Physics of the Solar System Bodies

6

In this section we bring briefly the most essential results of the study of the bodies of the solar system. The sun itself is treated separately. The study of the atmospheres of other planets and their development and structure enables conclusions to be drawn about our Earth; the formation of our planetary system can be better understood by comparison with extrasolar planetary systems.

6.1 Overview

The dominant role of the Sun around which the other bodies of the solar system orbit is evident from their physical parameters such as mass, diameter, etc.

6.1.1 Sun and Planets

The dominant body in the solar system is the *Sun*. Let us consider some of its physical parameters

- Radius $R_\odot = 696,000$ km, this corresponds to 109 Earth radii.
- Mass $M_\odot = 1.989 \times 10^{30}$ kg, this corresponds to 333,000 Earth masses.
- Gravity acceleration at the surface $g_\odot = 274\,\mathrm{m/s}^2$, this corresponds to 28 times the acceleration due to gravity.

The Sun contains 99.8% of the mass of the entire solar system.

A. Hanslmeier, *Introduction to Astronomy and Astrophysics*,
https://doi.org/10.1007/978-3-662-64637-3_6

Furthermore, the solar system includes the known eight large *planets*. Since the decision of the IAU[1] in 2006, Pluto no longer counts as a large planet. The planets have diameters between some 10^3 km up to 10^5 km; they move around the Sun in nearly circular orbits, all of which lie almost exactly in the plane of the ecliptic, and the total mass of all the planets together is 448 Earth masses. Enumerating the planets according to their distance from the sun, we have Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. The newly defined group of the *dwarf planets* include Pluto and other objects (Sedna, Ceres, and others).

The *asteroids* or minor planets (also called Planetoids) are, with a few exceptions, smaller than 100 km, and most are located between the orbits of the planets Mars and Jupiter, but there are also some that cross the Earth's orbit, for example. Outside the orbit of Neptune lie the objects of the *Kuiper belt,* to which also Pluto belongs.

The *Moons* or satellites are companions of the major planets (Mercury and Venus have no moon), dwarf planets (Pluto has five moons, the last two discovered in 2012), and asteroids.

Many *Comets* are located in the *Oort's comet cloud.* This envelops the solar system spherically symmetrically. Disturbances cause comets to enter the interior of the solar system, where evaporating gases produce the comet tail. They are small in diameter (less than 100 km).

As the last component of the solar system there is still the *interplanetary matter* (meteoroids, gas and dust). In good conditions, the matter distributed along the ecliptic can be seen after sunset or before sunrise as a *Zodiacal light* when dark enough.

6.1.2 A Model of the Solar System

Consider a 1:10^9 scale Solar System Model (Table 6.1). In this model, the 12-mm Earth would orbit the 1.4-m Sun at a distance of 150 m. The nearest star (apart from the Sun) would be about 40,000 km away (equivalent to the circumference of the Earth).

Table 6.2 gives a summary of the most important properties of the planets.

Units of distance in the solar system are often expressed in *astronomical unit, AU*). This is the average distance from the Earth to the Sun (150 million km).

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[1] International Astronomical Union.

Table 6.1 Model of the solar system, scale 1:10^9

Object	Diameter	Distance from sun
Sun	1.4 m	
Mercury	5 mm	60 m
Venus	12 mm	110 m
Earth	12 mm	150 m
Mars	7 mm	230 m
Jupiter	14 cm	800 m
Saturn	12 cm	1.5 km
Uranus	5 cm	3 km
Neptune	5 cm	4.5 km
Pluto	2 mm	6 km

Table 6.2 The most important properties of the planets and of Pluto; d—distance from the Sun

Planet	$d[10^6$ km]	Orbital time	Rotation time	Equator. inclination [^{o}]
Mercury	57.9	87.9d	58.65 d	0
Venus	108.2	224.7	243.01 d	2.01
Earth	149.6	1.00 a	23 h56 min	23.5
Mars	227.9	1.88	24 h 37 min	24
Jupiter	779	11.87	9 h 50 min–9 h 56 min	3
Saturn	1432	29.63	10 h 14 min–10 h 39 min	24
Uranus	2888	84.66	17 h 06 min	98
Neptune	4509	165.49	15 h 48 min	29
Pluto	5966	251.86	6.3 d	122.5

6.1.3 The Solar System Seen from Outside

From the nearest star (α Cen) the solar system would appear as follows: The Sun would have an apparent magnitude of $0.^{m}4$, so it would be a bright star. Earth would have a brightness of $23.^{m}4$ and would be only $0.''76$ from the Sun. The largest planet in the solar system, Jupiter, would have a brightness of $22.^{m}0$ and would be $3.''94$ from the sun. Theoretically, Earth and Jupiter would be detectable with the largest telescopes from our neighboring star, however they would be too close to the Sun.

Planets do not shine themselves, so they are very faint and are also outshone by their parent star. For this reason, the search for planets outside our solar system *(extrasolar planets)* is very difficult. So far, they can usually only be detected indirectly, for example by the motion of the center of gravity of the parent star when a large, massive planet is near it or when a transit of a planet in front of its host star occurs.

A completely new method of detecting extra solar planets is provided by the *microlensing effect*. As is shown in the Cosmology section, the path of a beam of light bends in the presence of gravitational fields. Microlensing events can be observed by a change in the

Table 6.3 The major planets. D—Equatorial diameter, v_e—escape velocity, gravity is the surface gravitational acceleration

Planet	D[km]	M[M_{Earth}]	ρ[g/cm^3]	Gravity Earth = 1	v_e [km/s]
Mercury	4878	0.055	5.43	0.4	4,25
Venus	12,104	0.815	5.24	0.9	10.4
Earth	12,756	1.0	5.52	1.0	11.2
Mars	6794	0.107	3.93	0.4	5.02
Jupiter	142,796	317.8	1.33	2.4	57.6
Saturn	120,000	95.15	0.70	0.9	33.4
Uranus	50,800	14.56	1.27	0.9	20.6
Neptune	48,600	17.20	1.71	1.2	23.7

brightness of an object as it moves into the light path of a background source. If planets are present with this object, additional changes in brightness occur. For example, evaluations of an event in 1999 showed that the gravitational lensing in question was a binary star, with the masses of the two components behaving as 4:1 and being only 1.8 AU apart. Furthermore, a planet of three Jupiter masses is suspected at a distance of 7 AU.

There are two groups of planets in our solar system:

The *terrestrial planets* are Mercury, Venus, Earth and Mars. They have a relatively high density and a solid surface.

The *Giant planets* (sometimes called Jovian planets) are Jupiter, Saturn, Uranus, and Neptune. They are gas planets with no solid surface. Sometimes Uranus and Neptune are also called ice planets (have a large core of ice).

The most important physical properties of the planets are given in Table 6.3.

> Planets around other stars are only directly observable in exceptional cases because of the large difference in brightness and proximity to the star.

6.2 Properties of the Planets

In this section, we briefly cover how to derive the most important properties of the planets, most of which are already known from Earth-based observations.

6.2.1 Rotation Period

Planet rotation determination in some cases simply follows from the observation of permanent surface phenomena. This works quite well for Mars and Jupiter, however,

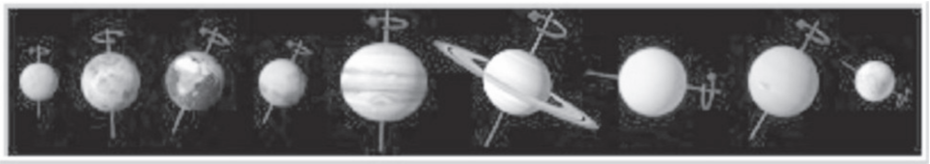


Fig. 6.1 Inclinations of the rotational axes of the planets as well as Pluto. Note the inclination of the rotation axis of Uranus. Planets in order as seen from the Sun. The sizes are not to scale. © Photobucket.com

e.g. Venus has a dense cloud cover and thus not reveal any surface details. One can also determine planet rotation from the *Doppler shift* of the reflected *Fraunhofer lines* of the solar spectrum or from the absorption lines originating from the planet's atmosphere itself. In the case of the nearest planets, the *Radar technology* apply: Annular zones around the center of the planet disk are distinguished according to the transit time differences of the radar waves. In 1964/1965 the 300 m parabolic antenna at Arecibo on Puerto Rico was used for the first time to determine the rotation of the planets Venus and Mercury.

Figure 6.1 shows the inclinations of the *rotational axes* of the planets. Mercury, Venus, and Jupiter have the least inclinations. Venus, however, rotates retrograde, i.e. in opposite sense of its solar orbit. The inclination of Uranus is extreme, as well as the inclination of the rotation axis of the dwarf planet Pluto.

6.2.2 Mass Distribution

The Mass distribution in the interior of the planet, i.e. the planetary structure, can be determined by:

- Measurement of *flattening,* due to rotation,
- gyroscopic motions in the gravitational field as well as precise determination of the gravitational potential by means of artificial satellites in orbit; from this one deduces the internal structure of a planet.

On Earth, Mars and the Moon, *seismic measurements* are possible, from the analysis the inner structure follows. In the Table 6.4 the proportion of the core of the planets in % of the total mass is given for the Earth-like planets and the Earth's moon.

6.2.3 Albedo

Albedo describes the ratio of the sunlight reflected or scattered in all directions to the incident light. Its strength and wavelength dependence provide clues to the nature of the planet's surface.

Table 6.4 Terrestrial planets and earth's moon: proportion of the core in the total mass

Planet	Core%
Mercury	42
Venus	12
Earth	16
Earth moon	4
Mars	9

The *Bond's Albedo* is defined by:

$$A = pq \tag{6.1}$$

Let r be the sun-planet distance in AU, Δ the distance between earth and planet in AU, ρ the diameter of the major semimajor axis of the planet's orbit in AU, α the *Phase angle* (= angle between the sun and the earth as seen from the planet), $\phi(\alpha)$ the phase law, p is the ratio of planetary brightness at $\alpha = 0$ to a perfectly diffuse surface, then holds:

$$\log p = 0.4(m_{\odot} - m_{\text{planet}}) + 2\log(r\Delta/\rho) \tag{6.2}$$

Whereby m is the apparent magnitude of the object.

The magnitude q is determined by the law of reflection:

$$q = 2\int_0^{\pi} \phi(\alpha)\sin\alpha d\alpha \tag{6.3}$$

According to Lambert's law $q = 1.50$, according to the law of *Lommel-Seeliger:* $q = 1.64$. Here the luminosities are given in *Magnitudes* $^{\text{m}}$. Brightest stars are 1st magnitude stars, faintest stars just visible to the naked eye are 6th magnitude (Sect. 8.1).

One then has the following laws:

- Mercury: $p = 0.093$, $q = 0.65$, $A = 0.060$ (Moon 0.070). At its greatest easterly elongation $r\Delta = 0.357$, and the visual magnitude of Mercury is :

$$m_V = -0.21 + 5\log r\Delta + 3.82 \times 10^{-2}\alpha - 3.37 \times 10^{-4}\alpha^2 \ldots . \tag{6.4}$$

- At Jupiter the dependence on phase angle is already very small (why?): $p = 0.37$, $q = 1.10$, $A = 0.41$. At its opposition one has:

$$m_V = -9.1 + 5\log r\Delta + 0.015\alpha \tag{6.5}$$

In both formulas m_V stands for the brightness measured in the visual.

6.2.4 Spectrum

With spectroscopic observations, gases in the planetary atmospheres can be detected by absorption bands. The terrestrial H_2O-, CO_2- and O_3 bands can be bypassed from satellites. The *Intrinsic radiation* of a information about its temperature in the atmosphere.

6.2.5 Global Energy Budget

The irradiance from the Sun at Earth distance (1 AU) is referred to as the *Solar constant S*.

$$S = 1.37\,\mathrm{kW\,m^{-2}} \tag{6.6}$$

On an area of $1\,\mathrm{m}^2$ we obtain on the earth a radiant power of this amount with perpendicular incidence of solar radiation and without absorption in the earth's atmosphere.

If there is a planet at distance r, then its solar constant (amount of power from the Sun to $1\ \mathrm{m}^2$):

$$S(r) = S\left(\frac{r}{1\,\mathrm{AU}}\right)^{-2} \tag{6.7}$$

A planet with radius R takes from this the amount $\pi R^2(1-A)S(r)$ on. The mean albedo of the earth is $A \approx 0.3$. This albedo depends essentially on the mean the cloud fraction (clouds: Aldebo = 0.5).

If the radiation takes place according to the *Stefan-Boltzmann law* for a black body, is valid for the total power:

$$4\pi R^2 \times \sigma T^4, \qquad \sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}}\,K^{-4} \tag{6.8}$$

Further, one has to consider the internal heat flux. Consider Q coming from internal heat sources of a planet. Such heat sources can be (i) radioactive decay, (ii) residual heat from the time of the formation of the planet (but small planets cool down quickly) and (iii) so-called tidal heating, caused by strong tidal forces (plays for some moons of the large Planet a role).

Now we make a balance:

Irradiation + Q = radiation:

$$\pi R^2(1-A)S(r) + 4\pi R^2 Q = 4\pi R^2 \sigma T^4 \tag{6.9}$$

For the Earth Q is due to the decay of the radioactive elements and amounts to $0.06\,\mathrm{W\,m^{-2}}$. Infrared measurements show that the planets Jupiter, Saturn, and Neptune have thermal radiation that exceeds the absorbed Solar radiation around by a factor of 1.9 and 3.5 and 2.4 respectively.

Actual temperatures of planets differ from values derived above, because planets rotate, furthermore atmospheric currents occur, as well as due to *greenhouse effect,* heating of individual layers (e.g. *Ozone layer* of the earth's atmosphere) etc.

6.2.6 Hydrostatic Equilibrium

We consider a volume element at distance r from the center of a planet with base area dA and height dr. Let its mass be $\rho(r)dAdr$, and for the mass within r holds:

$$M(r) = \int_0^r \rho(r')4\pi r'^2 dr' \qquad \frac{dm(r)}{dr} = 4\pi r^2 \rho(r) \tag{6.10}$$

The gravitational acceleration by $M(r)$ is:

$$g(r) = \frac{GM(r)}{r^2} \tag{6.11}$$

In the area of the considered volume element the pressure changes p um:

$$-dpdA = \rho(r)dAdrg(r) \tag{6.12}$$

we have thus the relation: force = mass $(\rho(r)dAdr)$ × acceleration $(g(r))$.

This gives us the condition for the *hydrostatic equilibrium* of a planet:

$$\frac{dp}{dr} = -g(r)\rho(r) \tag{6.13}$$

Special case: homogeneous sphere with $\rho(r) = \bar{\rho} = \text{const}$. Estimation for the central pressure p_c: M is the total mass, and it holds: $M(r)/M = (r/R)^3$.

$$p_c = \int_R^0 \frac{dp}{dr}dr = \bar{\rho}\int_0^R \frac{GM}{r^2}\left(\frac{r}{R}\right)^3 dr = \frac{1}{2}\bar{\rho}\frac{GM}{R} \tag{6.14}$$

This estimation gives for the center of the earth : $p_c = 1.7 \times 10^{11}\mathrm{Pa}$. This value is lower than the actual one by a factor of 2.

The hydrostatic equilibrium condition is also a basic equation of stellar structure.

To build a planet, one still needs an equation of state of the form $p = p(\rho, T,$ chemical composition).

6.2.7 Stability of a Satellite, Roche Limit

Here the question is, how close e.g. a moon can come to its mother planet before it is torn apart by the tidal forces. Let there be a central body (planet) with mass M, radius R, and an average density $\bar{\rho}$ and a satellite with the parameters M_S, R_S, $\bar{\rho}_S$. We think of the satellite as consisting of two halves $M_S/2$ which attract each other at a distance R_S:

$$F \approx G\frac{M_S M_S}{4R_S^2} \tag{6.15}$$

So this force holds the two halves of the satellite together.

The *tidal force* acts to the Satellite to be torn apart. Consider the tidal acceleration exerted by the Earth on the Moon. At lower culmination, this is equal to the difference between the gravitational acceleration due to the Earth's attracting mass M at the lunar center (distance Earth-Moon r) and the acceleration acting on the lunar surface (distance $r - R_S$). The tidal acceleration is therefore:

$$b_G = \frac{GM}{r^2} - \frac{GM}{(r - R_S)^2} \sim \frac{2GM}{r^3} R_S \tag{6.16}$$

In our case, the tidal force of M on M_S is then:

$$2GMM_S R_S/r^3 \tag{6.17}$$

The condition for the *Stability* of a satellite is therefore:

$$G\frac{M_S M_S}{4R_S^2} \geq k2G\frac{MM_S}{r^3} R_S \tag{6.18}$$

Where k is a constant of order 1. Because of $M_S = (4\pi/3)\bar{\rho}_S R_S^3$ and for the planet with $M = (4\pi/3)\bar{\rho} R^3$ follows:

$$\frac{r}{R} \geq (4k)^{1/3} \left(\frac{\bar{\rho}}{\bar{\rho}_S}\right)^{1/3} \tag{6.19}$$

Roche has 1850 showed that for the stability of a satellite it holds:

$$\frac{r}{R} \geq 2.44 \left(\frac{\bar{\rho}}{\bar{\rho}_S}\right)^{1/3} \tag{6.20}$$

→ A larger satellite, having the same density as its parent planet, must not come nearer to it than 2.44 planetary radii, otherwise it will be torn apart by the tidal forces of the parent planet.
→ In the case of smaller satellites, the cohesive forces also become effective, and one gets $r/R = 1.4$.

6.2.8 Planetary Atmospheres

If the expansion of a planet's atmosphere is small compared to the planet's radius *R*, then the gravitational acceleration can be assumed to be constant: $g = GM/R^2$. The altitude is $h = r - R$. At hydrostatic equilibrium

$$\frac{dp}{dh} = -g\rho(h) \tag{6.21}$$

We use the equation of state:

$$p = \rho\frac{kT}{\bar{\mu}m_u} = \rho\Re T/M = nkT \tag{6.22}$$

Where $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ is the Boltzmann constant, $\bar{\mu}$ the mean molecular weight, and $\Re = 8.31\,\mathrm{J\,K^{-1}\,mol^{-1}}$ the Gas Constant and $m_u = 1.66 \times 10^{-27}\,\mathrm{kg}$. From this we calculate ρ and put this into the condition for hydrostatic equilibrium.

This leads to:

$$\frac{dp}{p} = -\frac{g\bar{\mu}m_u}{kT}dh = -\frac{dh}{H} \tag{6.23}$$

where here the *Equivalent Height (scale height) H* is introduced:

$$H = \frac{kT}{g\bar{\mu}m_u} \tag{6.24}$$

If we assume *H* is constant, so follows the *barometric altitude formula:*

$$\ln p - \ln p_0 = -h/H \qquad p = p_0 e^{-h/H} \tag{6.25}$$

Here p_0 is the pressure at the bottom (h = 0).

Now we investigate a *convective atmosphere:* Hot matter rises adiabatically (without heat exchange) upwards and cooled matter downwards. Then the adiabatic equation:

$$T \approx p^{1-(1/\gamma)} \tag{6.26}$$

Where $\gamma = c_p/c_V$, the ratio of the specific heat capacities at constant pressure (c_p) or constant volume (c_v). If we differentiate this logarithmically to h, it follows:

$$\frac{1}{T}\frac{dT}{dh} = \left(1 - \frac{1}{\gamma}\right)\frac{1}{p}\frac{dp}{dh} \tag{6.27}$$

Here we insert the hydrostatic equation as well as the condition $c_p - c_v = k/\bar{\mu} m_u$ and get for the *adiabatic temperature gradient:*

$$\frac{dT}{dh} = -\frac{g}{c_p} \tag{6.28}$$

The lowest layer of the Earth's atmosphere, which is about 12 km high, the *Troposphere,* is convective. Since $g = 9.81\,\mathrm{m/s^2}$, $c_p = 1005\,\mathrm{J\,kg^{-1}\,K^{-1}}$ we get a gradient of $9.8\,\mathrm{K\,km^{-1}}$. This is only true for dry air. For humid air *latent heat,* released during condensation will reduce the gradient by half. So we get an average temperature decrease with altitude in the Earth's atmosphere of $6.5\,\mathrm{K\,km^{-1}}$.

Finally, on the question of when a planet can have its own atmosphere. We consider molecules of mass m of a gas of temperature T. From the kinetic theory of gases, the most probable velocity depends on the temperature and the mass of the particle:

$$v_{\mathrm{th}} = \sqrt{\frac{2kT}{m}} \tag{6.29}$$

A molecule of velocity v can escape from a planet of mass M if holds:

$$v^2/2 \geq GM/R \tag{6.30}$$

A planet can hold an atmosphere only if holds:

- Its mass is sufficiently large;
- due to the temperature at the surface v_{therm} sufficiently small.

> Therefore, the Moon (too low mass) and Mercury (too low mass, due to the proximity to the Sun, the thermal velocity of the particles is too high) cannot hold an atmosphere.

The outermost layers of a planetary atmosphere are called the also *exosphere.* Here the density of the gas particles is low, only few collisions take place. *Ionisation processes* (solar UV radiation) produce charged particles. Their motion is determined by the planetary magnetic fields.

6.3 Earth and Moon

6.3.1 Structure of the Earth

The Figure of the earth is, in consequence of its rotation, an ellipsoid with:

Equatorial radius a =6378.1 km.
Polar radius b =6356.8 km.

The Flattening is:

$$\frac{a-b}{a} = 1/300 \tag{6.31}$$

The average density of the Earth is $\bar{\rho} = 5520\,\mathrm{kg/m^3}$. The density of the rocks at the earth's surface is $2800\,\mathrm{kg/m^3}$ but near the center, where the metals are located, is $13{,}000\,\mathrm{kg/m^3}$. The interior of the earth is shell-like constructed:

- *Earth's crust:* $3300\,\mathrm{kg/m^3}$, it is divided into: (a) *Lithosphere,* which consists of granitic rocks and reaches a depth of 35 km under the continents, the basalts under the ocean floors reach only 5 km deep; (b)*Hydrosphere:* 70% of Earth's surface is water.
- *Mantle:* The crust is floating in large blocks on the Earth's mantle, where silicates such as olivine occur. Density values range between 3400 and $5500\,\mathrm{kg/m^3}$. The mantle extends to a depth of 2900 km.
- Liquid outer *Earth's core:* about 2000 km thick, Fe, Ni.
- Solid inner core with radius 1300 km, Fe, Ni.

The theory of *Plate tectonics* was developed around 1960. Even before that a drift of the continents was suspected (*A. Wegener,* "The Origin of the Continents", 1915). 225 million years ago there was only one supercontinent, *Pangaea.* The distribution of the continents determines the ocean currents, and these in turn exert a significant influence on climate. For example the Mediterranean Sea evaporated several times during the last 6 million years, as can be seen from the massive salt deposits. The Strait of Gibraltar was closed several times by tectonic shifts. During the *Würm Ice Age* (115,00–10,000 years before today) the sea level was 120 m lower, and the upper Adriatic was land, and many Greek islands were connected to Anatolia. Plate tectonics is driven by convection in the Earth's mantle.

Due to the propagation of *earthquake waves (seismology)* we can study the Earth's interior. Earthquake waves occur in two forms:

- as longitudinal compression waves *(p-waves),*
- as transverse waves *(s-waves).*

Only the p-waves can pass through a liquid zone. You don't see s-waves going through the core because the outer core of the Earth is liquid. The Earth's core is predominantly Ni and Fe and should rotate faster than the outer regions (The Earth's core rotates once in 900 years more than the outer regions, super-rotation).

In the *oceanic deep-sea trenches* lava flows upwards and pushes the plates away from each other. The present plates were formed about 200 million years ago by the breakup of the great supercontinent. Continental drift is a few centimeters a year. The deep ocean basins are the youngest areas of the earth's surface because lava is constantly flowing up there.

The *age* of the Earth as well as the earth's rocks can be determined from the *radioactive decay*. Let n be the number of radioactive atoms, λ the decay constant:

$$-dn = \lambda n dt \qquad dn/n = -\lambda dt \qquad n = n_0 \exp(-\lambda t) \tag{6.32}$$

The *Half-life* τ indicates when the number of particles has decreased to half the original number $n = n_0/2$.

$$\tau = (ln 2)/\lambda = 0.693/\lambda \qquad n/n_0 = \exp(-0.693 t/\tau) \tag{6.33}$$

From this you get the radioactive age (t_h is the half-life):

$$\frac{n(t)}{n_0} = 2^{-\frac{t}{t_h}} \tag{6.34}$$

The rate of radioactive decay is given in the unit *Becquerel*:

1 Bq = 1 decay/second.

Some values for half-lives: ^{14}C (5730 years), ^{239}Pu (24,000 years), ^{235}U (800 million years), ^{238}U (4.5 billion years), ^{232} Th (14.5 billion years), ^{40}K (1.2 billion years).

One observes an increase in temperature with depth. The *geothermal depth gradation* is about 30K km^{-1}. This temperature increase is due to the heat generation of radioactive substances such as ^{238}U, ^{232}Th, ^{40}K as well as by the slow outward heat transport due to heat conduction and convection of the magma. In the Earth's core the temperature is $\leq$10,000 K.

6.3.2 Geological and Biological Evolution

At the time of the *Precambrian* (more than 590 million years ago) there were three *Mountain building phases* (Laurentian, Algonquian as well as Assynitic mountain building). The oldest traces of life are the stromatolites and cyanobacteria (age approx 3.5×10^9 years). At the time of the Cambrian (590−500 million years from today) the algae time (Eophytic) began, the oldest vertebrates come from the time of the Ordovician (505−438 million years before today). In the Silurian (438−408 million years before today) there was the Caledonian mountain building, trilobites as well as oldest vascular plants. In the Devonian (408−360 million years before today) the Armoured fish emerges. Towards the end of the Carboniferous (360−286 million years before today) the Variscan mountain building begins (as well as vascular spore plants), and at the beginning of the Permian age (286−248 million years before today) there are the first reptiles. The dinosaur age begins with the Triassic (248−213 million years before today), the first gymnosperms appear. At the beginning of the Jurassic period (213−144 million years before today) one finds the first mammals. The oldest birds come from the Cretaceous period (144−65 million years before today), also the oldest angiosperms appear now. At the beginning of the Tertiary period (65−2 million years before today) the dinosaurs died out and the Alpidic mountain building began. The first humans are found at beginning the Quaternary period (two million years ago).

6.3.3 Earth's Magnetic Field

Our Earth has a magnetic field which resembles a *Dipole field* (dipole means two poles, thus one magnetic north and south pole): The magnetic flux density at the equator is 0.31 Gauss. The magnetic moment **M** points in the direction of the dipole axis, and by gradient operation one obtains the vector of *magnetic flux density* **B**.

$$\mathbf{B} = -\mathrm{grad}\frac{\mathbf{M}.\mathbf{r}}{r^3} = -\mathrm{grad}\frac{M \sin\lambda}{r^2} \tag{6.35}$$

Here λ is the magnetic latitude, i.e. at the magnetic poles $\lambda = \pm 90°$. The axis of the earth's magnetic field is inclined by 12° against the rotation axis of the earth. The earth's magnetic field is maintained by a self-exciting *dynamo process*. Paleomagnetic studies showed that the Earth's magnetic field changes direction randomly in periods from 10^4 to 10^5 years. It is observed today that the field is slowly decreasing.

At the *Magnetopause*, the Earth's magnetosphere encounters a stream of particles coming from the Sun, the *solar wind.* On the side facing the Sun, the Earth's magnetic field is compressed and extends only about ten Earth radii (Fig. 6.2).

On the side facing away from the sun, the magnetic field expands to form a *tail* (engl. Magnetotail) off. In the magnetopause, the incoming protons and electrons emitted by

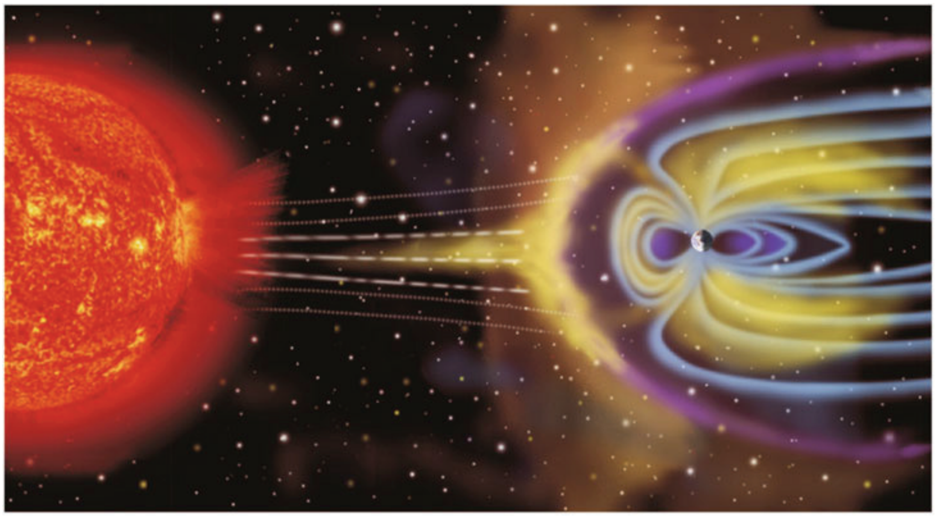


Fig. 6.2 Sketch of the Earth's magnetic field compressed on the side facing the Sun. Sun and Earth are not at the correct scale (Source: NASA)

the Sun are deflected (movement transverse to the field lines is not possible, only along the field lines). Some of them do get into the magnetosphere, and these particles become trapped in the Van Allen *radiation belts*. The *inner belt* extends between one and two Earth radii and contains protons with an energy of 50 MeV and electrons with 30 MeV. Then follows a gap, and between three and four Earth radii is the *outer belt*, where less energetic electrons and protons are present. The inner belt is relatively stable, the outer depends on the activity of the Sun and can vary greatly. Particles trapped in the belts make a spiral motion around the magnetic field lines, bouncing back and forth between the so-called magnetic mirror points with periods between 0.1 and 3 s. The particles of the inner belt can be trapped by the magnetic field lines. Particles of the inner belt can interact with the atmosphere, causing then *aurorae* (northern lights, southern lights). These normally appear at height of about 100 km within earth-atmosphere. Here the *magnetic reconnection* plays an important role. Areas with opposite magnetic fields come together, and the field lines collapse and combine into new combinations. Such processes take place in the Earth's magnetic tail at a distance of about 100 Earth radii. If the solar wind adds enough energy, then the field lines overstretch and reconnection occurs at distances as small as 15 Earth radii. The field collapses, electrons enter the atmosphere, and the auroras appear.

In Table 6.5 the data of the planets with magnetospheres given. Note the huge dimensions of Jupiter's magnetic field! The magnetic moment is given in units related to magnetic moment of the earth = 1, the distance of the magnetopause in multiples of the respective planetary radius.

Table 6.5 Comparison of magnetospheres of some planets. Distance Magn. means distance of the magnetopause in units of the planet radius from its surface

Planet	Distance to Sun	Magnet. moment ME (Earth=1)	Solar wind-pressure	Distance magn.
Mercury	0.4 AU	4×10^{-4}	20 nPa	1.5
Earth	1.0	1.0	3.0 nPa	10
Jupiter	5.2	1.8×10^{4}	0.1 nPa	70
Saturn	9.5	580	30 pPa	21
Uranus	19.2	50	8 pPa	27
Neptune	30.1	24	3 pPa	26

The force **F** which acts on a particle of the charge q is the *Lorentz force*:

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \tag{6.36}$$

Here the electric field **E** was set equal to zero. This simplification is often made in astrophysics.

The particles move in a homogeneous magnetic field on a circular path where the equilibrium between centrifugal force and Lorentz force gives the radius of this gyration motion:

$$mv^2/r = qvB \tag{6.37}$$

Particles of cosmic rays originating from outside the solar system interact with the Earth's high atmosphere. Thereby the high energetic cosmic protons produce free neutrons, which decay into protons p and electrons e^- and neutrinos $\bar{\nu}$.

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu} \tag{6.38}$$

In a magnetic field, particles of positive and negative charge move in different directions. The particles produced in this way accumulate in the radiation belts. There they have a relatively long lifetime due to their small effective cross-section. A 20-MeV proton at an altitude of 2000 km has a lifetime of about one year. The particles move very fast around the earth (one orbit takes about 2 min). The particles of the radiation belt cause damage to space missions.

With the help of the NASA-operated imager mission, the faint UV glow of the relatively cool plasma around the Earth was seen in August 2000 (Fig. 6.3). The ring of aurorae (northern lights) is clearly visible. as a small faint luminous circular ring in the center. The particles are trapped by the Earth's magnetic field. The satellite was above Earth's north pole at the time the image was taken, and the Sun was outside the image at the upper right edge. Note also the shadow of the Earth (towards the lower left).

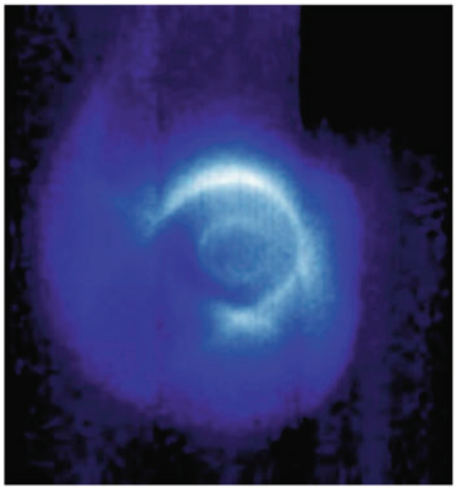


Fig. 6.3 Luminous plasma in the Earth's magnetosphere; the small oval ring is the region of the aurorae (here around the magnetic South Pole)

Without the Earth's magnetic field, we would be without protection against the energetic charged particles from the cosmos and life would not be possible on the Earth's surface.

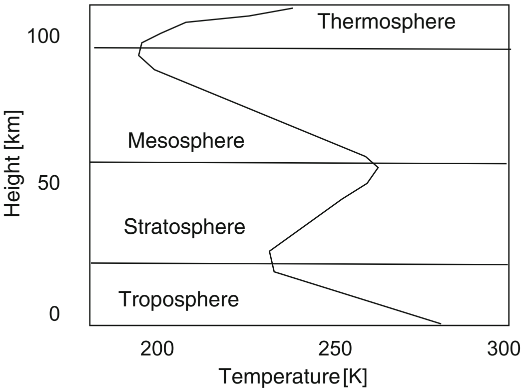
6.3.4 Earth's Atmosphere

The Earth's original atmosphere consisted of H_2, He and hydrogen compounds. Through volcanism and degassing processes the atmosphere was then enriched with H_2O, CO_2, N_2, Ar. The Table 6.6 shows the composition of the today's atmosphere near the ground.

Table 6.6 Composition of the earth's atmosphere

Element	Volume percent
Nitrogen N_2	78.08
Oxygen O_2	20.95
Argon Ar	0.934
Carbon dioxide CO_2	0.033
Neon Ne	0.0018
Helium He	0.00052
Methane CH_4	0.00015
Water vapor H_2O	$\approx 10^{-4}$

Fig. 6.4 Course of the temperature in the earth's atmosphere



The Earth's atmosphere is divided into the following layers (Fig. 6.4):

- *Troposphere:* reaches up to the tropopause in 15 km height. Up to this height the temperature decreases to about −50 °C down.
- *Stratosphere:* Up to the stratopause (about 50 km height) the temperature increases slightly to −20 °C.
- *Mesosphere:* The temperature decreases again, at 90 km altitude you have another temperature minimum of about −100 °C
- *Ionosphere, Exosphere:* Here the temperature increases in the range of the thermosphere (90−250 km) up to 1500 K (at the base of the exosphere). At these heights (from 700 km) molecules escape into space. Ionization also increases strongly—this is also referred to as the ionosphere.

In the region of the Earth's atmosphere, electromagnetic radiation arriving from outside is absorbed, scattered, or refracted, depending on the wavelength. Radiation from most wavelength regions of the electromagnetic spectrum is absorbed, except for two windows where the atmosphere is transparent to electromagnetic radiation:

- *optical window:* from 290 nm (near UV) to 1 µm (near infrared),
- *radio window:* 20 MHz to 300 GHz.

We can therefore study the radiation of stars and galaxies only n these wavelength ranges from Earth-based observing stations. In the ozone layer (10–40 km) radiation from 300 nm to 210 nm is absorbed (UV range). In the infrared range (1 µm up to 1 mm) the radiation is absorbed by the molecules N_2, O_2, CO_2, H_2O . At wavelengths greater than 15 m (below 20 MHz) there is reflection,

In the visible light range (410–650 nm) it comes to

- Refraction,
- scattering,

- extinction,
- dispersion.

In the case of scattering of light, one must consider: (a) the wavelength of the light, (b) the size L of the scattering particle. When light is scattered by molecules in the earth's atmosphere, the intensity of the scattered light is given by the *Rayleigh scattering law:*

$$I_{\mathrm{scatter}} \propto \frac{1}{\lambda^4} \tag{6.39}$$

Light of shorter wavelengths is therefore scattered more strongly, and that is why the sky is blue. If the sun or a star is low on the horizon, it appears reddened.

If you have dust particles of size 1 μm, there is Extinction, whereby here the following scattering law applies:

$$I_{\mathrm{scatter}} \propto \frac{1}{\lambda} \tag{6.40}$$

And if $L \gg \lambda$ is (water droplets in clouds), then the scattering is independent of the wavelength—therefore clouds appear as white.

Light is also refracted in the Earth's atmosphere, and density in homogeneities cause stars to twinkle *(Seeing)*.

All planets with atmospheres have *Weather.* This can be understood as the circulation in the atmosphere. Weather patterns are driven by solar radiation, which heats the surface of the planet. Other factors include the rotation of the planet and seasonal changes. At Earth, oceans and ocean currents play an important role. Heat is transported towards cooler regions.

The Earth's global circulation system is sketched in Fig. 6.5 .At the equator heated air rises, near the ground colder air flows towards the equator. Due to the rotation of the earth *(Coriolis force)*, there is a rightward deflection (northeast winds) in the northern hemisphere of the Earth, and a leftward deflection in the southern hemisphere. At the pole, high air masses sink. At about 30° latitude, the air masses that have risen from the equator have cooled down to such an extent that they sink. Air masses flowing from the poles towards the equator rise up to 60° latitude.

Climate refers to effects of the atmosphere that change over decades or centuries. A hot summer alone does not indicate a change in climate. Climate thus contrasts with random changing weather conditions from year to year. Modern agriculture is very sensitive to temperature changes. A consistent drop in temperature of only 2 °C would cut U.S. and Canadian grain production in half. During the ice ages, large-scale glaciations and temperature decreases occurred in the northern hemisphere. In 1920 *Milankovich* indicated that the tilt of the Earth's axis was changing, which may have led to the *Ice ages* led to the climate change. We now know that there have been also global climate changes on Mars.

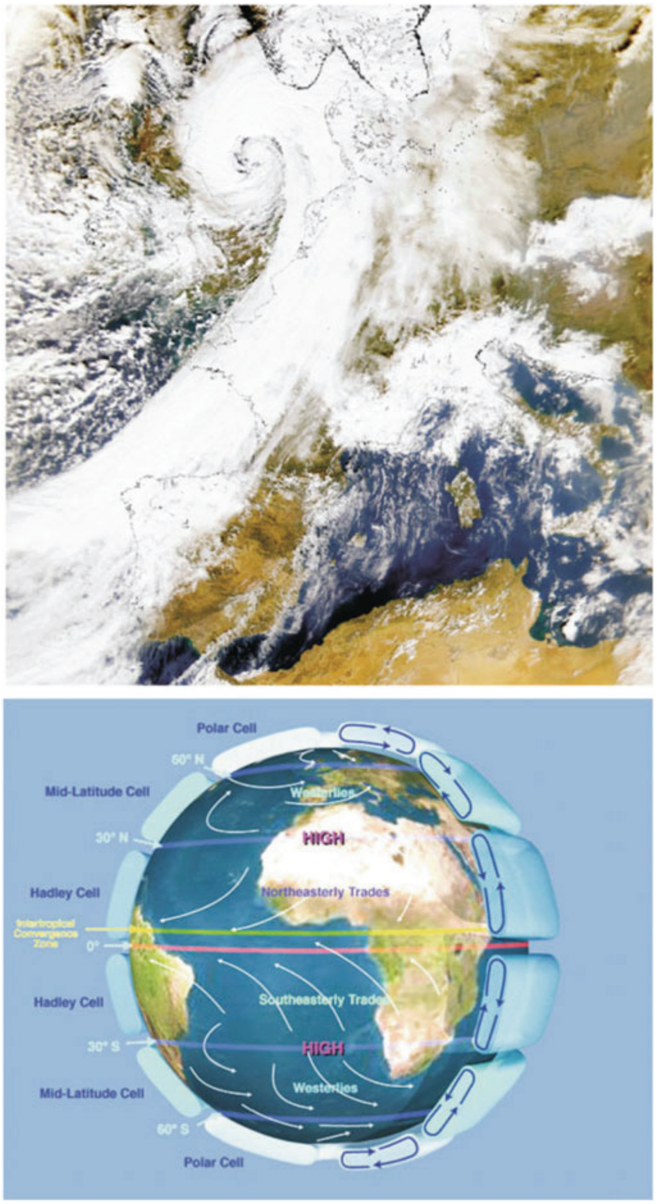


Fig. 6.5 Top: storm low. Bottom: the complex flow system in Earth's atmosphere, global circulation (Photocredit: sealevel.jpl.nasa.gov)

> The first living beings emerged 3.5 billion years ago (*stromatolites,* still exist today, they are actually biogenic sedimentary rocks). However, there have only been species-rich fossils for 600 million years.

Two billion year old rocks do not yet contain oxygen (O_2), although plants have already released oxygen through photosynthesis here. Probably this oxygen immediately reacted with rocks of the earth's crust. After this time the atmosphere was enriched with O_2 oxygen, and the *ozone layer* formed. By the formation of ozone, O_3, life-hostile UV-Radiation was absorbed. The *Chapman reactions* describe the *photolysis* (splitting by electromagnetic radiation) of the O_2 by short-wave UV ($\lambda < 240$ nm) and the formation of O_3 and the destruction of the O_3 by longer wavelength photons ($\lambda > 900$ nm). There is an equilibrium:

$$3O_2 \rightleftharpoons 2O_3 \tag{6.41}$$

Only when the ozone layer was sufficiently strong could living beings leave the protective oceans. Most of the CO_2 is now bound in the sediments in the form of carbonates or in the fossil fuels coal and petroleum.

The *greenhouse effect,* which is mainly due to the content of CO_2 and H_2O has caused the global temperature to be 33 °C higher than would be expected from solar radiation. Modern industrial society, however, increases the amount of CO_2 by burning fossil fuels and by cutting down tropical rainforests. Within 1900–2000, the amount of CO_2 increased by 25% and is increasing by 0.5% each year.

It is interesting to note that throughout the history of the earth, there have always been *Mass Extinction* of animal species. Half of all animal species became extinct within a short period 65 million years ago *(KT event).* This is thought to have been caused by the impact of an asteroid and the dust particles kicked up by the impact caused global cooling. The dinosaurs died out 65 million years ago, and the triumph of mammals began. The mass of the asteroid was a trillion tons, the diameter was only about 10 km, and it is believed to have impacted in the Peninsula area of *Yucatan* (Mexico). That it was an asteroid is indicated by the unusually high Ir content in sediments from this period. The heavy metal *Iridium* sank into the deeper interior of planets like the Earth when the Earth was still liquid. Such a *Differentiation process* could not take place with smaller bodies like asteroids. The crater was 250 km in diameter, and the explosive force was equivalent to that of 5 billion Hiroshima bombs. The material hurled into the atmosphere spread all over the world, and the sun was darkened for several months. Further, there was acid rain and large-scale fires. Almost certainly there was also a period of intense volcanism at that time.

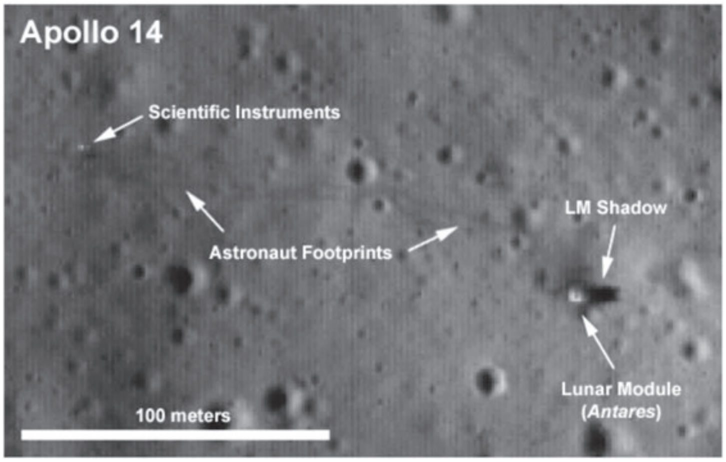


Fig. 6.6 Image of the Apollo 14 mission landing site taken from a lunar orbiter. From Earth, even with the largest telescopes, the lander modules left on the lunar surface cannot be seen (NASA)

6.3.5 The Moon-General Porperties

The mass of the Moon is only 1/80 of Earth's mass and its equatorial diameter is 3476 km; therefore, the Moon's surface gravity is too low to sustain an atmosphere. Between 1968 and 1972, nine manned spacecraft were launched to the Moon as part of the *US Apollo program* , and twelve astronauts have walked on its surface. The Russian space probe Luna 9 made a soft landing on the moon back in 1966. On July 21, 1969, the astronaut *N. Armstrong* became the first man to walk on the moon. The cost of the American manned lunar landing program was approximately 100 US for each American, spread over ten years.

Figure 6.6 shows the Apollo 14 landing site made by a probe orbiting the Moon.

A general map of the Moon is given in Fig. 6.7.

The Moon has an average density of only $3.3\,\mathrm{g/cm^3}$, that is, it is composed mainly of silicate rocks, and there is no Fe or other metals, and no water or volatile elements. The moon appears to be composed of the same material as the earth's crust. Seismometer records showed that there is no metal core, the moon is cold and solid inside. There are barely moonquakes.

The Early telescope observers gave the lunar formations fanciful names such as *Mare Imbrium* (Sea of Rain). The surface, which has numerous craters (Fig. 6.8), is called *Terrae* (Highlander). It consists of bright silicate rocks, anorthosites. The highlands are the oldest areas on the moon. The Craters are impact craters from early in the formation of the solar system. The dark large plains with only a few craters are called the *Maria* (seas). They make up 17% of the lunar surface, most of them are on the side of the moon facing the Earth. These are huge impact basins, which were formed by asteroid impacts and then

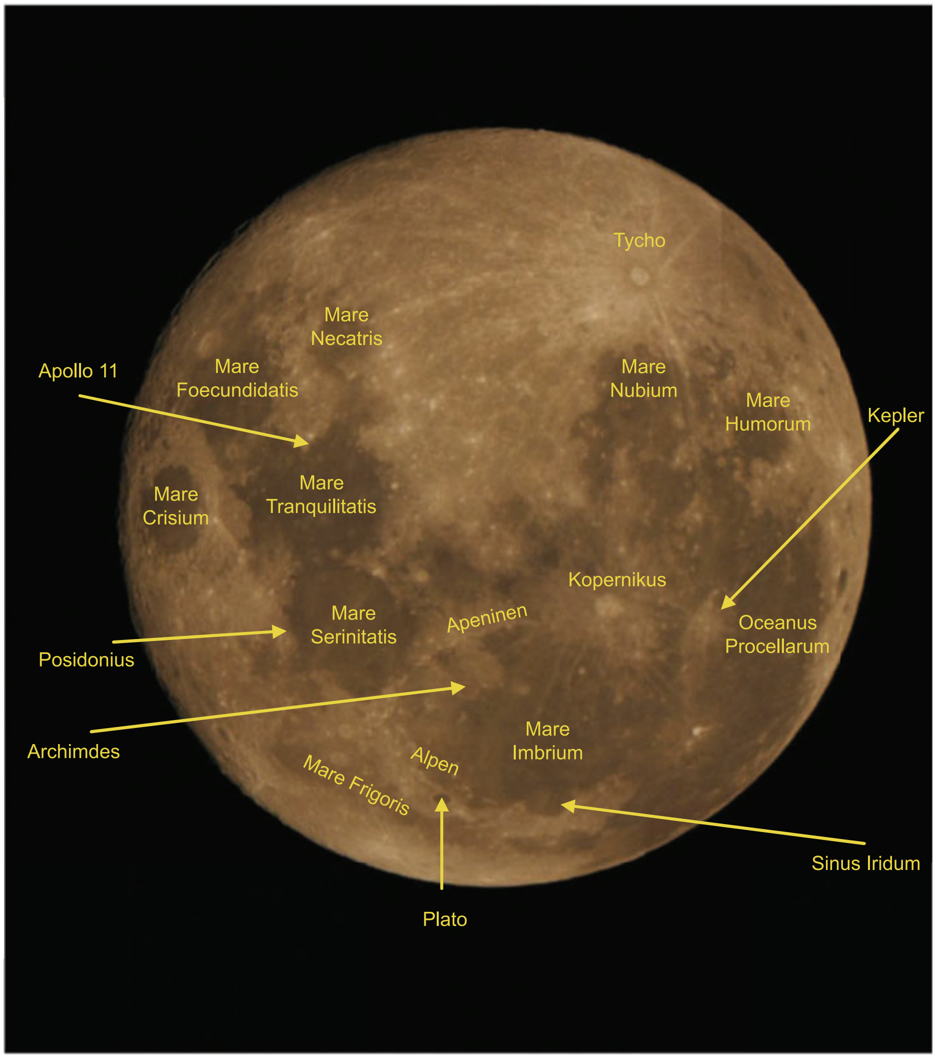


Fig. 6.7 Lunar map with some designations (A. Hanslmeier)

flooded with lava. They are composed of basalt (similar to the composition of Earth's oceanic crust). These areas are younger than the highlands by about a billion years.

The lunar mountains, mostly named after terrestrial mountain ranges (Alps. . .), are also the result of impacts, and occur at the edges of the great maria. The surface of the Moon is covered with a layer of dust created by the impacts. The astronauts sank several inches deep, leaving footprints that will be admired for many millions of years to come (Figs. 6.9 and 6.6).

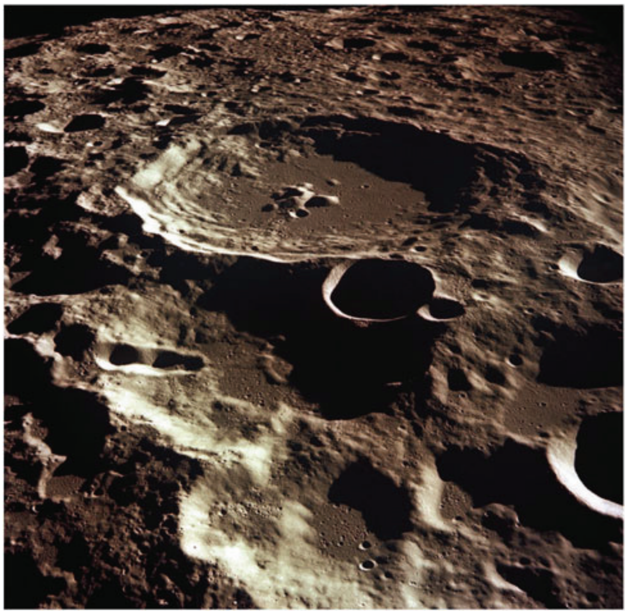


Fig. 6.8 Lunar landscape (Apollo 11, taken in 1969)

Fig. 6.9 First excursion of a human being on the moon. (1969, Apollo 11)

The lunar night, which lasts two Earth weeks, is very cold: −173 °C, since there is no protective atmosphere, the surface is highly porous and thus cools easily. During the lunar day the temperature is 120 °C.

The number of craters a given area has can be used to infer its age if a planet or moon has low internal activity or erosion. The rate of crater formation has been constant for several billion years, that is, the number of craters is proportional to the length of time the surface has been exposed to impacts. During the last 3.8 billion years, the rate of crater formation has been similar to today (age of oldest maria, lunar oceans). However, more than 3.8 billion years ago, the impact rate was much higher than today. There are ten times as many craters on the older terrae as in the maria. If the impact rate were the same, then the highlands would have an age of 38 billion. years. On the moon, therefore, a phase of intense Bombardments took place more than 3.8 billion years ago. Similar results are found for Mercury and for Jupiter's and Saturn's moons. For the other planets, but also e.g. for Saturn's moon Titan, erosion plays a role.

On Earth, a crater impact of 1 km diameter occurs on average every 10^4 years. Craters of a few 10 km are formed every few million years; a 100 km crater every 50 million years.

Important for future moon missions is the (almost certain) discovery of water ice near the two poles. This could have been deposited by comet impacts. How can water be detected? The moon has neither a magnetic field nor an atmosphere. Therefore particles of cosmic rays can fully impact and produce fast neutrons. With a *Neutron spectrometer* of the Lunar Prospector in 1998 slow neutrons were detected near the two poles, these are slowed down by collisions with protons—an indication of water ice in the polar regions which are permanently in shadow. The ice volume at the North Pole is estimated at 10,000–50,000 km^3 for the North Pole. For comparison: the ice masses of Antarctica are estimated at $29 \times 10^6\ \mathrm{km}^3$, Greenland about 1/10 of this value. For the South Pole 5000–20,000 km^3. However, the ice deposits at the South Pole are doubted, since no water-containing cloud was registered near the South Pole during the controlled impact of the Prospector probe, 1999.

One source of hydroxyl ions on the Moon could be protons (H^+) transported by the solar wind. The first Indian lunar satellite, Chandrayaan-1, as well as NASA's Moon Mineralogy Mapper (M3) satellite, detected traces of water or hydroxyl molecules near the lunar surface. Other measurements also showed that water is found on the Moon, above a latitude of 10, most of the water is located in at the polar regions.

6.3.6 Origin of the Moon

Capture hypothesis: The moon had been formed somewhere elsewhere in the solar system and then came close to the Earth and was captured. This is conceivable in principle, but a close encounter between the Moon and Earth would be more likely to result in a collision, or the Moon would accelerate so much as to preclude another encounter. It is known from the Apollo missions that oxygen isotopes occur in lunar rocks in similar proportions to terrestrial ones.

Secession hypothesis: Already advocated by Darwin (1845−1912). When the Earth formed, it rotated very rapidly, a bulge formed at the equator from which the material for the Moon came loose. This would explain why the Moon is composed mainly of materials similar to those of the Earth's mantle. The Earth would rotate on its axis in just two hours at that time, but this is unlikely. The Apollo missions did show some similarities in the compositions of the Moon's rocks and the Earth's crust, but there are also marked differences, with hardly any potassium or sodium compounds on the Moon.

Double planet: Moon and Earth formed almost at the same time from the protoplanetary gas and dust cloud. Problem: Moon has only a very small metallic core.

Collision hypothesis: Was set up in 1975 by *Hartmann* and *Davis*. The young Earth was struck by a celestial body about the size of Mars, which knocked out the material from which the Moon was then formed. This can easily explain why there are hardly any metals in the moon's core: The core of the impacting celestial body got stuck in the Earth's core. The moon was formed from the silicate parts of both celestial bodies. The different ratio of iron to magnesium oxide in the Earth and Moon can be explained in this way: The lunar rock is mostly material from the impacting body. The angular momentum problem of the Earth-Moon system can also be explained: The impacting body was of Martian size, hit the Earth sideways, and thus increased the Earth's rotational velocity to its present value.

In a simulation calculation, it was also shown that without the Moon, the Earth's axis would undergo much larger tilt fluctuations (from 15 to 30°), which would make our Earth's climate become extremely unstable. The tilt of the Earth's axis essentially determines the seasons, and a greater inclination would have resulted in greater contrasts between the seasons.

Our moon was formed by Earth's collision with a Mars-sized planet in the early days of the solar system.

6.3.7 The Interior of the Moon

The interior of the earth can be studied by evaluating the propagation of earthquake waves. Seismometers have been positioned on the lunar surface, but they have registered practically no moonquakes. The only tremors recorded came from

- from meteorite impacts,
- tidal forces from the Earth to the Moon.

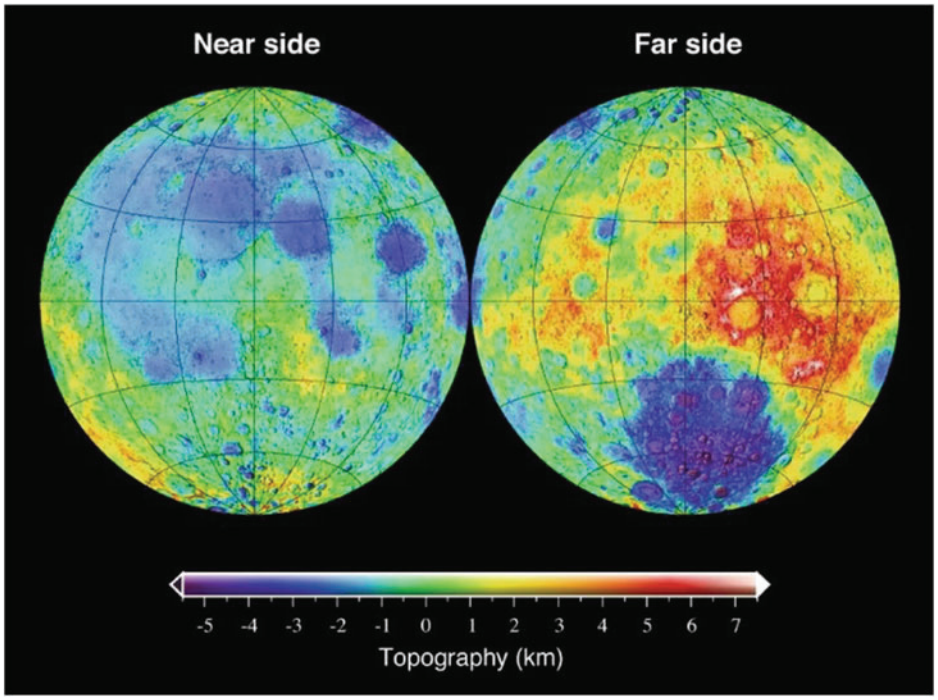


Fig. 6.10 Topographic map of the Moon's front and back surfaces. (NASA)

So the Moon is geologically inactive and has a cold core, while the Earth's core is about 6800 K hot. The moon does not have an iron core, which is already evident from its relatively low density of 3300 kg/m^3. That is why there is no magnetic field.

The surface of the Moon is different: On the side facing Earth, you find the large lunar seas, which were filled in with heavier basaltic lava after asteroid impacts. The lunar crust is thick here, the mass somewhat heavier, and therefore this side faces Earth (Fig. 6.10).

6.3.8 The Far Side of the Moon

From Earth, we see only one hemisphere of the Moon because the Moon exhibits a 1:-1 spin-orbit resonance. The Moon rotates once on its axis in the same amount of time it takes to orbit the Earth. In fact, we see a little more than 50% of the Moon's surface because its rotation is uniform, but its orbit around the Earth is not. The Moon's orbit is elliptical; it moves faster near Earth (perigee) than far away (apogee). In addition, the Moon's axis of rotation is slightly tilted, and we still have to take into account the parallax effect on the Earth. So we see nearly 60% of the moon's surface, this effect is also called *libration.* The back side of the Moon shows significantly fewer large basaltic plains (maria) than the front, and also lacks the lunar mountains formed by large impacts on the front. In 1959, a

Fig. 6.11 Release of a lunar rover at the far side of the Moon. Chang'e 4 Mission.(Chinese Space Agency)

Russian probe first radioed images of the Moon's far side to Earth. In January 2019, the Chinese space probe Chang'e 4 succeeded for the first time in taking a soft landing on the Moon's far side (Fig. 6.11).

The far side of the Moon would be an ideal base for scientific experiments and observatories.

6.4 Mercury and Venus

The planet closest to the Sun, Mercury, is difficult to observe from Earth. However, space missions have brought surprising results and Mercury is the target of further missions. Venus is considered Earth's sister in size, but is the planet with the most extreme greenhouse effect.

6.4.1 Mercury: Basic Data

The apparent diameter of the planet disk as seen from Earth is between $4.5''$ and $13''$, the maximum brightness is $-1.^{\mathrm{m}}9$. Like Venus, Mercury appears as a morning and evening star.

Similar like our Moon, Mercury has a surface littered with craters (Fig. 6.12) as well as no permanent atmosphere. Its orbit has a high eccentricity of 0.26, so its distance from the Sun varies between 46 million and 70 million km. The Orbit is tilted 7° from the

Fig. 6.12 Mercury (Image: Messenger probe)

ecliptic plane. Its mass is 1/18 that of Earth and its diameter is only 4878 km, making it the smallest planet in the solar system. Its density is 5.4 $\mathrm{g/cm^3}$ relatively high, which means that it consists mainly of metals. The metallic Fe-Ni core makes up 60% of its mass, and the diameter of the core is 3500 km. The outer rocky crust makes up only 700 km. Mercury has a weak magnetic field, which suggests a partially metal core (cf. dynamo process on Earth). The field strength is only 0.0035–0.007 Gauss, or about 1% of the surface field strength of Earth. Nevertheless, Mercury's field is stronger than the fields found at Mars and Venus. The planet is also surrounded by a thin shell of He gas; the planet's magnetic field traps He nuclei originating from the solar wind. As on Earth, the field lines are compressed by the pressure of charged particles from the solar wind on the side facing the Sun.

In 1985 one has spectroscopically detected an extremely thin Na atmosphere. The extremely thin *sodium atmosphere* of Mercury produces an exosphere, which is pronounced like a comet tail behind Mercury. The particles of the exosphere are created by bombardment of Mercury's surface with solar wind particles and micro meteorites.

6.4.2 The Rotation of Mercury

The *rotation period* is 58.85 days, this corresponds to 2/3 of its *orbital period* around the sun (88 days). This coupling between orbital angular momentum of Mercury and spin angular momentum comes from the tidal effect of the Sun. The rotation of Mercury has been determined from radar observations, since no details on Mercury's surface are discernible from Earth-based observations. If radar signals are sent to a rotating planet, then they are reflected there. The planet can be thought of as consisting of two halves:

one half is moving towards the observer, so the radar signal reflected there is blue-shifted, the other half is moving away from the observer, so the radar signal reflected there is red-shifted. Overall, the reflected radar signal thus appears broadened, and from the broadening one can infer the rotation speed. Mercury is the planet with the largest temperature contrasts between day and night: 700 K during the day, 100 K at night.

6.4.3 The Surface of Mercury

In 1974 the US probe Mariner 10 passed Mercury at a distance of only 9500 km and sent images to Earth with a resolution of 150 m. The surface of Mercury is covered with craters, the most conspicuous being the Caloris Basin *Caloris* Basin, 1300 km in diameter. This was created about 3.8 billion years ago by an impact body over 100 km in size. Gravity at Mercury's surface is twice that on the Moon, and therefore material ejected from a primary impact crater will cover only 1/6 the area on Mercury that it would on the Moon. Thus, the secondary craters are closer to the primary craters. The large basins resemble the maria on the Moon, and there is evidence of lava flooding. Mercury shows no tectonic activity. However, there are furrows that could be from slight compression of the crust. In 1992, signs of *Ice* below the surface (due to increased radar reflection) at the poles were detected.

The crater density on Mercury's surface is greater than that on the Moon. This indicates a very old surface, and there is no braking atmosphere.

Why does Mercury have such a thin crust and such a massive core? During the formation phase of the planet there were many impacts, with much of the crust being thrown away.

In August 2004, the spacecraft *Messenger* was launched, the and it entered in a Mercury orbit since 2011 due to a braking maneuver. The orbit lies between 200 and 15,000 km altitude above the Mercury surface. Color images (see Fig. 6.13) of Mercury's surface is obtained by means of MDIS (Mercury Dual Imaging System). The Camera MDIS works in visible light and near infrared (up to 1.1 μm). With the Gamma Ray and Neutron Spectrometer (GRNS) can man detect elements such as O, Si, S, or H on the surface of the planet. The Gamma Ray Spectrometer measures gamma rays produced by either galactic cosmic ray bombardment (O, S, Si, Fe, and H) or natural radioactive decay (K, Th, and U) down to a soil depth of about 10 cm. The neutron spectrometer measures low-energy neutrons. These are produced when cosmic rays are decelerated by hydrogen-rich material. With this we are able to explore the upper 40 cm of the planet's surface.

Because of its proximity to the Sun, it was thought that there were few light elements on Mercury's surface, yet sulfur and other elements have been found. Mercury's magnetic field is strongly distorted. The center is shifted 480 km to the north. Therefore, solar wind particles can increasingly penetrate above Mercury's magnetic south pole.

At the end of 2018, the ESA mission *BepiColombo* to Mercury was launched. After several swing-by maneuvers at Earth and Venus and also Mercury, it will become an artificial Mercury satellite in 2025.

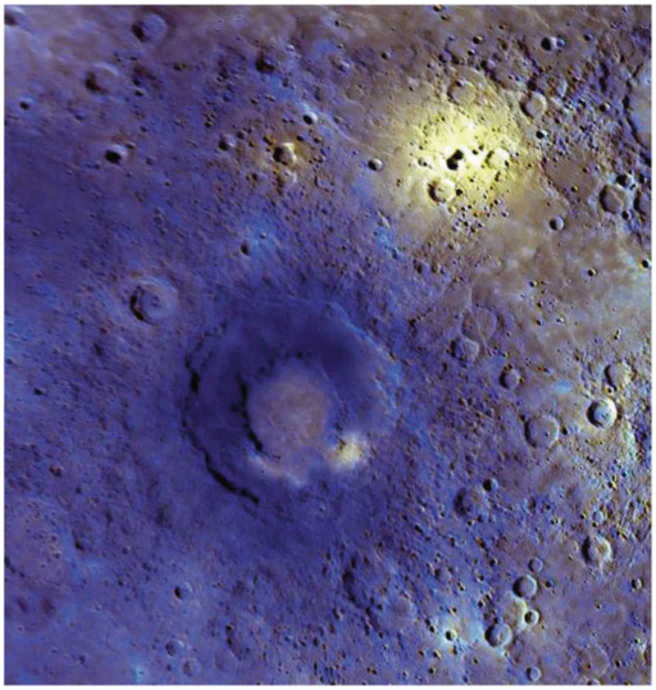


Fig. 6.13 Color-enhanced image of Mercury's surface (Messenger spacecraft, 2011). From the colors, one can infer the composition and evolution of the surface details

6.4.4 Venus: Basic Data

The apparent diameter of the planet's disk ranges from 9.7″ (upper conjunction) and 66″ (lower conjunction). The greatest brightness is $-4.^{m}6$. From all planets in the solar system, Venus and Earth are closest (to within 42 million km). The orbit is almost circular, and the planet is 108 million km from the Sun. Venus sometimes appears as an evening star and sometimes as a morning star, and is the brightest object in the sky after the Sun and Moon. Except that Venus shows phases like the Moon (and also Mercury), the planet is featureless even in large telescopes due to its dense cloud cover. Similar to Mercury, it was possible to determine the rotation period of Venus from radar observations and a peculiarity became evident: The sidereal period is 243.08 days, and Venus rotates retrograde (i.e., from east to west; thus, on Venus, the Sun rises in the west). The Rotation period is about 19 days longer than the sidereal orbital period of 224.7 days around the Sun, and a Venusian day thus lasts 116.75 Earth days. The reason for this slow and retrograde rotation could have been a collision with an asteroid in the early days of the formation of the solar system. Furthermore there are *resonance effects:* At each upper and lower conjunction, Venus shows the same side to Earth.

The *distance* Venus-Earth can be determined very precisely with radar measurements. At the upper conjunction of Venus (just before or after), the radar signal passes through the Sun's gravitational field—space is curved according to Einstein's theory of general relativity. Therefore the transit time of the radar signals is 200 μs longer than according to the classical calculation *(Shapiro Effect).*

The first European Venus space probe was *Venus Express* (since April 2006 until the end of 2014).

6.4.5 Surface of Venus

Radar measurements with the telescope in Arecibo show details on the *Venus surface* with up to 20 km resolution. The *Atmosphere* consists for the most part of CO_2 surface has temperatures of 460 °C and the pressure is 90 times that of the Earth's atmosphere. Radio radiation with wavelengths of a few centimeters can penetrate these clouds. In 1978, the US spacecraft Pioneer and the Soviet *Venera probes* sent images of the surface. Venera 9 and 10 (Fig. 6.14) landed softly on the surface in 1975 and delivered the first television pictures. Better pictures were taken in 1982 by Venera 13 and 14 (colour pictures). The hard conditions on the surface of Venus ($T = 740\,\mathrm{K}$, $p = 90\,\mathrm{bar}$) only allowed measurements of one to two hours. Since the sun does not shine directly through the dense clouds, the surface of the planet is about as illuminated as the Earth on a heavily clouded

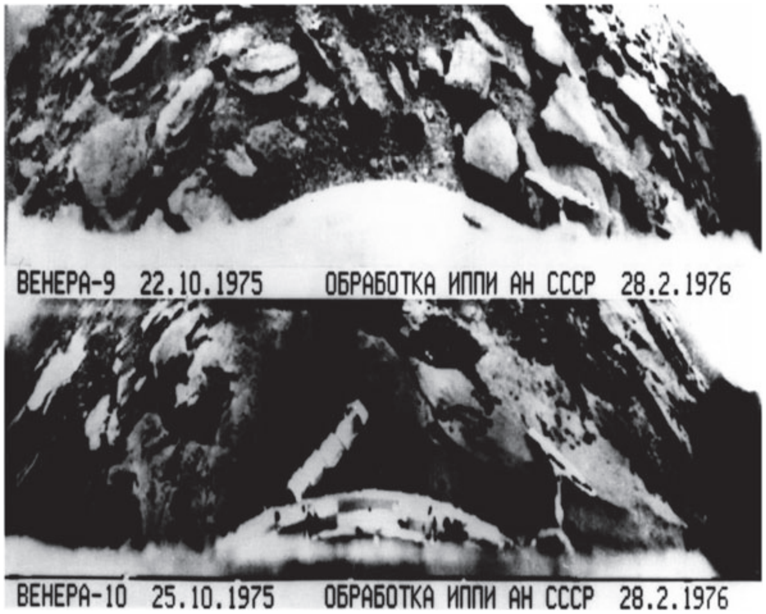


Fig. 6.14 Venus surface. (Taken by Venera 9, Venera 10)

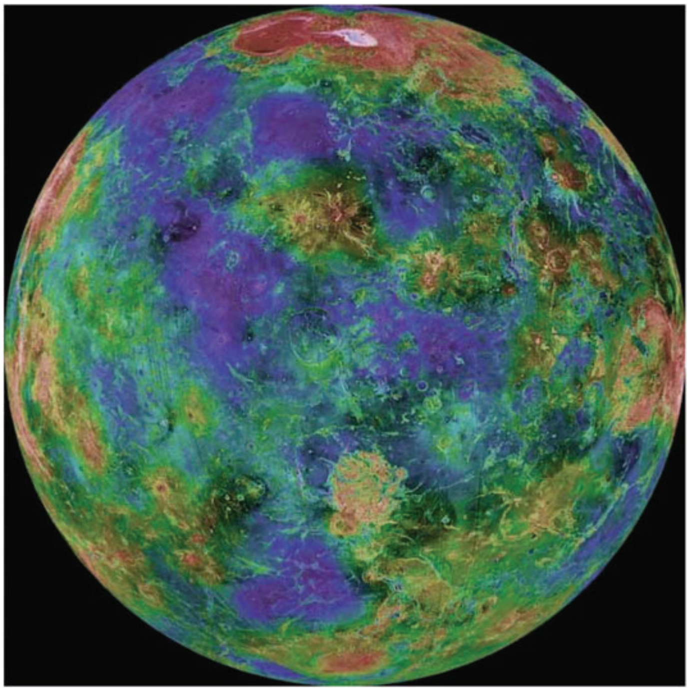


Fig. 6.15 Surface of Venus (Image Magellan)

day, but there is a strong reddish tinge to the *Venusian sky,* because the atmosphere scatters blue very strongly. 70% of the surface is plains, 20% depressions up to 2000 m deep, and 10% continental highlands *(Ishtar Terra, Aphrodite Terra).*The Ishtar continent, formed by uplift processes, and its high *Maxwell mountains* remind of the highlands of Tibet with the Himalayan massif. Crustal compression is also likely to have occurred here, and there is evidence for mantle convection of Venus.

In 1990 the probe *Magellan* the scanned the surface with the *Synthetic aperture radar method* and detected details up to 120 m in diameter (Fig. 6.15). The surface of Venus appears to be relatively young: 100 million years to 1 billion years old. Terraced volcanic calderas and extensive lava flows are found—but no evidence of plate tectonics as on Earth. Many impact craters have been flooded by lava.

There are hardly any winds on the surface (only in the higher Venusian atmosphere). Nevertheless, there are also signs of deposits caused by winds. Many impact craters are strongly asymmetric—this is explained by the influence of the dense Venusian atmosphere on the trajectory of the impacting meteors. Erosion valleys resembling river beds are also found. At the high temperatures liquid water on the surface can be excluded. Here one assumes thin lava flows (Fig. 6.16).

Venera 13 and 14 explored the surface of Venus by irradiating rock samples. From the X-ray fluorescence radiation, they were able to detect rocks similar to basalts.

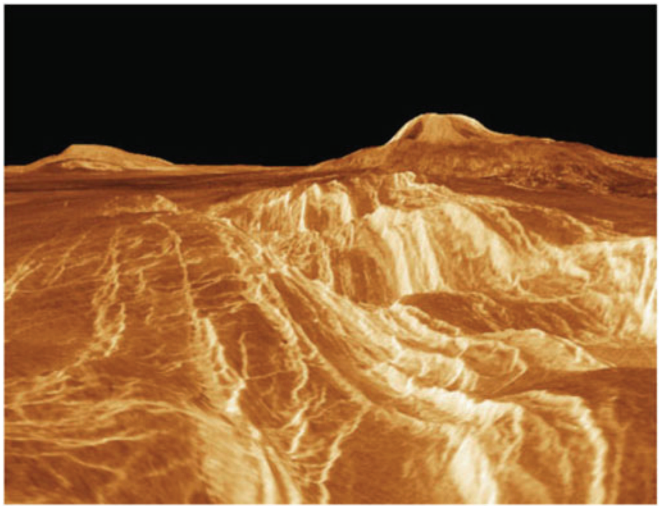


Fig. 6.16 The volcano Gula Mons on Venus (height 3 km). On the left you can see the Sif Mons volcano, which has a diameter of 300 km and a height of 2 km (Image: Venus-Magellan)

Table 6.7 Comparison of the atmospheres of Venus, Earth and Mars. Volume fractions in percent

Gas	Venus	Earth	Mars
CO_2	96.5	0.03	95.3
N_2	3.5	78.1	2.7
Ar	0.006	0.93	1.6
O_2	0.003	21.0	0.15
Ne	0.001	0.002	0.0003

6.4.6 Atmosphere of Venus

Table 6.7 shows the comparison of the atmospheres of Venus, Earth and Mars.

The main constituent of the atmosphere of Venus, CO_2, was first detected spectroscopically by Earth-based observations in 1932.

The pressure of the Venus atmosphere on the surface is equivalent to the pressure at 1000 m ocean depth on Earth. There is a *Troposphere* that extends to an altitude of 50 km. Within this, as on Earth, the gas below is heated and circulates slowly, rising at the equatorial region and falling down at the poles. Since Venus rotates very slowly, this convection current is very steady. The *clouds* are located at an altitude of more than 30–60 km and consist of H_2SO_4 droplets. This sulfuric acid forms from the reaction of SO_2—which is formed by volcanic outgassing—and H_2O. On earth the SO_2 is washed out by precipitation, which does not exist on Venus. Measurements with the space probe *VEGA* (USSR, 1985. showed that at a height of 53 km room temperature prevails at a pressure of 0.5 bar. The high surface temperature can be explained by the *greenhouse effect*. The atmosphere of Venus contains much more CO_2 than the Earth's atmosphere. The diffuse sunlight heats the surface, and the CO_2 reflects the resulting IR radiation from the ground. Thus, the surface continues to warm until it emits enough heat to reach equilibrium with the incoming sunlight. In the uppermost cloud layers (60−70 km height) the UV radiation of the sun splits atmospheric SO_2 into molecular components, and these radicals undergo various chemical reactions until they form sulphuric acid droplets with the water droplets, which have also been split. These sink downward, collide with other droplets, and below the clouds they decay again into SO_2 and H_2O and the process begins again.

Winds on Venus are governed by an east-west circulation that extends around the entire planet, in the uppermost cloud layer at 360 km/h. Cloud formations rotate around the planet in only four Earth days. Thus, Venus' atmosphere rotates much more rapidly than the planet. Earth's atmosphere rotates in sync with Earth. The solar radiation drives the atmospheric circulation on Venus, flow patterns form in N-S direction *(Hadley cells).*

Surface temperatures on Venus change very little, even between day and night. The lower atmospheric layer has a very large thermal inertia, similar to the oceans on Earth, and stores large amounts of heat. The most important difference between the atmospheres of Venus and Earth is as follows:

- Earth: cold below, hot above;
- Venus: hot at the bottom, cold at the top, this is called the *Cryosphere.*
- Solar wind: Because the magnetic field of Venus is very weak, this directly affects the atmosphere. On the side facing the Sun, neutral atoms are ionized by the high-energy UV radiation and carried away by the solar wind.

ESA's Venus Express mission has detected *Ozone* in the atmosphere of Venus. The occultation of a star by Venus was observed with the spacecraft. Ozone in the atmosphere of Venus reduced the UV content of the star occulted by Venus (cf. Absorption of UV radiation by the ozone layer in the Earth's atmosphere). Ozone in the atmosphere of Venus is formed by the splitting of CO_2 molecules by UV sunlight. The split molecules are also transported to the night side of Venus' atmosphere, where oxygen atoms react with each other to form either O_2 or ozone, O_3. The ozone layer is located at an altitude of 100 km. The discovery of ozone in the Venusian atmosphere is very interesting for astrobiology, because until now it was believed that ozone O_3 that ozone was a biomarker, since atmospheric free oxygen could only be formed by biological processes. Oxygen on Earth was formed by photosynthesis of Plants, by which O_2 is released.

> Venus is the planet with the most extreme greenhouse effect.

Through interaction with the *solar wind* (charged particles continuously repelled by the Sun), Venus loses charged particles of its upper atmosphere. In Fig. 6.17 we can see the influence of the solar wind to the shape of Venus' ionosphere. Very low solar wind density

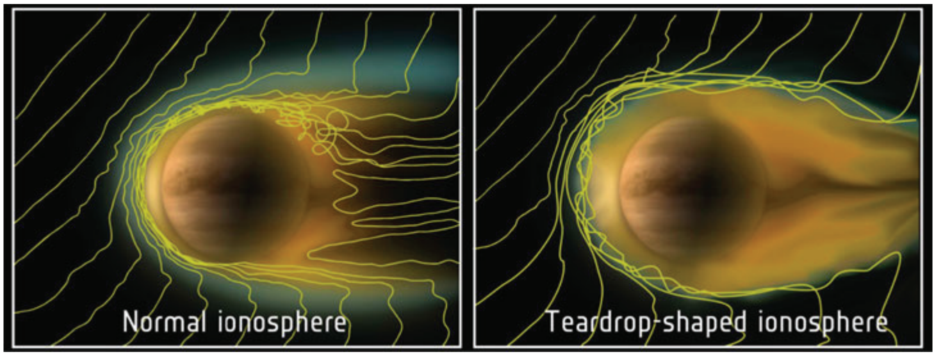


Fig. 6.17 The ionosphere of Venus is not protected by a magnetic field. Its shape depends strongly on the solar wind. The figure on the right shows a comet-like ionosphere at very low solar wind in 2010 (Venus Express, ESA/Wei)

in 2010 revealed a comet-like structure, which is also thought to be present in exoplanets close to the stars. The yellow lines indicate the solar magnetic field. The solar wind density in the figure on the right was about 0.1 particles per cubic centimeter, which is 1/50th of the normal density. The state of extremely low solar wind density lasted about 18 h.

6.4.7 Venus and Climate Change on Earth

The Climate Change on Earth is in all the media, and there are numerous proposals to mitigate climate warming. One whimsical idea has been to introduce droplets of sulfuric acid into Earth's high atmosphere. That way, less solar radiation reaches the Earth's surface.

Sulfuric acid clouds form at altitudes between 50 and 70 km in Venus' atmosphere, as mentioned above. SO_2 combines with H_2O. In 2008, the Venus Express orbiter detected a SO_2 layer at an altitude of about 100 km. This sulfur dioxide is formed by fission from the sulfuric acid clouds further down. If an attempt were made to stop global warming by the process described above, a similar effect to that seen on Venus could occur in the Earth's atmosphere. Thus this measure would be pointless, apart from other possible dangers.

This example is meant to illustrate the importance of comparative planetary research and how findings about the atmospheres of other planets can be applied to Earth's atmosphere.

Was Venus formerly a *habitable planet?* Water is one of the most important elements for life. There's a big difference between Earth and Venus here: If we were to combine the total present *Water resources* on both planets Venus and Earth and distribute them evenly over their entire surfaces, then the thickness of the water layer would be

- Earth: 3 km,
- Venus: 3 cm.

Venus is therefore extremely dry at present.

Nevertheless, a few billion years ago Venus could have had a similar amount of*water* as on Earth today. Due to the more intense solar radiation on Venus H_2O split into H_2 and O_2, the lighter hydrogen escaped into space, and oxygen rapidly combined with other elements. Venus Express measurements show that this process is still occurring today: a ratio of 2 H to 1 O atoms is found, so a water molecule was split. Some of the water on Venus could also have been formed by *Comet impacts* brought there.

So liquid water in the form of oceans could only persist on Venus for a short time, if at all. Water is also an important sink for CO_2. This greenhouse gas is reduced by the oceans on Earth.

Also important for astrobiology is *Lightning*. Electrical discharges were detected on Venus. These cause molecules to split and new compounds can form. Electrical discharges have only been found on four planets in our solar system: Earth, Venus, Jupiter and Saturn.

6.5 Mars

Mars is the most Earth-like planet in the solar system. Few other planets have fascinated mankind as much as Mars. There are several reasons for this. Mars strongly changes its brightness and color; it appears reddish at high brightness and it has long been considered a candidate for life in the solar system. All major space-faring nations therefore undertook missions to the red planet.

6.5.1 Mars: General Data

Due to the large orbital eccentricity, we only give the extreme values of the apparent diameter or opposition brightness (for near-Earth oppositions): The diameter of the planet's disk at the time of its opposition is $25.7''$, at the time of the greatest Earth distance only $3.5''$. The maximum Opposition brightness is $-2.^{m}91$.

Observations from Earth reveal surface structures on the planet's disk, as the surface is barely obscured by clouds. One can see details up to 100 km in size from Earth with telescopes, similar to the details seen with the naked eye on the lunar surface. In 1877, the astronomer *Schiaparelli* observed the Martian canals, *canali*, but these soon proved to be optical illusions. The *Rotation Period* Mars is $24^{h}37^{m}23^{s}$. The *Rotation axis* has a tilt of 25°, and therefore Mars has *Seasons* similar to Earth. You can see *Polar caps* as well as changing fuzzy dark areas depending on the season. The *mass* of Mars is 1/9 of the Earth's mass. The density is $3.9\,\mathrm{g/cm^3}$. The planet has only an extremely weak *Magnetic field*. Besides there are magnetic field concentrations in small areas.

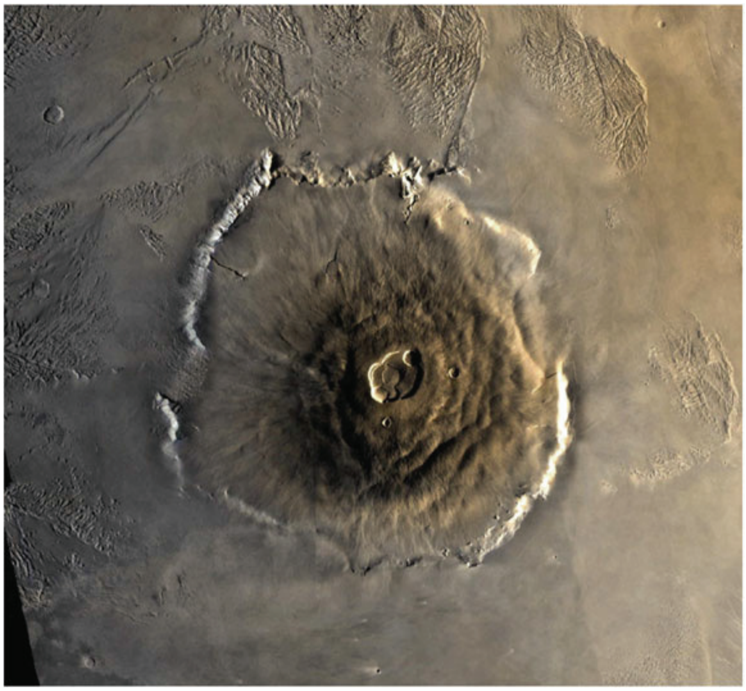


Fig. 6.18 Olympus Mons, the largest volcano in the solar system (NASA)

In 1965, a US probe visited Mars for the first time, *(Mariner 4),* and the photographs revealed details more like the surface of the Moon. In 1971, for the first time, *Mariner 9* space probe orbited another planet and photographed details up to 1 km in size. *Viking 1* landed softly on the surface in 1976 and transmitted images and data until 1982 (Fig. 6.18).

6.5.2 Martian Surface

The total surface of Mars (Fig. 6.19) roughly equals the area of all Earth's continents. About half of the planet consists of highlands dotted with craters, most of which lie in the southern hemisphere. The lava plains, which are about 4 km lower, are found in the northern half. *Hellas* is a huge impact basin 1800 km in diameter.

The *Tharsis region* is about 10 km high and contains four volcanoes that rise another 15 km. The largest volcano in the solar system is *Olympus Mons* (Fig. 6.18) (500 km diameter, 25 km high). Some volcanoes show impact craters on their slopes, so must be about 1 billion years old. Olympus Mons has very few impact craters, and its surface can therefore only be at most 1 million years old, there is also evidence of lava flows that still are much younger. There are numerous canyons on Mars, the most impressive being the

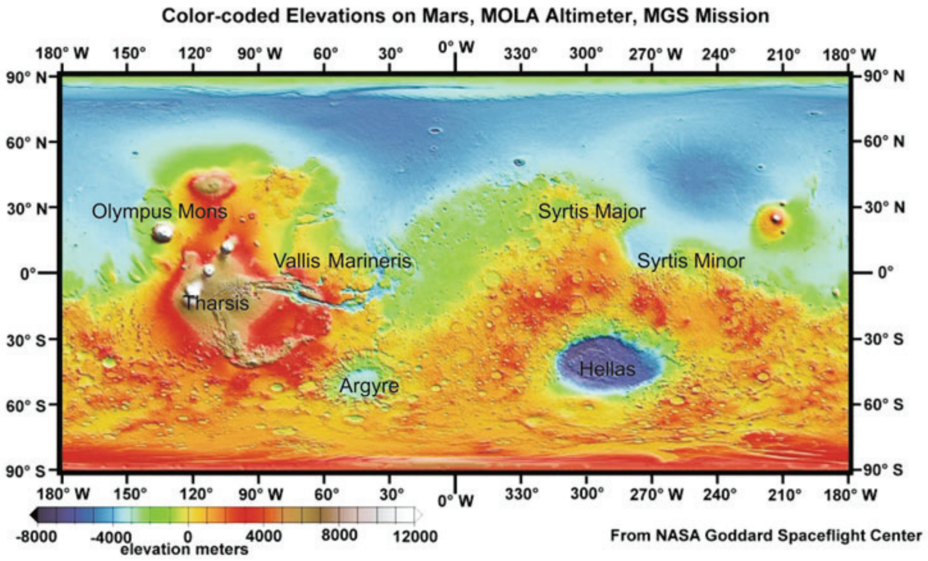


Fig. 6.19 Map of Mars (Source: NASA)

Vallis Marineris (5000 km extended, 7 km deep and 100 km wide). These are tectonic rifts. The polar cap was also investigated, Fig. 6.20.

Viking 1 landed on 20 July 1976 in a 3 billion year old plain. At the landing site there are many 1 m large rock debris, and dune-like deposits of sand are found. The landing site of Viking 2 is similar, the landing took place on 1 September 1976. Wind speeds up to 100 km/h were measured. The weather stations on board measured larger changes in the Martian atmosphere than in the Earth's atmosphere. In summer, the maximum temperature was −33 °C and at the end of the night of −83 °C. Viking 2 photographed during the winter on the Martian soil. X-ray fluorescence spectrometers were used to determine the composition of the Martian samples. The composition differs significantly from that of terrestrial rocks: The Martian soil consists of basic rocks rich in Mg and Fe.

In 1997, a Mars probe landed softly on Mars and, with the help of a small robotic car *(Sojourner)* it was also possible to make a short trip on Mars. This mission, called "Pathfinder," provided 90 days of data to Earth. Sojourner worked 12 times as long as its planned lifetime (7 days). The landing took place on 04.07.1997, and 16,000 images were obtained from the lander and 550 from the rover. The mass of the lander was 264 kg, that of the rover 11 kg.

In 2004, the two Mars rovers Spirit (until 2011) and Opportunity started to be in operation (Fig. 6.21). Opportunity covered a distance of more than 40 km on the surface of Mars by 2015. The Mars orbiter Odyssey has been in Mars orbit since October 2001. The European mission Mars Express has been in Mars orbit since Christmas 2003, and the lander Beagle 2 was unfortunately lost.

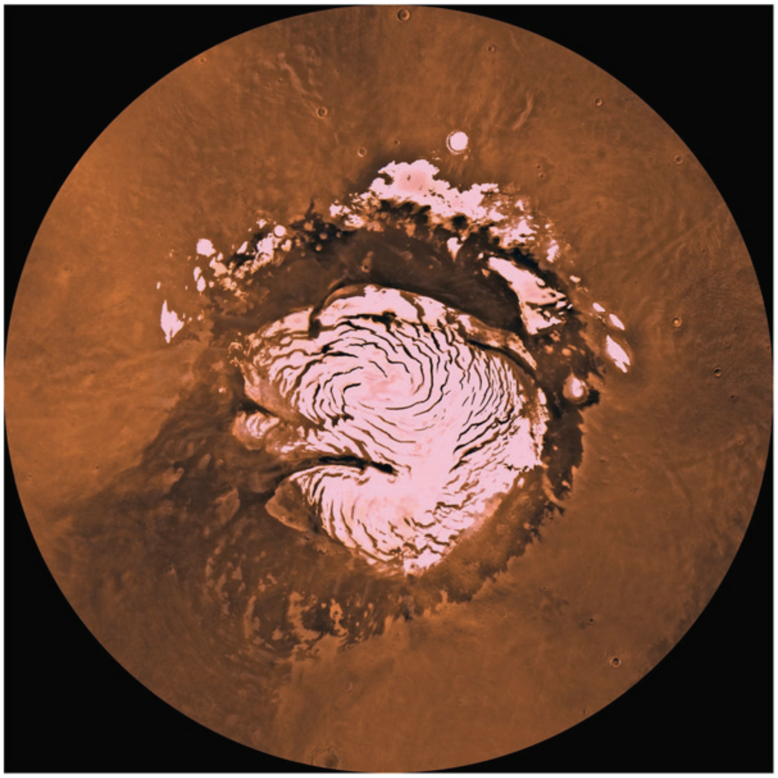


Fig. 6.20 The northern polar cap of Mars (NASA, Viking 1)

Fig. 6.21 The Mars rover Opportunity photographed the landing site. The large white braking parachute can be seen to the right of the lander module (NASA)

Details of a Martian crater partially covered with ice can be found in Fig. 6.22.

The SNC meteorite found *SNC meteorites* found in the Antarctica are only about 1.3 billion years old and may have come from Mars because of their composition (Moon

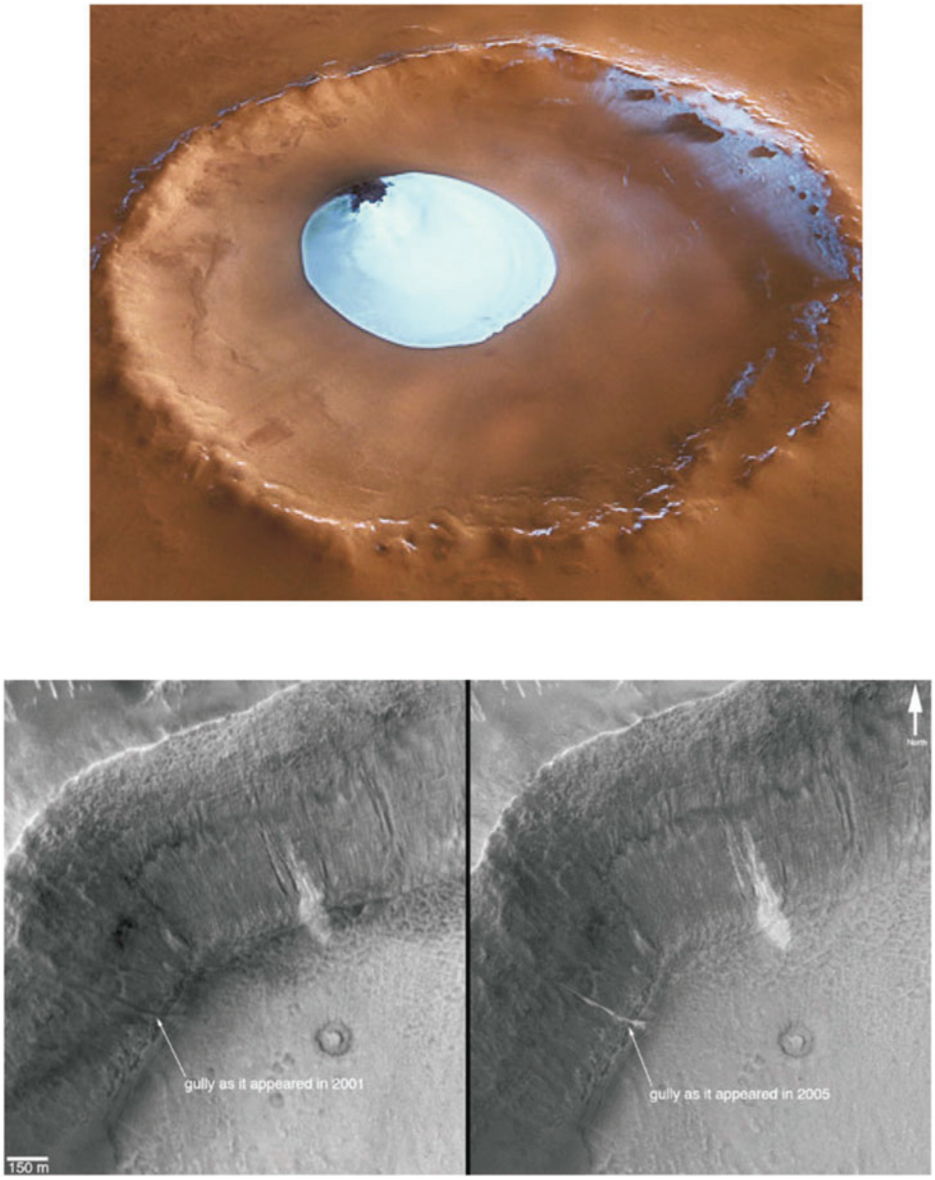


Fig. 6.22 Top: Martian crater, 30 km, covered with water ice. The image resolution is 21 m per pixel point. ESA/DLR/FU Berlin (G. Neukum); bottom: formation of so-called gullies, a system of outflows within two images taken five years apart (Image credit: NASA/JPL/Malin Space Science Systems)

is ruled out because of different composition, Venus because of its dense atmosphere and higher gravity as well). Gas bubbles were found in the SNC meteorites, whose composition resembles that of the Martian atmosphere. This gas was trapped during the impact of a body on Mars and subsequent ejection of the material or heating.

The *Mars interior* will be investigated with a seismometer (SEIS experiment on board the Mars Insight Mission, launched 2018). This will be used to investigate frequencies in the range 0.05 mHz to 50 Hz. Previous data show that Mars has a core that is liquid in the outer region (core size between 1500 and 1800 km). The presumed Martian earthquakes are expected to be 100 times stronger than on the Moon and are mainly due to thermal tensions.

6.5.3 Mars Atmosphere

The Surface pressure is only 0.007 bar, less than 1% of Earth's surface pressure, and 95% of Mars' atmosphere is composed of CO_2. There are several types of *Clouds* in the Martian atmosphere:

- Dust clouds: these are formed by swirling dust from the Martian soil; they are driven into the atmosphere by winds, and can cover much of the planet's surface.
- Clouds of water ice: These form around mountains, much like on Earth.
- Clouds of carbon dioxide: Form veils of dry ice.

The *polar ice caps* are made up of two components. Seasonally changing polar ice caps consist of CO_2-ice. The southern permanent cap is about 350 km in diameter, the northern about 1000 km, and this consists of frozen H_2O. One therefore finds large water reserves in the polar caps. Up to 80° latitude, sediment deposits are found in both hemispheres due to the expanding polar caps. All this points to *Climate changes* on Mars with periods of a few 10 000 years. At present, no water can exist in liquid form on Mars. However, one finds evidence of large water flows in the past. Perhaps there is frozen water beneath the Martian floor that has been thawed by volcanic activity. This still gives rise to speculation about possible lower life forms on Mars. However, experiments by the Viking probes (looking for signs of metabolism) turned out negative.

Numerical calculations showed that the inclination of the rotation axis of Mars can change by up to 60° which could have a significant effect on the climate. This would increase the seasonal contrast between north and south. At high and mid latitudes, summer temperatures would then rise above the freezing point of water. Released CO_2 from the melting polar cap increases the density in the atmosphere, the greenhouse effect takes effect, and large amounts of surface water can form. Add to this chemical reactions form salts and limestone (calcium carbonate), and so the amount of carbon decreases again, and the greenhouse effect is reduced. As soon as the inclination of the axis decreases, the planet cools down, dry ice and snow fall, and Mars is again in its cold state. The last warm period may have been 300 million years ago. In late Martian history, warm periods may have lasted only about 1 million years. In earlier Martian history, however, they may have been longer, and lower forms of life may have evolved, perhaps surviving in sheltered areas to the present day.

> Mars is the planet with the largest climate changes. The search for life has been fruitless so far, but will continue.

6.5.4 Mars: Terraforming?

One finds many similarities between Mars and Earth:

- Polar caps
- Atmosphere with clouds
- Seasons
- Weather with storms

However, there are also differences:

- Mars: no permanent magnetic field; particles of the solar wind reach the Martian surface almost unhindered
- Atmosphere very thin on Mars
- At present, water in liquid form is not possible on Mars.

Very often *Terraforming* of Mars is discussed. To make Mars habitable, its atmosphere would have to be made much denser, which would warm the surface of Mars. At the same time, however, the atmosphere must not be destroyed by processes of splitting molecules (e.g. CO_2, H_2O). It is assumed that enough frozen or bonded CO_2 exists in the Martian soil or at the poles to increase the pressure in the Martian atmosphere to 300 mbar. This would raise the temperature enough to melt ice at the poles and in the Martian soil, allowing plant life. There are other proposals for Martian terraforming. However, in the best-case scenario, it would take several thousand years before Mars would be habitable for humans.

The Mars rover *Curiosity* landed on Mars in August 2012 to conduct extensive chemical soil sample analyses and determined whether there was any water in the past on Mars (Fig. 6.23). On average, the rover can travel 30 m per hour on the Martian surface, overcoming obstacles up to 75 cm in height. Energy is supplied by decaying radioisotopes (plutonium) and lasts for one Mars year (687 Earth days). In total, between 5 and 20 km should be covered on the Martian surface. An example of an area of highly probable

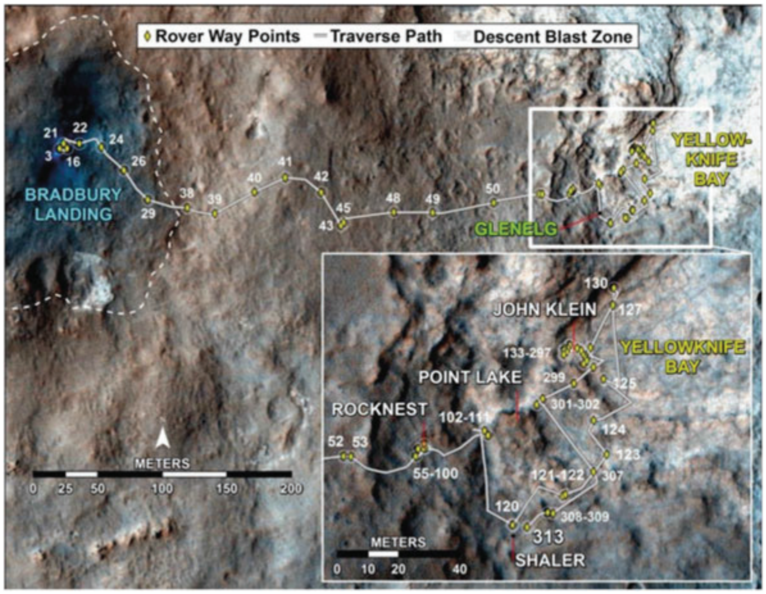


Fig. 6.23 The distance traveled by the Mars rover Cursiosity. The numbers indicate the Martian days since landing (Image credit: NASA/JPL/Malin Space Science Systems)

sedimentary deposits is given in Fig. 6.24. Figure 6.25 shows sediment deposits against a mountain in the background.

6.5.5 Martian Moons

In the year 1877 *A. Hall* first saw the two tiny Moons of Mars Phobos and Deimos.

The orbital period of Phobos is only $7^{h}39^{m}$; it is thus shorter than the planet's rotation period. The moons are irregularly shaped and are about 20 and 12 km in size, respectively. Both resemble a triaxial ellipsoid:

- Phobos: $27 \times 21 \times 19$ km,
- Deimos: $15 \times \times 11$ km.

Phobos is only 2.8 Mars radii from the surface of Mars, Deimos 7 Mars radii (orbital period 30.3^{h}). Deimos moves W to E and very slowly, staying above the horizon for almost three Martian days, passing through all phases several times.

The Martian moon Phobos is very close to the Roche boundary and will be torn apart, or crash into Mars, within the next 100 million years (Fig. 6.26).

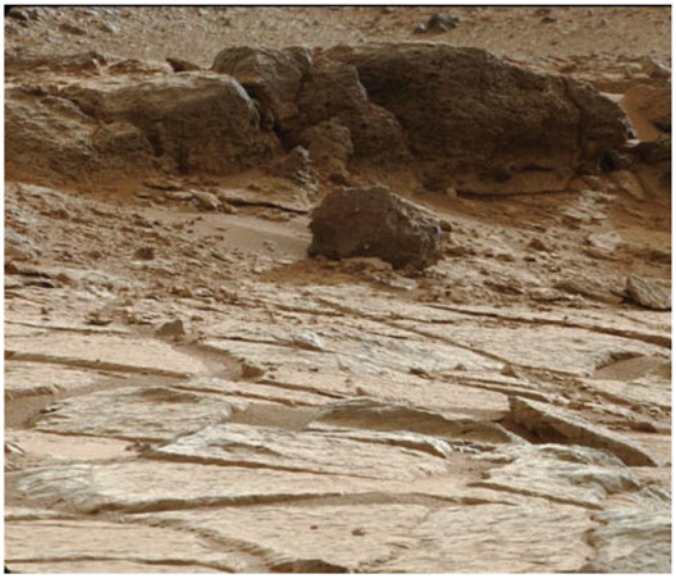


Fig. 6.24 Details of the Martian surface (NASA/Curiosity)

Fig. 6.25 Details of the Martian surface; the layered deposits in the foreground indicate formerly flowing water (NASA/Curiosity)

6.6 Jupiter and Saturn

Jupiter is the largest planet in the solar system. The properties of Jupiter and those of the other gas planet Saturn are fundamentally different from those of the terrestrial planets. Saturn is especially known among the planets for its bright ring system. But also the exploration of its moons showed unexpected results; for example, water geysers were found on one of its moons.

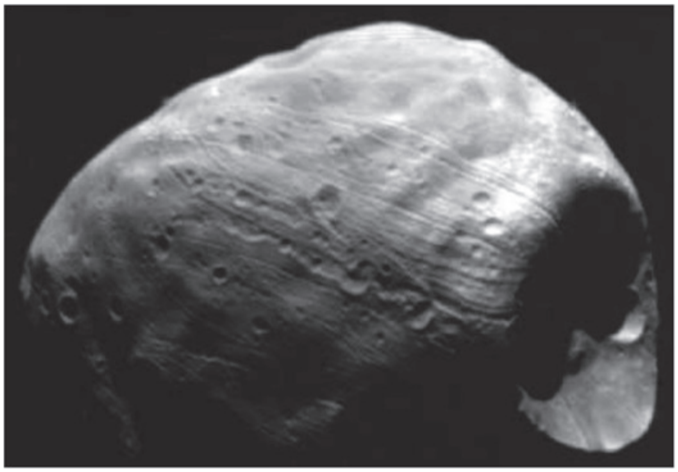


Fig. 6.26 Phobos (NASA)

6.6.1 Jupiter: General Properties

The largest planet of the solar system is due to its fast *rotation* noticeably flattened:
polar diameter: 133,700 km
Equatorial diameter: 142,984 km.
Jupiter rotates differentially, so it does not rotate like a rigid body:

- At the equator, the rotation period is 9 h 50 min 30 s (System I).
- At the polar regions 9 h 55 min 41 s (system II).

The apparent diameter of the planetary disk at the time of its opposition is 49″ at the time of its greatest distance from Earth only 30″. The opposition brightness is $-2.^{m}9$ and it is the brightest planet in the sky after Venus (only rarely at near-Earth oppositions Mars appears brighter). Jupiter has about 1/1000 the mass of the Sun, or 318 Earth masses, but has 2.5 times the mass of all the other planets in the solar system combined. The center of gravity of the Sun-Jupiter system is 1.068 solar radii, $R_\odot$, outside the sun's center.

Jupiter is 778 million km from the Sun, and it takes 12 Earth years to orbit the Sun. Its mean density is $1.3\,\mathrm{g/cm^3}$. Its axis is inclined only 3° from the orbital plane, and therefore there are no seasonal changes.

6.6.2 Space Missions to Jupiter

The first spacecraft explored Jupiter in 1974/1975 (*Pioneer* 10, 11, launched 1972/1973). *Voyager 1* reached Jupiter in 1979 and subsequently investigated Saturn (1980). *Voyager*

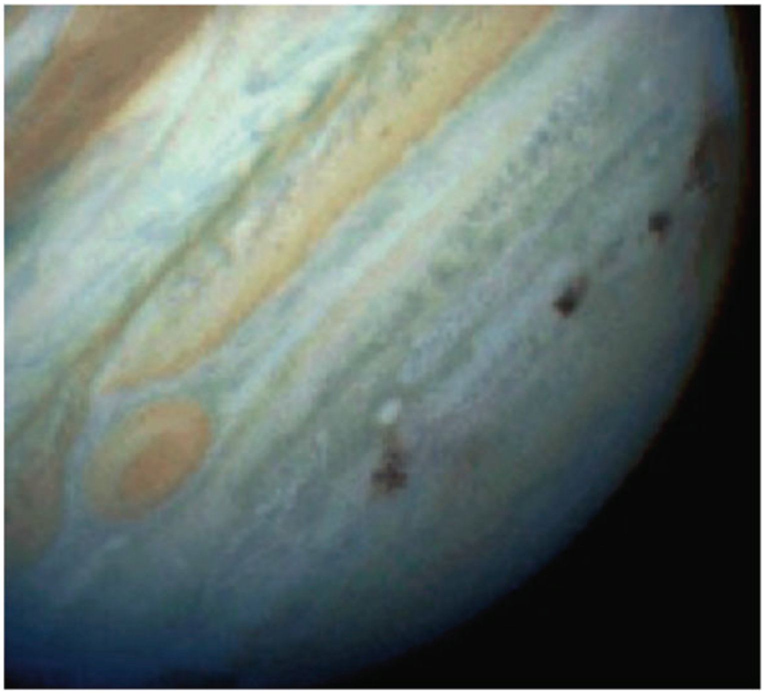


Fig. 6.27 After the impact of the fragments of Comets Shoemaker-Levy in July 1994 in Jupiter's atmosphere, visible traces appeared (HST image)

2 reached Jupiter a few months later and studied Saturn in 1981, Uranus in 1986 and Neptune in 1989.

The space probe *Galileo* orbited Jupiter from 1995 to 2003, and on its flight in 1994 was able to observe the impact of comet Shoemaker Levy on Jupiter (Fig. 6.27). Upon its arrival, a descent capsule separated in December and plunged into Jupiter's atmosphere. At a depth of 160 km it was finally destroyed by the external pressure, and the last reading was 22 bar at a temperature of 150 °C. The Galileo probe itself was then crashed in 2003 to avoid hitting Jupiter's moon Europa (Contamination with terrestrial bacteria). The space probe *Cassini* passed Jupiter in 2000/2001.

In July 2016, the Jupiter Polar Orbiter (JUNO) spacecraft entered orbit around Jupiter (it was launched in 2011). The polar orbit of this probe allowed the use of solar cells for power supply. Figure 6.28 shows a close-up of Jupiter's south polar region.

6.6.3 Structure of the Giant Planets

The internal structure of the giant planets (Table 6.8) differs in principle from that of terrestrial planets:

Fig. 6.28 Jupiter's south pole photographed from about 100,000 km away by the Juno spacecraft in February 2017. Note the many cloud swirls (NASA)

Table 6.8 Comparison of the structure of the giant planets; distance from the center in 1000 km

Planet	Molecular H	Metallic H	Ice	Rock
Jupiter	71–59	59–14	14–7	0–7
Saturn	60–30	30–16	16–8	0–8
Uranus	26–18		18–8	0–8
Neptune	25–20		20–10	0–10

- They are surrounded by a dense atmosphere.
- A few 1000 km below the surface, the pressure becomes so high that hydrogen changes into its liquid state. Even deeper H behaves like a metal. Most of Jupiter is composed of metallic H. Metallic hydrogen is formed when hydrogen is subjected to high pressure. A lattice of protons (distance smaller than Bohr's radius) forms as well as free electrons.
- The core of the giant planets consists of rock and ice (up to about 20 Earth masses).

A strong internal heat source generates 4×10^{17} W, equivalent to the amount the planet receives from the Sun. Jupiter's atmosphere is therefore a mixture between a normal planetary atmosphere and a stellar atmosphere that is heated from below. This involves a cooling process in the interior: Jupiter is about 20,000–30,000 K hot at its core.

6.6.4 Jupiter Atmosphere

In the spectrum of reflected sunlight, absorption lines of gaseous methane and ammonia can be detected. In fact, however, Jupiter's atmosphere consists mainly of hydrogen and has a composition similar to that of the Sun. Furthermore, nitrogen, carbon, water vapour and hydrogen sulphide have been detected. The colors in the atmosphere come from different forms of molecular sulfur (S_n, n is an integer natural number), this forms brown and yellow particles. The highest clouds glow red, below them white and then brown clouds, and still further below then blue clouds. The main constituents of the clouds are ammonia at the top, then ammonium hydrosulphide and water at the bottom. The NH_3 cloud cover marks the upper limit of the convective troposphere, the temperature there is 140 K. Within the troposphere, the temperature increases downward. At a pressure of 10 bar liquid water as well as ice crystals are assumed to exist.

Due to rapid rotation, the N-S flow in the atmosphere becomes less important and an east-west flow is formed. On Jupiter, a pattern of dark bands and bright zones is seen extending parallel to the equator. Gas flows upward in the bright zones, culminating in the white NH_3-Clouds. In the dark bands the cooler atmosphere moves downwards; here there are fewer NH_3 clouds, and one can see the NH_4SH-clouds.

One also finds large oval-shaped, very persistent regions of high pressure, of which the *Great Red Spot* (GRF, Fig. 6.29) which has an extent of 30,000 km is the best known and has been observed for 300 years. In it there is a counter clock wise rotation in six days. On Earth, a hurricane (which here, however, is a depression) has a lifetime of a few weeks, as it loses energy through friction with the land masses. Jupiter does not have a solid surface, and therefore such storms can be very long-lived. In March 2003 we observed the formation of another "red spot". *(Red Spot Jr.).* This structure appeared as an oval BA as early as 2000, but it didn't turn reddish until 2006. The extent was about 1/2 that of the

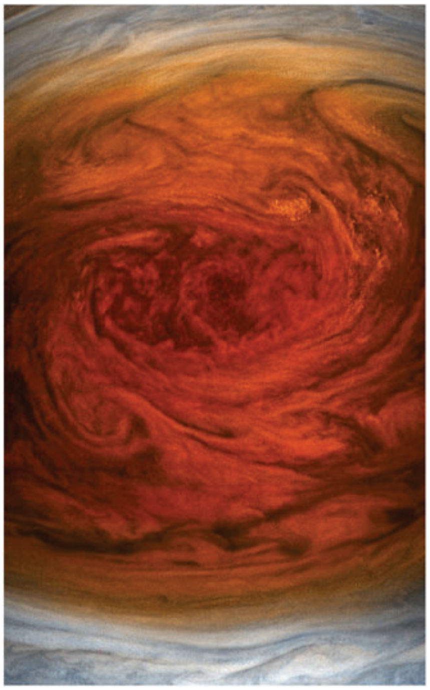


Fig. 6.29 The Great Red Spot in Jupiter's atmosphere taken by the Juno spacecraft (NASA)

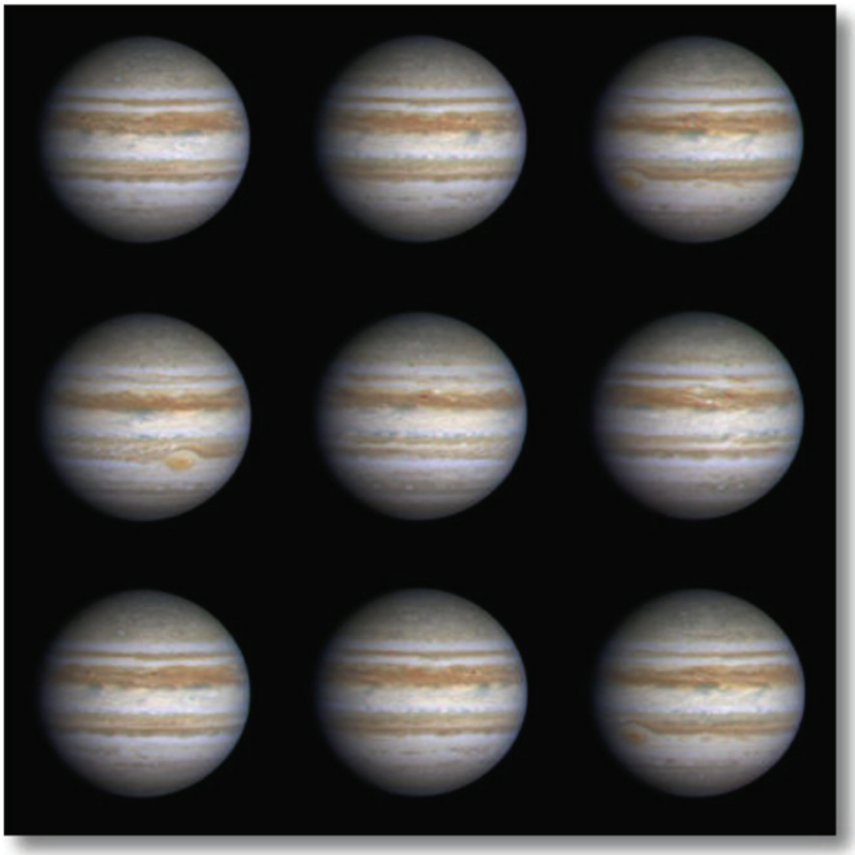


Fig. 6.30 Sequence of Jupiter images taken on October 22 and 23, 2000. Clearly seen is how the Great Red Spot (GRF) continues to move due to Jupiter's rotation. The clouds in the GRF rotate counter clock wise. The equatorial zone is currently bright, suggesting high clouds. Twenty years ago, the equatorial zone consisted of dark bands (Images: Cassini mission, NASA)

Great Red Spot. It has since disappeared again, and the Great Red Spot also appears to be undergoing a major change. A sequence of Jupiter images clearly shows how the cloud formations change within a few hours because of Jupiter's rapid rotation (Fig. 6.30).

It is believed that there is a 70-year climate cycle on Jupiter. According to this, there was a decrease in cyclone activity on Jupiter until about 2011; now activity should be increasing again. The last minimum in cyclone activity dates back to 1939. The turbulent south polar region of Jupiter is shown in Fig. 6.28.

6.6.5 Magnetosphere of Jupiter

At In 1950 Jupiter’s Radio emission was measured as a synchrotron radiation (the intensity increases with increasing wavelength; it is caused by charges accelerated in a magnetic field, which radiate). This radiation was shown to originate from an area outside the planet, and therefore charged particles must be moving around Jupiter, similar to the Van Allen belts in the Earth’s magnetosphere. Jupiter’s field is much stronger than Earth’s magnetic field. The magnetic field axis is inclined by 10° from the axis of rotation and 18,000 km from the centre and has the opposite polarity to the Earth’s magnetic field. If Jupiter’s magnetic field could be seen in the sky from Earth with the naked eye, it would be three times the size of the Moon. The magnetic field of Jupiter is compressed by the solar wind similar to the earth on the side facing the sun to 6×10^6 km, while on the side facing away from the sun it rises up to 700×10^6 km, i.e. almost as far as Saturn’s orbit.

The sources of ions in Jupiter’s magnetosphere are:

- Protons and electrons from the solar wind,
- particles from the atmosphere,
- particles from Jupiter’s inner moons. These may either have been knocked out by the infall of energetic ions, or come from the active volcanoes of the moon *Io*, that is, S and O ions. Io loses about 10 tons per second. These ions create a Plasmatorus.

In 1992 the space probe Ulysses explored Jupiter’s magnetic field and was ejected from the ecliptic plane by a *Gravity Assist* out of the ecliptic plane and then returned to the interior of the solar system to study the Sun’s polar regions.

6.6.6 Jupiter’s Rings and Moons

The Jupiter’s ring system, consisting of tiny black dust particles, was first photographed by Voyager 1 in 1979. The fine dust particles will spiral down on Jupiter in a few 10^4 years. The dust particles are charged by Jupiter’s magnetic field and slowed down by collisions. By absorption and re-emission of radiation they also lose orbital angular momentum (*Poynting-Robertson effect*). The material of the rings comes from dust released by the impact of small meteorites on Jupiter’s innermost moons: Adrastea and Metis, for example, produce the main ring. The moons Thebe and Amalthea feed the two fainter Gossamer rings. An extremely thin outer ring circles Jupiter retrograde.

Jupiter has 79 natural satellites (Fig. 6.31) (As of 2019). In 1610 *Galileo*, discovered the four largest moons; these are called *Galilean moons*: Io, Europa, Ganymede, and Callisto. The two moons, Europa and Io, are about the size of our moon, Ganymede and Callisto are larger than Mercury. Jupiter’s other moons, however, are much smaller.

The surface of *Callisto* is littered with impact craters. It is an icy moon, and the craters look shallower than those of Mercury or the Moon. The ice crust heats up to 130 K, and

Fig. 6.31 The large red spot in Jupiter's atmosphere and, by comparison, the Galilean moons (NASA)

this causes the ice to have less resistance, making the impact craters shallower. Callisto is the Jupiter moon with the oldest surface. *Ganymede* (Fig. 6.35) is the largest moon in the solar system, and a billion years after its formation, there has been a restructuring of its surface (striking groove patterns), which otherwise appears rather featureless.

At *Io* (Fig. 6.32) there are active volcanoes, emitting sulfur or sulfur dioxide. There are also snowfalls of sulfur dioxide. A hot spot has also been found on Io, extending 200 km, where there is a temperature of 300 K. The cause of volcanism is heating due to tidal action. Io is at the same distance from Jupiter as the Earth's moon is from the Earth, but Jupiter's mass is 300 times that of the Earth, and therefore Io is virtually kneaded.

Jupiter's moon *Europa* (see also Fig. 6.33) is a white glowing sphere covered by ice with dark stripes, which may be cracks in this ice shell. Perhaps internal parts of this ice shell had melted as a result of heating from radioactivity, and the cracks formed during solidification. It is possible that there is liquid water underneath the ice shell even now, and this would make this moon of Jupiter a candidate for life. This ocean is a result of Jupiter's strong tidal heating. The surface temperature of Europa is only about −150 °C. Since very few impact craters are seen on Europa, the age of the surface (Fig. 6.34) is estimated to be about 30 million years old. Measurements from space probes have shown that Europa has a weak changing magnetic field. This is strong evidence for a saline ocean beneath the surface.

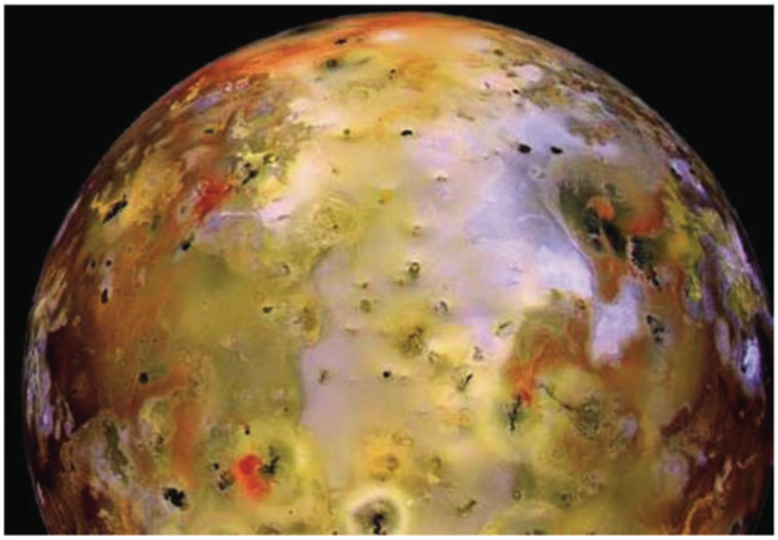


Fig. 6.32 Jupiter’s volcano-covered moon Io (NASA)

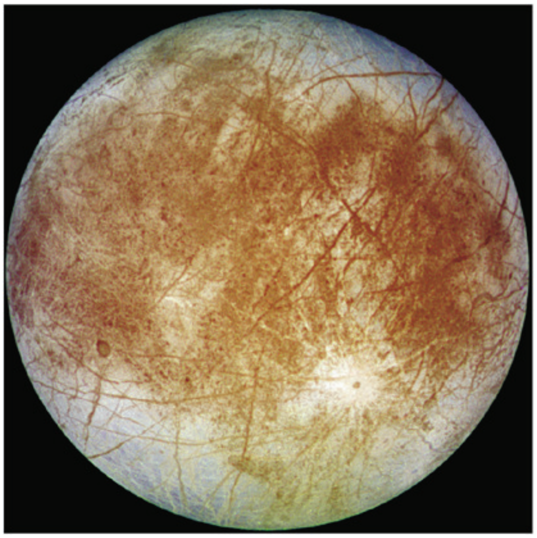


Fig. 6.33 Europa, the moon of Jupiter covered by a thick ice shell. The many grooves are clearly visible, but there are hardly any impact craters

In 2023, the mission *JUICE* (JUpiter ICy Moon Explorer, ESA project) will be launched to Jupiter, reaching the Jupiter system in 2030. After several approaches to Europa and Callisto, the probe will enter to orbit Ganymede in 2032.

Also *Ganymede* has a magnetic field and a salty ocean lying under an ice crust (Fig. 6.35).

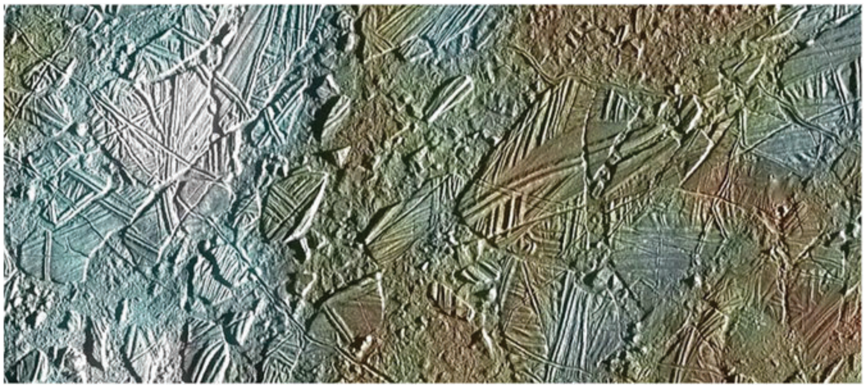


Fig. 6.34 Details of the surface of Jupiter's moon Europa (NASA)

Fig. 6.35 Jupiter's moon Ganymede (NASA)

The Galilean moons of Jupiter are extremely interesting objects for *astrobiology*. Altogether, Jupiter's moons (with J1, J2, . . . is also referred to as) are classified as:

- Four innermost moons: small irregular bodies, except for *Amalthea* (240 km diameter) no structures detectable.
- Galilean moons: distance 6−26 Jupiter radii, they are inside Jupiter's magnetosphere.
- Four moons of the middle group: the largest are Himalia (170 km) and Elare (80 km), distance 155−164 Jupiter radii, orbital inclinations up to 29°, eccentricities 0.13−0.21.
- Outermost group: 10–30 km diameter. 290–332 Jupiter radii away, very large orbital inclinations (147–163°) and high eccentricities. Probably captured minor planets.

> Jupiter's moon Europa is a candidate for life in the solar system because of its ocean beneath the ice crust.

6.6.7 Saturn: Basic Data

Saturn (Fig. 6.36) was already known to ancient civilizations: the diameter of the planet's disk at the time of its opposition is 20.1″, at the time of the greatest distance from Earth only 14.5″. The opposition brightness is $0.^{m}43$.

The ring planet requires 30 years to orbit the Sun and is on average 1 427 million km from the Sun. It has 95 times the mass of the Earth and the lowest density of all planets, with only $0.7\,\mathrm{g/cm^3}$. The rotation period at the equator is $10^{h}40^{m}$ and at the poles $10^{h}39^{m}$. The causes a strong *Flattening:* equatorial diameter: 120,536 km, pole diameter 107,812 km.

Fig. 6.36 Saturn. You can see very clearly the broad Cassini division and the fine Encke div.sion on the outside (NASA)

The *axis of rotation* is around 27° inclined, i.e. one observes seasonal effects.

The *Structure* of Saturn resembles that of Jupiter and has been shown in Table 6.8 outlines. Its internal energy source is only half that of Jupiter. It is assumed that in the liquid H-mantle the heavier He-drops sink downwards and in this way gravitational energy is released. This does not happen with Jupiter because it is warmer than Saturn. This is supported by the finding that Saturn contains only half the He that Jupiter has.

The temperatures in the *Atmosphere* is slightly lower than Jupiter's, and the atmosphere is more extended as a result of its lower gravity. There are fewer large storms than on Jupiter, but their occurrence here varies seasonally. Every 30 years an eruption of spots is observed in the equatorial region (most recently in 1990). The strength of its magnetic field is 0.2 Gauss, and the magnetic field axis is only 1° inclined with respect to the axis of rotation. The yellowish-brown cloud cover contains mainly ammonia crystals.

6.6.8 Saturn's Rings

The Saturn's rings have been known for a long time, and they orbit Saturn in the equatorial plane, which is inclined by 27° inclined to the orbital plane of the planet. We therefore look at one side of the rings for 15 years. The brightest rings are the A ring (radius 136,780 km), the B ring, and the innermost C ring (only 12,900 km from Saturn's surface). The brightest ring is the B ring, and its total mass is equivalent to that of a satellite 300 km in diameter. The A and B rings are separated by the *Cassini division* (discovered in 1675 by *Cassini*). Although the rings are 70,000 km wide, they are only 20 m thick. The rings consist of countless ice particles about the size of tennis balls. Voyager showed a D-ring further inside and an F-ring outside the A-ring. This resembles the rings of Uranus and Neptune. One recognizes innumerable single rings on satellite photographs. Important for structure of rings resp. occurrence of gaps are *Resonances.* One speaks of a resonance when two objects have orbital periods that are in an integer ratio to each other (Figs. 6.36 and 6.37).

Cassini division: a particle at the inner edge would have half the orbital period of the satellite Mimas. The outer sharp edge of the A ring is in 7:6 resonance with the Satellite Janus and Epimetheus. Spiral density waves are also observed in the rings. New theories explain these spoke-like structures by electrical discharges. Density waves are also important for explaining the spiral structure of galaxies.

The found blue glow of the E-ring is interpreted like this: The ring is made of ice crystals, which derived from geysers of the moon *Enceladus*.

6.6.9 Saturn's Moons

As of end of 2022 83 moons of Saturn are known. The Saturn's moon *Titan* (Fig. 6.38) is the second largest moon in the solar system after Jupiter's moon Ganymede, with a diameter of 5150 km, and has 1.9 lunar masses. The density is 1.9 g/cm^3. It was discovered

Fig. 6.37 Details of Saturn's ring system (NASA)

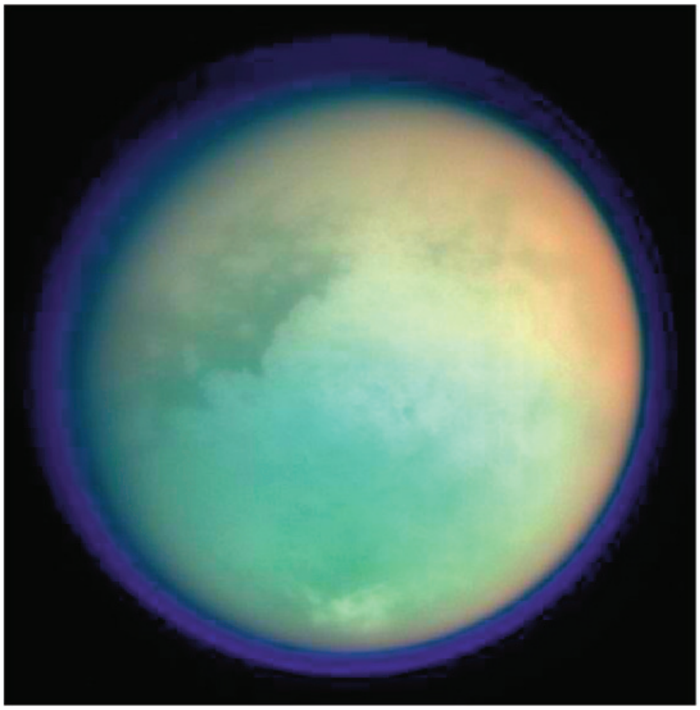


Fig. 6.38 Titan (NASA/JPL/Space Science Institute)

in 1655 by *Huygens*. In 1944, an atmosphere was discovered on Titan. The space probe Voyager passed Titan at a distance of only 4000 km and was covered by Titan as seen from Earth. During this occultation, the radio signals had to pass through various layers of Titan's atmosphere *(Radiooccultation),* so that it could be probed. The main component could be N_2 CH_4 and Ar make up only a few percent. Furthermore, one found HCN which is a basic building block for DNA. The low clouds reach up to 10 km altitude and consist of CH_4. This gas plays a similar role on Titan as H_2O on Earth. Titan's surface temperature is 90 K, and it is thought that there are lakes of liquid methane here. The difference in temperature between the poles and the equator is less than 3 K. There may also be continents of water ice.

In June 2004, the spacecraft *Cassini* after seven years of flight, entered into the Saturn system. 14 January 2005 marked a high point in European space travel: the probe detached from Cassini *Huygens* landed softly on Saturn's moon Titan and transmitted images of its surface to Earth. Instead of the oceans that had been suspected, sand dunes up to 150 m high were found. They consist of fine particles, possibly frozen ethane. Furthermore volcanoes are suspected on Titan, but not fire volcanoes like on Venus, Mars or Earth, but *Cryovolcanoes.*

Radar measurements show lakes of methane at the North Pole, some of which are evaporating. The seasons on Titan last seven Earth years each!

Titan is the only moon in the solar system with a dense atmosphere and organic compounds are also found.

Cryovolcanoes (ice volcanoes) were also found on *Enceladus.* In the case of cryovolcanoes, substances such as methane, carbon dioxide, ammonia and frozen water are melted in the interior of a moon by heating (e.g. tidal forces) and penetrate to the surface. Images taken by the space probe *Cassini* (launch 1997, reached Saturn 2004) suggest that liquid water is present in chambers just below the surface of Enceladus (Fig. 6.39). This is ejected in fountains up to 500 km high. In 2008, Cassini passed Enceladus at a distance of only 52 km. The ejected material was analyzed during a stellar occultation, and traces of organic material were also found.

Thus Enceladus, which is only 500 km across, is another candidate for life in the solar system.

Figure 6.40 shows the moon Tethys. After Titan are *Japetus* and *Rhea* the largest moons of Saturn (both about 1500 km in diameter). Japetus is 60 Saturn radii away from Saturn, Rhea only nine. Between the two moons are Titan and Hyperion. Japetus has a density of only 1.1 g/cm^3. It has a bright and a dark hemisphere. It is believed that impacting micrometeorites on *Phoebe* release dark particles that rain upon Japetus.

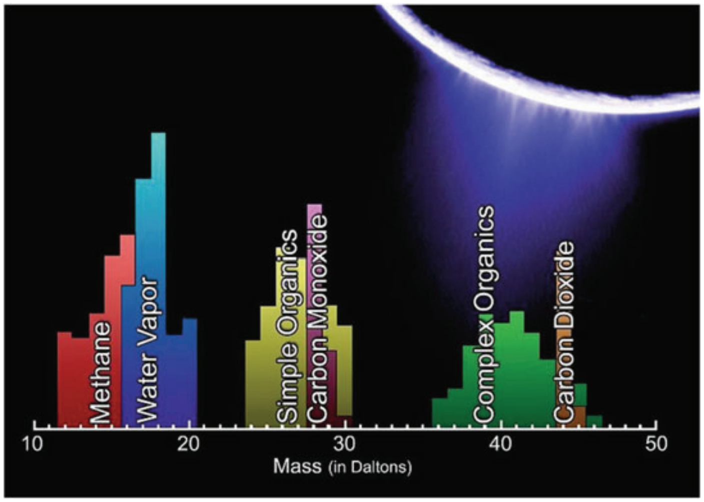


Fig. 6.39 Geyser-like fountains ejected from the surface of Enceladus. Below is the chemical analysis. The Cassini spacecraft flew through the fountain (plume) in March 2008. A dalton is the term used in the United States for the atomic mass unit, 1 Da = 1 amu = 1.66×10^{-27} kg (Credit: Cassini Mission)

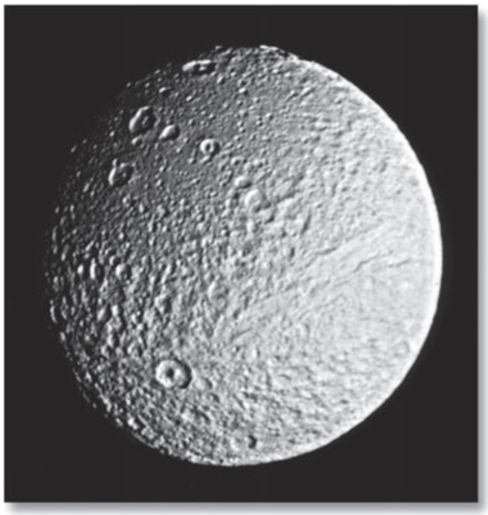


Fig. 6.40 Saturn's moon *Tethys*. Image taken by Voyager 2 from a distance of 282,000 km. The rift system visible on the right may have developed as Tethys expanded (NASA/Cassini)

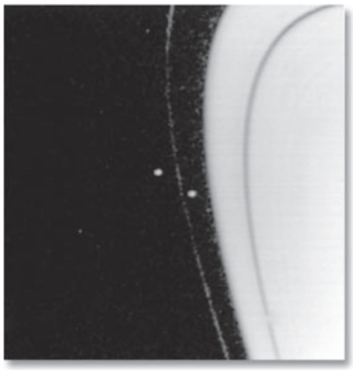


Fig. 6.41 Saturn’s F ring with the shepherd moons Pandora (outside) and Prometheus (© NASA/JPL/Space Science Institute)

The two moons Janus and Epimetheus (Fig. 6.41) move in nearly identical orbits. Every four years they approach each other and then exchange orbits.

6.7 Uranus and Neptune

The two outermost planets of the solar system are sometimes described as ice giants(as opposed to the gas giants Jupiter and Saturn).

6.7.1 Discovery of Uranus and Neptune

Uranus was discovered on 13 March 1781 by *W. Herschel*. At the time of its opposition the diameter of the planet disk reaches $4''$ and the apparent brightness is $5.^{m}5$ so it can be seen with binoculars if you know its exact position in the sky.

Uranus takes 84 years to orbit the Sun, while Neptune takes 165 years.

Neptune was discovered by *Galle* after predictions from perturbations of the orbit of Uranus on September 23, 1846. At the time of its opposition, the diameter of the planet’s disk reaches about $2.3''$ and the visual magnitude is $7.^{m}8$. With a diameter of 49,258 km, Neptune is the fourth largest planet (Uranus: 51,118 km), and in terms of mass it is the third largest.

Both planets have approximately 15 times Earth’s mass and densities of $1.2\,\mathrm{g/cm^3}$ (Uranus) and $1.6\,\mathrm{g/cm^3}$ (Neptune). Neptune’s rotation axis is inclined by 29° but that of Uranus is inclined by 98°. Each pole of Uranus is exposed to the Sun for about 40 years. The cause of this unusual tilt may have been a collision with a large planet in the early stages of the solar system. The rotation period for both planets is about 17^{h}. Uranus rotates retrograde. Both planets lack metallic hydrogen in their interiors. Neptune has an internal energy source, and although it is farther from the Sun than Uranus, both planets have the same surface temperatures. Uranus appeared featureless at the time of the Voyager

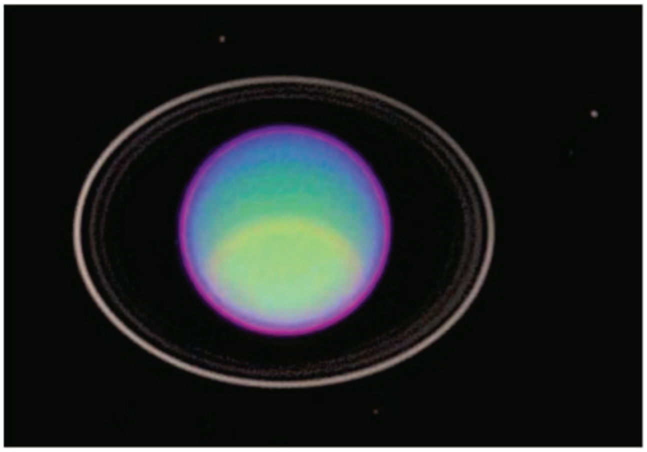


Fig. 6.42 Uranus with ring (Image: HST)

2 flyby (1986). Instead of NH_3clouds (which are found on Jupiter and Saturn), here they found CH_4-clouds. Since it has no internal heat sources, there is no convection, and the atmosphere is very stable. Neptune also has CH_4-clouds, and at the upper limit of the troposphere the temperature is 70 K at a pressure of 1.5 bar. The atmosphere is clear, and the scattered sunlight causes the blue coloration of the planet Neptune. Furthermore, there are strong east-west winds on Neptune with wind speeds up to 2100 km/h. Both planets have a magnetosphere, the field strength is 0.3 Gauss (Uranus) resp. 0.2 Gauss (Neptune), the inclination of the magnetic field axis to the rotation axis is 60° (Uranus) resp. 55° (Neptune).

In addition to satellite images, modern large telescopes (Fig. 6.42) can be also used to observe details on the two planets from Earth (e.g., Keck telescope). Long-lived large storms were found in the atmosphere of Uranus.

6.7.2 Rings and Satellites of Uranus and Neptune

The *rings* of Uranus were only discovered by chance in 1977: the planet was occulting a star. Shortly before the disappearance of the star one observed repeated light attenuations, which one interpreted as attenuation by four rings. Today 13 rings and 27 moons are known (end of 2006). The brightest ring is called ϵ-ring. The ring particles consist of dark chunks up to 10 m in diameter. In 2005 with the Hubble Space Telescope Uranus moon *Mab* was discovered and this moon appears to dissolve from meteorite impacts, providing material for new rings (fine ice crystals). The five largest moons range in size from 500 to 1600 km. The ring system of Neptune is still little explored, there seem to be thickenings—by gravitation of the moon *Galatea.* The rings were named after *Adams, Le Verrier, Galle, Lassel* and *Arago* .

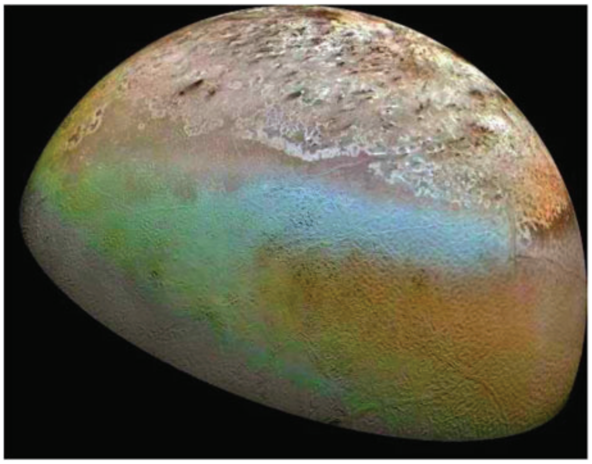


Fig. 6.43 Neptune's moon Triton (NASA/Voyager 2)

Neptune has 13 moons. The Neptune moon *Triton* (Fig. 6.43) was found 17 days after the discovery of Neptune. It has an atmosphere as well as volcanism. The diameter is 2720 km and the density $2.1\,\mathrm{g/cm^3}$. It is probably consists of 75% rock and 25% water. The surface temperature is between 35 and 40 K. The atmosphere consists of N_2-steam. The lava (cryovolcanism) here consists of H_2O and NH_3. The distance to Neptune is about 350,000 km. It orbits Neptune in five days 21 h retrograde (i.e., opposite the direction of rotation), and the orbital inclination to the equatorial plane of Neptune is 156°. It is thought that it will be torn apart in about 100 million years due to the large tidal forces, and the particles will then give Neptune a spectacular ring system.

Triton has an extremely thin atmosphere consisting of 99% nitrogen, with a pressure of only 1/70,000 of that of Earth's atmosphere. Solar radiation causes convection currents and geyser-like eruptions at the surface. Similar to the dwarf planet Pluto, Triton's surface is 55% frozen nitrogen, 35% water ice, and 20% CO_2-covered by ice. Due to the strong inclination of the rotation axis, the poles are alternately illuminated by the sun, similar to the planet Uranus.

The *Cantaloupe terrain* (Fig. 6.44) consists of craters flooded with dirty ice. However, these craters, about 30 km in size, are unlikely to have been formed by impacts, but rather by Cryovolcanism.

In 2006, at the Lagrange point L_4 four Neptune Trojans were found. At L_5 no objects have been found yet.

> Jupiter and Saturn (about 10 times Earth's size) are also called gas giants, Uranus and Neptune (about 4 times Earth's size) are called ice giants.

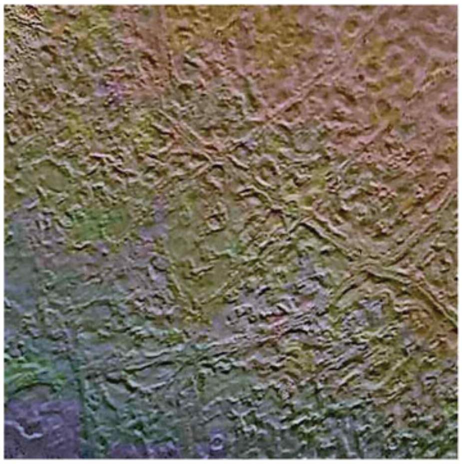


Fig. 6.44 The cantaloupe terrain on Triton (NASA/Voyager 2)

6.8 Dwarf Planets and Asteroids

Since the decision of the International Astronomical Union in the summer of 2006, there a new group of objects was defined in the solar system: the *dwarf planets* Pluto is also counted as one of them.

Dwarf planets are defined as follows: Their masses are enough to make their shape approximately spherical, but unlike planets, they do not have their orbits cleared of other objects.

6.8.1 Pluto

Pluto is very similar to Triton. It was detected on February 18, 1930 by *C. W. Tombaugh*. Its orbit is around 17° inclined against the ecliptic, and it has a large orbital eccentricity ($e = 0.24$). Its distance from the Sun therefore varies between 4.4 billion and 7.3 billion km and its magnitude between magnitudes 13.6 and over 16. It was inside Neptune's orbit until February 11, 1999, and has been outside since then, reentering inside Neptune's orbit on April 5, 2231. To orbit the Sun Pluto requires 248 years. In 1978, the Pluto moon *Charon* was discovered. This moon moves retrograde around Pluto (distance is only 20,000 km) and has a diameter of 1200 km. The diameter of Pluto is 2200 km (so it is smaller than our moon). The density is 2.1 $\mathrm{g/cm^3}$ and from the high reflectivity of the surface one assumes there frozen CH_4 as well as NH_3 with surface temperatures at 50 K (aphelion) and 60 K (perihelion). It has an atmosphere of CH_4 and N_2. The measured Bond's albedo is 0.14 for Pluto (0.31 for Earth). The axis of rotation is inclined by 122°, so it rotates retrograde. The mass is only 0.0021 Earth masses. Pluto rotates around its own axis in 6.3 days. The HST was used to discover two tiny Pluto moons, Nix and Hydra, in 2005

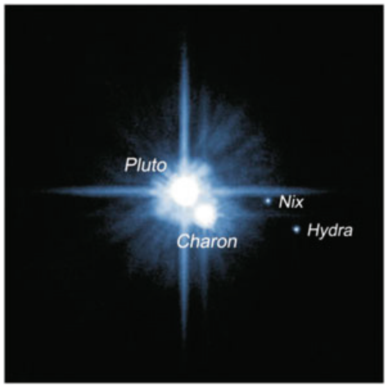


Fig. 6.45 Pluto with its moons Charon, Nix, and Hydra (HST telescope image)

Fig. 6.46 The first time Pluto was studied at close range by the New Horizons probe in 2015 (NASA)

(estimated diameters between 40 and 160 km). In 2011 and 2012, respectively, another tiny satellite of Pluto was discovered (Fig. 6.45).

Pluto has a very thin predominantly nitrogen atmosphere.

Pluto and Charon are in a Synchronous rotation, caused by the tidal effect; both objects always show the same side to each other.

In 2006 the probe *New Horizons* was sent to the Pluto system; it arrived there in 2015. In 2007, the probe flew by Jupiter and took data. For example, the eruption of a volcano on *Io* was observed (Fig. 6.46).

Pluto was reached in the summer of 2015 (Figs. 6.47 and 6.48). New Horizons flew past this dwarf planet at a distance of 12,500 km. Because of the large distance Earth–Pluto the data could not be transmitted directly, but had to be stored temporarily on an 8 Gb memory.

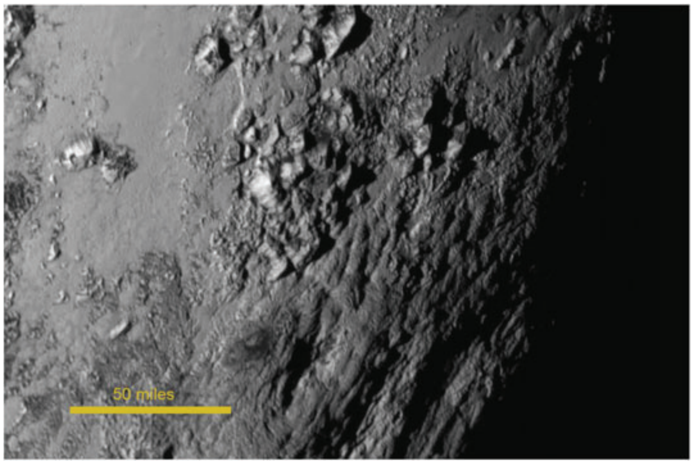


Fig. 6.47 Ice-covered mountains on Pluto's surface (New Horizons/NASA)

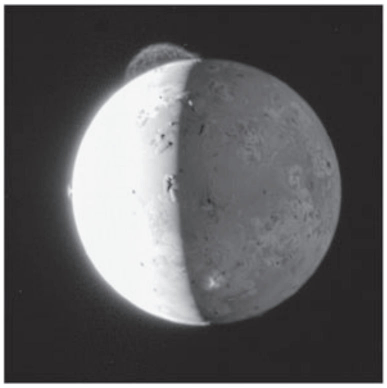


Fig. 6.48 Eruption of a volcano in February 2007 on Jupiter's moon Io, observed by the New Horizons probe en route to Pluto (NASA)

The data transfer took place between 05/09/2015 and 25/10/2016 and thus the data transfer took more than a year.

Outside of Neptune's orbit, there is the *Kuiper belt,* which consists of many thousands of objects (asteroids, comet nuclei). Pluto is one of the brightest objects of them. Also the moon Triton captured by Neptune might have been a member of this belt.

Kuiper Belt objects will be other targets of the New Horizons mission.

6.8.2 Ceres and Other Dwarf Planets

Ceres was discovered in 1801 by *G. Piazzi* and is the largest object in the *Asteroid belt* between Mars and Jupiter. The orbital semimajor axis is 2.77 AU, the sidereal orbital

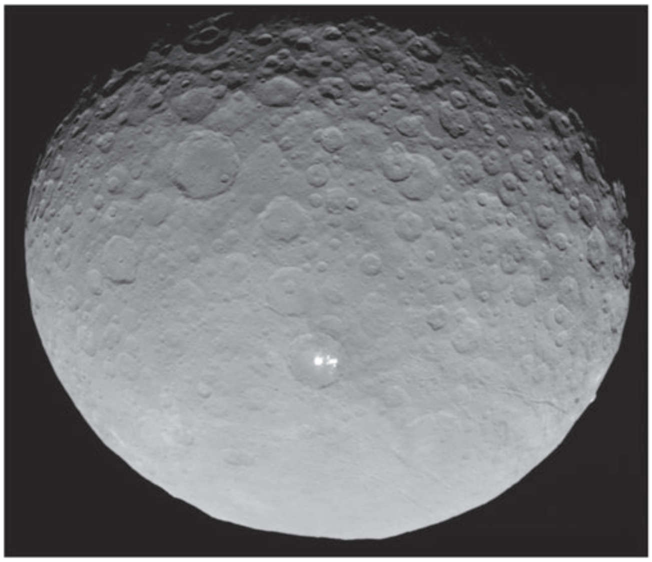


Fig. 6.49 Ceres with two bright spots (NASA/Dawn mission)

period 4.6 years. The mean equatorial diameter is 975 km. This dwarf planet was observed by the Dawn spacecraft in 2015 from a distance of 13,000 km. Ceres has about 1/4 of the total mass of all objects in the asteroid belt. The bright spots found are probably salt deposits (Fig. 6.49). Ceres has a rocky core surrounded by a mantle of minerals and water ice. On the surface is a dusty thin crust. During the radioactive decay of the aluminum isotope ^{26}Al could have formed a mantle of liquid water in the early days of the solar system, except for the outer crust which is about 10 km thick. With the IR telescope *Herschel* one could detect *Water Vapor* around Ceres, a water release of about 6 kg/s takes place at two locations on the surface. The water release is greatest when Ceres is close to the Sun in its elliptical orbit. Aliphatic *Carbon compounds* on Ceres have also been detected.

Further dwarf planets are the objects *Sedna* ($\approx$1400 km, strongly eccentric orbit, perihelion distance 76 AU, apohelion distance 900 AU, orbital period around Sun 10,787 years, strongly reddish color). Another object is *Quaoar* , diameter $\approx$1250 km, semimajor axis 43.5 AU, with the 8-m Subaru telescope in 2004 crystalline water ice was detected on its surface—an indication of internal water sources kept liquid by radioactive decay heating. *Eris* (also as Xena larger than Pluto) has a diameter of 2400 km, perihelion distance 37.8 AU, apogee distance 97.5 AU.

In August 2001, the European Southern Observatory (ESO) discovered a minor planet even larger than Ceres; the object was given the provisional designation 2001 KX76 and has a diameter between 1200 and 1400 km. The mean distance of this object from the Sun is more than 1.5 times that of Neptune. Its size corresponds to that of the Pluto moon Charon, and the object belongs to the Kuiper belt.

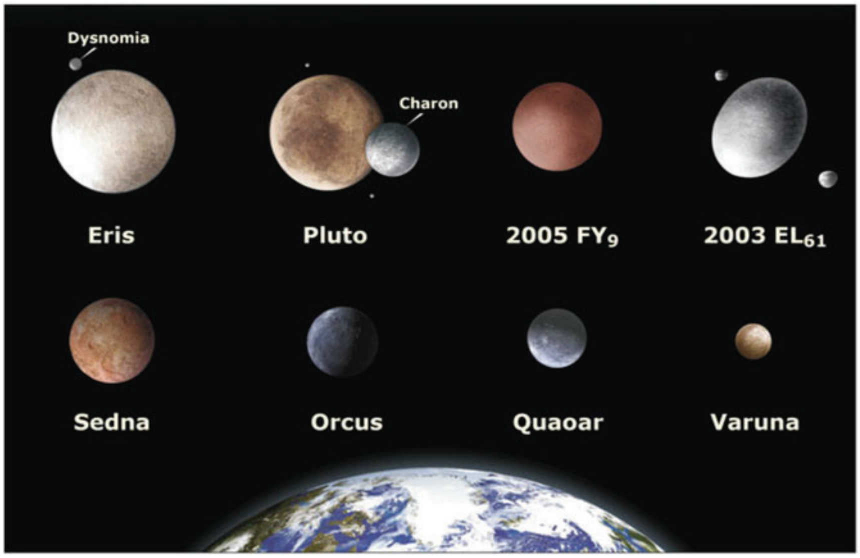


Fig. 6.50 Known dwarf planets and size comparison with Earth (NASA sketch)

In 2008 the dwarf planet *Makemake* (diameter 1500 km, it also has a moon) was found in the Kuiper belt, as well as *Haumea* which should be strongly oblate because of the rapid rotation (equator diameter 2200 km, pole diameter only about 1100 km). In the asteroid belt is likely to be located next to Ceres Object the object *Hygiea* (diameter 430 km) (Fig. 6.50).

The dwarf planets Pluto (thin atmosphere) and Ceres (water ice) showed unexpected details.

6.8.3 Asteroids: Naming and Types

We now come to the asteroids or minor planets. Their exact number can only be estimated, but is certainly several 100,000 objects. Their arrangement in belts is striking. Some asteroids also cross the Earth's orbit and could collide with the Earth at some point.

After the discovery of *Ceres* in 1801, 300 objects were already known around 1890 with orbits between Mars and Jupiter, all smaller than 1000 km (Figs. 6.49 and 6.50).

The *Designation* of newly discovered asteroids is done today with a combination of letters. The first letter marks the month half of the discovery (thus 24 letters, A–Y, without I), and then follows after the order of the discovery the second letter A–Z (without I). Ex:

Table 6.9 The four Galilean moons of Jupiter

Name	Diameter [km]	Mass Earth moon = 1	Density [g/cm^3]	Reflection [%]
Callisto	4820	1.5	1.8	20
Ganymede	5270	2.0	1.9	40
Europa	3130	0.7	3.0	70
Io	3640	1.2	3.5	60
Earth's moon	3476	1.0	3.3	12

Table 6.10 Data of the largest minor planets

Name	Discovery	Major semimajor axis [AU]	Diam. [km]	Class
Pallas	1802	2.77	540	C
Vesta	1807	2.36	510	–
Hygeia	1849	3.14	410	C
Interamnia	1910	3.06	310	C
Davida	1903	3.18	310	C
Cybele	1861	3.43	280	C
Europe	1868	3.10	280	C
Sylvia	1866	3.48	275	C
Juno	1804	2.67	265	S
Psyche	1852	2.92	265	M

2006 AB is the second object (letter B) found in the first half of January (letter A) 2006. If these combinations are not sufficient, simply write a number (Table 6.9).

About 300,000 asteroids are known. 14 asteroids (or minor planets or planetoids) are larger than 250 km (Table 6.10). The *total mass* of all asteroids but is much smaller than that of the Moon, so they were not formed by the breakup of a large planet. The *Asteroid Belt* is located between 2.2 and 3.3 AU, and accordingly the orbital periods around the sun are between 3.3 and 6 years. 75% of all minor planets are located in this belt, nevertheless the average distance between them is more than 1 million km. It is therefore safe to cross the asteroid belt with a space probe.

> Most asteroids are arranged in belts (e.g. between Mars and Jupiter), some also cross the Earth's orbit.

Regarding asteroid group composition, asteroids are divided into three *groups*:

- C asteroids: carbon-rich, e.g. *Ceres* (now, however, defined as a dwarf planet) or *Pallas.*
- S asteroids: rocky; there are no dark carbon compounds, and thus higher albeda (reflectivity 16%, like Earth's moon); consist of silicate compounds.

- M asteroids: *Psyche* is the largest of the M-type. Consist of metals. Just one 1-km M asteroid could supply the world's consumption of industrial metals for decades.

Vesta orbits the sun in 2.4 AU and has a reflectivity of 30%, so it is very bright, and if you know exactly where this minor planet is, it can be observed with the naked eye. Its surface is covered with basalt, which means that the minor planet must have been volcanically active at one time. In any case, this is probably where Differentiation process had taken place. The minor planet had melted, and the heavier elements sank downward as a result of gravity. The group of *Eucrite meteorites* may have originated from Vesta. In 1991 the Spacecraft Galileo radioed close-up images of an asteroid to Earth for the first time: *Gaspra.* It's an S asteroid. The surface is only about 200 million years old, i.e. this object was formed from a collision 200 million years ago from a larger minor planet.

In 1917 *Hirayama* put forward the thesis that there are families of minor planets and each family was formed by explosion or collision of a larger object.

For some asteroids companions have been found (i.e. asteroid *moons*): 243 *Ida* has a small companion *(Dactyl)* (Fig. 6.51), which was found during the *Galileo mission*. The object 4179 *Toutatis* consists of two pieces with diameters of 2.5 and 1.5 km respectively. On September 29, 2004, it came within 1.5 million km of Earth. One of the goals of the Galileo Mission was also to send a probe into Jupiter's atmosphere and an orbiter around Jupiter. The probe was released on the STS-34 mission on 18.10.1989, and a VEGA course was followed. VEGA stands for "Venus-Earth Gravity Assist". So the probe was first sent to the interior of the solar system and then received gravity assists from Venus and passed Earth twice at two-year intervals. On its way to Jupiter, the probe passed through the asteroid belt, where the asteroids Gaspra and Ida were observed, and—as already mentioned—it was able to observe the impact of the fragments of comet Shoemaker

Fig. 6.51 Asteroid Ida with moon Dactyl (right) (NASA)

Levy on Jupiter. Power was supplied by RTGs (Radioisotope Thermal Generators), which provided 570 W.

On 12 February 2001 the mission *NEAR/Shoemaker* landed on the minor planet *Eros*. First the probe approached the small planet up to 26 km, then the descent and a landing with a touchdown speed of 1.5 m/s took place. A gamma ray spectrometer was used to analyse the surface for seven days. The temperatures at the Eros surface at the time of landing were around $-150\,^\circ$C.

In 2005, a Japanese spacecraft took samples from the asteroid *Itokawa* and in 2010 a capsule carrying these samples landed on Earth.

In 2007, the spacecraft *Dawn* was launched. Dawn flew past Mars in 2009 *(Gravity Assist)* and was thereby placed in orbit toward *Vesta*, where it arrived on July 16, 2011 (Fig. 6.52). Images of Vesta's surface show one of the highest mountains in the solar system in the southern hemisphere. Moreover, this area is only 1–2 billion years old, much younger than the northern hemisphere. This conclusion is arrived at simply by crater counting. Fewer craters means younger surface. The Dawn spacecraft used *ion propulsion*; xenon ions are accelerated by an electric field and the outgoing ion beam accelerates the probe. In this process, the ion propulsion system was in operation for almost 70% of the entire journey time. Per day about 250 g of xenon were consumed, a total of 450 kg Xenon was in the tank.

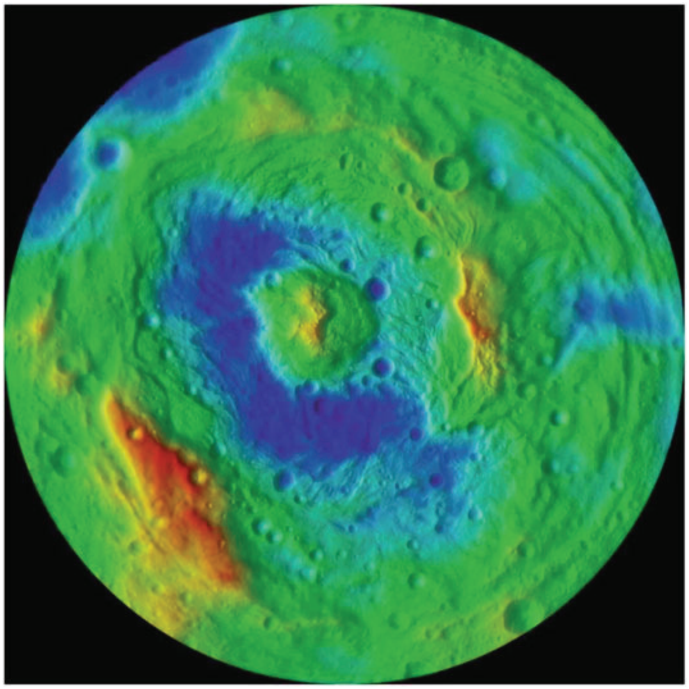


Fig. 6.52 Asteroid Vesta. False-color image shows distinct structures on the surface (NASA/Dawn)

6.8.4 Distribution of Asteroids

The asteroids in the main belt between Mars and Jupiter show peculiarities regarding their distribution, which can be explained by resonances: There are gaps or clusters of minor planets at those distances where the orbital period is in a *commensurable* (integer) ratio to Jupiter's orbit.

- *Gaps* occur at 2:1 (Hecuba gap), 3:1 (Hestia gap), 5:2, 7:3;
- *Accretions* at 1:1 (Trojan), 3:2 (Hilda) 4:3 (Thule) (4:3 means, for example, that the duration of 4 minor planet orbits around the Sun is equal to the duration of 3 Jupiter orbits around the Sun).

The group of *Trojan asteroids* has the same distance as Jupiter from the Sun (5.2 AU). They are located at Lagrange points L4 and L5, i.e. they always form an equilateral triangle with Jupiter and the Sun. In 1990 a similar family of minor planets was found near Mars. Furthermore there are asteroids with special orbits. *Hidalgo* has a large semimajor axis of 5.9 AU and an eccentricity of 0.66. Its farthest point from the Sun (aphelion) lies outside Saturn's orbit. *Chiron* has a large orbital semi-axis of 13.7 AU, and its perihelion lies outside Saturn's orbit, its aphelion outside Uranus' orbit.

Especially interesting for us on earth are *earth crossing asteroids.* About 200 objects are known, with the total number of all objects larger than 1 km estimated at 2000. They can either collide with the terrestrial planets or be accelerated so strongly that they are ejected from the inner solar system. Such an event occurs every 100 million years. One-third of all Earth-orbiting minor planets are likely to crash into Earth, and observational programs are therefore in place to detect all such objects, preferably combined with early warning. The asteroid *Icarus* dips into Mercury's orbit (its perihelion is at 0.19 AU). The objects coming very close to the Earth, *Apollo objects*, are listed in Table 6.11.

Since the minor planets are irregularly shaped, there is a change in brightness as a result of their rotation.

The asteroid 2002 AA discovered in 2002AA$_{29}$ has a diameter of about 50−110 m. Its orbit is very similar to Earth's orbit, and it crosses it at aphelion. Also the asteroid discovered in 1986 Cruithne is in a 1:1 resonance with the Earth's orbit. One also speaks of coorbital objects.

Table 6.11 Some Apollo objects

Object	Minimum distance to Earth
Eros	0.15 AU
Apollo	0.07
Adonis	0.03
Hermes	0.004 = 2 times the distance to the moon

Table 6.12 Dates of known NEOs. *Date* means the time of closest approach to Earth, where distance is the distance that will occur at that time

Designation	Date	Distance in AU	diam. m	Circulation a
1998 WT24	16.12.2001	0.0124	1250	0.61
4660 Nereus	22.01.2002	0.0290	950	1.81
1998 FH12	27.06.2003	0.0495	680	1.14
1994 PM	16.08.2003	0.0250	1200	1.80
1998 FG2	21.10.2003	0.00360	220	1.48
1996 GT	12.11.2003	0.0479	860	2.10
1998 SF 36	25.06.2004	0.0137	750	1.53
4179 Toutatis	29.09.2004	0.0104	2400–4600	1.10
1992 UY4	08.08.2005	0.0404	110	4.33
4450 Pan	19.02.2008	0.0408	1570	3.00
1999 AQ10	18.02.2009	0.0118	360	0.91
1994 CC	10.06.2009	0.0169	1100	2.09
1998 FW4	27.09.2013	0.0075	680	3.95
1998 WT24	11.12.2015	0.0277	1250	0.61
4660 Nereus	11.12.2021	0.0263	950	1.82
7482 1994 PC1	18.01.2022	0.0132	1900	1.56
7335 1989 JA	27.05.2022	0.0269	2000	2.35

6.8.5 NEOs

At the acronym NEO (Table 6.12) means *Near Earth Objects,* i.e. objects which are close to the Earth or which could come close to the Earth (associated with this is also the designation *PHAs,* Possible Hazardous Asteroids). With the so-called *Torino Scale* a kind of Richter scale has been established, which is supposed to give an estimate of what an impact of a certain object on Earth could cause. When a new NEO asteroid or comet is discovered, the orbit calculations are still mostly uncertain, but most calculations show that a collision with Earth is unlikely. The levels range from 0 to 10, with 0 meaning that the probability of a collision with Earth is extremely low or that the object will burn up in the atmosphere. 10 means a collision is certain and it will have catastrophic global climate impacts. The color scale means

- White: No practical implications.
- Green: One should monitor the orbit of these objects.
- Yellow: One should be careful; objects should be monitored more closely to better calculate their orbits.
- Orange: Threatening objects; one should immediately calculate their paths more accurately.
- Red: It is best to provide yourself with enough wine or beer. . . .

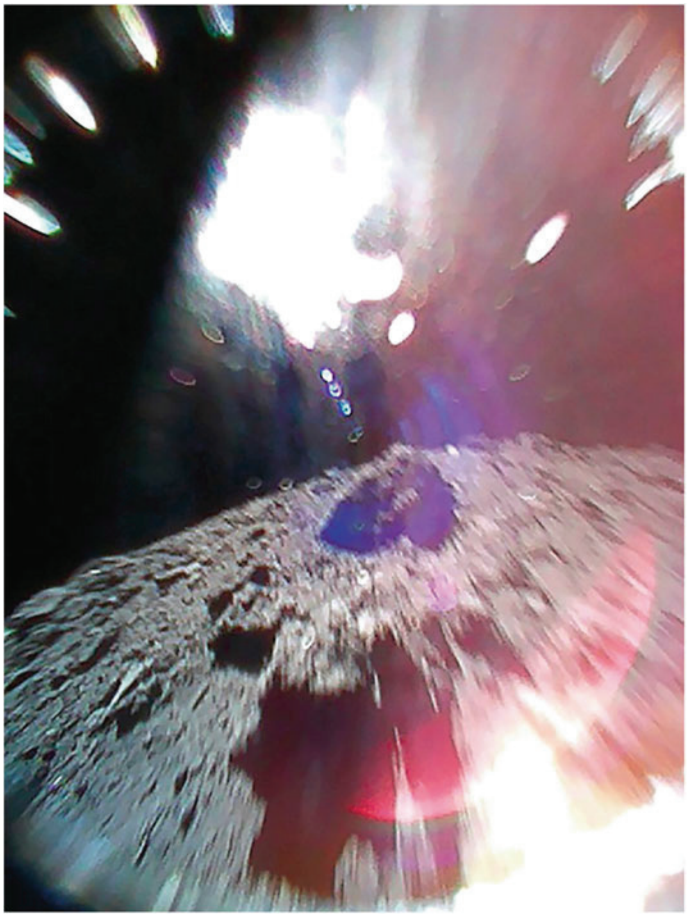


Fig. 6.53 Image taken when the spacecraft bounced on the asteroid Ryugu (Photo: JAXA)

Important: The assessment of an object according to the Torino scale can change with time, when more precise observations are available.

The object 4660 *Nereus* comes very close to us on 2060–02–14: The closest distance is only 0.008 AU. The minor planet 433 *Eros* (Extension 33 km× 13 km) passed us on 31.01.2012 in only 0.179 AU.

In late September 2018, a Japanese space probe (MASCOT) landed on asteroid *Ryugu.* Due to the asteroid's low gravity the spacecraft explored its surface by hopping—equipped with a special suspension (Fig. 6.53). The asteroid is only about 1 km in size. This asteroid can come as close as 90,000 km to us and is one of the potentially dangerous asteroids, as it could one day collide with Earth.

Table 6.13 Large known Impact crater on earth. Diam denotes the diameter in km

Name	Location	Geograph. latitude	Geograph. longitude	Age 10^6 a	Diam.
Vredefort	South Africa	27.0 S	27.5 E	2023	300
Sudbury	Canada	46.6 N	81.2 W	1850	250
Chicxulub	Mexico	21.3 N	89.5 W	65	170
Manicougan	Canada	51.4 N	68.7 W	214	100
Popigai	Russia	71.7 N	111.7 E	35	100
Chesapeake B.	USA	37.3 N	76.0 W	36	90
Acraman	Australia	32.0 S	135.5 E	590	90
Puchez-Ktunki	Russia	57.1 N	43.6 E	175	80
Morokweng	South Africa	26.5 S	23.5 E	145	70
Kara	Russia	69.2 N	65.0 E	73	65
Beaverhead	USA	44.6 N	113.0 W	600	60
Tookoonooka	Australia	271. S	142.8 E	128	55
Charlevoix	Canada	47.5 N	70.3 W	357	54
Kara-Kul	Tajikistan	39.0 N	73.5 E	5	52
Siljan	Sweden	61.0 N	14.9 E	368	52

In the past, there have been repeated impacts of such objects on Earth (associated with the extinction of many species). Traces of large impact craters are also found on Earth, although here, of course, erosion is rapidly blurring them (Table 6.13).

The *Chicxulub crater* is the remnant of an asteroid impact 65 million years ago. This event is thought to be responsible for the extinction of the dinosaurs.

6.9 Comets

Comets have always been considered special celestial phenomena, especially since they appear suddenly and do not move along the ecliptic in the sky. They were usually considered harbingers of a near disaster.

6.9.1 Comets: Basic Properties

Comet sightings is already found in records from ancient times. *Halley* recognized that the comet sighted in 1531, 1607, and 1682 was always the same one, reaching its closest point to the sun every 76 years. The first sighting dates back to 239 B.C., and the last sighting was in 1986. In 2061, Halley's comet will again be seen in the sky.

Table 6.14 Data of some known short-period comets. a = large semi-axis

No.	Name	Circulation-period	Perihel-passage	Perihelion distance	a [AU]
1P	Halley	76.1	09.02.1986	0.587	17.94
2P	Encke	3.3	28.12.2003	0.340	2.21
6P	d'Arrest	6.51	01.08.2008	1.346	3.49
9P	Temple 1	5.51	07.07.2005	1.500	3.12
21P	Giacobini-Zinner	6.52	21.11.1998	0.996	3.52
73P	Schwassmann-Wachmann 3	5.36	02.06.2006	0.937	3.06
75P	Kohoutek	6.24	28.12.1973	1.571	3.4
	Hale-Bopp	4000	31.03.1997	0.914	250
	Hyakutake	40,000	01.05.1996	0.230	≈1165

Fig. 6.54 Comet Hyakutake

There are relatively many comets whose aphelia lie near the orbit of Jupiter; they are referred to as the *Jupiter family.* Jupiter's gravitational effects have turned long-period comets into short-period ones (Table 6.14 and Fig. 6.54).

Comets consist of:

- *Nucleus:* 1–50 km in diameter. *Whipple* established the model of a dirty snowball around 1950: Water vapor and other volatiles escape from the nucleus to form the characteristic comet tail. This happens once a comet is within the orbit of Mars. The nucleus of Halley's comet is 8 km by 12 km. The evaporation is not uniform, and it comes to unexpected eruptions.

- *Coma:* extension about 10^5 km.
- *Dust tail* and *ion tail*: extension many million km.

The atmosphere of a comet consists mainly of H_2O and CO_2. UV radiation from the Sun breaks up the water molecules and huge H clouds form around the comet. Comet tails always point away from the Sun. The comet's dust tail is directed away from the Sun by the light pressure of sunlight, but the ion tail (usually bluish) is directed directly by the solar wind. The ion tail is long and narrow, the dust tail is broad and diffuse and often curved; because of its lower velocity, the dust lags behind in the comet's orbital motion (the ejected particles travel in Keplerian orbits around the Sun, particles farther away from the comet slower than particles near the comet, hence the curvature).

The actual comet nucleus is only a few tens of km in size, but the tail can extend over several million km.

Comets can break up: in 1976, comet *West* broke into four pieces. The comet *Shoemaker Levy* broke up 1993 into 20 pieces, which impacte onto Jupiter in 1994 with an energy release of 100 million megatons of TNT. This event could already be followed on Earth with amateur telescopes. The energy released was equal to that of the impact on Earth 65 million years ago.

The naming of comets is confusing: first with a year with a small letter in the order of discovery, then with a year and Roman numeral in the order of perihelion passage. Short-period comets still get a P: 1810 II-P/Halley. The discoverer is at the very end.

The brightness of a comet depends on the distance comet-sun (r) and the distance comet-Earth (Δ):

$$h = \frac{H}{r^2 \Delta^2} \tag{6.42}$$

h—Intensity of observed brightness, H—absolute brightness at $r = \Delta = 1$.

The *GIOTTO mission* was launched on July 2, 1985, with the goal of studying Comet Halley. The closest approach to Halley (Fig. 6.55) occurred on March 13, 1986, at a distance of only 600 km from the nucleus. The probe was equipped with a dust shield. 14 s before the closest approach, the probe was hit by a large dust particle from the comet, and during 32 min there were disturbances in the data recordings.

Comets Encke and d'Arrest were to be visited as part of the CONTOUR mission, but the probe exploded in 2002 just six weeks after launch.

Fig. 6.55 Halley comet nucleus (Image ESA/GIOTTO)

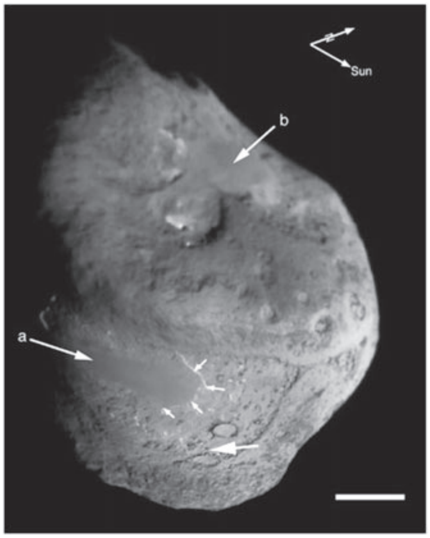


Fig. 6.56 Comet Temple 1 with impact site marked by thick arrow. The white line on the lower right marks 1 km (Photo: NASA/UM M. F. A'Hearn)

In July 2005, the probe *Deep Impact* bombarded comet *Temple 1* (Fig. 6.56) with a piece weighing 370 kg. The impact created a crater, and the ejected material was analyzed. Organic material was also found inside the comet, and the first definite evidence of water at the comet surface. The target of the 2004 launched ESA's *ROSETTA mission* was comet *67 67P/Churyumov-Gerasimenko*. After flybys of two asteroids (*Steins,* 2008; *Lutetia* 2010),

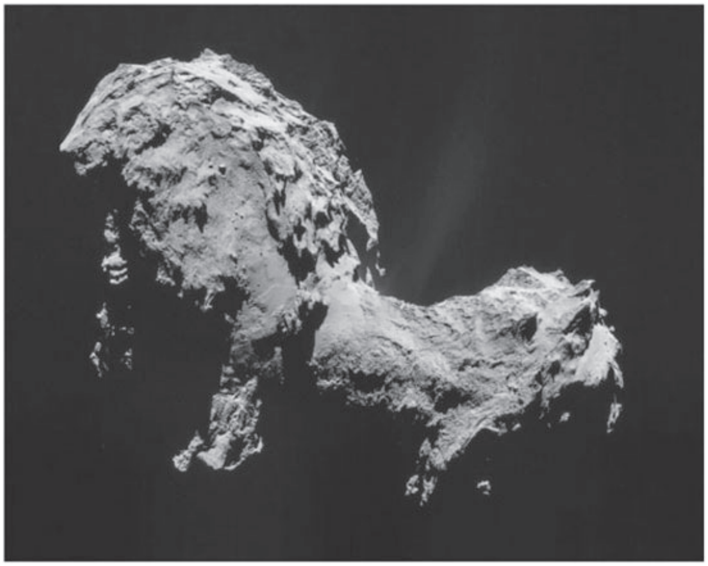


Fig. 6.57 Close-up view of comet 67P/Churyumov-Gerasimenko, September 19, 2014 (Rosetta/ESA)

the Lander *Philae* landed on its surface (Nov.12, 2014). Detailed images of a comet's surface that had never been obtained before (Fig. 6.57) were send to earth.

6.9.2 Kuiper Belt and Oort's Cloud

In 1943. *K. Edgeworth* was the first to suggest the existence of a belt consisting of numerous comets outside Pluto's orbit. *G. Kuiper* then studied it in more detail in 1951, and in 1980, calculations were made to prove that this belt of objects was a source of short-period objects. Then, in 1992, the first member of the Kuiper belt was found: *1992 QB1(D. Jewitt* and *J. Luu).* The object had an apparent magnitude of $22.^{m}5$ and was discovered with a 2.2-m telescope on Mauna Kea. The dwarf planet Pluto is located within this belt. 1992 QB1 has a diameter of 283 km, and the orbit has a semi-axis of 44.0 AU. In addition, there are also so-called plutinos (this term should be abolished again), which are objects with orbits similar to Pluto's. At present more than 100 objects are known in the Kuiper belt.

One can divide the members of the Kuiper belt into:

- Classical objects: 2/3 of all objects observed so far, $42 < a < 47$ AU, no resonances.
- Resonance objects: Mostly a 3:2 resonance with Neptune; they orbit the Sun twice in three Neptune orbits (they are also called plutinos, because Pluto also has a similar orbit).

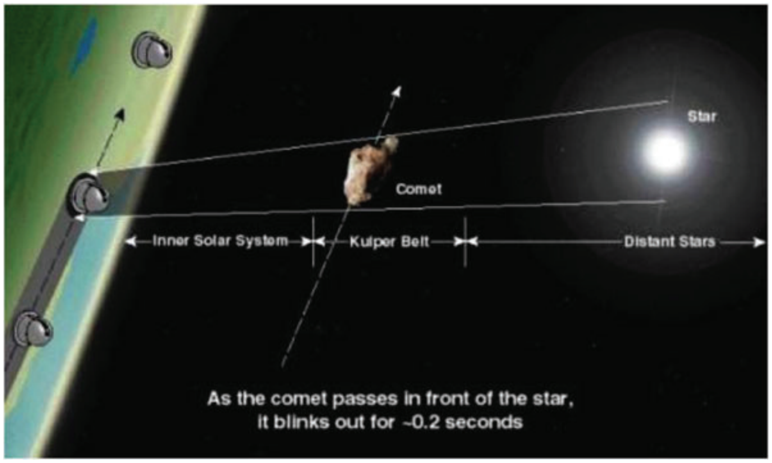


Fig. 6.58 The TAOS project for automatic detection of Kuiper belt objects (Credit: TAOS)

- *Scattered Kuiper Belt Objects (KBO):* These are likely to be on extreme orbits, but only a few objects have been discovered so far, including TL66 in 1996; it has an aphelion distance of 84 AU and a perihelion distance of 30 AU, and its orbital period is 800 years.

The total number of objects larger than 100 km in the Kuiper belt is estimated to be 100,000. The TAOS project (Fig. 6.58) is trying to find these objects. Three small robotic telescopes have been set up on Taiwan along a 7 km line, automatically targeting the same object. If there is an occultation of a star by a KBO, then this is registered with a time shift (which is, however, very small) on all three telescopes.

Between Jupiter and Neptune nine objects are known (among them 2060 *Chiron* and 5145 *Pholus*). Their orbits are unstable, i.e. they are outliers from the Kuiper belt due to gravitational interactions.

In 1950 *J. Oort* postulated the existence of a giant cloud of comets enveloping our solar system. This is based on three observational facts:

- No comet has been observed with an orbit showing that it comes from interstellar space. Thus, there are no hyperbolic velocities (In this context, hyperbolic velocity is the velocity an object would have to reach to leave the solar system).
- The aphelia of many long-period comets appear to be at a distance of 50,000 AU.
- There is no main direction of comets.

From statistics, it follows that in the Oort cloud about 10^{12} Comets could exist. However, because of the great distances involved, these objects cannot be seen directly. The total mass may be more than one Jupiter mass.

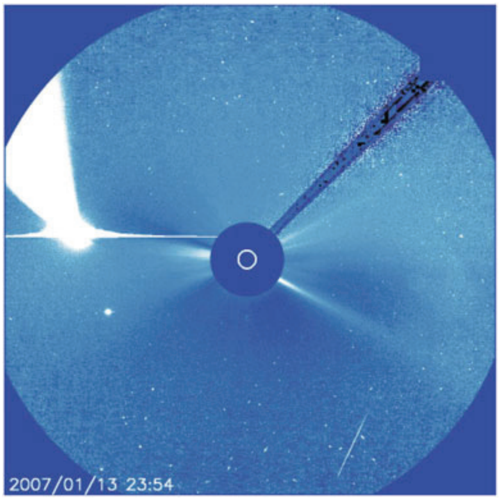


Fig. 6.59 Comet McNaught, also brightly visible for a short time in our evening and morning sky (early January 2007). Around the time of the perihelion passage it appeared on images of the solar satellite SOHO. Below the bright comet the planet Mercury is visible. The Sun itself is covered (its size is indicated by a white circular ring) (Photo: ESA/NASA SOHO Mission)

6.9.3 Sungrazer

These are comets that come very close to the Sun (Fig. 6.59). Some move through the corona of the Sun. The SOHO probe (launched in 1995), built to study the Sun, has found about 1000 such objects so far. Their total number is likely to be well over 10^5. They are often torn apart by the strong tidal forces of the Sun. Most of them are only small fragments of a few meters in diameter. The Kreutz Group comes from the disintegration of a larger comet. A large comet passed by the Sun in 1860 at a distance of only 200,000 km. The last bright comet in this group was White-Ortiz-Bolelli in 1970. A very bright comet apparition of objects in this group is thought to occur on average every 20 years.

6.10 Meteoroids

We now come to the smallest objects in the solar system. Their study is important because the matter and structure have changed little since the formation of the solar system.

6.10.1 Nomenclature

We make the following distinctions:

- Meteor: light appearance when a body enters the Earth's atmosphere.

  One can calculate the mass M of a meteor as a function of the geocentric velocity v and the brightness m in the zenith:

$$\log M = 3.6 - 0.4\,m - 2.5 \log v \tag{6.43}$$

- Meteoroid: matter orbiting the sun, in interplanetary space; goes up to micrometeoroids.
- Meteorite: meteoroid that reached the earth's surface.
- Shooting stars: small meteors.
- Fireballs: large meteors.

The parabolic heliocentric velocity of meteoroids at the location of the Earth is 42 km/s. The orbital velocity of the Earth around the Sun is 30 km/s. Therefore, the relative velocity reaches up to 72 km/s. Meteors can therefore be observed in the morning, when the relative velocity is greatest, or in the evening, when it is small. The *meteoroids* are not attracted by the earth, but there is a collision with the earth. Due to the high velocity, melting and burning up occurs as the meteor enters the Earth's atmosphere. In order to see a meteor, it must be within 200 km of the observer. On the whole earth about 25 million meteors fall per day. The typical mass is only 1 g. A *fireball* is already about the size of a golf ball. Per day 100 t of meteor material fall on the earth's surface. The strong deceleration and the flashing occurs at an altitude of 140–100 km, and they extinguish between 90 and 20 km. An ionized air tube is formed which reflects electromagnetic waves, and thus meteors can be observed by radar echoes even during the day and when it is cloudy.

6.10.2 Classification

A subdivision according to origin and orbital shape is made:

- Planetary meteorites: 50%, elliptical orbits of short orbital period, fragments from the asteroid belt.
- Meteorites with near-parabolic orbits: 30%, unknown origin, but certainly from the solar system.
- Cometary meteorites: 20%, from the dissolution of comets. These dissolution products spread along the orbit, and when Earth's orbit and the original comet's orbit intersect, then meteor showers can be observed *meteor showers* (about 50 known). The best known meteor streams are the *Leonids* (maximum 16.11, rest of comet 1866 I), *Perseids* (11.8, remnant of comet Temple-Tuttle) and the *May Aquarids* (5.5, remnant of comet Halley). They are named after the constellation where the point *(radiant)* from which they seem to come from is located. The effect of meteor streams coming from a point in the sky is the same as dense snowflakes hitting the windshield of a moving car.

Larger chunks melt only up to 1 mm and then fall to earth = meteorites. There are 700 finds, whose fall down was observed, and again as many, whose fall down could not be observed. One divides the meteorites into:

- Iron meteorites, where there are the metal meteorites (pure Fe and Ni) and the sulfide meteorites: FeS. . .

- Stony meteorites: SiO_2, MgO, FeO . . ..
- Tektite: glass meteorites, mainly SiO_2. Often roundish or circular in shape. They are found only in certain areas (Moldavite in Bohemia).

Other classification:

- Undifferentiated meteorites (chondrites).. They contain about 1 mm large silicate spheres (chondrules); there are also the carbonaceous chondrites.
- Differentiated meteorites: achondrites, metal-rich meteorites.

With masses, which are larger than 10 t and fall to earth, an impact crater is formed: One knows 13 craters with found meteorite. Very well known is the *Arizona crater:* diameter 1 200 m, 170 m deep, impact 60,000 years ago; diameter of Fe-Ni meteorite may have been 50 m, mass 150,000 t and explosion equivalent to 2.5 megatons of TNT (150 Hiroshima bombs); *Nördlinger Ries:* Diameter 20 km, impact 14 million years ago, the meteorite had a diameter of 1 km. In 1908, in Siberia (Tunguska) a bright fireball was observed and within a radius of 70 km the forest was destroyed. However, no meteoritic material was found. Most likely, this was the impact of a comet, which vaporized.

In the case of very small particles (micrometeorites) the air resistance is so high that the particles do not burn up but float to the ground and form deposits.

The iron meteorites have a typical arrangement of their Fe-Ni crystals: If you etch them, you get the *Widmanstetter's etching patterns.*

On February 15, 2013, in *Chelyabinsk*, Russia, more than 1200 km east of Moscow, a spectacular meteorite was seen (Fig. 6.60), which coincidentally occurred a few hours before the approach of an NEO asteroid on the same day. The shock wave generated by

Fig. 6.60 On February 15, 2013, a spectacular meteorite fall occurred in Russia, which was photographed and filmed by many people

the impact of the fragments caused glass fragments from shattering window panes and more than 1000 people were injured. The object, which was about 20 m tall and weighed 11,000 t, exploded in the atmosphere at an altitude of about 23 km, and an energy of 400 kt TNT was released on impact. For comparison, the explosion of the Hiroshima atomic bomb was equivalent to that of 15 kt TNT.

6.10.3 Interplanetary Matter

Still Smaller particles ($<10\,\mu$m, $<10^{-8}$ kg) are summarized as interplanetary dust. In spring, shortly after sunset in the west, or in autumn, shortly before sunrise in the east, because the ecliptic is steeply upward in our latitudes, a faint cone of light can be seen along the ecliptic, the *Zodiacal light.* This is caused by the reflection and scattering of sunlight by 10–80 μm large particles. Opposite the sun one observes the Gegenschein. This is caused by increased backward scattering. The F-Corona is the continuation of the sun's corona (the outermost layer of the sun's atmosphere), where one can see a Fraunhoferspectrum of the sun—it is the link between zodiacal light and Corona. Due to the Poynting-Robertson effect (particles crash into the Sun in spiral orbits), there is a constant loss of mass of interplanetary matter (10^5 g/s). However, this is constantly compensated by comets and asteroids.

The interplanetary gas either comes from interstellar matter itself or is formed by diffusion from planetary atmospheres and comets. The other fraction comes from the *solar wind.* The heating of the corona accelerates it. The magnetic field is carried along, the field lines go radially outwards and are curved due to the rotation of the sun. That is why there are sectors with different field directions (cf. lawn sprinkler). The solar wind consists of currents with high velocity ($v > 650\,\mathrm{km/s}$) and low velocity ($v < 350\,\mathrm{km/s}$). Near the earth one measures a proton density of $9 \pm 6/\mathrm{cm}^3$ and a velocity of $v < 470\,\mathrm{km/s}$. The solar wind changes with solar activity, and the influence on geomagnetic disturbances depends on the velocity. The expansion continues until the kinetic pressure is equal to the interstellar total pressure . This defines the *Heliopause* (up to 80–120 AU).

On board the *Stardust mission* (launched in 1999) there were 130 Aerogel detectors,2 cm $\times$ 4 cm in size and 3 cm thick, in which decelerated interplanetary particles were trapped. Dust particles from the environment of the small planet *Anne Frank* were captured and brought back to Earth in a capsule (2006).

6.11 Origin of the Solar System

From the study of meteorites, moon rocks (which were brought to Earth by the Apollo astronauts or by unmanned Soviet probes), interplanetary dust (which was studied, for example, by the Giotto mission), the age of the solar system can be estimated: 4.55 billion years.

6.11.1 Extrasolar Planetary Systems

Today, the formation of other planetary systems is directly observed and conclusions can be drawn about the formation of our planetary system. Especially important in this context are the so-called *protoplanetary nebuale* (PPN's). With the Hubble Space Telescope, the VLT of the ESO and IR telescopes in space it is also possible to observe very young stars. Many young stars are surrounded by a gas shell, which is only a few million years old, indicating that planet formation is in progress.

An example of a protoplanetary disk is the star *Beta Pictoris,* whose disk can be observed by new observation techniques (adaptive optics, occultation of the central star) up to a distance of 25 AU from the star. The star itself is 63 light-years away from us and has a diameter of 1.4 solar radii.

In Fig. 6.61, the dimmed star or disk is seen above in visible light. The observer sees almost *edge on* (to the edge), hence the spindle-shaped form. The disk consists of small dust particles (ice, silicate particles) and glows by reflection of the starlight. Since there appears to be no matter in the area around the center, it is assumed that it was captured there by one or more planets. The lower false color image shows more structure. The luminous inner edge is slightly tilted with respect to the plane of the outer disk. This could be from gravitational influences by a planet.

More detailed information on exoplanets can be found in Chap. 16 about astrobiology.

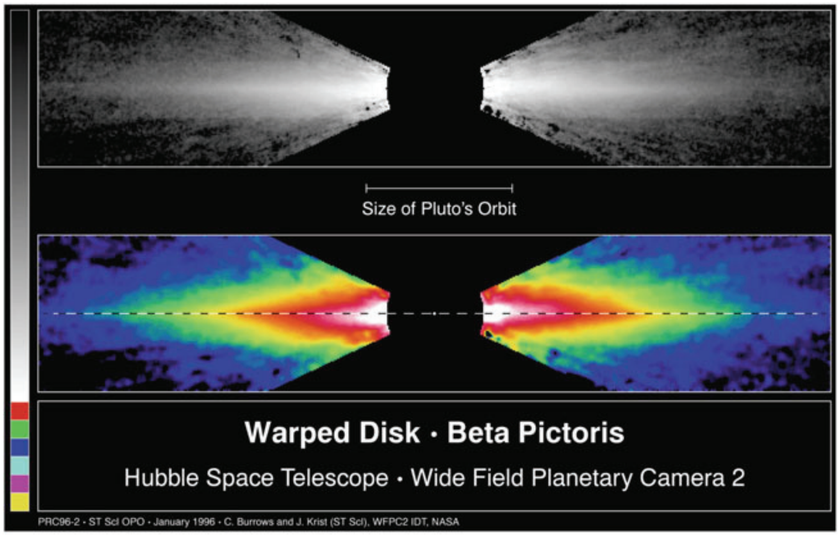


Fig. 6.61 Beta Pictoris (Image taken by HST, Wide Field Planetary Camera)

Table 6.15 Titius-Bode law: comparison between the calculated and the actual distances a in AU from the Sun

Planet	n	$a_{\text{calculated}}$	a_{actual}
Mercury	$-\infty$	0.4	0.39
Venus	0	0.7	0.72
Earth	1	1.0	1.0
Mars	2	1.6	1.52
Minor planets	3	2.8	2.9
Jupiter	4	5.2	5.20
Saturn	5	10.0	9.55
Uranus	6	19.6	19.20
Neptune	–	—	30.09
Pluto	7	38.8	39.5

6.11.2 Theories of Formation

Any Theory of the formation of our solar system must following explain special features:

1. All objects in one plane.
2. Orbits nearly circular; orbits and rotation nearly all in the same sense (prograde).
3. Law of distance (Titius-Bode law, n See Table 6.15):

$$a = 0.4 + 0.3 \times 2^n \tag{6.44}$$

4. Sun has 99.87% of the total mass, but only 0.54% of the total angular momentum of the entire solar system.
5. Nature of planets: (a) inner planets: high density, metals, rocks, slow rotation, few (no) moons; (b) outer planets: low density, composition similar to Sun, fast rotation, many moons.
6. Rotational axes of planets (angular momentum vectors) and satellite systems approximately parallel to the total angular momentum vector (perpendicular to the invariant plane).

There are the following theories:

- Old theories: already in the 16./17. century pioneers were *Copernicus* (heliocentric world system), *Galileo* (first telescope observations) and *Kepler* (laws of planetary motion). *René Descartes*In 1644, was the author of the first paper suggesting that the original matter had been in rotation and that vortices had formed as a result; the sun was formed from the large central vortex.
- Collision *(Chamberlain-Jeans):* Close passage of a star past the sun; tidal forces pull out matter that condensed to form planets. Problem: The distances between stars are

extremely large, so there is a very low probability of such a process. If this theory were correct, there would possibly exist only two solar systems in our galaxy! This is refuted by the observation of more than 5000 extrasolar planetary systems.

- Accretion Theory: The sun passes through an interstellar cloud, gathering matter as it goes.
- Primordial Nebulae: *(Kant* 1755, *Nebular hypothesis):* The protosun is formed as a result of gravitational collapse of an interstellar gas cloud; comes very close to modern ideas (Sect. 11.1 star formation).
- Modern theories: Gravitational collapse of a cloud; gravitational forces outweigh the gas pressure of the cloud's particles, this is called *Jeans instability*; rapid rotation at the beginning (conservation of angular momentum → As the cloud contracts, it rotates faster and faster), causing it to flatten. The dust condenses into what are called Planetesimals. Magnetic fields frozen in the plasma transfer the angular momentum of the protosun to the rotating envelope. The composition of the present-day planets then follows from the condensation sequence of various substances. Methane condenses at 100 K, water at 273 K, silicates at 1000 K, etc. The Sun is hot, and therefore no icy moons could form near the Sun, or large planets massive enough to hold the light elements H and He in their atmospheres.

6.11.3 Protoplanetary Nebula

The composition of the protoplanetary nebula, from which the Sun and planets formed, corresponded to the general cosmic element abundance. 99% consisted of gas (H, He), 1% of solid dust particles, which were about 0.1 μm in size. These were formed in the atmospheres of *Red Giant Stars,* were then physicochemically altered by the bombardment of cosmic rays. Their surface was covered with ice molecules, and due to low temperatures this ice is in a state of crystallization unknown on Earth. Brownian motion causes random collisions in the gas cloud, the particles become larger, the collisions become less frequent, the collision process is thus stopped. Centimetre-sized particles thus decouple from the general gas field of the nebula, fall towards the equatorial plane of the rotating nebula and describe Kepler orbits around the already formed primordial sun. They are decelerated by the surrounding gas and form meter-sized clumps. The orbits of these clumps do not remain stable, and collisions give rise to the *Planetesimals,* clumps several kilometers in size.

The elements hydrogen and helium were formed in the Big Bang and account for almost all observable matter in the universe. It is important to note for further consideration that these elements remain gaseous even at near absolute zero temperatures. 98% of the solar primordial nebula was therefore gaseous. Elements such as carbon, nitrogen, oxygen condense (e.g. H_2O above 110 K). Therefore it is expected that ice was formed in the cooler outer regions of the solar system. All other elements (less than 0.3% of mass of primeval nebula) react with oxygen and form molecules, silicates and so on. These are the Earth-like planets: They consist essentially of a metallic core surrounded by a silicate mantle. The Earth could therefore only form from a protoplanetary nebula of more than 300 present-day Earth masses (0.3% corresponds to about 1/300), as did Venus. For Mercury it was 15 Earth masses, for Mars 30 Earth masses and for the asteroids 0.15 Earth masses. The mass of the nebula to form Jupiter was 1000 Earth masses and for Saturn 500 Earth masses. Altogether then a value for the mass of the nebula, which was necessary for the formation of the planets, results: about 3000 earth masses (=1% of the sun mass). There are also other theories that assume a much more massive primordial nebula.

6.12 Further Literature

We give a small selection of recommended further literature.

The Solar System, Encrenaz, Th., Bibring, J.-P., Blanc, M., Springer, Berlin, 2004
Encyclopedia of the Solar System, McFadden, L.A., Weissman, P., Johnson, T., Academic Press, 2nd ed. 2007
Fundamental Planetary Science, J.J. Lissauer, Cambridge Univ. Press, 2019
Planetary Sciences, I.d.Pater, J.J. Lissauer, Cambridge Univ. Press, 2015
Asteroids, T.H. Burbine, Cambridge Univ. Press, 2016
The Atlas of Mars, K.S. Coles, K.L. Tanaka et al, Cambridge Univ. Press, 2019
Comets and their Origin, U. Meierhenrich, Wiley-VCH, 2014.
The Formation of the Solar System, M. Woolfson, Icp, 2014
Apollo 50, O. Sentinel, Pediment Publ, 2019

Tasks

6.1 Suppose a wooden part of a building still had 80% of the original proportion of ^{14}C. How old is the wood (half-life $t_h = 5730$) years?

Solution
$t = t_h \log_2(0.8) = 5730 \times \log_2(0.8) = -1845$. $\log_2 a = \log_{10} a / \log_{10} 2$. Therefore, the wood was cut 1845 years ago.

6.2 Why is the interior of the moon cold and the interior of the earth hot?

Solution
Compare (a) the surface area/volume ratio of the two bodies, (b) the masses of the two bodies.

6.3 GPS measurements show that the Atlantic Ocean floor is spreading by about 2.5 cm per year. When did this spreading begin, that is, when was the Atlantic Ocean formed?

Solution

If we take 6000 km as the mean east-west extent of the Atlantic Ocean, then:
$t = d/v = 6{,}000{,}000/0.025 = 240{,}000{,}000$ Years

6.4 Consider a proton with velocity $v = 10^8$ m/s and a magnetic field with $B = 10^{-4}$ T. What is the radius of gyration?

Solution

Substitution gives $r = 10$ km.

6.5 Compare the solar radiation on Venus with that on Earth!

Solution

$$\frac{F_{\mathrm{Venus}}}{F_{\mathrm{Earth}}} = \frac{E_{\mathrm{Sun}}}{4\pi d^2_{\mathrm{Sun-Venus}}} \Big/ \frac{E_{\mathrm{Sun}}}{4\pi d^2_{\mathrm{Sun-Earth}}} = \frac{1^2}{0.72^2} = 1.9$$

6.6 Why can volcanoes get much taller on Mars than on Earth?

Solution

(a) On Earth plate motions, location of hot spots shifts over time, cf. Hawaii island chain,
(b) On Mars lower gravity, higher structures collapse later under the influence of gravity.

6.7 The escape velocities are approximately the same for our moon and Titan. Why does Titan have an atmosphere unlike our moon?

Solution

Compare surface temperatures and geological activities of both celestial bodies.

6.8 The irradiance from the Sun at the Earth's location is 1 365 W/m^2. Calculate the corresponding insolation on Pluto.

Solution

Assume by how many times Pluto is farther from the Sun than Earth.

6.9 Calculate the kinetic energy of a 1000 kg meteorite impacting at 30 km/s. Note: 1 kt TNT= 4×10^{12} J.

Solution

$E_{\mathrm{kin}} = 1/2mv^2 = 1/2(1000)(30,000)^2 = 4.5 \times 10^{11}$ J thus: 0.5 kt TNT.

6.10 You observe hydrogen lines in the spectrum of Jupiter. How can you tell if these are from Earth's atmosphere or actually from Jupiter?

Solution
The strength of telluric lines changes with Jupiter's altitude in the sky.