Fig. 2.1) surrounding our planet.

The Earth magnetosphere protects our planet and all space below the Van Allen belts from most radiations coming from the Sun and deep space. A diagram of the Earth's magnetosphere is shown in Fig. 2.2.

Owing to the protection by the magnetosphere, radiation is moderate in LEO, even during strong solar activity (solar flares). However, there is an anomaly in Earth magnetic field off the cost of Brazil and in that zone much stronger radiation reach the upper atmosphere. The Van Allen radiation belts are symmetric about the Earth's magnetic axis, which is tilted with respect to the Earth's rotational axis by an angle of $\approx$11 degrees. This tilt, together with an offset of $\approx$450 kilometers causes the inner Van Allen belt to be closer to the Earth's surface over the south Atlantic

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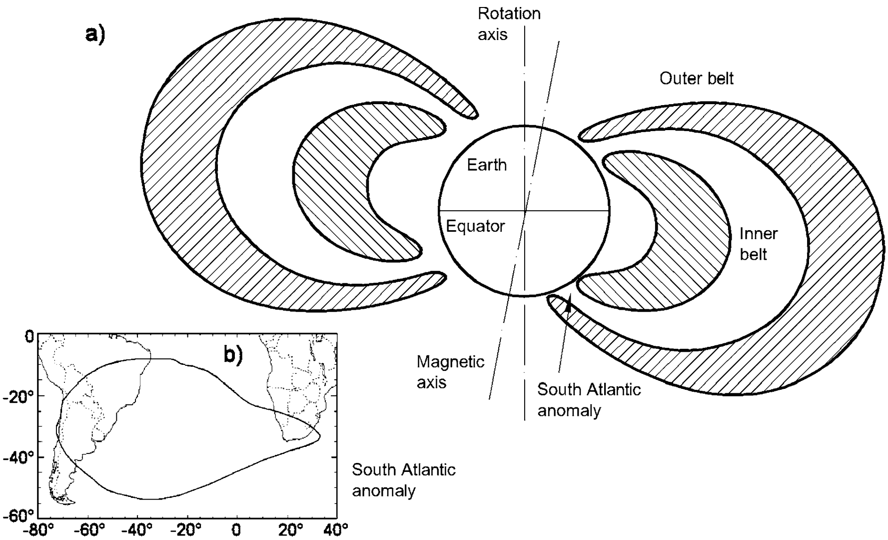

Fig. 2.1 (**a**) Schematic cross section of the Van Allen radiation belts. (**b**) Earth zone interested by the South Atlantic Anomaly

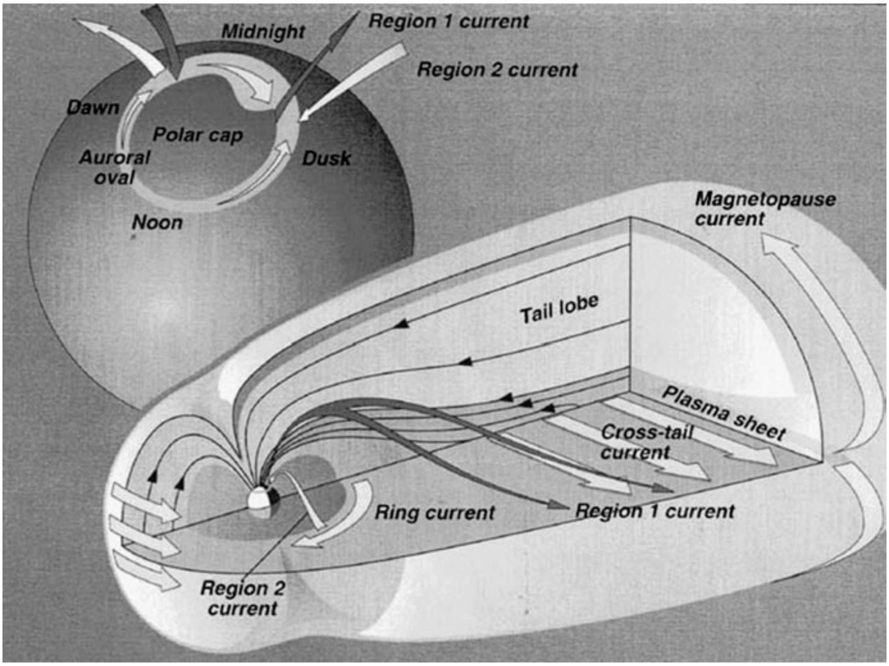

Fig. 2.2 Diagram of the Earth's magnetosphere—the volume occupied by the geomagnetic field in space—and, *in the upper left*, the northern polar region. Large electric currents (millions of Amperes) flow through space (from G. Genta, M. Rycroft, *Space, The Final Frontier*? Cambridge University Press, Cambridge, 2003)

Table 2.1 Some values of atmospheric temperature, pressure and density in LEO from the US Standard atmosphere

Altitude (km)	T (K)	p (Pa)	ρ (kg/m^3)
0	288.15	1.01×10^{5}	1.23
100	195.08	3.20×10^{-2}	5.60×10^{-7}
200	854.56	8.47×10^{-5}	2.08×10^{-9}
300	976.01	8.77×10^{-6}	1.92×10^{-11}
400	995.83	1.45×10^{-6}	2.80×10^{-12}

ocean, causing the South Atlantic Anomaly (SAA), and farthest from the Earth's surface over the north Pacific ocean.

Remark 2.1 The boundaries of the SAA vary with altitude and its shape changes over time. At an altitude of 500 km, the SAA ranges between −90° and +40° in longitude and −50° to 0° in latitude. Its extent increases with increasing altitude.

The characteristics of the upper atmosphere and of space above it are quite variable, both with the altitude and time. In the zone between 90 and 1,000 km the average values of pressure, density and temperature stated by the US Standard atmosphere can be used (see Table 2.1).

The atoms in the upper atmosphere are strongly ionized and the atmospheric layer between 50 and 600 km altitude is referred to as the ionosphere. They are mostly oxygen ions, but above 300 km the composition changes gradually to mostly hydrogen ions.

The conditions in that zone of space are well known, but much variable depending on the *space weather*, a term commonly used to define the phenomena involving ambient plasma, magnetic fields, radiation and other matter in a region of space. The space weather close to the Earth is a consequence of the behavior of the Sun, the Earth's magnetic field, and our location in the solar system and affects deeply not only the space activities of humankind, but also our planet and our technological activities on Earth.

In the whole solar system space weather is greatly influenced by the speed and density of the solar wind (see Sect. 2.2). Data on the current solar wind speed and density and on solar flares are continuously available, for instance on www.spaceweather.com.

The density reaches maxima at the peak of solar activity cycles, every 11 years. During such periods the drag on satellites gets much stronger and the danger of losing altitude and deorbiting increases. To remain in LEO between 200 and 400 km satellites require periodical reboost, particularly if their surface/mass ratio is large. The International Space Station (ISS) is particularly subject to high atmosphere drag, owing to its large solar panels. Reboost becomes even more important in high solar activity periods.

At greater altitudes the pressure and density decrease fast; at about 1000 km a satellite may remain in orbit indefinitely (at least with reference to normal service time of man-made machines) without reboost.

Apart from plasma, space is full of debris of various type, both natural and artificial. Natural ones consist mainly in very small meteorites, micrometeorites and dust grains that are captured by Earth's gravitational field and enter the atmosphere to be destroyed by air drag. Occasionally, larger meteorites able to reach the surface occur.

Most items of space debris in LEO are, however, artificial. The large pieces of space debris are accurately tracked using radars and telescopes; their number and positions are well known. In 1996 there were about 4,000 detectable objects, and now there are some 8,500 objects with sizes about 10 cm or greater. Although new debris is always being produced, the older debris decays owing to upper atmospheric drag and eventually re-enter the atmosphere, being completely destroyed before reaching the ground. Only meter-sized objects have some chance of getting to the ground, and so constituting a danger for people, a danger which is much lower than that due to natural objects.

Remark 2.2 The 11 year solar cycle has a strong effect on space debris since, as already stated, the density of the high atmosphere is much greater near solar maximum conditions than at solar minimum. A periodic clean-up of debris in the lowest orbits thus occurs.

Smaller pieces of debris are produced by the explosion, whether accidental or intentional, of upper stages or satellites. It has been computed that about half of the centimeter-sized debris has been produced in this way. Military satellites are most responsible for this type of pollution. Dangerous debris has been produced when the core of the nuclear reactor of military satellites is jettisoned in order to be placed in a safe (higher) orbit after the satellite is decommissioned. While doing this, the cooling system of the reactor lets swarms of droplets of the coolant, a liquid sodium-potassium alloy, to escape. These liquid droplets are dangerous sub-centimetric projectiles, which can penetrate the skin of satellites.

International treaties forbidding the intentional explosion of satellites are being prepared; they state that precautions must be taken against accidental events which may produce space debris. They also state that decommissioned satellites must be de-orbited and destroyed in the atmosphere or, if this is impossible as in the case of geosynchronous satellites, moved into a less used orbit.

Remark 2.3 The most critical orbits are those lying between 1,000 and 1,400 km altitude, where the air drag is insufficient to cause debris to decay and re-enter.

The ultimate danger is a situation in which there are so many objects that collisions are frequent enough to produce new fragments continuously. This sort of chain reaction would end up creating a debris belt in which no object could survive. But this nightmare scenario will not occur for several centuries.

Apart from the much publicized accident when a *Progress* cargo craft hit a solar panel of the *Mir* space station (but in this case the cause was a wrong rendezvous manoeuvre), only two space collision between two unrelated objects involving a working satellite occurred to date. The first was when a suitcase-sized fragment from the explosion of the upper stage of an *Ariane* rocket hit, after ten years in space, the small French satellite *Cerise*. The damage in that case was not too large—a boom protruding from the satellite for stabilization purposes was cut off—but the satellite might well have been wiped out.

The second, occurring on February 10, 2009, involved a US commercial Iridium satellite and an inactive Russian satellite Cosmos 2251. Both were completely destroyed, generating a cloud of thousands of pieces of debris. Two other collisions between unrelated non-working objects were also recorded. One occurred in late December 1991, and involved a Russian decommissioned satellite (Cosmos 1934) and a piece of debris from Cosmos 929; the other is more recent (January 17, 2005) and involved a 31 years old US Thor rocket body and a fragment from a Chinese CZ-4 launch vehicle.

The probability that a large piece of debris will come closer than 100 m from a satellite in LEO is about one in 100 years. In the case of a space station, a large piece of debris identified in advance can be avoided by suitable manoeuvres. Very small objects do not cause damage and debris smaller than a few mm should be stopped by the shields of the International Space Station. The most dangerous particles are those which cannot be detected from the ground but are larger than a few mm. It has been computed that the probability that a 1 cm sized particle will pierce through the hull of the ISS is about 1% in its 20 years life.

There are well consolidated design practices for commercial and scientific satellites in LEO, so this can be considered an environment that does not pose great problems.

2.2 Interplanetary Medium

Space beyond the Van Allen Belts is pervaded by the *solar wind*, which fills the whole solar system The solar wind is mainly made of hydrogen ions (protons) flowing at high speed out of the Sun's corona. The temperature of the corona is so high that the coronal gases are accelerated to a velocity of about 400 km/s. This component of the solar wind, the so called *slow solar wind*, has a temperature of $(1.4\text{–}1.6) \times 10^6$ K and a composition similar to that of the corona. Over coronal holes the speed of solar wind can reach 750–800 km/s and a temperature of about 8×10^5 K. The composition of this *fast solar* wind is closer to that of Sun's photosphere. Over those parts of the outer layers of the Sun that are colder, the solar wind can be as slow as 300 km/s.

While the slow solar wind is mostly ejected from the regions around the equator of the Sun, up to latitudes of 30°–35°, the fast solar wind originates from the coronal holes, which are located mostly in the regions about the Sun's magnetic poles.

The interaction of the particles with different velocities and the rotation of the Sun causes the solar wind to be quite unsteady and the space weather in the whole solar system to be much variable. In 1997 the Advanced Composition Explorer (ACE) satellite was launched and placed into an orbit about the L1 point between the Earth and the Sun. This point, located at about 1.5 million km from the Earth on the line connecting the Earth with the Sun, is characterized by the equilibrium between solar and Earth's attraction, so that a body located there (or better in a halo orbit about L1, since in this point the equilibrium is unstable), can remain between the Earth and the Sun indefinitely. The ACE monitors continuously the solar wind, providing real-time information on space weather.

From time to time, fast-moving bursts of plasma called Interplanetary Coronal Mass Ejections (ICME) may disrupt the standard pattern of the solar wind, launching in the surrounding space electromagnetic waves and fast particles (mostly protons and electrons) to form showers of ionizing radiation. When these ejections impact the magnetosphere of a planet they temporarily deform the planet's magnetic field. On Earth they induce large electrical ground currents and send protons and electrons toward the atmosphere, where they form the aurora.

Remark 2.4 Solar flares are one of the causes of interplanetary coronal mass ejections. They constitute a danger to spacecraft, manned and unmanned.

Owing to the motion of these charged particles, an interplanetary magnetic field (IMF) pervades the whole solar system.

The interplanetary medium is filled by radiation, *cosmic radiation*, not only from the Sun but also from extrasolar objects. The cosmic radiation that enter Earth's atmosphere are made up mostly by protons (90%), plus about 9% helium nuclei (alpha particles) and about 1% of electrons (β particles), plus photons and neutrinos. Their energy is in the range of over 1000 eV.

Apart from the radiation from the Sun, *Galactic cosmic rays* (GCRs) come from outside the solar system but generally from within our Milky Way. They are atomic nuclei trapped by the galactic magnetic field with all of the surrounding electrons taken away during their travel through the galaxy at a speed close to the speed of light. As they travel through the very thin gas of interstellar space they emit gamma rays. Their composition is similar to the composition of the Earth and solar system.

Another component of the cosmic radiation are the Anomalous Cosmic Rays (ACRs) They are due to the neutral atoms of the interstellar matter that flow through the solar system (the charged particle are kept outside the heliosphere (see Sect. 2.3) by the interplanetary magnetic field), at a speed of about 25 km/sec. When closer to the Sun, these atoms undergo the loss of one electron in photo-ionization or by charge exchange, and are then accelerated by the Sun's magnetic field and the solar wind. ACRs include large quantities of helium, oxygen, neon, and other elements with high ionization potentials.

Apart from these heavy particles, there is also the cosmic microwave background radiation, consisting of very low energy photons (energy of about 2.78 Kelvin) which are remnants from the time when the universe was only about 200,000 years old. Neutrinos, photons of different energies (produced by the Sun, other stars, quasi-stellar objects, black-hole accretion disks, gamma-ray bursts and so on), electrons, muons, and other particles are also present.

Remark 2.5 All these particles are not dangerous on Earth since they are deflected by the Earth's magnetic field or are stopped by the atmosphere. On other celestial bodies, which have no magnetosphere and whose atmosphere is thin (the Moon, Mars, etc.) they reach down to the surface and constitute a danger.

Giant planets, like Jupiter, have a strong magnetosphere, shielding the planet but causing zones of strong radiation, like the Van Allen belts of Earth. Spacecraft entering these zones must be designed taking this factor into account.

Apart from plasma, there is also a tiny amount of neutral hydrogen: at the distance of Earth's orbit from the Sun, the concentration of neutral hydrogen is about 10^4 atoms per m^3. As said above, some of these atoms come from interstellar space.

A relatively small amount of dust particles—micrometeroids—exist in the solar system. Much of this dust is thought to have been produced in collisions between asteroids and in the shedding of material from comets while passing close to the Sun. About 30,000 tons of interplanetary dust particles are estimated to enter Earth's upper atmosphere annually.

The vacuum is much higher than in LEO, and hydrogen ions from the Sun substitute oxygen ions from Earth's atmosphere. So, while the environment in LEO is oxidizing, that in deep space is reducing.

2.3 Interstellar Medium

The Sun moves, with the planets and all the bodies of the solar system, through the very rarefied medium that fills the interstellar space, the *interstellar medium*. Most of this medium is gas (about 99%), and the remaining is dust. Although very rarefied, it constitutes about the 15% of the matter of our Milky Way. The density and composition of the interstellar medium is quite variable from place to place. Its density ranges from a few thousand to a few hundred million particles per cubic meter with an average value of a million particles per cubic meter.

The gas is roughly 89% hydrogen (either molecular of atomic), 9% helium and 2% heavier elements. It forms cold clouds of neutral atomic or molecular hydrogen. Hot newly born stars ionize the gas with their ultraviolet light, giving way to hot ionized regions. In the outer regions of the galaxy, the interstellar medium blends smoothly into the surrounding intergalactic medium.

Interstellar dust is made of small particles, with a size of a fraction of a micron, of silicates, carbon, ice, and iron compounds.

In its motion through the interstellar gas, the interplanetary medium creates a shock wave ahead of it, in a way which is similar to what happens when a supersonic aircraft flies through the air. This shock wave is called the *bow shock*. A sketch of the bow shock is shown in Fig. 2.3a.

The solar system is contained in a magnetic bubble, the *heliosphere*, that extends well beyond the orbit of Neptune. Although electrically neutral atoms from interstellar space can penetrate this bubble, virtually all of the material in the heliosphere emanates from the Sun itself.

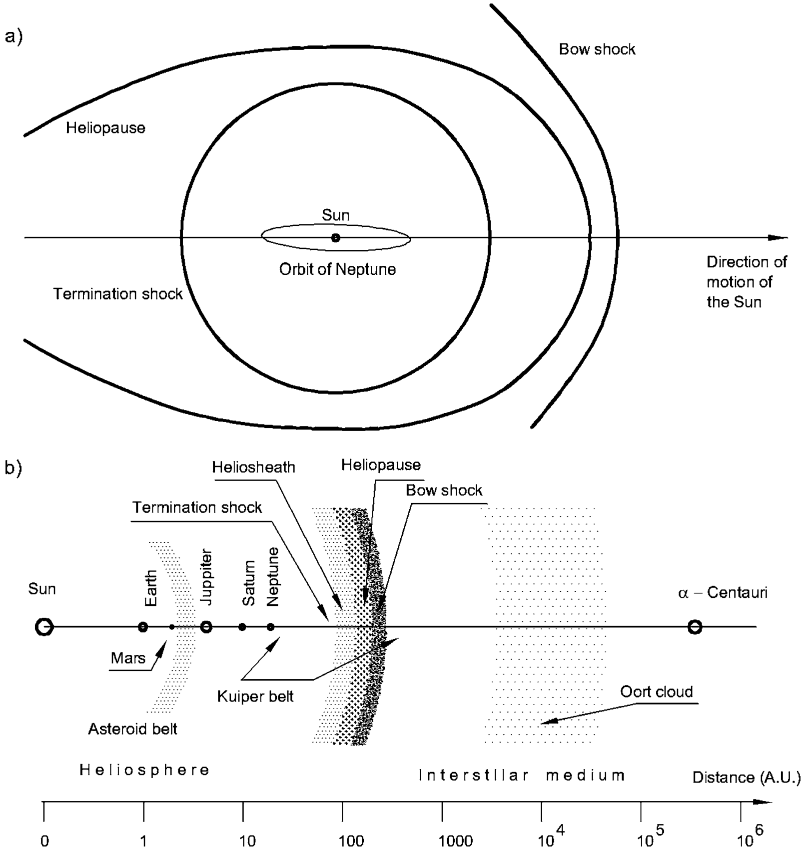

Fig. 2.3 (**a**) Diagram of the heliosphere, showing the termination shock, the heliopause and the bow shock. (**b**) Distances (in Astronomical Units) from the Sun of the various objects up to the nearest star. Pseudo-logarithmic scale (in a true logarithmic scale the origin cannot be represented)

The solar wind travels at supersonic speed; as it approaches the heliopause, it slows suddenly, forming a shock wave where it passes from supersonic to subsonic. This standing shock wave is called the *termination shock*.

The termination shock is believed to be 75 to 90 AU from the Sun. In 2007, *Voyager 2* passed through the Sun's termination shock at about 84 AU from the Sun. Since the position of the termination shock is not fixed (its distance from the Sun changes due to changes in the solar activity), *Voyager 2* actually passed through the termination shock several times. Similar symptoms of being through the termination shock were shown by *Voyager 1* in 2004 at 94 AU. from the Sun. The termination shock may be also irregularly shaped, apart from being variable in time.

Once subsonic, the solar wind may be affected by the ambient flow of the interstellar medium. This subsonic region is called the *heliosheath*. The limit of the heliosheath is at about 80 to 100 AU. at its closed point. Since it has a comet-like shape, its tail trails behind the Sun for a distance of several hundreds AU.

The outer surface of the heliosheath, where the heliosphere meets the interstellar medium, is called the *heliopause*. The outer limit of the heliopause is the bow shock. The heliopause and the termination shock are shown in the sketch of Fig. 2.3a.

A region very rich in hot hydrogen, named the *hydrogen wall*, is assumed to be located between the bow shock and the heliopause. The wall is composed of interstellar material interacting with the edge of the heliosphere.

The solar system, in logarithmic scale, showing the outer extent of the heliosphere, the Oort cloud and out to Alpha Centauri is shown in Fig. 2.3b. Note that the scale is not a true logarithmic scale, since it should not show the zero, and that α Centauri is actually not in the direction of motion of the Sun.

Remark 2.6 Most of the galactic cosmic radiation is deflected by the heliosphere, which protects the whole solar system from this harsh galactic environment. The Earth has thus two protective layers against cosmic radiation: its own magnetosphere and the heliosphere. Outside the heliosphere the radiation environment is thus much worse than in the solar system in general.

2.4 Lunar Environment

The lunar environment is dealt with separately, since it is much better known than other planetary environments and the recent decision to return to the Moon makes it more important.

Since the Moon is gravitationally locked in its orbit around the Earth, it shows always the same side (the near side) to the Earth. The other side (the far side) cannot be seen from our planet. However, small variations (libration) in the angle from which the Moon is seen allow about 59% of its surface to be seen from the Earth. The rotation and orbital periods are equal to 27.322 days, while the average length of lunar day is 29.531 days.

The gravitational acceleration at the surface of the Moon is 1.62 m/s^2 (at the equator), however, the lunar gravity field is not completely uniform due to mass concentrations (mascons) beneath the surface, associated at least in part with the presence of dense basaltic lava flows in some of the giant impact basins. Although the variations in acceleration due to these irregularities are generally less than one-thousandth of the surface gravity, they greatly influence the orbit of spacecraft about the Moon.

The escape velocity is 2.38 km/s at the equator.

The atmosphere is very thin and can practically be considered as a vacuum: the total mass of gases surrounding the Moon has been evaluated as only 104 kg. The mean atmospheric pressure is about 3×10^{-15} bar, but it has large variations mainly with the night and day cycle. The gases come mostly from surface outgassing and are lost in space owing to solar light pressure and, for ionized particles, solar wind magnetic field. The elements detected, both using Earth based spectrometers and instruments on space probes, are hydrogen, helium-4, sodium, potassium, radon-222, polonium-210, argon-40 plus molecular gases like oxygen, methane, nitrogen, carbon monoxide and carbon dioxide. Likely, hydrogen and helium come from the solar wind, while argon originates from the lunar interior. Vacuum must be accounted for when choosing the materials and many common plastics and rubbers are unsuitable, as their strength and flexibility is reduced by outgassing of their volatile components. Even materials approved for use in LEO may not be suitable for use on the Moon.

The thin atmosphere does not refract light, but the moon is not a black and white world: very deep black and blinding white are accompanied by a vast range of browns, tans, and grays, with a few shades of purple and rusty reds. There are no blues and greens, except from objects human will bring with them.

Due to the lack of a substantial atmosphere and the long duration of the day, the surface temperature varies greatly from day to night and also from place to place. The average temperature is −23°C, but during the day the average surface temperature is 107°C, with maximum values as high as 123°C and up to 280°C at noon on the equator. At night, the average temperature is −153°C but can fall as low as −233°C in the areas of the south basin that are permanently shaded. A typical non-polar minimum temperature is −181°C (at the Apollo 15 site). During the month long day, quite strong temperature variation rates can occur. Average temperature also changes about 6°C between aphelion and perihelion. Temperatures just below the surface remain relatively constant; at a depth of 1 m, it is almost constant at −35°C.

Objects on the lunar surface are heated during the day more by the hot ground than by direct sunlight: the sky is seen as a heat sink with a tiny hot spot, while the ground is seen as a large hot surface, emitting strong infrared radiation.

There have been reports of lunar geothermal activity at a few locations, like the Aristarchus Crater region, where "glowing clouds" have been reported. Photographic evidence of recent small-scale volcanic activity has also been recorded. If these findings are confirmed, warm magma close to the surface might be exploited as an energy source.

The Moon has a very weak magnetic field, from 3×10^{-3} to 0.33 μT (as a comparison, the Earth's magnetic field is 30–60 μT—more than hundred times larger) While on Earth the magnetic field is dipolar, generated by a geodynamo in its core, this effect is completely absent, at present, on the Moon, and the lunar magnetic field originates in the crust and is local in nature. Possibly, it is a remnant of a global magnetic field, which was present in the past when a geodynamo effect was active, but this theory is debatable. The fact that the largest crustal magnetizations appear to be located near the antipodes of the giant impact basins seems to suggest, on the contrary, an impact origin.

Additionally, on the lunar surface there is an external magnetic field, of about 5×10^{-9}–10×10^{-9} T, due to the solar wind.

The main features of the lunar surface are the dark and relatively featureless plains called maria (singular mare, Latin for sea), the lighter-colored, hilly regions called terrae (singular terra, Latin for land), or more commonly highlands, and the craters, almost absent on maria, but abundant on terrae. The far side almost completely lacks maria, which represent just about 2.6% of the far side, against 31.2%

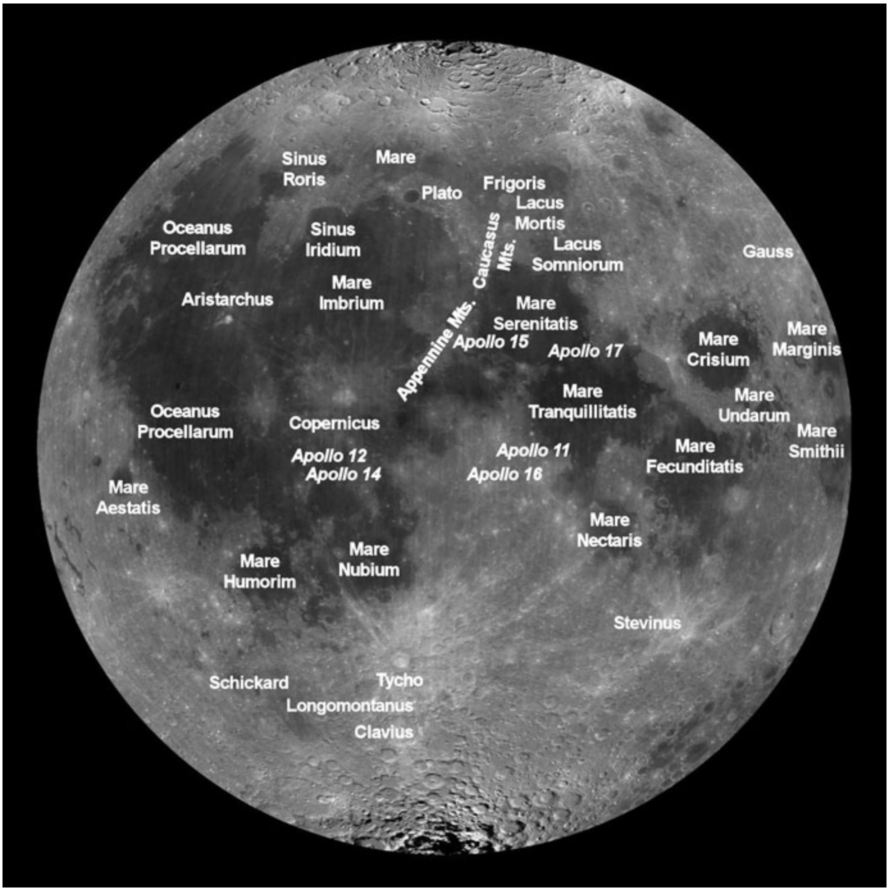

Fig. 2.4 Simplified map of the near side, with the landing point of some American spacecraft

of the near side. A map of the near side, with the landing point of some American spacecraft, is shown in Fig. 2.4. A map of the far side is shown in Fig. 2.5.

Maria are vast solidified pools of ancient basaltic lava, containing iron, titanium, and magnesium. In most cases these lava outflows are attributed to impacts due to large meteorites, whose impact basins can be identified. At the periphery of these giant impact basins many of which have been filled by basalt maria, many large mountain ranges can be found. These are believed to be the surviving remnants of the impact basin's outer rims. No major lunar mountains are believed to have formed as a result of tectonic events like on Earth. Slopes are mild, as an average, with grade angles of 15°–20° (compared to 30°–35° on Earth) in spite of the low lunar gravity which would allow steeper grades to be stable. Faults and depressions on the Moon are called rilles and clefts. Snaking rilles are lava channels or collapsed lava tubes, which were probably active during the maria formation. Lava tubes are

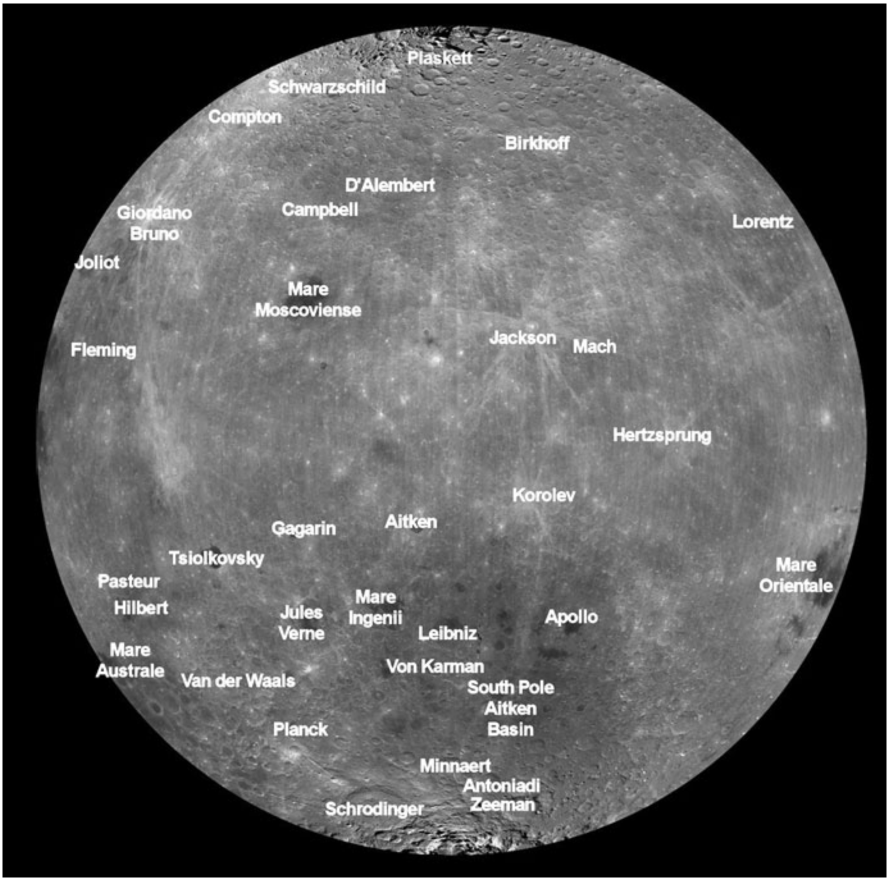

Fig. 2.5 Simplified map of the far side of the Moon

supposed to be frequent and much larger than similar formations on Earth. They may be hundreds of meters across.

Some peaks at the north pole are always in sunlight, owing to the small tilt of the lunar axis on the ecliptic plane. Similarly, at the south pole, the rim of Shackleton crater is illuminated for about 80% of the lunar day. The bottom of some craters in the polar regions are always in the shade.

Highlands are thickly cratered, owing to collisions of asteroids and comets: about half a million craters have diameters greater than 1 km. Since impact craters accumulate at a nearly constant rate, the number of craters per unit area can be used to estimate the age of the surface. The lack of an atmosphere, weather and recent geological processes ensures that many of these craters have remained relatively well preserved in comparison to those on Earth. The largest crater on the Moon, which is also the largest known crater in the Solar System, is the Aitken basin on the far side, between the South Pole and equator; its diameter is about 2,240 km and its depth is 13 km. It has the lowest elevation of the whole Moon.

Table 2.2 Grain-size distribution of lunar regolith taken from the landing site of Apollo 11

Grain size (mm)	% by weight
10–4	1.67
4–2	2.39
2–1	3.20
1–0.5	4.01
0.5–0.25	7.72
0.25–0.15	8.23
0.15–0.090	11.51
0.090–0.075	4.01
0.075–0.045	12.40
0.045–0.020	18.02
Less than 0.020	26.85

Both maria and terrae are covered by regolith, i.e. pulverized rock with grain size between less than 20 and 270 μm, most grains being of the smallest size. The grain-size distribution from specimens taken by the Apollo 11 astronauts in Mare Tranquillitatis is reported in Table 2.2 (from Calina C. Seybold, http://www.tsgc.utexas.edu/tadp/1995/spects/environment.html).

The regolith of older surfaces is generally thicker than for younger surfaces. The thickness of the regolith layer varies from about 3–5 m in the maria, and about 10–20 m in the highlands. Beneath the finely comminuted regolith layer is what is generally referred to as the megaregolith. This layer is much thicker (on the order of tens of kilometers) and comprises highly fractured bedrock.

The lunar regolith is rich in sulfur, iron, magnesium, manganese, calcium, and nickel. Many of these elements are found in oxides such as FeO, MnO, MgO, etc. Ilmenite ($FeTiO_3$), most common in the maria regions, is the best source of in situ oxygen. The carbon, hydrogen, helium and nitrogen found in the soil are almost entirely due to implantation by the solar winds.

This dust is electrically charged, so it sticks to everything and constitutes a problem for both equipment and humans. The *Apollo* astronauts noted that after excursions dust was carried on board (they stated that is smells like spent gunpowder) and this may constitute a health risk. The dust is mostly made of silicon dioxide glass (SiO_2), most likely created from the meteors that have crashed into the Moon's surface. It also contains calcium and magnesium. Electrostatic devices for collecting the dust and preventing it from entering mechanisms and lungs of people are being studied.

Particles in lunar regolith are very jagged and abrasive, which causes them to interlock and increase their harmful effects on health when breathed. Unlike Earth sand grains, they do not flow over each other. Subjected to pressure, they jam against each other and resist like solid rock. All mechanisms must be properly sealed, particularly because, in absence of atmosphere and due to electric charge, once raised from the ground, the particles tend to fly on parabolic trajectories. Because of the hard vacuum they do not remain in the 'atmosphere', but quickly return to the surface. They usually reach no more than 1.5 m from the surface, and once they get on any surface, they tend to stick to it and are difficult to remove.

Dust can be lifted off the lunar surface by the thrusters of a landing shuttle, the wheels of a rover, impacts by meteorites and also by electric charging from ultraviolet radiation from the Sun.

The porosity at the surface is about 40–43%, but decreases quickly with depth. Owing to porosity, the density at the surface is quite low, about 1000 kg/m^3 but increases quickly with depth. At 200 mm below the surface it is of 2000 kg/m^3.

The cohesive bearing strength is about 300 Pa at the surface and 3 kPa at a depth of 200 mm. Some tests on material brought by the Luna 16 and Luna 20 probes showed a compression resistance up to 1.2 kPa. Then the regolith flows as if the edges on the grains start to break, to lock again for pressures above 50 kPa. Lunar regolith has thus a good carrying capacity for vehicles and structures, as seen during the excursions in the *Apollo* missions, but can make digging and grading quite difficult. Techniques based on vibrating devices may be worth experimenting.

The Moon received large quantities of water mostly by cometary bombardment, but liquid and solid (ice) water are not stable in the conditions present on most of the lunar surface and would quickly change to water vapor. Sunlight splits much of this water into hydrogen and oxygen, which then escape into space, together with water vapor, over time, because of the Moon's weak gravity. However, since there are regions that are permanently in the shadow, water ice can be stable for long periods of time in some selected places.

Both the Clementine and the Lunar Prospector missions showed evidence of small pockets of water ice just below the surface. Estimates for the total quantity of water ice are close to one cubic kilometer, however, the question of how much water there is on the Moon is still open.

Because the atmosphere is too weak to provide protection, sunlight, solar wind and cosmic radiation strikes the lunar surface with its full strength (the latter is, however, already screened by the heliosphere). The lack of a magnetic field leaves the surface without protection to radiation, so that the radiation environment is similar to that of deep space. Since the atmosphere is so thin, it provides no protection against micrometeorite impacts. Lunar regolith is a good radiation shield: solar wind penetrates much less than a micron, and only radiation from solar flares is able to penetrate the surface by one centimeter. Hard cosmic radiation may penetrate a few meters.

Due to the lack of plate tectonics, seismic activity is quite limited. The 500 detectable moonquakes occurring each year fall within the 1–2 magnitude range on the Richter scale and then are not detectable without instruments (by comparison on earth there are 10,000 earthquakes/year). Only a few moonquakes up to 4 on the Richter scale have been observed.

Seismic activity is usually caused by tidal forces and secondary effects from impacts. Other, non-seismic activity includes astronaut activity and impacts (both meteorite and artificial). Owing to the low damping, seismic activity is registered over long distances. The good propagation of seismic waves suggests a possible communication way between places on the Moon. The very good wave propagation may be a danger too, since seismic activity can create widespread secondary effects, such as crater wall collapses and landslides.

The Moon is considered as a lifeless world; that not withstanding NASA implemented strict quarantine procedures for the *Apollo* landings, and the same is likely to be done in the future. The only fossil life-forms that may be found on the Moon are ancient life-forms from Earth, which may have been carried there on board of meteorites, detached from Earth by impacts and then impacting the lunar surface. Finding them may be the only way of obtaining information on very ancient terrestrial life, particularly if it started earlier than expected, when the initial meteoritic bombardment subsided and then was wiped out by a huge impact.

The two-way communication delay with the lunar surface is 2.5–3 s, but to communicate with the far side relay satellites, either in lunar orbit or in one of the Earth–Moon Lagrange points, must be used. In the latter case a longer delay is present.

2.5 Rocky Planets

Apart from Earth, the planets of the solar system with a hard surface are just three: Mercury, Venus and Mars. A miscellany of data regarding these three planets is reported in Table 2.3. The values related to Earth are reported for comparison.

2.5.1 Mars

Mars will be dealt with first, since it is the most interesting planet for both robotic and manned missions. Mars has the largest volcano in the solar system, Olympus Mons, 25 km tall (but there is no active volcano on Mars now), and a canyon, Marineris Vallis, which is likely the deepest and widest in the Solar system. It bears the traces of impressive and dramatic events in the past, which have remodeled its surface—the northern lowlands, Vastitas Borealis, probably due to the impact of a large meteorite, the Tharsis Bulge, probably of volcanic origin, with three huge volcanoes (Pavonis, Arsia and Ascraeus Mons), and a huge number of impact craters, chasms, and mountains. If Vastitas Borealis is considered an impact basing, it is the largest found in the solar system, four times the size of the lunar Aitken basin.

The poles are covered by ice caps which shrink in the summer and grow in the winter. The northern ice cap is made mainly of water ice, while the southern one has a frozen carbon dioxide upper layer and an underlying layer of water ice. About 25 to 30% of the atmosphere condenses during a polar winter, forming thick slabs of CO_2 ice, to sublime again when the pole is again exposed to sunlight. This creates huge wind storms from the poles with wind velocities up to 400 km/h. Both polar caps contain frozen carbon dioxide as well as water ice, and a figure of two million cubic kilometers of water ice has been forwarded for the norther ice cap.

Table 2.3 Main characteristics of the rocky planets of the solar system (the values regarding Earth are reported for comparison). The surface acceleration at the equator, taking into account the planet's rotation, is also included

	Mercury	Venus	Mars	Earth
Mass (10^{24} kg)	0.3302	4.8685	0.64185	5.9736
Volume (10^{10} km^3)	6.083	92.843	16.318	108.321
Equatorial radius (km)	2,439.7	6,051.8	3,396.2	6,378.1
Polar radius (km)	2,439.7	6,051.8	3,376.2	6,356.8
Ellipticity (flattening)	0.00	0.000	0.00648	0.00335
Topographic range (km)	–	15	30	20
Mean density (kg/m^3)	5,427	5,243	3,933	5,515
Surface gravity (m/s^2)	3.70	8.87	3.71	9.81
Surface acceleration (m/s^2)	3.70	8.87	3.69	9.78
Escape velocity (km/s)	4.3	10.36	5.03	11.19
Solar irradiance (W/m^2)	9,126.6	2,613.9	589.2	1,367.6
Orbit semimajor axis (10^6 km)	57.91	108.21	227.92	149.60
Sidereal orbit period (days)	87.969	224.701	686.980	365.256
Perihelion (10^6 km)	46.00	107.48	206.62	147.09
Aphelion (10^6 km)	69.82	108.94	249.23	152.10
Synodic period (days)	115.88	583.92	779.94	
Mean orbital velocity (km/s)	47.87	35.02	24.13	29.78
Max. orbital velocity (km/s)	58.98	35.26	26.50	30.29
Min. orbital velocity (km/s)	38.86	34.79	21.97	29.29
Orbit inclination (deg)	7.00	3.39	1.850	0.000
Orbit eccentricity	0.2056	0.0067	0.0935	0.0167
Sidereal rotation period (hrs)	1,407.6	−5,832.5	24.6229	23.9345
Length of day (hrs)	4,222.6	2,802.0	24.6597	24.0000
Inclination of rot. axis (deg)	≈0	177.36	25.19	23.45
Min. dist. from Earth (10^6 km)	77.3	38.2	55.7	
Max. dist. from Earth (10^6 km)	221.9	261.0	401.3	

The difference between the two ice caps is due to the fact that the orbit of Mars around the Sun is much more elliptical than is the Earth's and the inclination of the planet's axis of rotation makes the seasons far more extreme in the southern hemisphere than in the northern: Mars is near perihelion when in the southern hemisphere it is summer and near aphelion when it is winter. This is also believed to be the explanation for the occurrence of violent dust storms which can last for months at a time.

The martian day, usually referred to as a *sol*, is slightly longer than Earth's day (24 h, 39 min, 35 s). The tilt of the rotation axis is similar to that of the Earth's axis

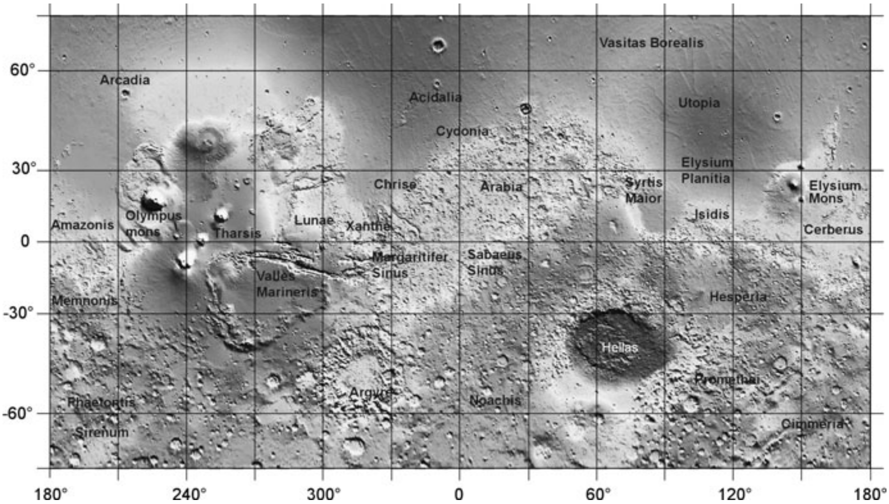

Fig. 2.6 Simplified map of the Martian surface (from a NASA image)

(25° while the latter is inclined of 23°), producing seasons similar to ours, although they last almost twice as long, owing to the much longer duration of the year.

Mars is smaller than Earth, its surface area being about as large as the sum of all the continents of our planet. A simplified map of the planet is given in Fig. 2.6.

Martian atmosphere is very thin: the pressure at the ground is less than one hundredth of the atmospheric pressure on Earth (it roughly equals atmospheric pressure on Earth at 35 km altitude) and has much variability with altitude and latitude. It varies from a minimum of around 0.3 millibar on Olympus Mons to over 11.6 millibar in the depths of Hellas Planitia, with a mean surface level pressure of 6.36 millibar, variable from 4.0 to 8.7 millibar depending on season The average surface density is about 0.020 kg/m^3.

The composition by volume of the atmosphere is 95.32% carbon dioxide, 2.7% nitrogen, 1.6% argon, oxygen 0.13%, carbon monoxide 0.08%, water 210 ppm; nitrogen oxide 100 ppm; neon 2.5 ppm, heavy water (in form of deuterium protium oxide HDO) 0.85 ppm; krypton 0.3 ppm and traces of methane, the latter concentrated in a few places during the northern summer. Since methane is broken down by ultraviolet radiation, for it to be present a mechanism producing that gas on the planet, like volcanic activity, cometary impacts or the presence of methanogenic microbial life forms, is needed. The mean molecular weight of the atmosphere is 43.34 g/mole.

Clouds of water ice were photographed by the *Opportunity* rover in 2004.

The atmosphere is quite dusty, containing particulates about 1.5 μm in diameter which give the Martian sky a tawny color when seen from the surface.

At the *Viking* landing sites, wind speeds of 2–7 m/s were recorded in the summer, 5–10 m/s in the fall, with occasional 17–30 m/s dust storms.

Remark 2.7 Although the wind speeds are high, the aerodynamic forces exerted by the wind are modest owing to the low atmospheric density: vehicles and structures on the Mars surface are thus not expected to be much loaded by the strong winds.

Winds carry large quantities of dusts that is even finer than the dust on the moon. The danger to machinery and human beings due to dust rich in iron oxide must be accounted for when planning missions to the Red Planet. Mars plains are frequently crossed by dust devils: the solar panels of the Spirit and Opportunity rovers were cleaned more than once by them, contributing to maintain these device operational for a long time.

The average temperature is $-63°C$, with marked variation with the time of the day and of the year. In the site of the *Viking 1* landing diurnal variations between -89 and $-31°C$ were recorded. Larger variations, from -120 to $-14°C$ were recorded during the years-long *Viking* missions. In the summer, in the southern hemisphere, temperatures as high as 20 to 30°C have been recorded. Liquid water cannot exist on the surface at these temperature and pressure combinations and most of the frost depicted in the images from the *Viking* landers is frozen carbon dioxide.

Martian atmosphere offers very little protection from the Sun's ultraviolet radiation and there is only very limited protection from cosmic rays due to the almost complete absence of a planetary magnetic field after Mars lost its magnetosphere about 4 billion years ago. There is evidence that at the beginning Mars had plate tectonics and a planetary dynamic effect, producing a global magnetic field. Some remnants are still found in the form of local magnetization.

Remark 2.8 From the point of view of radiation, Mars is only a slightly better place than the Moon, even if the thin atmosphere scatters light and the look from the surface is more like that on a planet than that in space.

The geography of planet Mars is complex. The main features are shield volcanoes, lava plains (mostly in the northern hemisphere) and highlands with a large number of impact craters and deep canyons. The four largest volcanoes, all extinct, have already been mentioned. A total number of 43,000 craters with a diameter of 5 km or greater have been found, together with a large number of smaller ones.

The largest canyon, Vallis Marineris, has a length of 4,000 km and a depth of up to 7 km. It was formed due to the swelling of the Tharsis area which caused the crust in the area of Vallis Marineris to collapse. Also Ma'adim Vallis is a canyon much bigger than the Grand Canyon of Earth.

Pictures of entrances of large caves, 100 to 250 m wide, were transmitted by the probes; moreover also on Mars it is possible that lava tubes exist, and are larger than those on Earth owing to the lower gravity. The interiors of caverns and lava tubes may be protected from micrometeoroids, UV radiation, solar flares and high energy particles that bombard the planet's surface and thus are good candidates for the search of liquid water and signs of life, apart from being also possible locations for human settlements.

Martian rocks seem mostly basalt, although a portion of the Martian surface seems more rich in silica than typical basalt. The plains are similar to rocky deserts on Earth, covered by red sand, with rocks and boulders scattered all around. The most interesting places are, however, the steep slopes of the mountains and canyons, which are very difficult to manage for wheeled and even tracked machines.

The soil is essentially regolith, rich in finely-grained iron oxide dust, which is thinner than on the Moon. Its granulometry and composition is more variable from place to place, due to water erosion in ancient times when water was flowing on the surface, and to wind erosion.

The soil of Mars is basic, and values of pH of 8.3 were obtained by the *Phoenix* lander. This, together with the results of the old *Viking* probes seem to exclude the possibility of finding life-forms on the surface of the planet. Even if some life-form might be found in the future, in particular in places shaded from radiation and direct sunlight, like the bottom of canyons or caves, it is easy to state that products of biological origin are not a widespread constituent of the surface of the planet.

The geological history of Mars is subdivided into three main periods, namely

- Noachian epoch (named after Noachis Terra), from 3.8 billion to 3.5 billion years ago.
- Hesperian epoch (named after Hesperia Planum): 3.5 billion years ago to 1.8 billion years ago.
- Amazonian epoch (named after Amazonis Planitia): 1.8 billion years ago to present.

The Tharsis bulge formation and extensive flooding by liquid water are ascribed to the Noachian epoch. Extensive lava plains are supposed to have been formed in the Hesperian epoch, while the Olympus Mons formed during the Amazonian epoch, along with lava flows elsewhere on Mars.

Owing to the in situ observations performed by robotic spacecraft, it is now certain that in ancient geological periods Mars had extensive water coverage, with liquid water running on the surface and geyser-like water flows. At that time the atmosphere was much thicker too.

Large quantities of water are thought to be trapped underground. In the northern hemisphere an ice permafrost mantle stretches down from the pole to latitudes of about 60° and large quantities of water ice have been observed both at the poles and at mid-latitudes. A large release of liquid water is thought to have occurred when the Vallis Marineris formed early in Mars's history, forming massive outflow channels. A much more recent (5 million years ago) outflow of water is supposed to have occurred when the Cerberus Fossae chasm formed. There are also clues of more recent flows of water on the surface, at least for short periods of time, but these findings are still debated.

Once the planet was much more suitable for living organisms than today, which does not imply that life actually existed. If so, fossil remnants may still exist. The controversial finding of fossils in the ALH84001 meteorite, which supposedly was blasted into space by a meteorite strike and wandered through space for 15 million years to land finally on Earth, still stirs much debate.

Table 2.4 Data of the satellites of Mars Phobos and Deimos

	Phobos	Deimos
Orbit's semimajor axis (km)	9,378	23,459
Sidereal orbit period (days)	0.31891	1.26244
Orbital inclination (deg)	1.08	1.79
Orbital eccentricity	0.0151	0.0005
Major axis radius (km)	13.4	7.5
Median axis radius (km)	11.2	6.1
Minor axis radius (km)	9.2	5.2
Mass (10^{15} kg)	10.6	2.4
Mean density (kg/m^3)	1,900	1,750

The two-way communication delay with Mars is much variable depending on the positions of the two planets. It is up to 30 minutes or more. However, things are usually much worse: taking into account the relative motions of the two planets and the unavailability of telecommunication satellites in Mars orbit, the *Pathfinder* probe had a communication window of just 5 minutes per day.

Mars has two small, irregularly shaped, moons, Phobos and Deimos, which orbit close to the planet. Their characteristics are reported in Table 2.4. They may be captured asteroids, similar to 5261 Eureka, a Martian Trojan asteroid, but their capture by an almost airless world is difficult to explain. Phobos' orbit is lower than synchronous orbit: it rises in the west, sets in the east, and rises again in just 11 hours. Deimos' orbit is just above synchronous orbit and then its apparent speed in the sky is low. Even if the period of its orbit is 30 hours, it takes 2.7 days from rising in the east to setting in the west.

Remark 2.9 Phobos' orbit is unstable: it decays owing to the tidal forces and it will either crash on the planet in about 50 million years or fragment producing a ring around it.

2.5.2 Mercury

Mercury is an extremely hostile environment. It is a small planet, the smallest in the solar system, very close to the Sun. Each square meter of its surface receives seven times the energy received by a square meter of the Earth surface. Its rate of rotation is very slow, with a sidereal rotation period of 58.7 Earth days, yielding a duration of the day of 175.94 Earth days. It performs three rotations about its axis every two orbits (is locked in a 3:2 resonance).

It has no true atmosphere and its general aspect is similar to that of the Moon with many craters and some smooth plains (Fig. 2.7). The faint gases that surround it are made by hydrogen, helium, oxygen, sodium, calcium, magnesium, silicon and

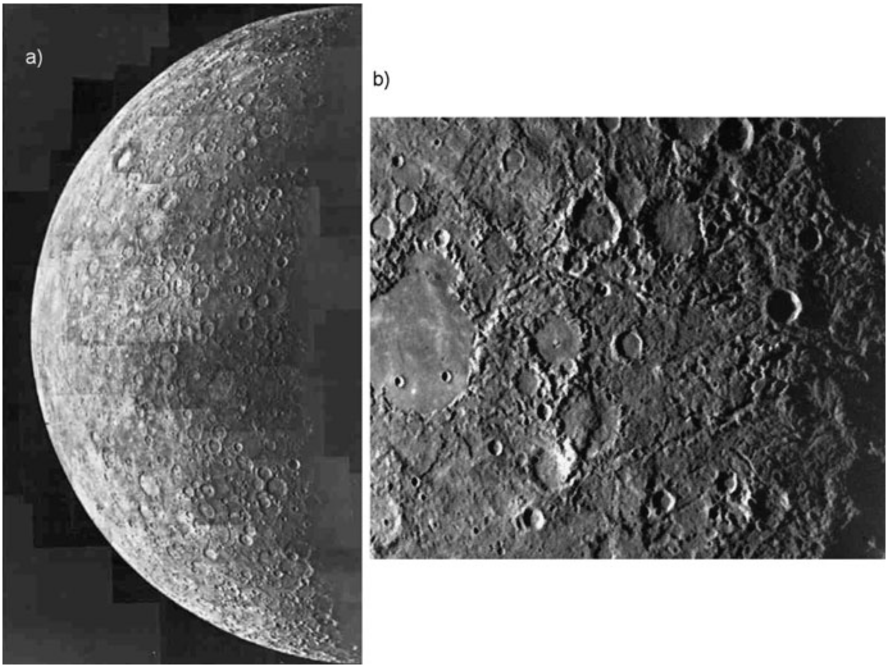

Fig. 2.7 Mercury as observed by Mariner 10 in 1974 (NASA photo)

potassium, with some water vapor and traces of other elements. This faint atmosphere is unstable, in the sense that the matter it contains is continuously lost to space and substituted by new matter from the solar wind, diffusing into Mercury's magnetosphere, and from the planet's surface. Atmospheric pressure on the surface is about 10^{-15} bar and the total mass of the atmosphere is evaluated in less than 1000 kg.

Its surface, likely covered with regolith like the Moon, has a mean temperature of 169.35°C. The slow rotation and the lack of an atmosphere cause extreme variations of temperature, which range from 427°C on the side facing the Sun (the hottest point being that directly facing the Sun) to −183°C during the night (the coldest points being in the bottom of the polar craters).

Remark 2.10 Space probes have found water ice in the bottom of polar craters, where the light of the Sun never reaches and the temperature remains below −171°C. A figure of 10^{14} to 10^{15} kg of ice has been forwarded.

The recent studies (2009) performed by the Messenger probe showed traces of recent volcanic activity. Mercury is thus not a geologically dead planet, as was believed. As can be deduced from a comparison of the chemical composition of the surfaces of Mercury and of the Moon, the two bodies seem to have evolved in different ways. Also, some findings suggest that the folds, widespread on the whole

Fig. 2.8 Venus, as seen by the Magellan probe using its synthetic aperture radar (NASA image)

surface, which were attributed to a planet's contraction, might have been caused by tectonic activity, although this is still a hypothesis.

Unlike the moon, Mercury has a large iron, likely molten, core, which generates a weak global magnetic field. Its strength is about 1% of that of Earth. The magnetic field strength at the equator is about 300 nT. Mercury's magnetic field is dipolar, but unlike Earth's magnetic field, its magnetic axis is nearly aligned with the planet's spin axis. Mercury's magnetic field is strong enough to create a magnetosphere which deflects the solar wind about the planet and to supply some protection to the surface.

Owing to the high eccentricity of the orbit, an observer would be able to see the Sun rise about halfway, then reverse and set before rising again, all within the same Mercurian day.

2.5.3 Venus

Venus is always covered by thick layers of clouds and its surface cannot be seen from space by optical observation. However, the Magellan probe mapped its surface accurately using a Synthetic Aperture Radar (SAR) (Fig. 2.8). The clouds of Venus extend from about 50 to 70 km and may be divided into three distinct layers. Below the clouds is a layer of haze down to about 30 km and below that it is clear.

The rotation of Venus about its axis is extremely slow, the day being about 243 Earth days long.

The planet has a very dense atmosphere: the atmospheric pressure at the surface is 92 bar and its density is 65 kg/m^3. Its main constituent is carbon dioxide (96.5% by volume), with about 3.5% of nitrogen. Minor constituents are sulfur dioxide (150 ppm), argon (70 ppm), water (20 ppm) carbon monoxide (17 ppm), helium (12 ppm) and neon (7 ppm). The mean molecular weight is 43.45 g/mole.

The presence of sulfur dioxide (sulfur is likely to have a volcanic origin, dating back from the beginning of the planet's evolution) gives way to sulfuric acid clouds in the high atmosphere but sulfur dioxide is also present in the haze layer.

Venus has no global magnetic field, and solar and cosmic radiation penetrates the high atmosphere. The surface should, however, be protected by the thick and dense gas layers.

The surface of Venus is hot, the average temperature being 464°C. Owing to the high density and opacity of the atmosphere, temperature variations with both time and place are limited, with maximum values of about 480°C, hot enough to melt lead.

The velocity of the wind at the surface is low, between 0.3 and 2.0 m/s, but in the upper layers of the atmosphere, above the clouds, jet streams, faster at the equator and slower at the poles, as fast as 200–400 km/h, are present.

The present environment on Venus is believed to be the outcome of a runaway greenhouse effect. An increase of the Venusian temperature caused the evaporation of the seas, if they ever existed, and the production of carbon dioxide from the carbonates in the soil. The increasing amounts of water vapor and carbon dioxide in the atmosphere caused a further increase of the greenhouse effect, and the very high temperatures which we now observe. The water vapor was decomposed by the Sun's light into oxygen and hydrogen, the latter light gas disappearing into space. Venus does not have more carbon dioxide than Earth; the point is that it is all in the atmosphere instead of being fixed in the soil and absorbed in the oceans.

The environment on the surface of Venus is harsh and the only two robotic probes that landed on it worked for just minutes, as they were designed to do. However, Venus is an interesting place to study and it would be interesting to perform robotic missions on its surface.

Remark 2.11 There are little chances that life could evolve in Venus' difficult environment, but there is some possibility that bacteria-like life-forms survive in the relatively cool high atmosphere or at least that life evolved when conditions were milder.

2.6 Giant Planets

The giant planets are essentially huge gas balls, without a true solid surface. The density of the gas constituting the outer part of the planet (whether there

Table 2.5 Main characteristics of the giant planets of the solar system. Radii, gravity and escape velocity are referred at the level at which the atmospheric pressure is equal to 1 bar. The surface acceleration at the equator, taking into account the planet's rotation, is also included

	Jupiter	Saturn	Uranus	Neptune
Mass (10^{24} kg)	1,898.6	568.46	86.832	102.43
Volume (10^{10} km^3)	82,713	6,833	16.318	6,254
Equatorial radius (1 bar level) (km)	71,492	60,268	25,559	24,764
Polar radius (km)	66,854	54,3648	24,973	24,341
Volumetric mean radius (km)	69,911	58,232	25,362	0.01708
Ellipticity (flattening)	0.06487	0.09796	0.02293	0.00335
Mean density (kg/m^3)	1,326	687	1,270	1,638
Surface gravity (m/s^2)	24.79	10.44	8.87	11.15
Surface acceleration (m/s^2)	23.12	8.96	8.69	11.00
Escape velocity (km/s)	59.5	35.5	21.3	23.5
Solar irradiance (W/m^2)	50.50	14.90	3.71	1.51
Black-body temperature (K)	110.0	81.1	58.2	46.6
Orbit semimajor axis (10^6 km)	778.57	1,433.53	2,872.46	4,495.06
Sidereal orbit period (days)	4,332.589	10,759.22	30,685.4	60,189.
Perihelion (10^6 km)	740.52	1,352.55	2,741.30	4,444.45
Aphelion (10^6 km)	816.62	1,514.50	3,003.62	4,545.67
Synodic period (days)	398.88	583.92	369.66	367.49
Mean orbital velocity (km/s)	13.07	9.69	6.81	5.43
Max. orbital velocity (km/s)	13.72	10.18	7.11	5.50
Min. orbital velocity (km/s)	12.44	9.09	6.49	5.37
Orbit inclination (deg)	1.304	2.485	0.772	1.769
Orbit eccentricity	0.0489	0.0565	0.0457	0.0113
Sidereal rotation period (hrs)	9.9250	10.656	−17.24	16.11
Length of day (hrs)	9.9259	10.656	17.24	16.11
Inclination of rot. axys (deg)	3.12	26.73	97.86	29.56
Min. dist. from Earth (10^6 km)	588.5	1,195.5	2,581.9	4,305.9
Max. dist. from Earth (10^6 km)	968.1	1,658.5	3,157.3	4,687.3

is a solid core is still debatable) increases going inside, as well as the temperature. Although the environment of the giant planets is extreme, there is no doubt that there is a region where temperature and pressure are manageable by robotic probes.

The characteristics of the four gas giants of the Solar system are summarized in Table 2.5. Since there is no true surface, the radii, gravity and escape velocity are referred at the level at which the atmospheric pressure is equal to 1 bar.

2.6.1 Jupiter

Jupiter is the only giant planet whose atmosphere was directly probed by a spacecraft, the *Galileo* probe, which sent back many data before being crushed by the pressure. It is the largest planet in the Solar System and its mass is equal to 70% of all the planets combined.

It rotates so fast about its axis that its shape is an oblate spheroid. Its atmosphere does not rotate as a rigid body, and the period of rotation changes with the latitude, with the equator having a period about 5 min shorter than the poles. The conventional period of rotation is that of the magnetosphere.

The major constituents of the atmosphere are molecular hydrogen (89.8% in volume) and helium (10.2%). Minor constituents are methane 3000 ppm, ammonia 260 ppm, hydrogen deuteride (HD) 28 ppm, ethane 5.8 ppm, water 4 ppm. The mean molecular weight is 2.22 g/mole. To these gas fractions some aerosols must be added, particularly in the outer layers, where they form belts of clouds: ammonia ice, water ice, ammonia hydrosulfite. Darker orange and brown clouds at lower levels may contain sulfur, as well as simple organic compounds.

The clouds are located in the tropopause and are arranged into bands of different latitudes, known as tropical regions. These are subdivided into lighter-hued zones and darker belts. The interactions of these circulation patterns cause storms and turbulence with wind speeds of 100 m/s being common. The zones have been observed to vary in width, color and intensity from year to year, but they have remained sufficiently stable for astronomers to give them identifying designations.

The cloud layer is only about 50 km deep, and consists of at least two decks of clouds: a thick lower deck and a thin clearer region. There may also be a thin layer of water clouds underlying the ammonia layer. Powerful electrical discharges may be present where water clouds form thunderstorms driven by the heat rising from the interior.

The largest storm, which has lasted since centuries ago and may be a permanent feature of the planet, is the Great Red Spot, a persistent anticyclonic storm located 22° south of the equator that is larger than 3 times the Earth. The Great Red Spot's dimensions are (24,000–40,000) km $\times$ (12,000–14,000) km and it rotates counterclockwise, with a period of about six days (Fig. 2.9). Its maximum altitude is about 8 km above the surrounding cloud tops.

The temperatures at 1 and 0.1 bar levels are, respectively, -108 and -161°C. The density at 1 bar level is 0.16 kg/m^3. The wind speed is up to 150 m/s in the equatorial region (latitude less than 30°), and up to 40 m/s at higher latitudes.

Temperature and pressure increase going inwards in the atmosphere, and are so high in the interior of the planet that matter behaves not as a gas but as a supercritical fluid. Pressures well above 1,000 bar are predicted. At a radius of about 78% of the planet's radius hydrogen becomes a metallic liquid. Likely Jupiter has a molten rock core, of unknown composition, located inside this thick metallic hydrogen layer. The temperature and the pressure at the core are estimated at about 36,000 K and 3,000–4,500 GPa.

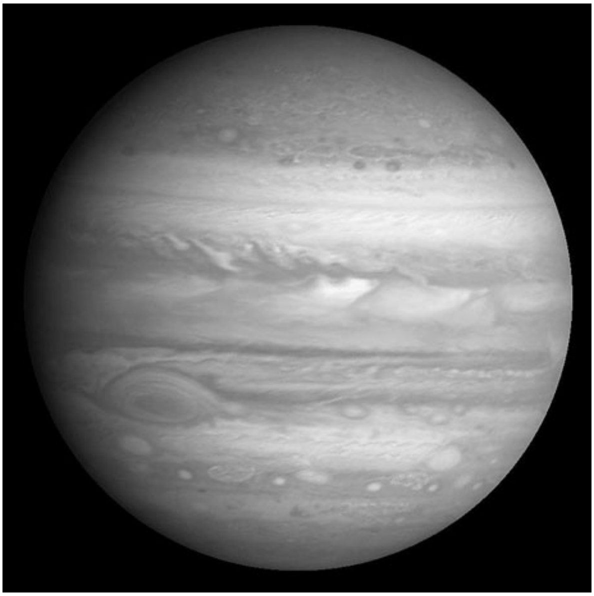

Fig. 2.9 A picture of Jupiter in which the great red spot is well visible (NASA image, based on a 1979 picture from the *Voyager 1* spacecraft)

Jupiter has a strong global magnetic field, 14 times as strong as the Earth's. Its strength ranges between 0.42 mT at the equator to 1.0–1.4 mT at the poles. It creates a large magnetosphere. The structure of the magnetosphere follows a pattern not much different from what is seen for the solar magnetic field with a bow shock at about 75 Jupiter radii from the planet. Around Jupiter's magnetosphere is a magnetopause, at the inner edge of a magnetosheath, where the planet's magnetic field becomes weak and the solar wind interacts with the matter from the planet. All four largest moons of Jupiter orbit within the magnetosphere.

Even if the presence of organic compounds has been verified, it is highly unlikely that there is any Earth-like life on Jupiter owing to the scarcity of water in the atmosphere. Moreover, any possible solid surface deep within Jupiter would be under extremely high pressures. However, there are hypotheses that ammonia- or water-based life could evolve in Jupiter's upper atmosphere.

Jupiter has four large moons, Io, Europa, Ganymede, and Callisto, discovered by Galileo in 1610, and a host of minor satellites, out of which 59 are known. It has also a faint planetary ring system composed of three main segments, likely made of dust rather than ice. The rings are related with particular satellites like Adrastea and Metis (main ring) or Thebe and Amalthea (outer ring).

2.6.2 Saturn

Saturn is the second largest planet in the Solar System. The compositions of the two inner gas giants are similar and that of Saturn is not unlike what was seen for

Jupiter: mostly hydrogen, with small proportions of helium and trace elements. Also its interior is thought to consist of a small core of rock and ice, surrounded by a thick layer of metallic hydrogen and a gaseous outer layer. The temperatures at the core are very high, although lower than those of Jupiter.

Also Saturn rotates fast and its shape is oblate; moreover, the rotation period depends on the latitude. Its average density is 0.69 g/cm^3: it is the only planet of the Solar System that is less dense than water.

The atmosphere consists of about 96.3% molecular hydrogen and 3.25% helium (the latter remarkably less abundant than on Jupiter), with trace amounts of methane (4,500 ppm), ammonia (125 ppm), hydrogen deuteride (HD, 110 ppm), ethane (7 ppm), acetylene (C_2H_2) and phosphine (PH_3). Also aerosols, ammonia ice, water ice, ammonia hydrosulfite are present and form clouds, like on Jupiter, which give a band pattern to the atmosphere of Saturn too, even if the bands are much fainter.

The mean molecular weight of the atmosphere is 2.07 g/mole.

The upper clouds on Saturn are composed of ammonia crystals, while the lower level clouds, about 50 km thick and with a temperature of −93°C, appear to be composed of either ammonium hydrosulfite or water. Over that, extending for 10 km and with a temperature of −23°C, is a layer made up of water ice. The temperature and density at the 1 bar altitude are −139°C and 0.19 kg/m^3. The temperature at the 0.1 bar altitude is −189°C. The pressure at the surface is greater than 1000 bar.

Saturn's winds are among the Solar System's fastest. Voyager data indicate peak easterly winds of 500 m/s (1,800 km/h). Average speed is 400 m/s in the equatorial zone (latitude less than 30°) and 150 m/s at higher latitudes. A Great White Spot, a unique but short-lived phenomenon which occurs once every Saturnian year, or roughly every 30 Earth years, around the time of the northern hemisphere's summer solstice, has been observed.

Saturn has a planetary magnetic field intermediate in strength between that of Earth and that of Jupiter. Its strength at the equator is 20 μT, slightly weaker than Earth's magnetic field. Its magnetosphere is much smaller than the Jovian and extends slightly beyond the orbit of Titan.

The most impressive characteristic of Saturn is its system of rings, consisting mostly of ice particles (containing 93% percent of water ice with tholin impurities, and 7% amorphous carbon) with a smaller amount of rocky debris and dust. They extend from 6,630 km to 120,700 km above Saturn's equator, with an average thickness of approximately 20 meters in thickness (Fig. 2.10a).

Sixty-one known moons orbit the planet, not counting hundreds of moonlets within the rings.

The rings have an intricate structure of thousands of thin gaps and ringlets. This structure is controlled by the gravitational pull of Saturn's many moons. Some gaps are cleared out by the passage of tiny moonlets, and some ringlets seem to be maintained by the gravitational effects of small shepherd satellites. Other gaps arise from resonances between the orbital period of particles in the gap and that of a more massive moon further out. Still more structure in the rings consists of spiral waves raised by the moons' periodic gravitational perturbations.

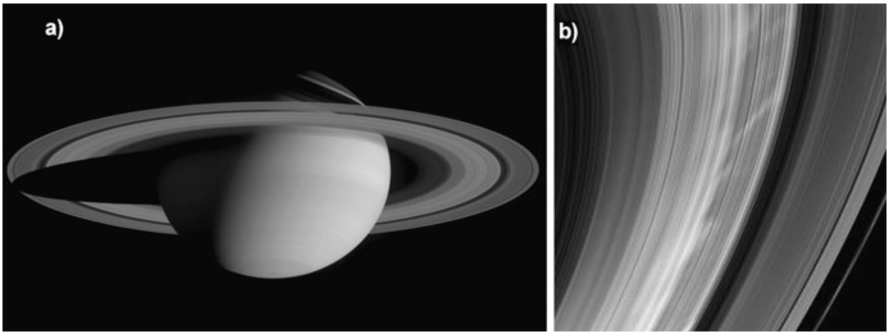

Fig. 2.10 (**a**) Mosaic image obtained from 126 images acquired in two hours on October 6, 2004 by the *Cassini* probe from a distance of about 6.3 million kilometers from Saturn. (**b**) Image of bright spokes in Saturn's B ring taken by *Cassini* in August 2009 (NASA images)

The rings of Saturn possess their own atmosphere, independent of that of the planet itself, composed of molecular oxygen gas produced when ultraviolet light from the Sun interacts with water ice in the rings, with some molecular hydrogen too. This atmosphere is extremely thin, so thin that if it were condensed onto the rings, its thickness would be about one atom thick.

Radial features, dubbed spokes, were discovered in some rings and explained exclusively as the action of gravitational forces (Fig. 2.10b). However, it seems that some cannot be explained in this way and the precise mechanism generating the spokes is still unknown.

The origin of the rings of Saturn (and the other Jovian planets) is unknown. Though they may have had rings since their formation, the ring systems are not stable and must be regenerated by some ongoing process, perhaps the breakup of larger satellites. The current set of rings may be only a few hundred million years old.

2.6.3 Uranus

Uranus and the other giant planet Neptune, although generally similar to the gas giants Jupiter and Saturn, have some significant differences, to the point that for them the term *ice giants* was formulated. Uranus consists of three layers: a small rocky core in the center, an icy mantle in the middle and an outer gaseous hydrogen and helium atmosphere.

Following the most common (but not universally accepted) model of the planet, the core has a density of about 9,000 kg/m^3, a pressure of 800 GPa and a temperature of 5,000 K. The bulk of the planet is represented by the mantle, composed of a hot and dense fluid consisting of water, ammonia and other volatiles. This fluid layer is sometimes called a water–ammonia ocean. Uranus has thus no solid surface: the gaseous atmosphere gradually transitions into the internal liquid layers.

The Uranian atmosphere, the coldest planetary atmosphere in the Solar System (colder than Neptune's, with a minimum temperature of −224°C), can be divided into three layers: the troposphere, between altitudes of −300 km (the zero-altitude level is that where the pressure equals 1 bar) and 50 km and pressures from 100 to 0.1 bar; the stratosphere, spanning altitudes between 50 and 4,000 km and pressures of between 0.1 and 10^{-10} bar and the thermosphere extending from 4,000 km to as high as 50,000 km from the surface.

The temperature and density at 1 bar level are −197°C and 0.42 kg/m^3; at the 0.1 bar level the temperature is −220°C.

The atmosphere is made primarily of molecular hydrogen (82.5%), helium (15.2%) and methane (2.3%), with traces of hydrogen deuteride (148 ppm). The abundance of less volatile compounds such as ammonia, water and hydrogen sulfide in the atmosphere is poorly known. Trace amounts of various hydrocarbons are found in the stratosphere, including ethane, acetylene, methylacetylene and diacetylene together with traces of water vapor, carbon monoxide and carbon dioxide.

Like in the atmospheres of the other giant planets, also in the atmosphere of Uranus there are aerosols such as water ice, ammonia ice, ammonia hydrosulfite and methane. Uranus has a complex, layered cloud structure, with the lowest clouds likely made of water and the uppermost layer of clouds, possibly made of methane.

Uranus has the shape of an oblate spheroid, with different rotation periods at different latitudes. What is unique is the tilt of the rotational axis of rotation, which is 97.86°. Seasonal changes are completely unlike those of the other major planets. Near the time of Uranian solstices, one pole faces the Sun continuously while the other pole faces away. Only a narrow strip around the equator experiences a rapid day–night cycle, but with the Sun very low over the horizon as in the Earth's polar regions. Each pole gets around 42 years of continuous sunlight, followed by 42 years of darkness Near the time of the equinoxes, the Sun faces the equator of Uranus giving day–night cycles similar to those seen on most of the other planets. The extreme axial tilt results in extreme seasonal weather variations, with changes in brightness and strong thunderstorms.

Uranus has a global magnetic field, but it is quite peculiar: it is tilted at 59° from the axis of rotation and is not centered on the planet's geometric center. The magnetosphere is highly asymmetric and the magnetic field strength on the surface in the southern hemisphere can be as low as 10 μT, while in the northern hemisphere it can be as high as 110 μT, with an average field at the surface of 23 μT. In other respects the Uranian magnetosphere is like those of other planets: it has a bow shock located at about 23 Uranian radii ahead of it, a magnetopause at 18 Uranian radii, a fully developed magnetotail and radiation belts.

Like the other giant planets, Uranus has a ring system, made of at least 13 distinct rings. Owing to the orientation of the axis of the planet, the rings are almost perpendicular to the orbit, and from time to time are seen from Earth as circling the planet. All rings of Uranus except two are extremely narrow, being a few kilometers wide. Some of them appear to be gray, some red and some are blue, but mostly made of quite dark matter.

Uranus has a number of moons, 27 of which were given a name.

2.6.4 Neptune

Neptune is similar in composition and structure to Uranus. Its interior, like that of Uranus, the other ice giant, is primarily composed of ices and rock. The pressure and the temperature at its center are about 700 GPa and 5,400 K, respectively, following the model at present considered as the most realistic.

Neptune's atmosphere is made of molecular hydrogen (80.0%), helium (19.0%) and methane (1.5%) with traces of hydrogen deuteride (192 ppm) and ethane (1.5 ppm). It contains aerosols like ammonia ice, water ice, ammonia hydrosulfite, methane ice in a higher proportion than that of gas giants. The absorption of red light by the atmospheric methane is thought to be a cause of the blue color of the planet. The difference of hue with Uranus is accredited to the fact that, being denser and heavier, more of the methane from the mantle leaks to the surface, giving it a richer color.

The temperature and density at the 1 bar level are −201°C and 0.45 kg/m^3. At 0.1 bar the temperature is −218°C. Neptune's outer atmosphere is one of the coldest places in the Solar System, although warmer than Uranus's. The mean molecular weight of the atmosphere is 2.53–2.69 g/mole.

Neptune's atmosphere is divided into three main regions; the lower troposphere, where temperature decreases with altitude, and the stratosphere, where temperature increases with altitude. Their boundary, the tropopause, occurs at a pressure of 10 kPa. The stratosphere then gives way to the thermosphere at a pressure lower than 1 to 10 Pa.

Like the other giant planets, also Neptune is an oblate spheroid and undergoes differential rotation. Since the differential rotation is the most pronounced of any planet in the Solar System, stronger latitudinal wind shear are present. Its axial tilt is 29.56°, not dissimilar to that of Earth and Mars. Climate variations are thus not so extreme as those on Uranus.

The atmosphere of Neptune carries visible weather patterns. The Great Dark Spot is an anticyclonic storm system spanning 13,000 × 6,600 km and is comparable to the Great Red Spot on Jupiter. Other climate patterns were dubbed Scooter and Small Dark Spot, a southern cyclonic storm. These weather patterns, which seem not being permanent (they are thought to last for several months), are driven by the strongest sustained winds of any planet in the Solar System, with average speeds from 400 m/s along the equator to 250 m/s at the poles. Wind speeds as high as 600 to 2,100 km/h were, however, recorded. Most of the winds on Neptune move in a direction opposite the planet's rotation at low latitudes, while blowing in the rotation direction at high latitudes. These patterns are thought to be driven by internal heat generation. Both Uranus and Neptune radiate more heat than that received by the Sun, but Neptune much more than Uranus. The process in which this heat is generated is not yet known.

Neptune's troposphere is banded by clouds of varying compositions depending on altitude. The upper-level clouds occur at pressures below one bar (100 kPa), where the temperature is suitable for methane to condense. For pressures between 100 and 500 kPa clouds of ammonia and hydrogen sulfide are believed to form.

Above a pressure of 500 kPa the clouds may consist of ammonia, ammonium sulfide, hydrogen sulfide and water. Deeper clouds of water ice should be found at pressures of about 5.0 MPa, where the temperature reaches 0°C. Underneath, clouds of ammonia and hydrogen sulfide may be found. High-altitude clouds on Neptune have been observed casting shadows on the opaque cloud deck below. There are also high-altitude cloud bands that wrap around the planet at constant latitude. These circumferential bands, with widths of 50–150 km, lie about 50–110 km above the cloud deck.

The magnetosphere resembles that of Uranus, with a magnetic field strongly tilted relative to its rotational axis at 47° and offset at least 0.55 radii from the planet's geometric center. The dipole component of the magnetic field at the magnetic equator of Neptune is about 14 μT, but the magnetic field has a complex geometry that includes relatively large contributions from non-dipolar components, including a strong quadrupole moment that may exceed the dipole moment in strength.

Neptune's bow shock occurs at a distance of 34.9 times the radius of the planet. The magnetopause lies at a distance of 23–26.5 times the radius of Neptune. The tail of the magnetosphere extends out to at least 72 times the radius of Neptune, and very likely farther.

Neptune too has a planetary ring system. The rings may consist of ice particles coated with silicates or carbon-based material, and have a reddish hue. The rings were given names like Adams (at 63,000 km from the center) Le Verrier Ring, (at 53,000 km), Galle (42,000 km), Lassell (a faint outward extension to the Le Verrier Ring) and Arago (at 57,000 km). Other larger incomplete rings were named Courage, Liberté, Egalité 1, Egalité 2 and Fraternité. Their shape can be explained by the gravitational effects of Galatea, a moon just inward.

2.7 Satellites of Giant Planets

As already stated, the giant planets have a large number of satellites, some of which are larger than Earth's Moon and even than Planet Mercury. The majority of them, however, are similar to asteroids and some are very small and have an irregular shape. Actually, the number of the small satellites of giant planets is unknown, and new ones are continuously discovered.

Jupiter has 63 satellites (data referred to the beginning of 2009), but only 4 of them, the Galilean satellites, have a diameter larger than 500 km (Fig. 2.11). The fifth one in size, Amalthea, is quite irregular, having dimensions 250 × 146 × 128 km.

In order of distance from the planet they are Metis, Adrastea, Amalthea, Thebe, Io, Europa, Ganymede, Callisto, Themisto, Leda, Himalia, Lysithea, Elara, S/2000 J 11, Carpo, S/2003 J 12, Euporie, S/2003 J 3, S/2003 J 18, Thelxinoe, Euanthe, Helike, Orthosie, Iocaste, S/2003 J 16, Praxidike, Harpalyke, Mneme, Hermippe, Thyone, Ananke, S/2003 J 17, Aitne, Kale, Taygete, S/2003 J 19, Chaldene, S/2003 J 15, S/2003 J 10, S/2003 J 23, Erinome, Aoede, Kallichore, Kalyke, Carme, Callirrhoe, Eurydome, Pasithee, Kore, Cyllene, Eukelade, S/2003 J 4, Pasiphaë,

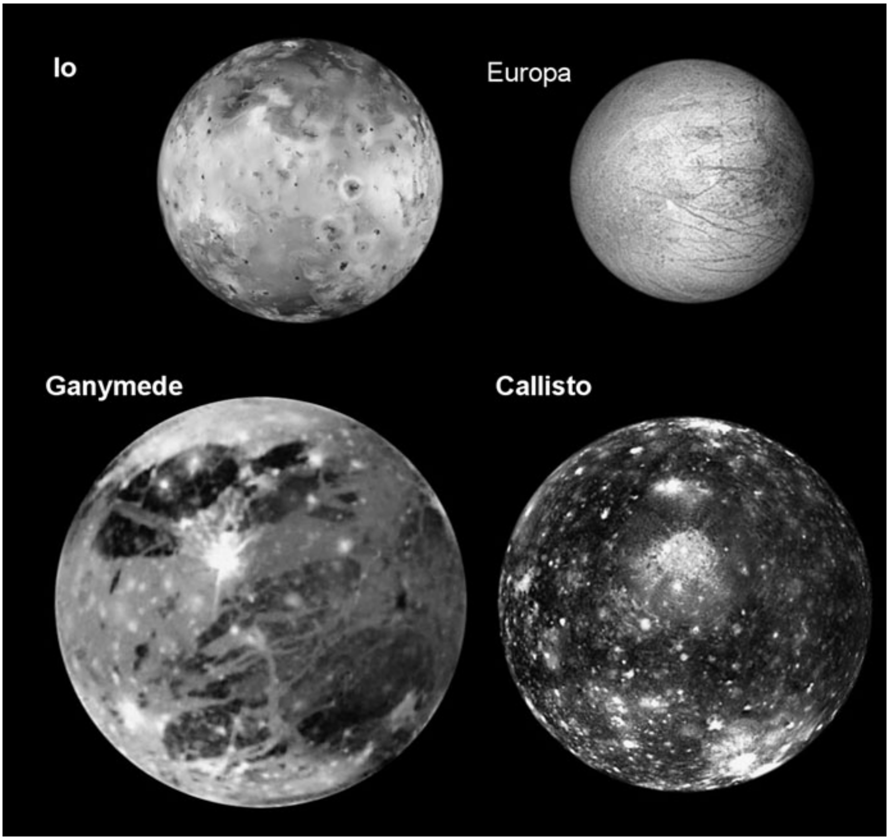

Fig. 2.11 Images of the four Galilean Satellites of Jupiter shown in the same scale. Pictures taken by the Galileo probe (NASA images)

Hegemone, Arche, Isonoe, S/2003 J 9, S/2003 J 5, Sinope, Sponde, Autonoe, Megaclite, S/2003 J 2.

Saturn has 61 confirmed satellites: Pan, Daphnis, Atlas, Prometheus, Pandora, Epimetheus, Janus, Aegaeon, Mimas, Methone, Anthe, Pallene, Enceladus, Tethys, Telesto, Calypso, Dione, Helene, Polydeuces, Rhea, Titan, Hyperion, Iapetus, Kiviuq, Ijiraq, Phoebe, Paaliaq, Skathi, Albiorix, S/2007 S 2, Bebhionn, Erriapus, Skoll, Siarnaq, Tarqeq, S/2004 S 13, Greip, Hyrrokkin, Jarnsaxa, Tarvos, Mundilfari, S/2006 S 1, S/2004 S 17, Bergelmir, Narvi, Suttungr, Hati, S/2004 S 12, Farbauti, Thrymr, Aegir, S/2007 S 3, Bestla, S/2004 S 7, S/2006 S 3, Fenrir, Surtur, Kari, Ymir, Loge, Fornjot. To these a number of moonlets must be added.

Many of the Saturn's moons are very small: 34 are less than 10 km in diameter, and another 14 less than 50 km. Only seven are massive enough to have collapsed into hydrostatic equilibrium under their own gravitation. Out of them, 6 (Enceladus, Tethys, Dione, Rhea, Titan and Iapetus) have a diameter larger than 500 km and Mimas is only slightly smaller.

Table 2.6 Diameter d, mass m, gravitational acceleration g, escape velocity V_e and orbital data (semimajor axis a, period T, inclination i and eccentricity e) of the satellites of the giant planets having a diameter larger than 500 km. A negative orbital period indicates retrograde motion

Name	d (km)	m (10^{21} kg)	g (m/s^2)	V_e (km/s)	a (km)	T (days)	I (deg)	e
Jupiter								
Io	3,643	89	1.80	2.56	421,700	1.769	0.050	0.0041
Europa	3,122	48	1.32	2.02	671,034	3.551	0.471	0.0094
Ganymede	5,362	150	1.43	2.74	1,070,412	7.154	0.204	0.0011
Callisto	4,821	110	1.24	2.45	1,882,709	16.689	0.205	0.0074
Saturn								
Enceladus	504	0.108			237,950	1.370	0.010	0.0047
Tethys	1,066	0.617			294,619	1.887	0.168	0.0001
Dione	1,123	1.095			377,396	2.737	0.002	0.0022
Rhea	1,529	2.307			527,108	4.518	0.327	0.0013
Titan	5,151	134.520	1.35	1.86	1,221,930	15.945	0.3485	0.0280
Iapetus	1,472	1.806			3,560,820	79.321	7.570	0.0286
Uranus								
Ariel	1,157.8	1.35			191,020	2.520	0.260	0.0012
Umbriel	1,169.4	1.17			266,300	4.144	0.205	0.0000
Titania	1,577.8	3.53			435,910	8.706	0.340	0.0011
Oberon	1,522.8	3.01			583,520	13.463	0.058	0.0014
Neptune								
Triton	2,707	21.4	0.78	1.45	354,800	−5.877	156.8	

Uranus has 27 known satellites, whose names are chosen from characters from the works of Shakespeare and Alexander Pope. They are Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Cupid, Belinda, Perdita, Puck, Mab, Miranda, Ariel, Umbriel, Titania, Oberon, Francisco, Caliban, Stephano, Trinculo, Sycorax, Margaret, Prospero, Setebos and Ferdinand.

Only 4 of them (Ariel, Umbriel, Titania and Oberon) are larger than 500 km diameter, while Miranda is slightly smaller.

Neptune has 13 satellites: Naiad, Thalassa, Despina, Galatea, Larissa, Proteus, Triton, Nereid, Halimede, Sao, Laomedeia, Psamathe and Neso. Only Triton exceeds 500 km diameter, while Proteus is slightly smaller.

The main characteristics of the satellites of the four giant planets larger than 500 km diameter are listed in Table 2.6.

The largest satellites are characterized by a gravitational acceleration similar to that of the Moon.

The satellites of the giant planets are quite different from each other and many of them are interesting targets for exploration missions. Some are here dealt with in some detail.

2.7.1 Io

The orbits of Io, Europa, and Ganymede form a pattern known as a Laplace resonance; for every four orbits that Io makes around Jupiter, Europa makes exactly two orbits and Ganymede makes exactly one. This resonance causes the gravitational effects of the three large moons to distort their orbits into elliptical shapes. The tidal force from Jupiter, on the other hand, works to circularize their orbits. The eccentricity of their orbits causes strong tidal effects that heat the moons' interiors via friction. This is seen most dramatically in the extraordinary volcanic activity of innermost Io.

Io orbits close to the cloud tops of Jupiter, within an intense radiation belt. The magnetosphere of Jupiter strips away about 1 ton per second of volcanic gases and other materials from the satellite, which remain in orbit about the planet, inflating its magnetosphere. Io is supposed to have a metallic (iron, nickel) core surrounded by a partially melted silicate rich mantle and a thin rocky crust.

Owing to the heat generated by tidal deformations, Io is the most volcanic body in the solar system. Volcanic plumes extending for more than 100 km have been recorded. The plumes are rich in sulfur dioxide, which forms clouds that rapidly freeze and snow back to the surface. The dark areas in the floors of the calderas that were discovered by the *Voyager* and *Galileo* probes may be pools of molten sulfur, a very dark form of sulfur.

Apparently about 15% of Io is made of water ice, and the presence of hot parts suggests that zones where liquid water can form may exist on the surface or underground. Owing to the absence of an atmosphere, water should evaporate quickly on the surface, but underground lakes cannot be excluded. Io is thus a candidate for the search of life-forms in the solar system, provided that these underground pockets supply some protection from the strong radiations due to the Jupiter magnetosphere.

2.7.2 Europa

Europa is very different from Io. It is covered by a layer of water ice that reminds us of our polar ice-pack and contains large quantities of water, probably 15% or more of the total mass of the satellite. Its surface is thus among the brightest in the solar system, owing to the fact that this ice layer is relatively young and smooth.

The high resolution images taken by the *Galileo* probe show that the ice is fractured in a way suggesting that some plates can move, floating on an underlying layer of water or more plastic ice, as happens with glaciers on Earth. Studies performed using radar altimeters and measuring the magnetic and gravitational fields also suggest that there is an ocean of water under the layer of ice, although neither the thickness of the ice nor the depth of the ocean are known.

The satellite is supposed to have a metallic core made, possibly, of iron and nickel, surrounded by a shell of rock and then by a layer of water in liquid form or ice. This ocean of liquid water, perhaps hundreds of kilometers deep, is then surrounded by a layer of ice whose thickness may be some kilometers, even ten or more.

A very tenuous oxygen atmosphere has been recently detected.

Europa is thus another candidate for the search of extraterrestrial life, in spite of its distance from the Sun, being heated by tidal effects caused by the proximity of Jupiter.

2.7.3 Ganymede

The two last Galilean satellites, Ganymede and Callisto, have a heavily cratered appearance.

Ganymede, the largest moon of Jupiter and in our solar system, is most likely composed of a rocky core with a very thick (about 50% of the outer radius) water/ice mantle and a crust of rock and ice. It has no known atmosphere, but recently a thin ozone layer was detected at its surface. This suggests that also Ganymede probably has a thin tenuous oxygen atmosphere.

The geological history of Ganymede is complex, with mountains, valleys, craters and lava flows and it shows light and dark regions. Contrary to the Moon, where the darker regions are the most recent, here the dark regions are more cratered, implying ancient origin. The bright regions show a grooved terrain with ridges and troughs.

At the center a dense metallic core seems to exist, which is the source of a global magnetic field discovered by the *Galileo* probe. Surrounding the metallic core, there should be a rock layer, overlaid by a deep layer of warm soft ice. Above it the surface is made by a water ice crust; images show features showing geological and tectonic disruption of the surface in the past.

2.7.4 Callisto

Callisto is about the same size as Mercury. It orbits just beyond Jupiter's main radiation belt. Its icy crust is very ancient and dates back 4 billion years, just shortly after the solar system was formed and is the most heavily cratered surface in the solar system. The largest craters have been erased by the flow of the icy crust over geologic time. Two enormous concentric ring shaped impact basins are Valhalla, with a bright central region 600 kilometers in diameter and rings extending to 3,000 kilometers in diameter, and Asgard, about 1,600 kilometers in diameter.

Callisto has the lowest density (1,860 kg/m^3) of the Galilean satellites.

The surface layer of ice is thought to be about 200 kilometers thick. Beneath this crust it is possible that a salty ocean more than 10 kilometers deep exists. The clues of this ocean are the Callisto's magnetic field variations in response to the background magnetic field generated by Jupiter.

Beneath the ocean, Callisto seems to have a not entirely uniform interior, composed of compressed rock and ice with the percentage of rock increasing toward the center.

2.7.5 Enceladus, Tethys, Dione, Rhea and Iapetus

These satellites of Saturn are heavily cratered icy worlds. Tethys has a large impact crater and many valleys and troughs stretching three quarters of the way around the satellite.

Dione and Rhea have bright, heavily cratered leading hemispheres and darker trailing hemispheres with thin streaks that are thought to be produced by deposits of ice inside surface troughs or cracks. The latter may have a tenuous ring system of its own.

Iapetus, the outermost of the large icy satellites, has a dark leading hemisphere and a bright trailing hemisphere.

Encedalus is the innermost of the large Saturn's satellites and is more heated than the others by the planet's tidal effects. The *Cassini* probe found evidence of liquid water reservoirs that erupt in geysers. Images had also shown particles of water in its liquid state being emitted by icy jets and towering plumes.

Many of the icy satellites of the giant planets, which are all more or less heated by tidal effects, may have liquid water oceans under a kilometers deep icy crust. In the case of Encedalus the icy crust above the ocean, or at least local liquid water pockets, may be no more than tens of meters deep below the surface.

Some broad regions of Enceladus are uncratered, showing that geological activity has resurfaced areas of the satellite within the last 100 million years.

At the beginning of the space Age, in 1958, when planning the Project Orion, Freeman Dyson chose Encedalus as the destination for a manned mission with a 10,000 tons interplanetary ship propelled by 15 kiloton nuclear explosions.

2.7.6 Titan

Titan, by far the largest of the satellites of Saturn, is larger than the planet Mercury and is the only moon in the Solar System to possess a significant atmosphere.

While apparently being similar to Earth's environment, the surface of Titan is completely different. The role played on the former by rock, on the latter is played by water ice. The hard cobblestones in the floodplain in the pictures taken by the *Huygens* probe that landed on its surface in 2005 (Fig. 2.12a) are actually chunks of

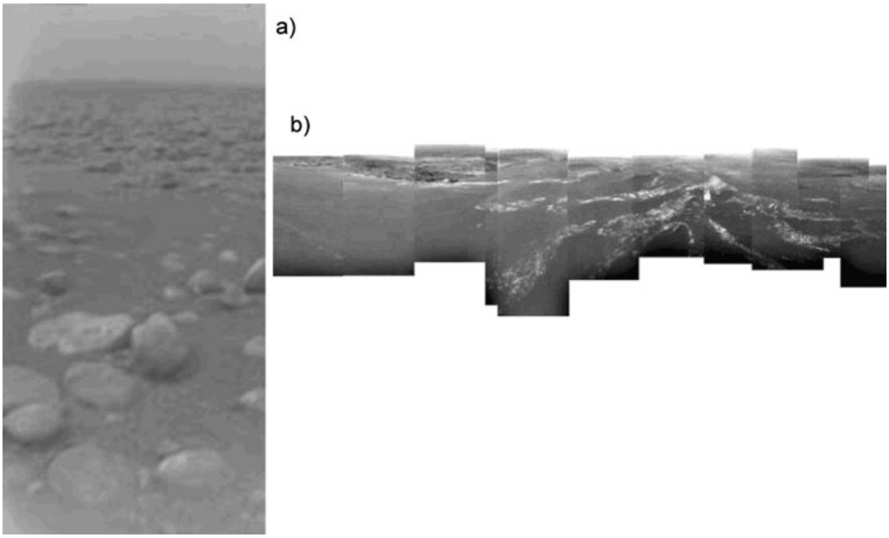

Fig. 2.12 Images of Titan taken by the *Huygens* probe. (**a**) Image of the ground taken after landing. (**b**) Image taken during the descent (images ESA/NASA/Univ. of Arizona)

ice, and the volcanoes (cold volcanoes) that remodel the surface erupt water mixed to ice (slush) which is the local equivalent of lava.

The liquids on the surface are hydrocarbons (methane and ethane), which show an evaporation-condensation cycle similar to the water cycle on Earth. The ground in the landing site of Huygens is soaked in liquid methane, but free from the dark hydrocarbon particles that fall from the sky, like snow on Earth. These hydrocarbon grains collect in some areas and are driven by the wind forming tall dunes.

Likely there are no tall mountains, although a range 150 km long, 30 km wide and 1.5 km high was discovered in the southern hemisphere by *Cassini* in 2006. Some impact craters have been discovered, but their small number shows that the surface is relatively young.

The temperature is in the range of -180°C. At this temperature water ice does not sublimate or evaporate, so the atmosphere is nearly free of water vapor. The haze in Titan's atmosphere cause an effect that is opposite to the greenhouse effect, reflecting sunlight back into space and making its surface significantly colder than its upper atmosphere. The clouds on Titan, probably composed of methane, ethane or other simple organic materials, are scattered and variable, punctuating the overall haze. This atmospheric methane conversely creates a greenhouse effect on Titan's surface, without which Titan would be far colder.

Hydrocarbon lakes, seas and rivers, mostly of liquid methane but with ethane and dissolved nitrogen, were discovered near Titan's north pole; the largest of the seas is almost the size of the Caspian Sea.

Titan's atmosphere is denser than Earth's, with a surface pressure more than one and a half times that of our planet. It supports opaque haze layers that block most visible light from the Sun and other sources. Titan's lower gravity means that its atmosphere is far more extended than Earth's; even at a distance of 975 km.

The atmosphere is 98.4% nitrogen with the remaining 1.6% composed of methane and trace amounts of other gases such as hydrocarbons (including ethane, diacetylene, methylacetylene, acetylene, propane), cyanoacetylene, hydrogen cyanide, carbon dioxide, carbon monoxide, cyanogen, argon and helium.

Titan has no magnetic field, although it seems to retain remnants of Saturn's magnetic field in occasions when it passes outside the Saturn's magnetosphere and is directly exposed to the solar wind.

2.7.7 Miranda, Ariel, Umbriel, Titania and Oberon

These moons of Uranus are ice-rock conglomerates composed of roughly fifty percent ice and fifty percent rock. The ice may include ammonia and carbon dioxide. Ariel appears to have the youngest surface with the fewest impact craters, while Umbriel's appears oldest. Miranda possesses fault canyons 20 kilometers deep, terraced layers, and a chaotic variation in surface ages and features. Miranda's past geologic activity is believed to have been driven by tidal heating at a time when its orbit was more eccentric than currently, probably as a result of a former 3:1 orbital resonance with Umbriel. Extensional processes associated with upwellings of ice are the likely origin of the moon's racetrack-like coronae. Similarly, Ariel is believed to once have been held in a 4:1 resonance with Titania.

2.7.8 Triton

Triton, the only large satellite of Neptune, has a retrograde orbit, indicating that it was captured rather than formed in place; it probably was once a small body of the Kuiper belt. It is close enough to Neptune to be locked into a synchronous rotation, and it is slowly spiraling inward because of tidal effects. It will eventually fall on the planet, or more likely be torn apart, in about 3.6 billion years, when it reaches the Roche limit. No other large satellite in the solar system has a retrograde motion.

A value of the surface temperature of -235°C was estimated for Triton, the lowest temperature recorded in the solar system, although it is likely that the Kuiper belt objects are colder.

It has an extremely thin atmosphere, with a pressure at the surface of about 15 microbars. Nitrogen ice particles might form thin clouds a few kilometers above the surface.

The higher density suggest that Triton contains more rock in its interior than the icy satellites of Saturn and Uranus.

Triton is scarred by enormous cracks. Active geyser-like eruptions spewing nitrogen gas and dark dust particles several kilometers into the atmosphere were imaged by *Voyager 2*.

2.8 Small Bodies

Apart from the satellites of the planets, there are many other small objects in the solar system. They can be roughly subdivided into some categories:

- Main belt asteroids
- Kuiper belt objects (KBO)
- Trojan asteroids
- Other asteroids
- Comets

The asteroids and Kuiper belt objects come in different sizes. The largest are spherical bodies, with characteristics not dissimilar to small planets or large satellites. The largest main belt asteroids are Ceres, Vesta, Pallas, and Hygiea, whose total mass amounts roughly to half the mass of all main belt objects. Ceres is now classified as a dwarf planet. Also a number of objects of the Kuiper belt, like Pluto. Quaoar, Eris, Sedna, Haumea, and Makemake are large enough to be spherical and to be given the status of dwarf planets. Pluto was considered the ninth planet of the solar system until the large objects of the Kuiper belt were discovered. Owing to their distance from the Sun, they are poorly seen, and it is likely that many other, yet undiscovered, large KBO exist.

The characteristics of some large minor bodies orbiting the Sun (dwarf planets and large asteroids) are reported in Table 2.7.

Smaller objects have an irregular shape.

2.8.1 Main Belt Asteroids

With a diameter of about 950 km, Ceres is by far the largest and most massive body in the asteroid belt and is assumed to be a surviving protoplanet, which formed 4.57 billion years ago in the asteroid belt. Like the planets, its structure should consist of a crust, a mantle and a core. The amount of water on Ceres is larger than that on Earth; it is possible that some of this water is (or at least was) in liquid form, an ocean located between the rocky core and ice mantle like the one that may exist on Europa. Ammonia may be dissolved in the water. Like for Europa, the possible existence of this liquid water layer suggests the possibility of finding extraterrestrial life.

The surface composition contains hydrated materials, iron-rich clays and carbonates which are common minerals in carbonaceous chondrite meteorites.

The surface of Ceres is relatively warm, with temperatures ranging from -106 to -38°C.

Ceres may have a tenuous atmosphere and water frost on the surface, which is expected to sublimate when exposed directly to solar radiation. Its rotational period is 9 hours and 4 minutes and the tilt of its rotation axis is about 3°.

Vesta, too, has a differentiated interior, though it is devoid of water and its composition is mainly basaltic rock such as olivine.

Table 2.7 Diameter d, mass m, gravitational acceleration g, escape velocity V_e and orbital data (semimajor axis a, period T, inclination to the ecliptic i and eccentricity e) of some large minor bodies orbiting the Sun (dwarf planets and large asteroids)

Name	d (km)	m (10^{21} kg)	g (m/s^2)	V_e (km/s)	a (10^6 km)	T (days)	i (deg)	e
Main belt								
Ceres	974.6	0.943	0.27	0.51	413.833	1680.5	10.585	0.079
Vesta	560	0.267	0.22	0.35	353.268	1325.2	7.135	0.089
Pallas	556	0.211	0.18	0.32	414.737	1686.0	34.838	0.231
Hygiea	407	0.0885	0.091	0.21	469.580	2,031.01	3.842	0.117
Kuiper belt								
Pluto	2,303	13.14	0.6		5,906.438	90,589	17.140	0.249
Haumea	1,518	4.01	0.44	0.84	6,452.000	103,468	28.22	0.195
Quaoar	1,260				6,524.262	105,196	7.985	0.037
Makemake	1,276	4.18			6,850.086	113,191	28.963	0.159
Eris	2,600	16.7			10,120.000	203,600	44.187	0.441
Sedna	≈1,500				78,668.000	4,404,480	11.934	0.855

Vesta's shape is relatively close to a gravitationally relaxed oblate spheroid, but its irregularity precluded it from being considered a dwarf planet. It has a very large impact basin of 460 kilometers diameter at its southern pole. Its width is 80% of the diameter of Vesta, its floor is about 13 kilometers deep, and its rim rises 4–12 km above the surrounding terrain. A central peak rises 18 kilometers above the crater floor.

Vesta is thought to consist of a metallic iron–nickel core, an overlying rocky olivine mantle, with a surface crust. The impact crater at the south pole is so deep that it exposed part of the inner core. The eastern and western hemispheres are markedly different; the former seems to be similar to lunar highlands while large regions of the latter are covered with more recent basalts, perhaps analogous to the lunar maria.

The rotation period is 5.342 h, with a tilt of the rotation axis of 29°. Temperatures on the surface have been estimated between −190°C and a maximum of −20°C.

Pallas is unusual in that it rotates on its side (the axis is tilted by 78°, with some uncertainty), like Uranus and its rotation period is 0.326 days. Its orbit has an unusually high inclination to the plane of the main asteroid belt, and eccentricity, the latter being nearly as large as that of Pluto. As a consequence, Pallas is a difficult target for space probes. Its composition is similar to that of Ceres: high in carbon and silicon.

Hygiea is largest of C-type asteroids with a carbonaceous surface and, unlike the other largest asteroids, lies relatively close to the plane of the ecliptic. Its rotation period is 27.623 h, and its surface temperature is between −26 and −109°C. Water ice might have been present on its surface in the past.

Hundred thousands asteroids are currently known, over 200 of them being larger than 100 km, and the total number ranges in the millions or more.

Remark 2.12 The asteroids are spread over such a large volume that the main belt is mostly empty: the popular idea of the main asteroid belt as a portion of space full of objects is thus a misconception. To reach an asteroid requires very careful navigation, and hitting one by chance is unlikely.

Most main belt asteroids belong to three wide categories: C-type or carbonaceous asteroids, S-type or silicate asteroids, and M-type or metallic asteroids.

Over 75% of the visible asteroids are C-type asteroids; they are rich in carbon and dominate the belt's outer regions. They are more red in hue than the other asteroids and have a very low albedo. Their surface composition is similar to carbonaceous chondrite meteorites.

About 17% of the asteroids are S-type. They are more common toward the inner region of the belt. Their spectra show the presence of silicates and some metal, but no significant carbonaceous compounds. They have a relatively high albedo.

Less than 10% of the asteroids are M-type; their spectra being similar to those of iron–nickel meteorites. However, there are also some silicate compounds that can produce a similar appearance. For example, the large M-type asteroid 22 Kalliope does not appear to be primarily composed of metal. M-type asteroids at any rate seem to contain a huge quantity of useful, and even precious, metals.

Remark 2.13 A standard 1 km diameter M-type asteroid is assumed to contain 200 million tonnes iron, 30 million tonnes nickel, 1.5 million tonnes cobalt and 7,500 tonnes of metals of the platinum group. Only the latter are worth 150 billion $ at current prices.

Clearly, if such asteroids can be mined, the price of precious metals would decrease sharply, but this would allow to use them for many technical applications at present impossible owing to their high cost. Mining asteroids is a possible future use for space robots.

Within the main belt, the number distribution of M-type asteroids peaks at a semimajor axis of about 2.7 AU. It is not yet clear whether all M-types are compositionally similar, or whether they are simply asteroids which do not fit neatly into the main C and S classes.

There are many other types, including G-type asteroids, similar to the C-type objects, but with a slightly different spectrum, D-type, A-type and V-type, or basaltic, asteroids. The latter were assumed to be the products of the collision that produced the large crater on Vesta and thus to be younger than other asteroids (about 1 billion years or less). This origin is, however, now less certain.

Some objects in the outer part of the asteroid belt show cometary activity. Since their orbits are different from the orbits of classical comets, it is likely that many asteroids in that region are icy, with the ice occasionally exposed to sublimation through small impacts.

The structure of irregular asteroids is not known in general. In the past, asteroids were often assumed to be mostly rubble piles, but now it is certain that many of them are more or less solid bodies.

The asteroid belt is quite wide, so that the temperature of the asteroids varies with the distance from the Sun. The temperature of dust particles located at the distance from the Sun of the asteroid belt ranges from −73°C at 2.2 AU to −108°C at 3.2 AU. The actual temperature of the surface of asteroids, however, changes while the asteroid rotates.

The orbits are not evenly distributed: orbital resonances with Jupiter destabilize some orbits, giving way to gaps, named Kirkwood gaps. They occur where the period of revolution about the Sun is an integer fraction of Jupiter's orbital period.

Collisions between main belt bodies with a mean radius of 10 km are expected to occur about once every 10 million years, which can be defined frequently, on astronomical time scales. As a result, an asteroid may fragment into numerous smaller pieces, leading to the formation of a new asteroid family. If the relative speed is low, the two asteroids may also join together.

Some asteroids, even small ones, have one or more satellites, usually just tiny rocks orbiting about them.

2.8.2 Kuiper Belt Objects

In the outer solar system there is a region where orbits have a 2:3 resonance with Neptune. These asteroids are said to be *Plutinos*, since are in the same resonance as Pluto. Other asteroids are in orbits with a 1:2 resonance with Neptune's orbit (they are said *twotinos*). All these asteroids, and others with orbits outside that of Neptune out to about 55 AU from the Sun are said to be Kuiper Belt Objects (KBOs). The region where they orbit is said the *Kuiper Belt*.

Many Plutinos, including Pluto, have orbits crossing that of Neptune, though their resonance means they can never collide. The eccentricity of their orbit is large, suggesting that they are not native to their current positions but migrated there under the gravitational pull of Neptune.

Apart from twotinos, whose orbits have a semimajor axes of about 47.7 AU, other resonances also exist at 3:4, 3:5, 4:7 and 2:5.

Kuiper belt objects are icy worlds, usually larger than the asteroids in the main belt. Like Jupiter's gravity dominates the asteroid belt, Neptune's gravity dominates the Kuiper belt. Also here there are zones where the orbits are unstable, and the Kuiper belt's structure has gaps, like the region between 40 and 42 AU.

Three of the KBO—Pluto, Haumea and Makemake—are classified as dwarf planets. They, and many smaller and irregular objects orbiting so far from the Sun, are different from the main belt asteroids: the former are mostly rock and metal, while the Kuiper belt objects are composed largely of frozen volatiles such as light hydrocarbons (like methane), ammonia and water, a composition not much different from that of comets. These substances are in ice form since the temperature of the belt is only about −220°C. Also the signature of amorphous carbon was discovered in the spectra of some Kuiper belt objects.

To distinguish these objects from asteroids and from comets, they are often referred to as cometoids.

At present over a thousand KBOs have been discovered and more than 70,000 other objects over 100 km in diameter are believed to exist between the orbit of Neptune and 100 AU from the Sun. Triton, the largest satellite of Neptune, is believed to be a captured KBO.

Pluto has a rotation period of 6.387 days. It has three satellites, the largest of which, Charon, has a diameter of 1,207 km, a mass of 1.9×10^{21} kg and could be considered as a dwarf planet if it were not orbiting Pluto. The Pluto–Charon system can be considered as a double planet, like other KBO. Nix follows a circular orbit in the same plane as Charon and, with an orbital period of 24.9 days is close to a 1:4 orbital resonance with Charon. Hydra orbits in the same plane as Charon and Nix, but on a less circular orbit. Its orbital period of 38.2 days is close to a 1:6 orbital resonance with Charon.

Also Eris and Haumea have satellites. Haumea has a very elongated orbit, and is the farthest object in the solar system, except for comets.

2.8.3 Trojan Asteroids

A *trojan* minor planet, asteroid or satellite is a celestial body that shares an orbit with a larger planet or satellite, but does not collide with it because it is located in one of the two stable Lagrangian points L4 or L5, which lead or lag by 60° the larger body. Actually, a trojan is not located exactly in the Lagrangian point, but orbits about it with a complex dynamics, also for the perturbations due to other bodies. Three-dimensional halo orbits are periodic, while other types of orbits are quasi periodic. This allows a large number of bodies to coexist in different orbits about the same Lagrange point without colliding. Trojans located at a certain Lagrange point are, at any moment, actually spread out in a wide arc on the orbit of the main body.

The term originally referred to two groups of asteroids orbiting the Sun in the same orbit as Jupiter. The first of them, lagging Jupiter by 60°, was discovered in 1904 by the German astronomer Max Wolf and named Achilles. The others were named after Greek (those lagging Jupiter) and Trojan heroes (those leading Jupiter) from the Iliad, with the exceptions of Hector and Patroclus, which are in the 'enemy camp'. Those later discovered on the orbits of other planets or satellites could be designated in a more generic way as *Lagrangian asteroids*, but the term trojans at the end prevailed. Currently over 1,800 trojan asteroids associated with Jupiter are known. About 60% of them are in L4, leading Jupiter in its orbit, while the other 40% are about L5 and trail the planet, like Achilles.

Eureka, discovered in 1990, is the first Mars trojan to be found (5 of them, all located at L5, are known at present). Six Neptune trojans were then discovered and now is believed they are much more numerous than those of Jupiter. Apparently

Saturn and the Earth have no trojans, but clouds of dust were fond at the Lagrange points L4 and L5 on the Earth's orbit and even on the Moon's orbit.

Four examples of trojan satellites are known: Telesto and Calypso, satellites of Saturn, are trojans to Tethys, and Helene and Polydeuces, are trojans to another Saturn's satellite, Dione.

The composition of Trojan asteroids is similar to that of the nearby asteroids, so those on Jupiter's orbit are likely to be similar to those of the outer main belt and those on Neptune's orbit are likely to be similar to KBOs. Some trojans, like Patroclus, seem to have a comet-like composition. Achilles, Hector and other Jupiter's trojans are D-type asteroids (a rare, low albedo, carbon rich, type). Eureka is an A-type asteroid.

2.8.4 Other Asteroids

Among the other asteroid, not belonging to the above categories, Near-Earth Asteroids (NEA), and more in general, Near-Earth Objects (NEO), i.e. objects whose orbit passes close to that of Earth. are the most important. NEOs having a diameter less than 50 meters are said to be Near-Earth Meteoroids (NEMs).

All NEOs have a perihelion distance less than 1.3 AU, and include (at the end of 2008), 5,857 NEAs and 82 Near-Earth Comets (NECs), for a total of 5,939 NEOs. Their number is, however, quickly growing with new discoveries. Out of them, up to 1,000 have a diameter equal to or larger than one km and are potentially able to cause a global catastrophe on Earth. 943 asteroids have been classified as potentially dangerous (PHA, Potentially Hazardous Asteroids), because they could get dangerously close to Earth.

To assess the potential danger posed by PHAs, a scale, named the Torino Scale, was devised. This scale, of the type of the Richter scale for earthquakes, aims to classify the danger represented by the asteroids and comets that are discovered. It has 11 degrees (from 0, no risk, to 10, certainty of generalized destruction), and five colors, (from white, certainty of no impact, to red, certainty of impact). The usefulness of this type of scale derives from the fact that when an asteroid is discovered, its orbit can only be calculated in an approximate way and the potential danger it represents may only be assessed in statistical terms. Even when the orbit is better known, it can be changed by gravitational perturbations of the planets or even of the Earth in such a way that the danger it represents changes. These perturbations cannot be computed with the required precision: a variation of a few thousand km, a trifle on an astronomic scale, may transform a harmless asteroid into a serious danger.

None of the known objects has a degree higher than one on the Torino scale. An example of an asteroid with a Torino Scale value equal to 1 is 2004 MN4 Apophis, which will make several close passes, coming very close in 2029, and has some probability of hitting the Earth on April 13, 2036. Its estimated diameter is 390 m.

Some NEOs are easier to reach than the Moon, since they require a lower ΔV. Not only they may present interesting scientific targets for direct geochemical and astronomical investigation, but are also potentially economical sources of extraterrestrial materials for human exploitation. Two near-Earth objects have been visited by spacecraft: 433 Eros, by NASA's Near Earth Asteroid Rendezvous probe, and 25143 Itokawa, by the JAXA Hayabusa mission.

Depending on their orbits, NEA are subdivided into three families

- Atens, orbiting inside Earth orbit (average orbital radii closer to the Sun than one AU and aphelia outside Earth's perihelion, at 0.983 A.U.). 453 Atens were known in May 2008.
- Apollos, whose orbit has an average orbital radius greater than that of the Earth and perihelion less than Earth's aphelion at 1.017 A.U. 2,053 Apollos were known in May 2008.
- Amors, orbiting outside Earth orbit (average orbital radii in between the orbits of Earth and Mars and perihelia slightly outside Earth's orbit (1.017–1.3 AU). They often cross the orbit of Mars. 2,894 Amors were known in May 2008.

Remark 2.14 Many Atens and all Apollos have orbits that cross that of the Earth, so they are a threat to impact the Earth on their current orbits. Amors do not cross the Earth's orbit and are not immediate impact threats.

However, their orbits may evolve into Earth-crossing orbits in the future. NEOs' orbits are actually the result of the gravitational perturbations of the outer planets, mainly Jupiter, and these objects come from the asteroid belt or even the outer solar system. The Kirkwood gaps, where orbital resonances with Jupiter occur, are the places from where most of them come. Their orbits are bound to change again in the future: new asteroids are constantly moved into near-Earth orbits and the present ones are moved away, even ejected from the solar system or sent into the Sun.

2.8.5 Comets

Comets are small bodies which, when get close enough to the Sun, exhibit a visible coma, and sometimes a tail, both because of the effects of solar radiation upon the comet's nucleus. Comet nuclei are themselves loose collections of ice, dust and small rocky particles, ranging from 100 m to more than 40 km across.

Remark 2.15 Comet nuclei are often described as 'dirty snowballs', but observation by spacecraft showed that their surface is made of dry dust or rock, suggesting that the ices are hidden beneath the crust.

The results of the *Deep Impact* probe suggest that the majority of a comet's water ice is below the surface, and that these reservoirs feed the jets of vaporized water that form the coma.

The nucleus is made of rock, dust, water ice, and frozen gases such as carbon monoxide, carbon dioxide, methane and ammonia. It contains also a variety of other organic compounds including methanol, hydrogen cyanide, formaldehyde, ethanol and ethane, and perhaps more complex molecules such as long-chain hydrocarbons and amino acids. Cometary nuclei are among the darkest objects known to exist in the solar system: Halley's Comet nucleus, for instance, reflects approximately 4% of the incoming light, and the surface of Borrelly's Comet is even darker, reflecting 2.4 to 3.0% of the incoming light. This darkness is ascribed to complex organic compounds.

Like small asteroids, comets have irregular shapes.

A wide variety of orbits of comets exists. Some of them dwell in the inner solar system and in the Kuiper belt, with orbital periods of a few years, while others get quite far from the Sun, with periods of hundreds of thousands years. Some are believed to pass only once through the inner Solar System before being thrown out into interstellar space.

Short-period comets are thought to originate in the Kuiper Belt, beyond the orbit of Neptune. Long-period comets are believed to originate in the Oort cloud, consisting of debris left over from the condensation of the solar nebula, located well beyond the Kuiper Belt. Comets are thrown toward the Sun and the inner solar system by gravitational perturbations from the outer planets (in the case of Kuiper Belt objects) or nearby stars (in the case of Oort Cloud objects), or as a result of collisions between objects within these regions.

The difference between asteroids and comets lies in their orbit and composition, but the latter distinction is more and more blurred, since outer solar system asteroid are now understood to contain much frozen volatile substances. In particular, centaurs are comet-like bodies that orbit among the gas giants, between Jupiter and Neptune. Their orbits are unstable and have dynamic lifetimes of a few million years. Until they remain so far from the Sun, they have no coma and seem to be asteroids, but when such bodies enter the inner solar system their cometary nature unfolds. Chiron, for instance, and other centaurs are listed both as asteroids and as comets.

In May 2009, 3,648 known comets had been reported, about 400 being short-period comets. This number is believed to represent only a tiny fraction of the total potential comet population: the outer solar system may contain something like one trillion cometary bodies.

As a comet approaches the inner solar system, solar radiation causes the volatile materials within the comet to vaporize and stream out of the nucleus, carrying dust away with them. Since the gases are not ejected from the comet in an isotropic way, they exert a thrust, so that the orbit of comets is affected by this sort of rocket propulsion.

The streams of dust and gas form a huge, extremely tenuous atmosphere around the comet and, under the pressure of the Sun's light, an enormous tail pointing away from the Sun. The streams of dust and gas form two distinct tails, pointing in slightly different directions.

Even if the coma and the tail are very thin by the standards we are used to, the region of space close to an active comet is believed to be dangerous for any spacecraft.

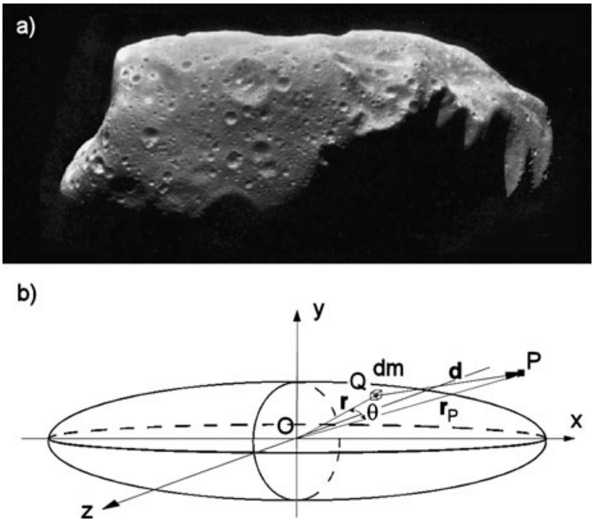

Fig. 2.13 (**a**) Asteroid 243 Ida imaged by Galileo spacecraft on August 28, 1993. The asteroid is 52 km long, and the image is a mosaic of five pictures acquired from distances from 3,057 to 3,821 kilometers (NASA-JPL image). (**b**) Ellipsoidal body attracting gravitationally point P

While the solid nucleus of comets is generally less than 50 km across, the coma may be larger than the Sun, and ion tails have been observed to extend 1 astronomical unit (150 million km) or more. Ionized gas particles attain a positive electrical charge which in turn gives rise to an 'induced magnetosphere' around the comet. A bow shock is thus formed upstream of the comet, in the flow direction of the solar wind.

Comets are also known to break up into fragments, as happened with Comet 73P/Schwassmann-Wachmann 3 starting in 1995. This breakup may be triggered by tidal gravitational forces from the Sun or a large planet, by an explosion of volatile material, or for other reasons not fully explained.

2.8.6 Gravitational Acceleration on the Surface of Non-regular Asteroids

The irregular shape of all asteroids, but the largest ones, causes the gravitational acceleration to be variable from place to place and to be not perpendicular to the ground. For instance, the gravitational acceleration on Eros varies between 0.0023 and 0.0055 m/s^2. A picture of asteroid Ida as imaged by *Galileo* probe is shown in Fig. 2.13a.

It is well known that in case of spherical bodies (with mass axial symmetry) the gravitational acceleration at the surface and above is exactly the same as that of a point mass located at its center. All major bodies and the dwarf planets are close enough to be spherical, to the point that it is possible to consider their mass concentrated at their center, at least for first approximation evaluations. When the precision required is such that the deviation from a spherical shape (and constant density) must be taken into account, it is possible to proceed using a perturbation approach, considering the gravitational field of a sphere and applying subsequent small correction terms, obtained from the potential of the gravitational field.

Consider the generic body in Fig. 2.13b (in the figure the body is plotted as an ellipsoid, but the computation holds in general) and assume that a generic point Q inside the body has coordinates x, y, and z. The external point P where the field has to be computed has coordinates x_P, y_P, and z_P. The reference frame $Oxyz$ is centered in the center of mass of the body and vectors $\overline{(P-O)}$, $\overline{(Q-O)}$ and $\overline{(P-Q)}$ are indicated as $\mathbf{r}_P$, $\mathbf{r}$, and $\mathbf{d}$.

The gravitational potential per unit mass in point P due to mass dm located in Q is

$$d\mathcal{U} = \frac{G}{|\mathbf{d}|}\, dm, \tag{2.1}$$

where G is the gravitation constant.

The potential per unit mass in point P due to the whole body is

$$\mathcal{U} = \int_M \frac{G}{|\mathbf{d}|}\, dm. \tag{2.2}$$

Since

$$|\mathbf{d}| = \sqrt{(x-x_P)^2 + (y-y_P)^2 + (z-z_P)^2} = \sqrt{|\mathbf{r}_P|^2 + |\mathbf{r}|^2 - 2|\mathbf{r}||\mathbf{r}_P|\cos(\theta)}, \tag{2.3}$$

where θ is the angle defined in Fig. 2.13b, it follows that

$$\mathcal{U} = \frac{G}{\mathbf{r}_P}\int_V \frac{G\rho}{\sqrt{1+\alpha^2-2\alpha q}}\, dV, \tag{2.4}$$

where ρ is the density of the body, in general a function of space coordinates, and

$$\alpha = \frac{|\mathbf{r}|}{|\mathbf{r}_P|}, \qquad q = \cos(\theta) = \frac{x x_P + y y_P + z z_P}{|\mathbf{r}_P||\mathbf{r}|}.$$

Since $q \le 1$ and, in case of points outside the body, $\alpha < 1$ the square root at the denominator can be written as a Taylor series in α. The potential can thus be written as[1]

$$\mathcal{U} = \frac{G}{|\mathbf{r}_P|}\sum_{i=0}^{\infty}\int_V \rho P_i \alpha^i\, dV = \sum_{i=0}^{\infty}\mathcal{U}_i. \tag{2.5}$$

The first term is easily computed, obtaining

$$P_0 = 1, \qquad \mathcal{U}_0 = \frac{GM}{|\mathbf{r}_P|}. \tag{2.6}$$

[1] A.E. Roy, *Orbital Motion*, Adam Hilger, Bristol, 1991.

The first term is thus the potential of a point mass with the same mass of the body, located in its center.

Since O is the center of mass of the body, the second term ($i = 1$) can be shown to vanish:

$$P_1 = q, \qquad \mathcal{U}_1 = 0. \tag{2.7}$$

The third term can still be obtained with straightforward computations, obtaining

$$P_2 = \frac{1}{2}(3q^2 - 1), \qquad \mathcal{U}_2 = \frac{G}{2|\mathbf{r}_\mathrm{P}|^3}(J_x + J_y + J_z - 3J_\mathrm{OP}), \tag{2.8}$$

where the various J_k are the moments of inertia about the axes and about line OP.

Note that also this term vanishes for spherical bodies.

The fourth term can be shown to vanish if the body is symmetrical about the coordinate planes, like in the case of a homogeneous ellipsoid. The same can be shown to happen for the sixth, eighth, etc. terms, i.e. all terms $\mathcal{U}_i$ with odd i. If the body is a revolution solid, but is pear-shaped, like in the case of Earth, these terms do not vanish.

This approach, based on the series expansion of the potential, is increasingly difficult when the higher order terms become important, i.e. when

- point P is close to the surface
- the shape of the body departs from a sphere by a non small quantity or the density is not constant

When computing the gravitational acceleration on the surface of very small bodies, like asteroids and comets, a large number of terms should be accounted for. Even if their shape is approximated as a spheroid (something that can be done only as a theoretical example), this approach becomes unpractical.

A different approach will be followed here to show that the non-spherical shape causes the gravitational acceleration at the surface not only to change from point to point, but also to be not perpendicular to the surface even in the case of a homogeneous spheroid.

Using the same notation as above (Fig. 2.13b), the gravitational force exerted on a mass m_1 located in point P outside the body can be computed as

$$\mathbf{F} = m_1 \nabla \mathcal{U} = -G m_1 \int_M \frac{1}{|\mathbf{d}|^3} \mathbf{d}\, dm. \tag{2.9}$$

The local gravitational acceleration at point P is

$$\mathbf{g} = -G \int_M \frac{1}{|\mathbf{d}|^3} \mathbf{d}\, dm. \tag{2.10}$$

If the coordinates of point P are x_P, y_P and z_P, it follows that

$$\mathbf{g} = -G \int_V \frac{\rho}{[\sqrt{(x - x_\mathrm{P})^2 + (y - y_\mathrm{P})^2 + (z - z_\mathrm{P})^2}]^3} \begin{Bmatrix} x - x_\mathrm{P} \\ y - y_\mathrm{P} \\ z - z_\mathrm{P} \end{Bmatrix} dx\, dy\, dz, \tag{2.11}$$

were V is the volume occupied by the body.

If the body is a homogeneous sphere with radius R and ρ is a constant, the integration can be performed in closed form, although not in rectangular coordinates. Using cylindrical coordinates, and setting x axis along the line connecting point P with the center of the sphere, it follows that

$$\mathbf{g} = \frac{4\pi G\rho R^3}{3x_P^2}\begin{Bmatrix}1\\0\\0\end{Bmatrix} = \frac{MG}{x_P^2}\begin{Bmatrix}1\\0\\0\end{Bmatrix}. \tag{2.12}$$

This amounts to state that the body behaves as a point mass located at its center, as stated above.

Consider a body whose shape is an ellipsoid with semi-axes a, b and c, respectively, in the direction of x, y and z axes, and assume that its density is constant. The gravitational acceleration is thus

$$\mathbf{g} = -G\rho\int_{-a}^{a}\int_{-b\sqrt{1-(\frac{x}{a})^2}}^{b\sqrt{1-(\frac{x}{a})^2}}\int_{-c\sqrt{1-(\frac{x}{a})^2-(\frac{y}{b})^2}}^{c\sqrt{1-(\frac{x}{a})^2-(\frac{y}{b})^2}}\frac{1}{|\mathbf{d}|^3}\begin{Bmatrix}x-x_P\\y-y_P\\z-z_P\end{Bmatrix}dx\,dy\,dz. \tag{2.13}$$

The innermost integral can be performed in closed form, yielding

$$\mathbf{g} = -G\rho\int_{-a}^{a}\int_{-b\sqrt{1-(\frac{x}{a})^2}}^{b\sqrt{1-(\frac{x}{a})^2}}\begin{Bmatrix}\frac{(x-x_P)}{d_1^2}\left(\frac{A}{\sqrt{d_1^2+A^2}}+\frac{B}{\sqrt{d_1^2+B^2}}\right)\\\frac{(y-y_P)}{d_1^2}\left(\frac{A}{\sqrt{d_1^2+A^2}}+\frac{B}{\sqrt{d_1^2+B^2}}\right)\\\frac{1}{\sqrt{d_1^2+B^2}}-\frac{1}{\sqrt{d_1^2+A^2}}\end{Bmatrix}dx\,dy, \tag{2.14}$$

where

$$A = c\sqrt{1-\frac{x^2}{a^2}-\frac{y^2}{b^2}}-z_P,$$
$$B = c\sqrt{1-\frac{x^2}{a^2}-\frac{y^2}{b^2}}+z_P, \tag{2.15}$$
$$d_1 = \sqrt{(x-x_P)^2+(y-y_P)^2}.$$

The other two integrals cannot be performed in closed form, but there is no difficulty in obtaining a numerical result, once the position of P and the geometrical characteristics of the ellipsoid are known.

For example, the gravitational acceleration on the surface of a prolate spheroid,[2] with the larger axis in x direction (i.e. $b = c < a$) is reported as a function of the

[2]A spheroid is an ellipsoid with two equal axes. If the third axis is smaller than the other two, the spheroid is oblate; if it is longer it is prolate.

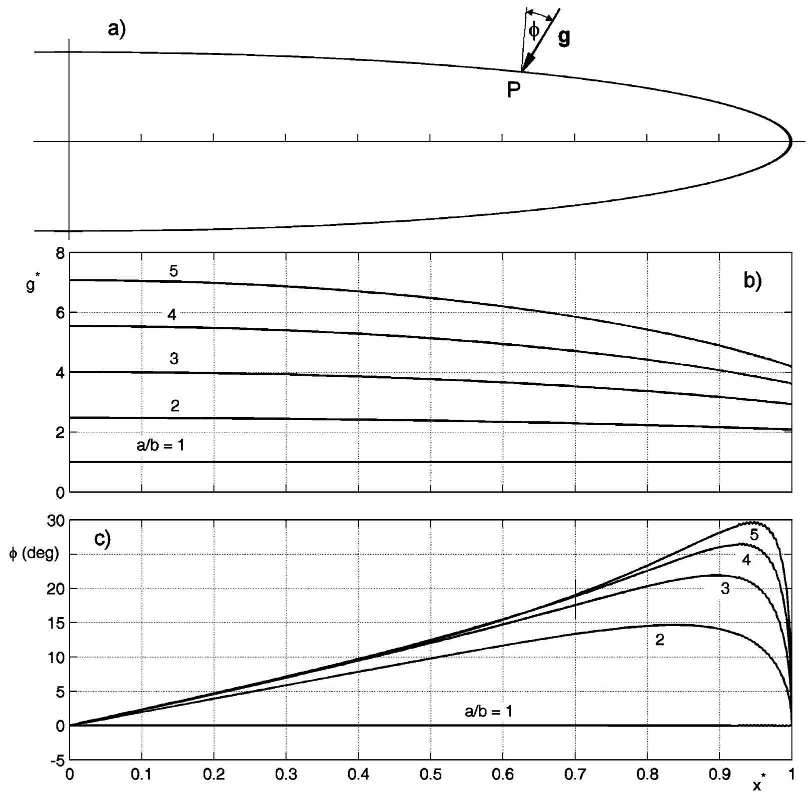

Fig. 2.14 Gravitational acceleration on the surface of a prolate spheroid. (**a**) Sketch; nondimensional value of the gravitational acceleration (**b**) and angle between the perpendicular to the ground and the vertical direction (i.e. the direction of the gravitational acceleration) (**c**) as functions of the nondimensional coordinate x^*

nondimensional $x^* = x/a$ coordinate of point P in Fig. 2.14b. The nondimensional value of the gravitational acceleration is

$$g^* = g\frac{a^2}{GM} \tag{2.16}$$

i.e. is made nondimensional by dividing it by the gravitational acceleration at the surface of a spherical body with the same mass and a radius equal to the semimajor axis of the spheroid.

The angle between the perpendicular to the ground and the vertical direction (i.e. the direction of the gravitational acceleration) is reported as a function of the nondimensional coordinate x^* in Fig. 2.14c.

It is clear that on a spheroidal body what matters is not so much the variability of the gravitational acceleration as the angle between the vertical direction and the perpendicular to the ground. Angles as large as 20° or even 30° are present.

Remark 2.16 An angle of 20° corresponds to a 18% grade. In places where the perpendicular to the flat ground has such an inclination with respect to the local vertical, any modest terrain irregularity may be very difficult or even impossible to overcome.

Remark 2.17 Actual asteroids are much more irregular than this and above all their shape may not be convex everywhere. There may be large zones where locomotion on the ground is very difficult and places that may be accessed, but from which it is quite difficult to get out.

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