Chapter 2
The Terrestrial Planets

General View

Unlike the gaseous giant planets, which are preserved essentially unmodified in structure and composition since their origin 4.55 billion years ago, the terrestrial (inner) planets (Fig. 2.1) experienced dramatic changes in the course of their evolution. This is evident in their interior structure, geology, surface landforms, and atmospheres (Fig. 2.2a). The evolution of the inner planets was mainly controlled by both endogenous and exogenous factors involving the original storage of radionuclides, impacts, and distance from the Sun. Endogenous factors were mostly driven by heavy bombardment by asteroid-size bodies in an early epoch dating back to 4.0 billion years ago, and internal heat due to long-lived radio isotope decay, their storage being strongly dependent on the size/mass of the planet. Impacts scarred the surface and left behind numerous craters, while internal heating was responsible for tectonic processes and widespread volcanism. Distance from the Sun determines the incident radiation input to the planet and, hence, its thermal balance. Heat release from the interior (internal flux) is negligible, in contrast to the case of the outer giant planets where it exceeds the solar incident flux. Exogenous factors significantly contributed to the planetary evolution through migration of small bodies from the outer solar system regions and collisional processes.

Planetary geology is closely related to differentiation of the planetary interiors into shells (core, mantle, and crust), accompanied by widespread tectonics and volcanism, as is clearly manifested by different patterns of the surface landforms. All terrestrial and gaseous-icy planets have differentiated interiors, as is supported by the measured quadrupole moments of their gravitational fields and the respectively deduced dimensionless moment of inertia, $I = C/MR^2$ (Fig. 2.2b). Here C is the moment of inertia about polar axis, M and R are mass and radius of the planet, respectively. Note that for an ideal sphere of uniformly distributed density, $I = 0.4$; the less uniform the mass distribution (massive heavy core and lighter mantle in the interior), the lower the I value. This is why for the only partially differentiated

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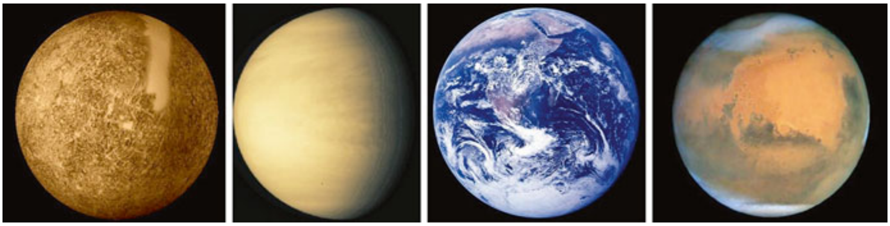

Fig. 2.1 Terrestrial planets (in order from the Sun) Mercury, Venus, Earth, Mars (not in scale) (Author's mosaics of NASA images)

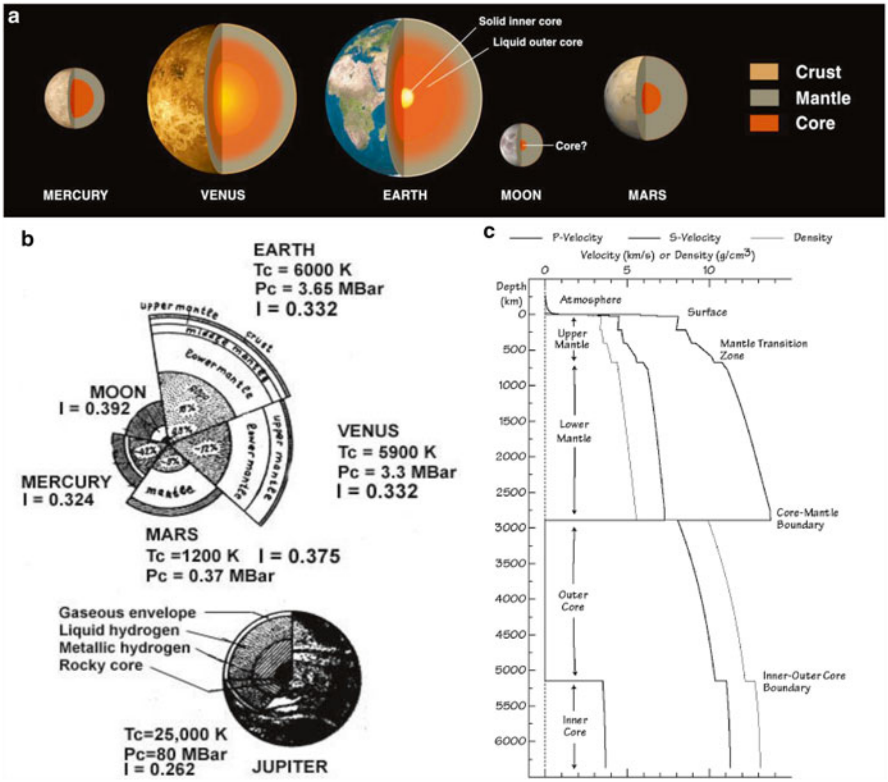

Fig. 2.2 (**a**) Internal structure of the terrestrial planets and the Moon. The order in the arrangement of main regions (core, mantle, crust) is a consequence of the differentiation of their constituent matter into shells, their extension depending on the size (mass) of the planet, the abundances of major components, and the condensation temperature in the formation zone. Mass of the body predetermines the core state and the crust (lithosphere) thickness (Adapted from Wikipedia). (**b**) Parameters of the interiors (temperature T, pressure P, and dimensionless moment of inertia I) of the terrestrial planets and the Moon as compared to those of Jupiter (Credit: the Author). (**c**) Velocity waves propagation and density variations within Earth based on seismic observations. The main regions of Earth and important boundaries are labeled. This model was developed in the early 1980s and is called PREM for Preliminary Earth Reference Model (Adapted from Wikipedia)

Moon with a small core I = 0.392, whereas the minimum I values (less than 0.3) are pertinent to the gaseous giants Jupiter and Saturn with heavy iron-silicate cores and light hydrogen-helium envelopes.

Impacted structures are most clearly seen on the atmosphereless bodies such as Mercury and the Moon. Heavily cratered terrains are also preserved on the Mars surface, though in the presence of its atmosphere, ancient craters were eroded by the processes of weathering. Unlike the main mechanism of global plate tectonics on Earth, the geologies of Mars and Venus are different. On Mars, there are great ancient shield volcanoes elevated up to 26 km above the mean surface level, which (despite the relatively small size of the planet) are among the highest in the solar system. Another remarkable geologic pattern is Valles Marineris—an enormous feature 100 km wide and 8 km deep that extends along the equator for more than 3,000 km. It is poorly associated, however, with the global tectonics. On Venus, geologic structures have been revealed only with radar techniques because its very thick atmosphere and clouds fully obscure the surface when it is observed in optical wavelengths. There are no obvious tectonic features on the planet. Instead, numerous volcanoes were mostly pertinent to the planet's thermal evolution. Volcanic activity appears to have terminated quite recently, less than 100 million years ago, though some planetary geologists believe that some limited activity is preserved today.

Thermal evolution is assumed to be partially responsible for the formation of an atmosphere of secondary origin on a terrestrial planet after the primary atmosphere (presumably retained in the process of the planet's accumulation) was lost. Atmospheres exist on all terrestrial planets, but Mercury has only an extremely rarefied gas envelope equivalent to the Earth's exosphere. The main properties of the atmospheres of these planets are summarized in Table 2.1.

Table 2.1 Properties of atmospheres of the terrestrial planets

Planet	Mercury	Venus	Earth	Mars
Chemical composition (percent by volume)	$He \leq 20$	$CO_2 = 95$	$N_2 = 78$	$CO_2 = 95$
	$H_2 \leq 18$	$N_2 = 3–5$	$O_2 = 21$	$O_2 = 2–3$
	$Ne \leq 40–60$	$Ar = 0.01$	$Ar = 0.93$	$Ar = 1–2$
	$Ar \leq 2$	$H_2O = 0.01–0.1$	$H_2O = 0.01–3$	$H_2O = 10^{-3}–10^{-1}$
	$CO_2 \leq 2$	$CO = 3 \cdot 10^{-3}$	$CO_2 = 0.03$	$CO = 4 \cdot 10^{-3}$
		$HCl = 4 \cdot 10^{-5}$	$CO = 10^{-5}$	$O_2 = 0.1–0.4$
		$HF = 10^{-6}$	$CH_4 = 10^{-4}$	$Ne = < 10^{-3}$
		$O_2 < 2 \cdot 10^{-4}$	$H_2 = 5 \cdot 10^{-5}$	$Kr = < 2 \cdot 10^{-3}$
		$SO_2 = 10^{-5}$	$Ne = 2 \cdot 10^{-3}$	$Xe = < 5 \cdot 10^{-3}$
		$H_2S = 8 \cdot 10^{-3}$	$He = 5 \cdot 10^{-4}$	
		$Kr = 4 \cdot 10^{-5}$	$Kr = 10^{-4}$	
		$Xe = 10^{-6}–10^{-5}$	$Xe = 10^{-6}$	
Mean molecular mass		43.2	28.97	43.5
Surface temperature				
T_{max}, K	700	735	310	270
T_{min}, K	110	735	240	148
Mean surface pressure P, atm	10^{-15}	92	1	$6 \cdot 10^{-3}$
Mean surface density, ρ, g/cm^3	10^{-17}	$61 \cdot 10^{-3}$	$1.27 \cdot 10^{-3}$	$1.2 \cdot 10^{-5}$

We see that the atmospheres of the neighboring planets, Venus and Mars, dramatically differ from that of Earth: the pressure at the Venusian surface reaches 92 atm and the temperature is 735 K, whereas at the surface of Mars the average pressure is only 0.006 atm and the average temperature is about 220 K. The composition of the atmospheres of both planets is mostly carbon dioxide with relatively small admixtures of nitrogen and argon and a negligible mixing ratio of water vapor and oxygen (on Mars). In contrast to Venus, which has no seasonal variations because of the very small obliquity of its equator to the ecliptic, Mars, whose obliquity is nearly similar to that of the Earth's, exhibits pronounced seasonal variations resulting in temperature contrasts between summer and winter hemispheres exceeding 100 K. At the winter pole the temperature drops below the freezing point for CO_2 and thus "dry ice" deposits cover the Martian polar caps, though their main composition is water ice. Seasonal evacuation and release of carbon dioxide in the polar regions is one of the important drivers of atmospheric planetary circulation on Mars involving both meridional and zonal wind patterns.

However, atmospheric circulation on Venus is mainly characterized by the mechanism of super-rotation, or "merry-go-round" circulation, such that a zonal wind velocity of less than 1 m/s at the surface increases up to nearly 100 m/s near the upper cloud level at about 60 km. Venus's clouds consist of quite concentric sulfuric acid droplets, and this unusual composition complements the picture of the very exotic and hostile environment of our closest planet, which until the middle of the last century was thought to be the Earth's twin.

In terms of natural environment, Mars is another extreme, though more favorable in its climate and therefore much more accessible for future human expansion throughout the solar system. Historically, this planet was regarded as a potential target for finding life beyond Earth, and it is still addressed as a possible site that could harbor life at the microbial level and where extant or extinct life could be found. Indeed, unlike Venus, where an assumed early ocean was lost soon after the runaway greenhouse effect responsible for its contemporary climate conditions developed, ancient Mars appears to have had plenty of water until a catastrophic drought occurred on the planet about 3.6 billion years ago for reasons that are not yet well understood. There is evidence that contemporary Mars preserved a substantial part of its water storage; its original bulk is estimated to be equivalent to nearly 0.5 km of an average ocean deep. It is thought to be stored deep under the surface as permafrost and water lenses. Recent space missions revealed many specific geologic structures which confirm such a scenario, as well as the existence of subsurface water at about 1 m depth unevenly distributed over the globe, mostly in the polar regions. Anyway, the general understanding is that ancient Mars had a much more clement climate when water covered much of its surface, until its quite dense atmosphere was lost and water ice was buried beneath thick sand-dust sediments.

We shall start the inner planets' description with our home planet Earth and its large satellite, the Moon; together they form the Earth-Moon system. Because Earth is our home, we address other terrestrial planets first of all in terms of better understanding Earth as a solar system planet and learning what predetermined the unique path of its evolution. In other words, Earth and the Moon should be perceived in the context of the family of Earth-like planetary bodies which store collectively invaluable data about our past history and may help to predict the future trends. However, Earth and the Moon also serve as an important basis for comprehending the peculiarities of natural conditions which formed on other inner planets. The Moon itself can be regarded as a frame of reference to highlight the key processes of the solar system evolution.

We then discuss in a bit more detail the nature of other terrestrial planets, emphasizing our neighbor planets Venus and Mars, which are located very close (on a space scale) to Earth but evolved along completely different paths. Therefore, we may address them as extreme models of potential unfavorable Earth evolutionary paths, provided that the acting natural feedback mechanisms are slowed down. An important implication is that mankind should bear this in mind and carefully control the growing anthropogenic influence on the environment to prevent the development of risky scenarios.

Earth

Main Properties. Earth is the third planet in order from the Sun and the largest body of the four terrestrial planets. It orbits the Sun at a distance equal to semimajor axis $a = 149.6$ million km (1 AU) with a very small eccentricity, $e = 0.017$, which means that the orbit is nearly circular, although the distance varies as the Earth moves from perihelion in January to aphelion in July. The Earth moves along its orbit with a velocity $V = 29.8$ km/s, and its period of revolution is $P_{orb} = 365.256$ days (1 year). The sidereal period of rotation around its axis (relative to the stars, or 1 sidereal day) is $P_{rot} = 23^h\ 56^m\ 4.99^s$. The inclination of the Earth's equator to the plane of circumsolar orbit (ecliptic) equals $i = 23°27'$, which ensures significant seasonal changes on the planet.

Earth is a rather small body by the cosmic scale. Its equatorial radius is $R_e = 6{,}378$ km, and its polar radius is $R_p = 6{,}356$ km; hence, its oblateness is 0.0034. The pear-shaped figure of the Earth is called the geoid. The mass is $\boldsymbol{M_E} = 5.974 \times 10^{24}$ kg, the mean density $r = 5.515$ g/cm^3, and the mean acceleration due to gravity is $g = 9.78$ m/s^2 (it is a bit more at the poles compared to the equator). The Earth's surface is represented by the continents and the oceans, the oceans occupying nearly two-thirds of the whole surface. 94 % of the Earth's bulk composition is O, Mg, Si, and Fe. Together with Al and Ca these are rock-forming elements, whereas C and N are volatile-forming elements. Their abundance is <1 %. The elemental composition of continents and oceans is quite different. The age of the Earth (dated as the time of the solar system origin based on the dating of calcium-aluminum inclusions (CAIs) in the Allende and Efremovka meteorites; see Chap. 4 for more details) is established to be $4{,}567.5 \pm 0.5$ million years.

Geology. Earth is a geologically evolved planet. The main geological mechanism is global plate tectonics, which means that its outer shell (lithosphere) is not homogeneous but split into 12 large plates that are laterally mobile (Fig. 2.3). The mechanism

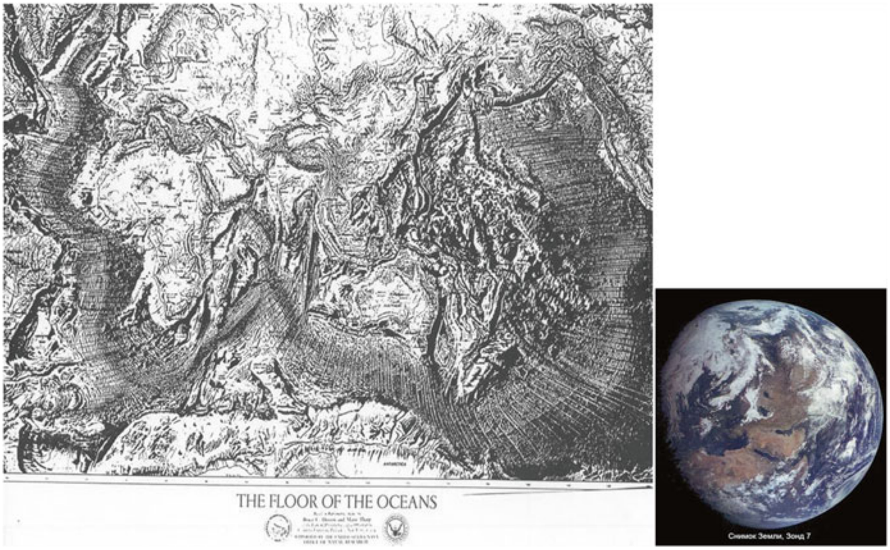

Fig. 2.3 The floor of the Earth's oceans. The relief bears traces of lithospheric plate tectonics involving middle-ocean spreading zone and subduction zones at the edges of ocens connected with the most powerful volcanic and erthquakes activity (Credit: B. Heizen. At the right—Image of Earth from the Moon orbit taken by the Soviet Zond 7)

involves a "spreading zone," where hot lava ascends from the upper mantle pushing the lithosphere plates apart and filling "cracks" (rifts) between them, and subduction zones, where plates covered with sediments slowly plunge deep under continents. The seafloor spreading hypothesis was proposed by the American scientist Harry Hess in 1960. The spreading zones coincide with the mid-ocean ridges that run globally at the bottom of all oceans. Both spreading and subduction zones are associated with the sources of the most powerful volcanic activity and earthquakes. There are about 800 active volcanoes on the Earth's surface, and numerous earthquakes occur annually.

Global plate tectonics is responsible for the drift of continents, which continuously retreat from each other, as was first suggested by the German scientist Alfred Wegener as early as 1912, although the idea was not accepted until Hess's hypothesis of spreading zones was known. Reconstruction of the process back in time has caused us to conclude that 300–200 million years ago there was a supercontinent Pangaea which disintegrated into several pieces, giving rise to the now existing continents. In support of this model, one may compare the contours of the eastern part of South America with the western part of Africa and see that they exhibit quite similar configurations. The model was also confirmed by in-depth studies of the bottom of the ocean and magnetic properties of the early emerged lava flows.

The oceans comprise nearly 97 % of all the water storage on Earth (called the hydrosphere) and contain a mass of about 10^{21} kg and cover 361 million km^2. The remaining 3 % is fresh water, found in rivers, lakes, glaciers, and in the atmosphere, as well as in the Arctic and Antarctic polar ice caps. The mean depth of the "world ocean" (if all the oceans were uniformly poured over the Earth's surface) is 3,900 m, while the maximal depth is 11,000 m—this deepest portion is the Mariana Trench in the Pacific.

Interior. The Earth's interior has a rather complicated structure, as revealed by the seismic sounding technique. The propagation rate of longitudinal *P* and transverse *S* seismic waves depends on the density and elasticity of rocks, and the waves also experience reflection and diffraction on the boundaries between different layers, while the transverse waves decay in liquids. The technique has distinguished the Earth's main zones, which are shown in Fig. 2.2c. They are the upper firm crust, partially melted upper and lower mantle, and liquid outer and inner rigid cores. The thickness of the crust amounts to 35 km on continents and about half that in the oceans. The region between the crust and upper mantle is the lithosphere, which is about 70 km deep, underlain by a more fluid layer, the asthenosphere, extending to 250 km in depth. The boundary between the crust and upper mantle is known as the Mohorovicic discontinuity, or just the Moho. As we said above, the lithosphere is split into a dozen large plates "floating" on the asthenosphere, ensuring the mechanism of global plate tectonics in action.

The crust is composed of bedrock (basalt and granite) having a mean density of ~ 3,000 kg/m^3, and it makes up less than 1 % of the bulk mass of the Earth. The mantle composes nearly 65 % and the core 34 % of the total mass. The thickness of the mantle is 2,900 km, and it is composed mainly of silicate rocks as well as silicate and magnesium oxides modified under high pressure. This results in a density increase to 5,600 kg/m^3, which is manifested as a sharp increase in seismic wave rates. The strong reflection and decay of these waves below 2,900 km (this level is called the Gutenberg discontinuity) marks the outer boundary of the Earth's liquid core, which is 2,250 km thick and composed of melted iron and nickel. Finally, inside the outer liquid core lies the inner rigid core, which has a radius of 1,220 km.

Let us note that near the Earth's surface the temperature gradient is about 20°/km; the temperature reaches ~ 1,800 K at 100 km and ~ 5,000 K at the mantle-core boundary, where the pressure amounts to $\boldsymbol{P} = 1.3 \times 10^{11}$ Pa (~1.3 million atmospheres, mil. atm). In the center of the Earth $\boldsymbol{T} = 8{,}000$ K, $P > 3.6 \times 10^{11}$ Pa (~3.6 mil. atm), and the density exceeds 10,000 kg/m^3. In the contemporary epoch, the liquid state of the core and the partially melted mantle are primarily maintained by the original storage of long-lived radionuclides—uranium, thorium, and potassium—in the Earth's interior. The liquid core and the planet's rather fast rotation are thought to be responsible for the significant magnetic field of the Earth, following the mechanism of a magnetic dynamo. The field strength is 0.31 oersted (roughly corresponding to a magnetic induction equal to 3×10^4 nanotesla) at the equator and 0.63 oersted at the poles. In the contemporary epoch, the North geographic pole is located close to the South magnetic pole (the angle between geographic and magnetic field axes is 11.5°). For the last 10 million years there were recorded 16 magnetic field inversions apparently caused by periodic core overturns. The region around Earth stretching out to 5–10 Earth's radii is controlled by its intrinsic magnetic field and is called the magnetosphere. The magnetosphere shields our planet from solar corpuscular radiation (energetic protons and electrons).

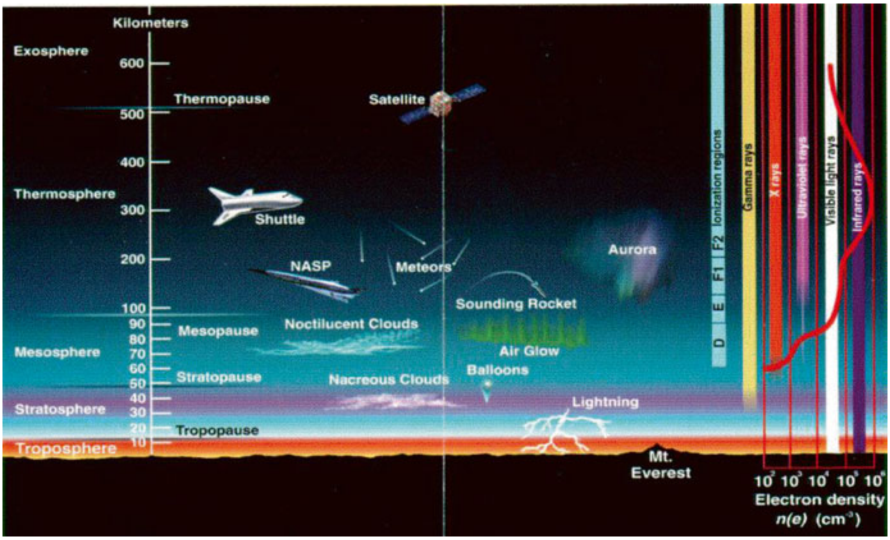

Fig. 2.4 Structure of the Earth's atmosphere from the surface to 600 km. Different regions (troposphere, stratosphere, mesosphere, thermosphere, and exosphere) in the lower, middle, and upper atmosphere are distinguished. Levels of penetration of the solar electromagnetic radiation, specifically that responsible for ionization of atmospheric species and ionosphere formation, are shown (Credit: R. Courtis)

Atmosphere. Earth has a unique atmosphere in the solar system. Unlike the other planets, its atmosphere is composed mainly of nitrogen and oxygen with an irregular temperature stratification. It has several distinguished regions, sometimes called layers (see Fig. 2.4), called the troposphere, stratosphere, mesosphere, thermosphere, and exosphere.

The troposphere stretches from the surface to 12 km (a bit higher at the equator and lower at the poles). The mean temperature at the surface is +12 °C with variations from −85 °C (inner regions of the Antarctic) to +70 °C (Western Sahara). The temperature lapse rate is roughly 6°/km, which nearly corresponds to the wet adiabatic gradient. A relatively small amount of carbon dioxide in the troposphere (0.03 %) is mainly responsible for the greenhouse effect, raising the Earth's effective temperature by about 20 °C. The troposphere has significant though variable humidity depending on location, season, time of day, and height. The mean gas density at the surface under a temperature of 15.0°C and relative humidity $f = 0$ % is $\rho = 1{,}225$ kg/m^3 (a standard atmosphere).

In the stratosphere (12–50 km above the Earth), the temperature first drops to −50 °C at 25 km and then rises due to solar ultraviolet (UV) radiation absorption in 200–300 nm wavelengths by ozone. This shields the planet from intense electromagnetic radiation and prevents biosphere destruction. Ozone raises the temperature of the upper stratosphere to nearly 0 °C at 50 km. Above this level is the mesosphere, where the temperature drops again, reaching its minimum (about −90 °C) at the level called the mesopause at 85 km. At the beginning of this level direct absorption of extreme ultraviolet (EUV, at wavelengths shorter than 200 nm) and soft X-ray radiation occurs, which is responsible for the photochemical processes of dissociation and ionization of predominantly oxygen and some other species and rarefied atmospheric gas heating. Here the temperature steadily increases up to 800–1,000 K, but it varies from about 500 to 1,500 K between the minimum and maximum phases of the 11-year solar activity cycle. The latter results in atmospheric density variations by more than two orders of magnitude at about 400 km and, hence, dramatically influences the lifetimes of artificial satellites and orbital stations. In the thermosphere is located the ionosphere with its most prominent layers E, F_1, and F_2, where the ion concentration is high enough to reflect radio waves in the short wavelength and thus provide long distance radio communication on Earth. The atmosphere itself is nearly transparent to radio frequencies between 5 MHz and 30 GHz, while the ionosphere blocks signals below this range. The thermosphere smoothly transits at about 500–600 km to the very outer upper atmosphere region called the exosphere, consisting mostly of hydrogen/helium atoms and extending to thousands of kilometers.[1] The transition layer is called the exobase, from which atoms not experiencing collisions when moving upward and having sufficient thermal velocity can dissipate into outer space.

The Earth exhibits quite complicated atmospheric dynamics. Generally, air mass transport on different planets depends on four forces acting on an elementary volume of gas (gravity force, Coriolis force, viscous friction, and pressure gradient). The ratio of the planetary rotation rate (frequency f) and thermal atmospheric relaxation involving these forces mainly defines the planetary circulation patterns. The relative contribution of the Coriolis force to the atmospheric dynamics is determined by the Rossby number $\boldsymbol{Ro} = U/fL$, where U and L are typical horizontal velocity and length scales for synoptic processes. If horizontal pressure gradients are balanced by the Coriolis forces ($\boldsymbol{Ro} \ll 1$), it results in geostrophic types of circulation flows. In the Earth's atmosphere $\boldsymbol{Ro} \approx 10^{-1}$, which means that the forces due to pressure gradients are essentially balanced by the Coriolis forces. Therefore, a geostrophic wind is a typical synoptic characteristic, and its zonal and meridional components can be determined from a known pressure distribution.

The combined effect of the planet's rotation and change of frequency f with latitude generates Rossby planetary waves, which are the main weather generators, cyclones and anticyclones being formed in their troughs and crests. In the Earth's atmosphere, these planetary waves propagating horizontally westward have a period exceeding both the planetary rotation period and the periods of three other types of atmospheric wave motions: tidal, acoustic, and internal gravity waves (IGWs). Short-period IGWs with relatively small amplitudes belong to the category of micro-meteorological atmospheric oscillations and, along with convection, serve as the source of small-scale turbulence. Thus, they energetically (through dissipation) affect the formation of large-scale weather processes.

[1] Note that an exosphere is the most abundant type of planetary weak atmosphere contiguous to the surface, and is characteristic of the Moon, Mercury, some satellites of the giant planets, and even some large asteroids.

The current state and ultimate fate of the Earth are entirely dependent on our Sun and its evolution. The Sun ensures all necessary energy resources including those accumulated in the past as organic fuels, and photosynthesis serves as the main biological factor for life persistence. Projecting into the future, we should not only be aware of short-term concerns such as climactic changes, resource exhaustion, and natural environment pollution/damage (temporarily putting aside the world's social problems and relevant conflicts), but we should also deliberate about very far-off perspectives. At its red giant phase the Sun will increase to 250 times its present radius, its high-temperature outer shell expanding beyond the Earth's orbit to swallow our planet. Should it escape incineration in the Sun, all its water will still be boiled away and its atmosphere will escape into space, ending all terrestrial life. However, provided civilization develops smoothly, future generations millions to billions of years from now will find an opportunity to avoid this catastrophic scenario by moving to a home planet that is harbored by another younger star.

The Moon

Main Properties. The Moon (Fig. 2.5) is the brightest object in our skies after the Sun: its maximum stellar magnitude is -12.7^m. The semimajor axis of the Moon's orbit $a = 383{,}398$ km and the eccentricity $e = 0.055$. The inclination of the Moon's orbit to the ecliptic equals 5°09′. The sidereal period of revolution around the Earth is 27 days, 7 hours, and 43 minutes, while its synodic period (relative to the Sun corresponding to the lunar phases change) is 29 days, 12 hours, and 44 minutes.

The Earth-Moon system is a unique formation in the solar system with the largest satellite-to-planet mass ratio: 1/81. This means that there is a significant mutual gravity influence, clearly manifested by the lunar tides on Earth, which significantly exceed those caused by the Sun. In turn, Earth locks the Moon's orbit and its intrinsic rotation in resonance, such that the period of its rotation equals the sidereal period. This means that the Moon orbits Earth for exactly the same time it takes to complete one rotation around its axis, and this is why the Moon permanently faces

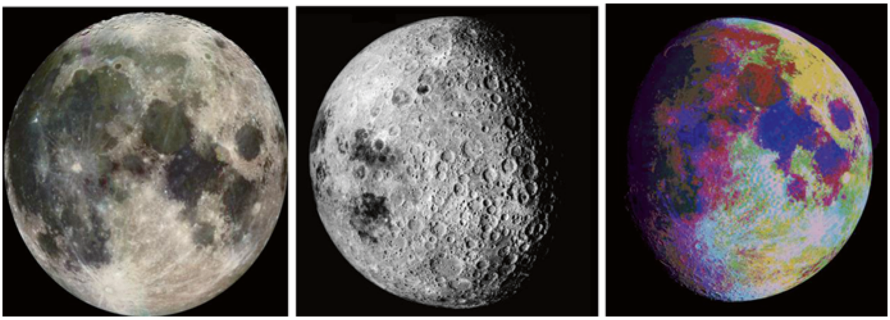

Fig. 2.5 Near (*left*) and far (*middle*) sides of the Moon and false color image of the Moon Near side showing different rocks composition (Author's mosaics of NASA images)

Earth with the same hemisphere. Nonetheless, because of its quite high eccentricity, the orbital motion of the Moon is irregular—faster near perigee and slower near apogee—whereas the intrinsic rotation of the Moon is regular. Both motions result in librations in longitude, the maximum value reaching 7°54′. This allows us to observe from the Earth's surface, besides the near side, very narrow strips on the far side of the Moon that make available about 59 % of its surface. It is of interest to note that the tidal energy exerted by the Earth on the Moon is responsible for a permanent small increase of the semimajor axis of its orbit, with the implication that the Moon moves steadily away from Earth by about 3 cm per year.

In size the Moon is nearly 3.7 times smaller than Earth, and its figure is very close to a sphere. Its equatorial radius $R = 1{,}737$ km, and its mass $M = 7.3476 \times 10^{22}$ kg, which is less than that of Earth by a factor of 81.3. Its bulk density, $\rho = 3.35$ g/cm^3, is comparable with the Earth's mantle density, which poses questions about the Moon's interior structure and origin. The acceleration due to gravity on the surface is only $g = 1.63$ m/s^2, which, from an energy viewpoint, makes the Moon a very efficient launch pad. Obviously, the mass of the Moon is too small to retain an atmosphere, whether or not one was formed in the past.

With no atmosphere and with sharp temperature contrasts on the surface amounting to 300° (from −170 °C at night to +130 °C during the day, both day and night lasting nearly half a month), the Moon is an inhospitable world. There is no surface water, although some water ice deposits are thought to be present in the polar regions and some water is assumed to store in the interior.

Surface, Interior, Geochemistry. A relief of the Moon is represented by high elevations and deep depressions (Fig. 2.6). These features still have the historical names given to them by Italian astronomer Giovanni Riccioli in the seventeenth century following the association of bright spots with continents and dark spots with oceans and seas (these were erroneously thought to exist on the Moon). Thus names such as Alps, Apennines, and Caucasus Mountains, Mare Tranquilitatis, Mare Crisium, and Mare Serenitatis are given to prominent morphological features on the Moon's surface. The surface is heavily cratered, and the large craters were also named long ago after great astronomers such as Tycho (Brahe), Ptolemy, Copernicus, and many others. The naming of features (including those on the far side of the Moon) exploded at the beginning of the space era, and currently about 2,000 names and events are commemorated on the Moon's surface.

Basically, craters are impact-formed in origin, and in the absence of an atmosphere they experience rather slight erosion caused only by meteorite bombardment and solar wind direct interaction with the surface. The rate of erosion is therefore small enough so that artifacts can be preserved on the surface for a long time. The impact origin is clearly manifested by such typical features as a ray system around many craters (which could be craters of secondary origin formed at the explosion), central hills, terraces on inner slopes of rims, etc. The range of sizes stretches from centimeters to hundreds of kilometers, the total number of craters with size more than 1 km on the near side of the Moon exceeding 300,000. Heavy cratering confirms the great importance of the above-mentioned collisional processes in the solar system. The Late Heavy Bombardment (LHB) culminated about four billion years

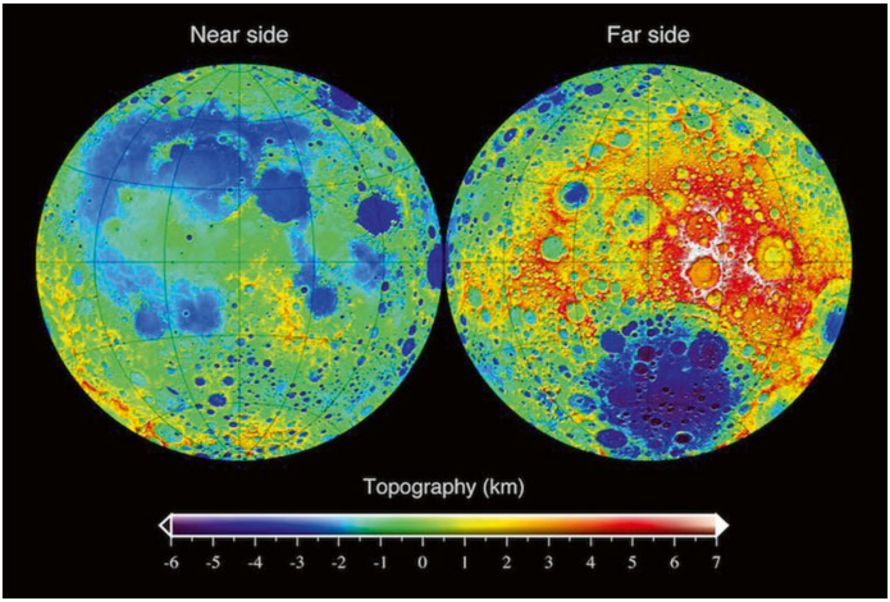

Fig. 2.6 Relief of Near side and Far side of the Moon marked in color from blue (low regions and basins) to *yellow-red* (elevations and mountains). Unlike the near side with many basins (mare) the far side is mostly represented by elevated areas (continents) with exception for the great basin nearby the South pole (Credit: NASA/J. Green)

ago when large primitive chondritic asteroids (remnants of planetesimals and sources of exogenous material) fell on the Moon's surface, leaving behind enormous basins which we now call the maria (seas). There were probably common Earth-Moon crossing impactors at the basin-forming epoch. At that time, the Moon is thought to have had a melted mantle close to the surface that was broken up by powerful impacts followed by cracks and lava extrusions that filled the basins. Indeed, the bottoms of the basins bear traces of lava emergence and flow. These very basins serve as sources of mass concentrations (*mascons*) which are responsible for the pronounced gravity field anomalies revealed by lunar orbiters as early as the 1960s.[2] Great basins are often surrounded by high elevations, probably associated with the catastrophic events. The mountains in the equatorial and middle latitudes reach heights from 2 km (Montes Carpatus) to 6 km (the Apennines). The most irregular relief represented mostly by "continents" is characteristic of the far side of the Moon and especially its polar regions. The Moon's topography generally correlates with the gravity field of the near and far sides of the Moon, inhomogeneities roughly corresponding to gravity anomalies—mascons—in basins (Fig. 2.7).

[2] NASA's twin Gravity Recovery And Interior Laboratory (GRAIL) lunar orbiting spacecraft, launched in 2011, halved the average operating altitudes to 23 km (taking them within 8 km of the highest lunar areas) and allowed researchers to obtain remarkable data on the gravitational influence of the Moon's surface and subsurface features.

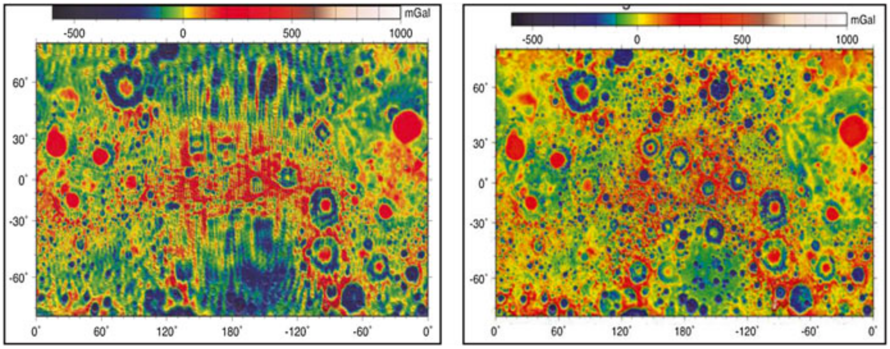

Fig. 2.7 Gravity field of the near (*left*) and far (*right*) sides of Moon in mGals marked in color from low (*blue*) to high (*yellow-orange*) values. Inhomogeneities roughly correspond to the Moon topography. Gravity anomalies in basins at the near side (mass concentrations—mascons) are clearly seen as red spots (Credit: NASA/J. Green)

Fig. 2.8 The main Moon's rocks in mare and continents (Credit: A. Basilevsky)

The surface of the Moon is generally of basaltic composition and is intrinsically related with its interior structure and geologic history. Lunar rocks contain the same common rock-forming minerals that are found on Earth, such as olivine, pyroxene, and plagioclase feldspar (anorthosite) (see Fig. 2.8). Plagioclase, an important rock-forming series of silicate minerals within the feldspar family, is a major constituent of the lunar crust, specifically rocks in the highlands. Plagioclase feldspar is composed primarily of iron-poor and calcium-rich anorthosite. Pyroxene and olivine are typically found in the lunar mantle.

The lunar maria are composed predominantly of basalts different from those in the lunar highlands, with a higher abundance of olivine and pyroxene and a lower

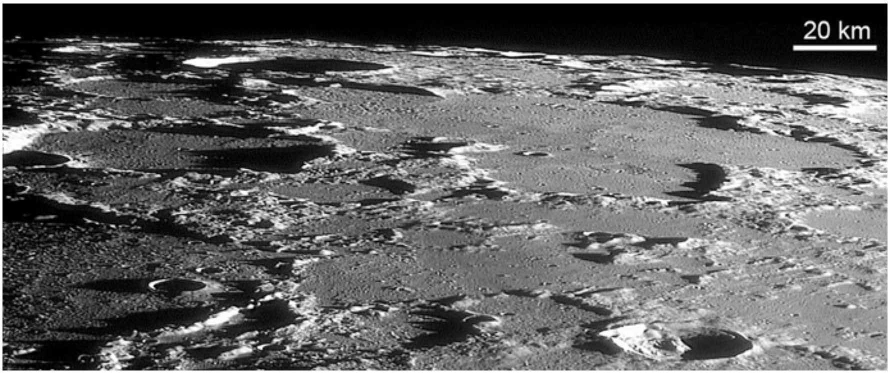

Fig. 2.9 South Pole of the Moon, heavily cratered terrain with potential water ice deposits. Telescopic view (Credit: NASA)

one of plagioclase. They are enriched with iron and especially the titanic iron oxide mineral called ilmenite (with an abundance of up to ~15 % compared to ~4 % in terrestrial minerals) and other related minerals. A special group of lunar basalts are the KREEP basalts, which are abnormally rich in potassium (K), rare earth elements (REE), and phosphorus (P).

Unfortunately, geochemical measurements are pertinent only to the upper layer of regolith; therefore, the composition of the lunar surface at a relatively small depth can differ from that of the underlying layer of igneous rocks because of the significant contribution of meteorite bombardment to the surface material. The bombardment left behind a special type of broken mineral fragments—the melt and other impact processes formed a surface layer called regolith.[3] The high abundance in regolith breccias of normally rare elements in basaltic rocks, such as nickel, osmium, and iridium, favors the idea of their contamination over time by chondritic meteorites. The composition of the meteorites is supposed to be quite similar to the primordial composition of terrestrial planets before these elements were sequestered into the planet's cores, and therefore, their presence in the crust is caused by meteorite bombardment.

Of special interest is the region on the far side of the Moon near the South Pole (Fig. 2.9). Here a multilayered structure known as the Aitken basin extends 2,500 km and 13 km in depth, the largest known impact crater in the solar system formed when a large asteroid impacted an estimated 3.9 Byr ago during the Late Heavy Bombardment period. There is convincing evidence that water ice deposits could lie inside this basin in the permanently shadowed regions. Assuming the collision of a

[3] Generally, "regolith" is the name for a planetary surface layer that is pulverized by meteor impacts; it is sometimes also called "soil." Regolith breccias are impact-derived melts, compacted and cemented into rocks. Many regolith breccias are present in the samples returned by lunar missions. The finer regolith, the lunar soil of silicon dioxide glass, has a texture like snow and smells like spent gunpowder.

comet with the Moon, the mass of delivered water could be as high as ~ 3×10^8 tons. Water ice deposit by comets is one of the plausible sources of water in the lunar soil (in the form of interparticle frost and crystalline water); other sources could be solar wind protons and pristine water exiled from the interior. The Moon could also preserve different volatiles and organics of regolith delivered through impact processes on the surface. Finding these substances is the main goal of future Moon exploration, and is closely related to our most intriguing astrobiological problems.

The lunar landforms and the mechanisms of their formation are intrinsically related to its interior structure, which is still quite poorly known. One of the most intriguing questions is whether the Moon preserved its liquid core and, if it did, what the size of the core is (see Fig. 2.2a, b). Other relevant questions are the nature of magma oceans and primary/secondary crustal formation. According to the modeling and partially supported by Apollo seismic data, the thickness of the upper crust ranges from 60 to 100 km, and the thickness of the upper and middle mantle layers below is about 400 and 600 km, respectively. Together they form a powerful solid lithosphere that fully excludes fissures and lava (if any) emergence, though volcanic activity was widespread on the early Moon. The lower mantle occupies a height range between 1,100 and 1,600 km; thus, the core could be roughly about 300 km in size. The size of the liquid core is also limited by the Moon's well-known dimensionless moment of inertia I. The very low magnetic field strength of the Moon (~10^{-4} that of Earth) could be related to a partly solidified core and/or the Moon's slow rotation.

The absolute age and dating of events in the Moon's history were determined from U-Pb, Rb-Sr, and K-Ar isotopic ratios in lunar rock samples. This led to the conclusion that the Moon was formed 50–70 million of years after the solar system formation, which is dated by the age of refractory CAI inclusions in the meteorites (see Chaps. 4 and 8). The Moon appears to have experienced interior differentiation with core separation within the succeeding 200 million years (Myr). Differentiation and impact processes left behind significant height changes on the lunar surface, reaching 18 km in the polar regions on the far side. The impact energy and the mantle heating by radiogenic isotopes led to the outflow of lava from the mantle to the surface from a depth of more than 100 km and to the filling up of lunar maria on the visible side, where the crust was considerably thinner. Some peculiarities of the lunar morphology are associated with lava cooling, which gave rise to faults, highlands, and valleys. The endogenous processes ceased 3.18 billion years (Gyr) ago, and the Moon was subsequently subjected only to impact bombardment by bodies mostly migrating from the outer solar system. The processes of meteorite pounding of the surface material, which is responsible for the origin of regolith, have a very slow time scale. As a result, the Moon stores the chronicles of events on its surface, including its interaction with the Sun and the interplanetary medium, over several billion years. Interestingly, under the average level of meteorite bombardment and small erosion, the tracks of astronauts and lunar rover wheels will be retained without noticeable changes for at least several million years (Fig. 2.10).

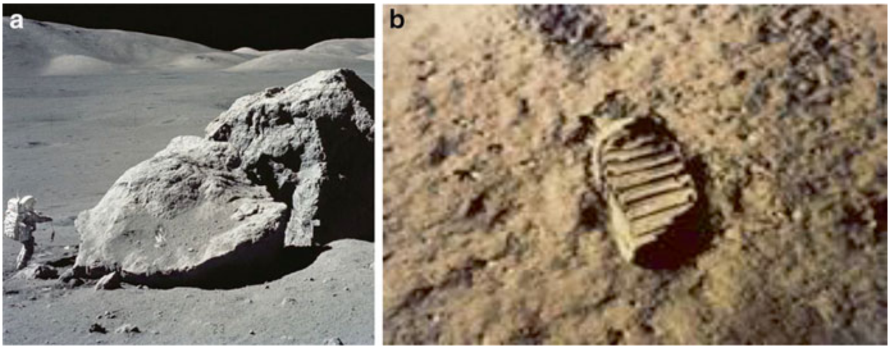

Fig. 2.10 (**a**) A large piece of rock on the Moon surface inspected by astronaut. (**b**) Astronaut's footprint on the Moon surface. In a rather weak erosion conditions on the Moon it is estimated to preserve millions years (Courtesy of NASA)

The knowledge we have gained allows us to argue that, as the body nearest to the Earth and a key proxy for the early Earth, the Moon is of primary interest for fundamental planetology and Earth sciences: geophysics, geology, and geochemistry. We pay special attention to the Moon in the context of better understanding the Earth's geological history, because the most ancient rocks are preserved only on the Moon's surface—on Earth they were eroded by the hydrosphere-atmosphere-biosphere system. Thus, we study the Moon as a window into the early Earth. Unfortunately, despite the great progress in our knowledge of the Moon provided by the unprecedented (both in scale and cost) American and Soviet space programs in the 1960s and 1970s, many problems remain unsolved. After a long break, interest in studying the Moon resumed in the 1990s with the flights of the American spacecraft Clementine and Lunar Prospector, followed by the Japanese Kaguya, Chinese Chang E, and Indian Chandrayaan-1 in the early 2000s. They were focused mostly on the study of lunar relief morphology and the gravity field. Chandrayaan-1 also found evidence of H_2O/OH distribution on the lunar surface. Recently, China's Yutu Moon rover and the Chang E-3 lander that carried it landed on the Moon, though they operated for only a short time.

A new breakthrough was accomplished by the launch of the US Lunar Reconnaissance Orbiter (LRO) and LCROSS—the final stage of the rocket which impacted the lunar surface to release volatiles through explosions. These experiments confirmed quite reliably that the surface of the Moon in the polar regions contains a significant abundance of hydrogen-bearing compounds associated with water ice (up to a few percent). Especially convincing results were obtained by the spectroscopic observations of plumes of volatiles released from ejected surface material, which accompanied the LCROSS impact. From an impact area of 30–200 m^2 heated to >950 K, ~300 kg of water ice sublimated, LCROSS detecting 155 ± 12 kg of water, or 5.6 ± 2.9 % by mass of excavated soil. Other trace molecule species such as H_2S, SO_2, CO_2, NH_3, OH, CH_4, C_2H_4, and CH_3OH were identified. As we can see, the relative abundance of water in the subsurface polar region of the

Moon turned out to be unexpectedly large. Moreover, the recent more detailed analysis of the lunar soil samples delivered by Apollo missions brought the earlier missed evidence that glasses embedded in the soil contain a small amount of water as well. Because water traces appear to connect with magma eruption from the interior, one may assume that the water content in the lunar mantle is close to that of Earth. This flurry of recent developments dramatically changed the persistent view of the Moon as an extremely dry planetary body to that of a rather wet one and has intensified interest in its further study.

Origin. The key unresolved problem is that of lunar genesis: the Moon's origin, accretionary history, and tidal evolution. Basically, there is a trade-off between two main hypotheses. The first one is based on the giant impact scenario first proposed by William Hartmann and Donald Davies in 1975: a catastrophic collision with early Earth of a Mars-size body, which struck Earth a glancing blow and sprayed nearby space with disk-shaped debris, and then the reassembly of exploded debris into a consolidated body in a near-Earth orbit. The second idea, proposed by Eric Galimov, which has received blows since the early 1990s, proceeds from the Moon forming jointly with the Earth from partially differentiated protoplanetary disk matter followed by the contraction of two separate gas-dust clumps of nearly similar chemical composition (Fig. 2.11). The former scenario is supported by the low bulk density of the Moon similar to that of the Earth's mantle from which it presumably has formed, while the latter idea is in much better accord with important cosmochemical constraints—an identity of certain isotope ratios (the so-called isotope shift) for Earth and the Moon. Basically, both scenarios satisfy important constraint placed by the resulting angular momentum of the Earth-Moon system. However, the most conclusive evidence that the Earth and the Moon were formed from a single gas-dust reservoir is the similarity in the mass-dependent fractionation of oxygen isotopes ^{16}O–^{17}O–^{18}O for both bodies, unlike that for other planets and meteorites (Fig. 2.12). This and other isotopic ratios (such as Hf/W, Ru/Sr, etc.) contradict the giant impact hypothesis when one considers the relative contribution to the Moon's formation of the target material (terrestrial mantle) and a projectile (cosmic body), because the latter would constitute up to ~80 % of the ejected matter, as modeling has shown. In other words, ~80 % of the projectile's material would enter the bulk mass of the Moon. Again, this contradicts the similarities in isotopic composition of both bodies. Moreover, there is no evidence of a separation of light and heavy isotopes (kinetic isotopic fractionation), which would accompany any high-temperature explosion in the framework of the giant impact hypothesis. Thus, the above evidence essentially deprives the giant impact hypothesis of geochemical support.

Unfortunately, geochemical measurements are pertinent only to the upper layer of regolith. Therefore, the composition of the lunar surface at a relatively small depth can differ from the underlying layer of igneous rocks because of the significant contribution of meteorite bombardment to the surface material. The modeling of the processes involved in both scenarios is also not yet sufficiently advanced. In particular, to remove the major geochemical problems of the giant impact hypothesis, a scenario involving an impactor an order lower in mass but with higher speed was suggested, though it results in an angular momentum much higher than what

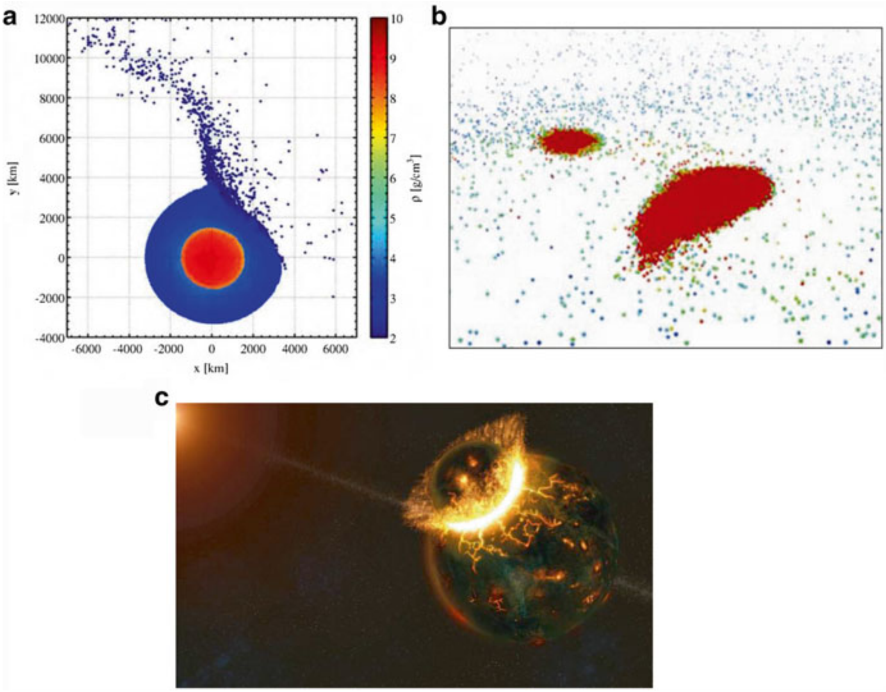

Fig. 2.11 (**a**) Diagram of the Moon formation according to mega impact scenario (Credit: W. Hartmann and D. Davies; A. Cameron and W. Ward). (**b**) Diagram of the common Moon-Earth system origin from the protoplanetary nebula (Credit: E. Galimov and A. Krivtsov). Mega impact hypothesis neatly explains the bulk density and dynamics of today's Earth moon system but not its geochemistry, the latter is in accord with hypothesis of the Moon-Earth common formation. (**c**) Artist's view of mega impact scenario: a planetesimal plowing into the young Earth (Credit: www.sciencemag.org; Science, 2013)

astrophysicists measure today. To avoid this difficulty, an evolution of the former Earth-Moon system toward its current state through a cyclic precession motion which slowed down until it became locked in its now-existing fixed position relative to the Sun—a rhythm known as evection resonance—was invoked. The problem of the Moon's origin remains one of the most challenging in the planetary sciences.

A Perspective. The Moon will probably be the first target along the track of humanity's expansion into outer space. Mastering the Moon and beginning to utilize its resources are on the agendas of space-faring countries. Stored Fe, Al, Si, Ti, and other elements and their compounds in rocks can be used to manufacture materials for building and in-site technology development and, in parallel, to produce air, water, and even fuel from H_2 and O_2 locked in rocks, and possibly to excavate stored water. However, we need to know more, including how lunar potential resources are distributed, the chemical reactivity of the lunar regolith, and which technologies should be applied most efficiently for the treatment/utilization of excavated soil. Solar incident radiation ensures essentially unlimited energy production. Some scientists

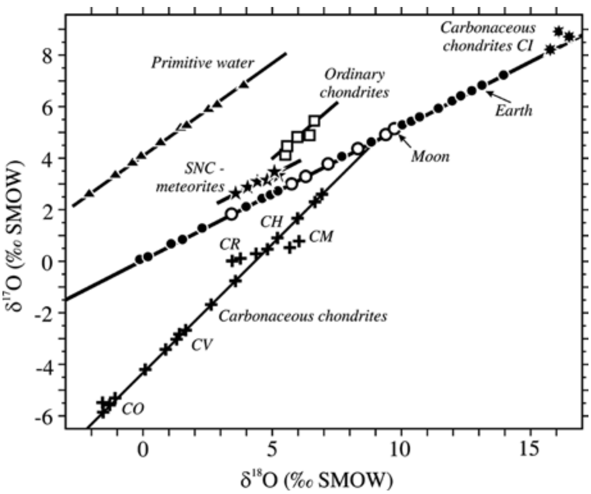

Fig. 2.12 Diagram of oxygen isotopes **δ**^{17}O and **δ**^{18}O ratio. The diagram characterizes shifts in the oxygen isotopes ratios $^{17}O/^{16}O$ and $^{18}O/^{16}O$ relative to adopted standard SMOW (*Standard Model Ocean Water*). Earth and the Moon matters fit the same line in contrast to different types of Chondrites and SNC meteorites (Courtesy of E. Galimov)

value an opportunity to extract the ^{3}He isotope deposited on the Moon's surface (whose abundance in ilmenite is estimated to be ~ 10 ppb) and in the far perspective even to deliver it to Earth for use in a "pure" nuclear reaction. In this reaction only protons are generated, which can be easily shielded, rather than energetic neutrons which are difficult to protect against. There is no doubt that deployment of the lunar infrastructure will provide a new stage of space explorations, especially in planetary science and radio astronomy, which could be referred to as "investigations on and from the Moon."

A great challenge for robotic missions and permanent human habitation is related to the Moon's South Pole. This is a target of the Russian projects Luna-Glob and Luna-Resource to be implemented before 2020. (Let us recall that in 1911 the Earth's South Pole was first explored by humans, and 100 years later Antarctica became a continuous habitation site for a few thousand people from about 30 countries doing innovative and critical scientific research.) The most promising lunar areas in terms of planetary science advancement, technology development, and lunar local resource utilization are the earlier mentioned Aitken basin, the largest known impact crater in the solar system, as well as Shackleton, Cabeus, and other permanently shadowed craters where water ice deposits are expected and water for life support and propulsion could be extracted. In turn, Mons Malapert offers a "peak of eternal light" which opens opportunities for permanent site illumination, power generation, and continuous line-of-sight communications with Earth. "One small step" on the Moon decades ago did not quench the human thirst for exploration of this body, or dull the exciting prospects for further expansion in outer space and settlements, probably using the lunar launch pad. There is no doubt that by the

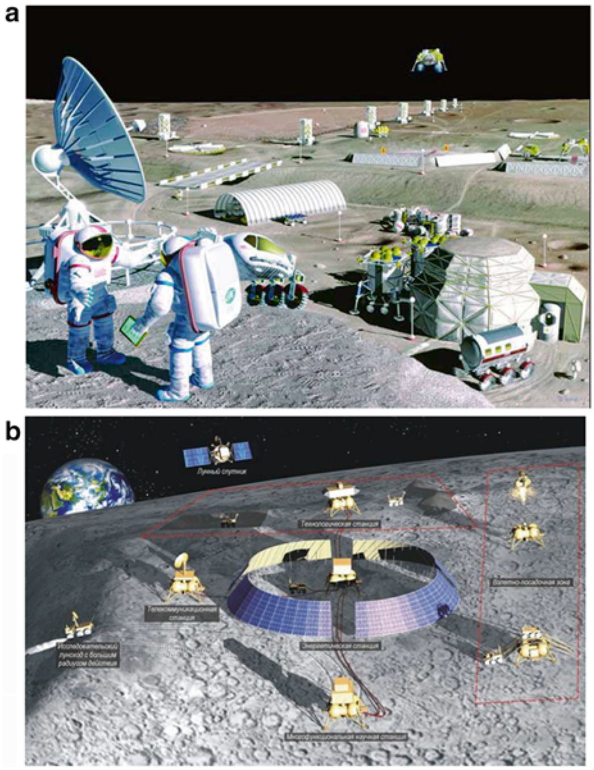

Fig. 2.13 Artist's view of Lunar Base deployment involving a lunar mining facility harvests oxygen and possibly water from regolith as the local resource—a precursor for the further development of the Moon infrastructure and industry with iron, aluminum, magnesium, and titanium production. (**a**) NASA concept (Credit: NASA/Pat Rawlings) (**b**) Roscosmos concept (Credit NPO Lavochkin)

middle of the twenty-first century lunar base deployment (Fig. 2.13) will become a new cornerstone in human space exploration and peaceful use, a worthy achievement for the centennial anniversary of the first satellite launch.

Mercury

Main Properties. Mercury (named in honor of the Roman god of trade, equivalent to Hermes in ancient Greece) is the closest planet to the Sun at less than 0.4 AU. Its semimajor axis a is 0.387 AU (57.9 million km), its eccentricity e is 0.205, its sidereal period of revolution around the Sun (Mercurian year) is about 88 days, and its inclination to the ecliptic plane is an unusually high 7.0°. Owing to its large eccentricity (and, hence, very elliptical orbit), Mercury approaches the Sun (at perihelion) at the minimal distance of 46 million km and moves off (at aphelion) at the maximal distance of 69.8 million km (nearly twice as far as in perihelion). As we have mentioned, because Mercury is locked in a spin-orbital resonance, it gives rise to a unique mode of Mercury's rotation relative to the stars and revolution around the Sun. As a result, one Mercurian stellar day (58.65 Earth days) equals two-thirds of the Mercurian year and turns out to be much shorter than one Mercurian solar day (176 Earth days). It is assumed that initially the intrinsic rotation of Mercury was faster but that it was slowed down by tides from the Sun which, by degrees, took a significant part of the Mercury's momentum. The orbit of Mercury in the Sun's proximity experiences a quite pronounced precession caused by the effects of general relativity. There were attempts to explain the peculiarities in the motion of Mercury by its origin as a satellite of Venus, but this idea was not confirmed in light of contemporary knowledge, specifically the planets' composition and geology. Obviously, Mercury formed independently in the inner region of the protoplanetary disk, depleted of volatiles and with a larger fraction of iron and other heavy refractory elements.

Mercury (see Fig. 2.1) is the smallest planet in the solar system, having a radius of only $2{,}439.7 \pm 1.0$ km. This is even smaller than the radii of the largest satellites of Jupiter (Ganymede) and Saturn (Titan). The mass of the planet is 3.3×10^{23} kg and its density is 5.43 g/cm^3, which is only slightly less than the Earth's density. The acceleration due to gravity on Mercury equals 3.70 m/s^2, and the escape velocity is 4.25 km/s. Its visual stellar magnitude varies between—1.9^m and 5.5^m, but it is difficult to observe because of its small angular distance from the Sun (28.3° at maximum elongation). The axis of Mercury's intrinsic rotation is nearly perpendicular to the plane of its orbit, and therefore there are no seasonal changes on the planet. Because it is located close to the Sun, Mercury attracts special interest like many discovered exoplanets in the proximity of their parent stars.

The most complete information about Mercury came via space flights. Mariner 10 was the first spacecraft to fly by the planet, doing so three times in 1974–1975 at a minimum distance of 320 km and sending back to Earth images of about 45 % of Mercury's surface. The second spacecraft, MESSENGER (MErcury Surface, Space Environment, GEochemistry, and Ranging), following three gravity assist maneuvers (one of Earth and two of Venus), made its first flyby of Mercury in 2008, and then after two additional gravity assists of Mercury was placed into orbit around the planet in 2011. Since then it has imaged more than 95 % of the planet's surface with rather high resolution and transmitted other important information as well.

Surface, Interior. The heavily cratered surface of Mercury resembles that of the Moon, though it is more uniform. There are no large basins with the exception of Caloris Planitia, a ring structure 1,550 km across of impact origin filled with lava formed at the hub (Fig. 2.14). Mercury's craters range in size from a few to hundreds of kilometers, the largest being the crater Rembrandt, which is more than 500 km across. Generally, craters are well preserved, giving evidence of no geological activity on the planet for the last 3–4 billion years and very weak erosion. However, evidence of widespread volcanism discovered in Mercury's northern plains implies that volcanic activity was of great importance in the thermal evolution history of the planet, in particular indicating that lava has been extremely hot (Fig. 2.15). Obviously, because of the rather small size of Mercury, the stored

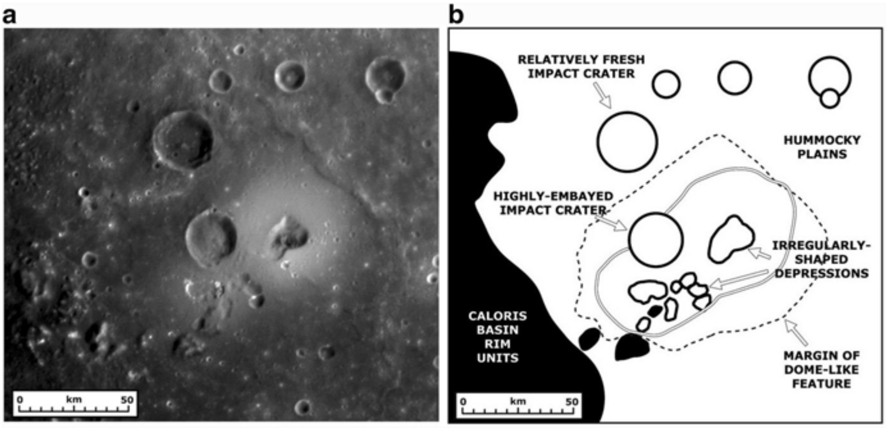

Fig. 2.14 (**a**) Messenger's image of impact craters around volcano in the largest basin on Mercury Caloris Planitia of ~1,600 km across. (**b**) Diagram of the main landforms right of Caloris basin rim units. (Credit: NASA)

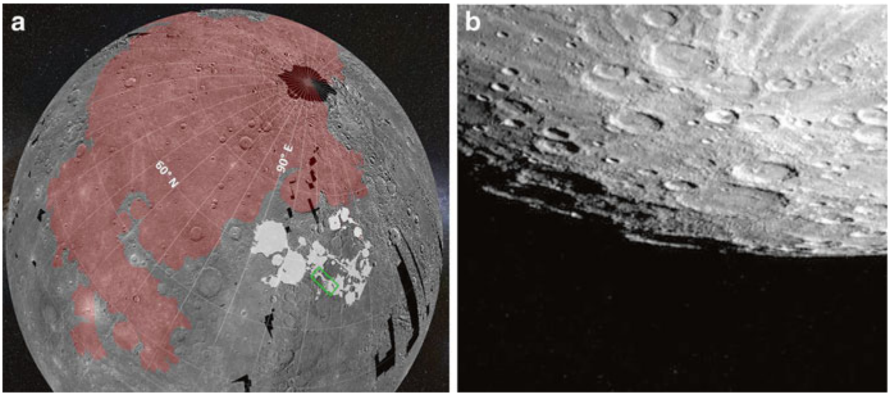

Fig. 2.15 (**a**) Mercury Northern plains where widespread volcanism was discovered. This serve as important implication for volcanic activity in Mercury's thermal evolution history and in particular indicates that some lavas were extremely hot. (**b**) Messenger's view of the South pole of Mercury (Credit: NASA/J. Green)

radionuclides responsible for heating the planet's interior were exhausted during its first 1–2 billion years, and since then Mercury, composed of 83 % iron stored mainly in its core, has steadily cooled and shrunk. This resulted in a dramatic deformation of the crust and a general decrease in the planet's surface area by about 1 % accompanied by the formation of sharp cliffs (lobate scarps) hundreds of kilometers long. For example, the giant lobate scarp Discovery Rupes, 3 km in height, extends for about 350 km.

Measurements of the elementary composition of Mercury's surface with X-ray fluorescent spectrometry showed that, in contrast to the lunar surface which is

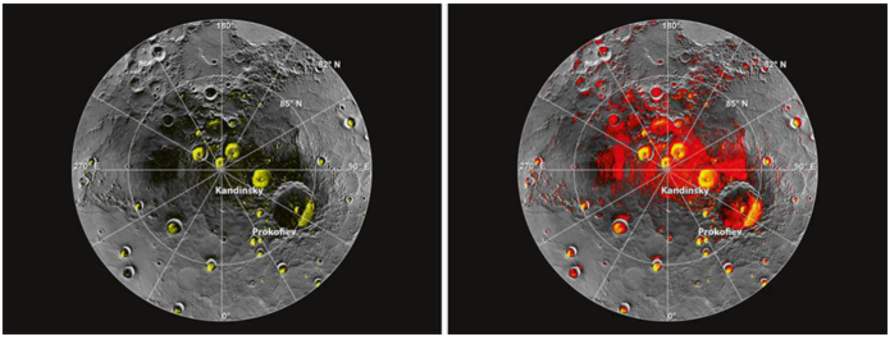

Fig. 2.16 A mosaic of Messenger radar images of Mercury's North (*left*) and South (*right*) polar regions. In the North polar region, all of the polar deposits are located on the floors or walls of impact craters. Deposits farther from the pole are seen to be concentrated on the north-facing sides of craters. In the South polar region, permanently shadowed polar craters were revealed (similar to those on the Moon) shown in *red*. The comparison of Messenger background mosaic with Earth-based radar data (shown in *yellow*) indicates that all of the polar deposits associated with water ice are located in areas of persistent shadow (Credit: NASA/John Hopkins University/Carnegie Institution/Arecibo Observatory)

enriched with plagioclases and feldspars, the surface rocks of Mercury are depleted of calcium, aluminum, titanium, and iron (all iron and siderophiles seem to have sunk down to the core) but contain more magnesium and sulfur. This means that the composition of Mercury's surface occupies an intermediate position between typical granites and ultramafic rocks and is similar to terrestrial komatiites - a type of ultramafic mantle-derived volcanic rock having low silicon, potassium and aluminium, and high to extremely high magnesium content. The most detailed data on the relief and composition of the planet's surface were obtained with the MESSENGER spacecraft. Of special interest are radar images of Mercury's north and south polar regions (Fig. 2.16). It was found that in the north polar region all of the polar deposits are located on the floors or walls of impact craters and deposits farther from the pole are concentrated on the north-facing sides of craters. In the south polar region permanently shadowed polar craters were revealed (similar to those on the Moon). They were compared with Earth-based radar data and provided additional evidence that all of the polar deposits associated with water ice are located in areas of persistent shadow.

Rather unusual is Mercury's interior, which is different from those of all other solar system planets. A major part of its mass occupies an iron-rich core with a radius of 1,800–1,900 km, overlaid by a solid silicate mantle 600 km thick and a 100–300 km solid silicate crust. The core is composed mostly of iron (with some admixture of sulfur) and is assumed to be at least partially liquid, as deduced from radar observations of the planet's specific rotation patterns. A liquid outer core and perhaps a solid inner core can be distinguished, as modeling suggests, in accord with the MESSENGER spacecraft tracking. The core liquid state is probably maintained by the pronounced tidal interaction of the planet with the Sun, stipulated by the high eccentricity of its orbit. Mercury appears to have formed from a high-temperature (refractory) fraction of its protoplanetary disk, and its original matter was rich with iron. Its extended iron-rich core occupying a major part of the body corresponds to the model of a planet having a quite uniform radial density distribution and fully satisfies a dimensionless moment of inertia $I = C/MR^2 = 0.353 \pm 0.017$, and has also been found to have three mass concentrations (mascons) of more than ~100 mGal deep resembling those of the Moon.

Based on the dynamo theory invoked to explain planetary magnetic fields, the circulation in a partially liquid core and its slow rotation together are assumed to be responsible for Mercury's rather weak magnetic field. Its field strength is a hundred times less than the Earth's (350 nanotesla). It has a quite regular dipole structure; its axis is shifted from the rotation axis by only 10°. Mercury's intrinsic magnetic field is sufficient to form a rather small magnetosphere and specific patterns of interaction with solar wind plasma. In particular, MESSENGER discovered peculiar magnetic eddies hundreds of kilometers across and breaks in the magnetosphere through which solar plasma may reach the surface, possibly caused by frequent reconnections of interplanetary and Mercurial magnetic field lines.

Natural conditions on Mercury's surface are extremely hostile. There is essentially no atmosphere: the surface pressure is 5×10^{11} times less compared to that of Earth (its density of $\sim 10^{-17}$ g/cm^3 is like that of the Earth's exosphere), and its integral spherical albedo *A* is quite low (0.12). The surface temperature exhibits sharp variations from 90 K at night to 700 K in the day (between −180 °C and +430 °C), the widest range in the solar system. However, because of the low thermal conductivity of the loose upper layer (regolith), the temperature at about a 1 m depth tends to stabilize to an average value of about +75 °C. The thin atmosphere is composed of oxygen (42 %), sodium (29 %), hydrogen (22 %), and helium (6 %), with admixtures of water, argon, nitrogen, potassium, calcium, and magnesium (altogether within 1 %). The atmosphere's origin is related to particles delivered by the solar wind (mostly hydrogen and helium), supplied by radioactive decay (helium, sodium, potassium), and sputtered by solar wind plasma from the surface (all other species). Interestingly, particles experience less frequent collisions in the very rarefied atmosphere than with the surface, the atmosphere being renewed about every 200 days. As mentioned above the permanently shadowed polar regions could preserve large water ice deposits covered with dust particles. This idea is supported by the higher reflectivity of polar regions revealed by radar observations and the discovery in the atmosphere of such ions as O^+, OH^-, and H_2O^+, which are closely related to water. The discovery of a comet-like tail of Mercury extending for more than 2.5 million km (angular size about 3°) showed another interesting phenomenon of the planet.

Venus

Main Properties. Venus is the second planet from the Sun (Fig. 2.1), at a mean distance of 0.723 AU (108 million km). Its name honors the goddess of love in the Roman pantheon (Aphrodite is Venus's analog in Greek mythology). The maximum visual stellar magnitude of Venus is -4.9^m (though typically -4.5^m), and it is the third brightest object in our skies (after the Sun and the Moon). The maximum elongation of Venus from the Sun is 47.8°. Because the planet is best observed in different seasons before sunrise or after sunset, it is often called the morning or evening star.

The planet orbits the Sun for 224.7 Earth days (this is the sidereal period relative to the stars, i.e., a Venusian year). The orbit of Venus is nearly circular (its eccentricity is only 0.0068). Its distance from Earth varies from 259 to 40 million km at the superior and inferior conjunctions, respectively. The rotation of the planet around its axis is extremely slow—one revolution in 243.02 Earth days. Venus rotates in a retrograde (clockwise) direction, in contrast to the anticlockwise (prograde) direction of all other planets except Uranus. The inclination of Venus's axis of rotation to the plane of the ecliptic is only 3.4° (2° to the plane of its orbit); therefore, there are essentially no seasonal changes on the planet. Because of its slow rotation, the shape of Venus has no oblateness. The combination of intrinsic rotation and revolution in orbit give rise to Venus's motion relative to the Sun (the synodic period) 584 Earth days. Its motion relative to the Earth is 146 Earth days, i.e., exactly four times less, whereas one solar day on Venus is 116.8 Earth days. Interestingly, in every inferior conjunction Venus faces Earth with the same side. It is not yet clear whether this is caused by the mutual gravitational interaction of the two planets.

Venus is very similar to Earth in size, total mass, and density. Its radius is 6,051.8 km (95 % of Earth's), its mass is 4.87×10^{24} kg (81.5 % of Earth's), and its mean density is 5.24 g/cm^3. Its acceleration due to gravity is 8.87 m/s, and its escape velocity is 10.46 km/s. Like Mercury, Venus has no satellites. Due to its proximity to the Sun, the solar constant at Venus's orbit is approximately twice that of the Earth ($S = 2{,}621$ W/m^2), although its integral spherical albedo is also approximately twice as much ($A = 0.76$). Therefore, the incident flux of solar energy to the rotating planet (insolation) on Venus (157 ± 6 W/m^2) is nearly the same. Let us note that while both planets derive comparable radiant energy from the Sun in the contemporary epoch, the situation was undoubtedly different at the earliest stages of both planets' evolution.

When observed from Earth in visible light, Venus looks like a completely featureless planet covered with a gaseous/hazy atmosphere (see Fig. 2.1); only in near-ultraviolet light are some features revealed (Fig. 2.17). The surface is impossible to see. This is why only very limited data about the nature of the planet were known until late in the space age. Original ideas regarded Venus as our sister planet with a favorable climate and pleasant conditions at the surface, including a wealth of vegetation. However, the reality turned out to be completely different. The first hints that Venus could have unusually high temperatures were revealed by ground observations in radio wavelengths (centimeter-decimeter waves), though their interpretation was not unambiguous. The principal breakthroughs in our knowledge about Venus occurred only with the beginning of space flights. The American Mariner 2 was the first spacecraft to fly by Venus in 1962, and it provided more reliable evidence that the recorded high radio brightness temperature could be caused by a hot surface on Venus. However, estimates of atmospheric pressure and composition remained fully speculative. The most reliable data about parameters of the

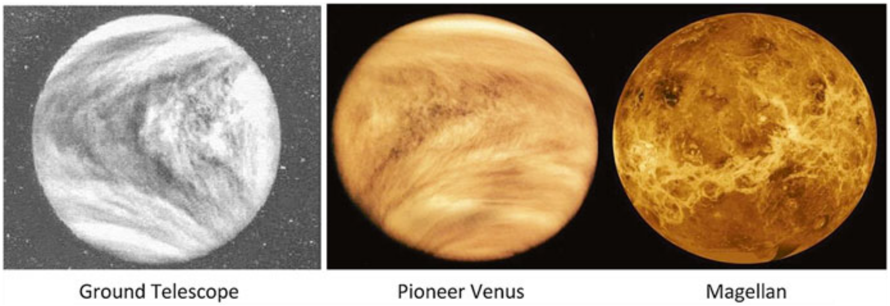

Fig. 2.17 Images of Venus obtained from the Earth in the ultraviolet spectral range (*left*); from Pioneer Venus Orbiter (*middle*); and in the centimeter radio wavelength—mosaic of images of the Venus surface obtained by aperture synthesis radar and returned by the Magellan spacecraft (*right*). While the visible range contains little information (only the isolated bands associated with the inhomogeneous structure of sulfuric-acid clouds can be seen) characteristic ordering structures are observed in the ultraviolet due to the presence of an absorber (probably sulfur particles) at the upper cloud boundary. These structures ("ultraviolet clouds") move over the Venusian disk with a speed of ~ 100 m/s that exceeds the wind speed near the surface by two orders of magnitude due to the superrotation of the atmosphere. The surface of Venus can be seen only in the radio wavelength for which the atmosphere and clouds are transparent. Radio mapping has revealed many relief features and peculiarities of the Venusian surface (Courtesy of NASA)

Venusian atmosphere were derived by direct in situ measurements of temperature, pressure, and composition made by the Soviet Venera landers. Venera 4 in 1967 was the first space vehicle to enter the planet's atmosphere, descending by parachute. It was followed by several more generations of Venera missions of much more complicated scenario and capability performance through Venera 14. The probes were able to survive on the surface in a very hostile environment and make unique scientific observations. Valuable information was also achieved by the American Mariner 10 and Pioneer Venus missions, and later by the European Venus Express. Space exploration revealed the planet to be fully different from our original views—a truly inhospitable world existing just beside us.

Atmosphere. Venus stands out among terrestrial planets of the solar system primarily by its massive gaseous envelope and thermal regime. The most intriguing question is what ultimately caused the formation of a hot atmosphere on this planet. The atmosphere is composed mostly (by ~ 97 %) of carbon dioxide (CO_2) with about 3 % nitrogen (N_2) and only trace contents of water, carbon monoxide CO, sulfur-bearing gases (SO_2, COS, H_2S), hydrogen chloride (HCl), and hydrogen fluoride (HF). There is essentially no oxygen. The temperature on the surface is 735 K (472 °C)—higher than that on Mercury which is located closer to the Sun, and well above the roast setting on your kitchen oven! Some metals are melted under such high temperatures. There are no essential temperature variations between the Northern and Southern Hemispheres because of the great thermal capacity (enthalpy) of the atmospheric gas. The pressure at the surface is 92 atm (like that in the Earth's oceans at nearly 1 km depth!), and the atmospheric density is only about an order of magnitude less than that of water. Diurnal and latitudinal temperature variations become pronounced only in the atmosphere above the cloud deck, in the stratosphere-mesosphere and thermosphere. Venus's clouds are also quite exotic: they are mostly composed of micrometer-sized sulfuric acid droplets and form a three-layered structure ~ 20 km thick between about 49 and 65 km. This and other unique properties fundamentally distinguish Venus from the other two terrestrial planets with atmospheres, Earth and Mars. As the closest analog of Earth, it is worthwhile and instructive to consider Venus as an extreme model of the home planet evolution. While Earth is the garden spot of the solar system, Venus is an awful place to visit.

Measurements of the monochromatic and integrated solar radiation fluxes as a function of solar zenith angle serve as the key limiting factor for thermal balance estimations. Measurements of solar flux attenuation in the Venusian atmosphere and illumination of the surface made with Venera landers 8, 9, and 10 and the Pioneer Venus probe showed that more than 65 % of the solar incident flux is absorbed in the upper cloud layer and the upper cloud haze (in a range of altitude of 60–90 km), about 8 % is absorbed in the middle and lower cloud layers (49–60 km), and approximately 27 % is absorbed by the lower atmosphere and the surface. Averaging the measured incident solar radiation flux over the entire surface of the planet gives rise to a flux per unit surface area of less than 20 W/m^2. This is only about 10 % of the averaged energy absorbed by Venus (~160 W/m^2). Since the surface albedo estimated by analyzing the photometric measurements and panoramas of Venus transmitted by the Venera landers does not exceed 10 %, this implies that almost 90 % of the solar radiation flux reaching the surface is absorbed. No direct solar rays reach the surface due to the large optical thickness of the atmosphere and clouds. Scattered radiation dominates below about 60 km, and the surface is illuminated rather poorly, from about 300 to 3,000 lux (meter-candles) depending on the solar zenith angle. Thus, illumination on the Venus surface in the daytime is like that in deep twilight on Earth. Attenuation of solar light in the short-wavelength range increases as the surface is approached (the blue part of the solar spectrum is "extracted"), and red rays dominate. An observer on the surface would see an orange sky and a reddish landscape.

Surface, Relief, and Geology. Radio waves, in contrast to optical wavelengths, are capable of penetrating through the dense atmosphere and cloud layer. We already mentioned how important the first ground radio measurements were in advancing our knowledge about Venus. Later the radar technique gave us an opportunity to map the Venusian surface with spacecraft (Fig. 2.17). This started with the Venera 15 and 16 orbiters, which mapped the Northern Hemisphere, and the technique was then performed globally and with better resolution by the Magellan spacecraft. These missions allowed us to investigate Venus's surface in great detail, as shown in the topographic map of Fig. 2.18. Numerous landforms preserving certain patterns of Venus's geological evolution which were not quite similar to terrestrial ones were revealed. Generally, on Venus terrains are represented by elevated areas, vast plains, and valleys. A typical landform is the plateau Lakshmi Planum in the near-equatorial region surrounded by numerous ridges (Fig. 2.19). Another example of plains typical

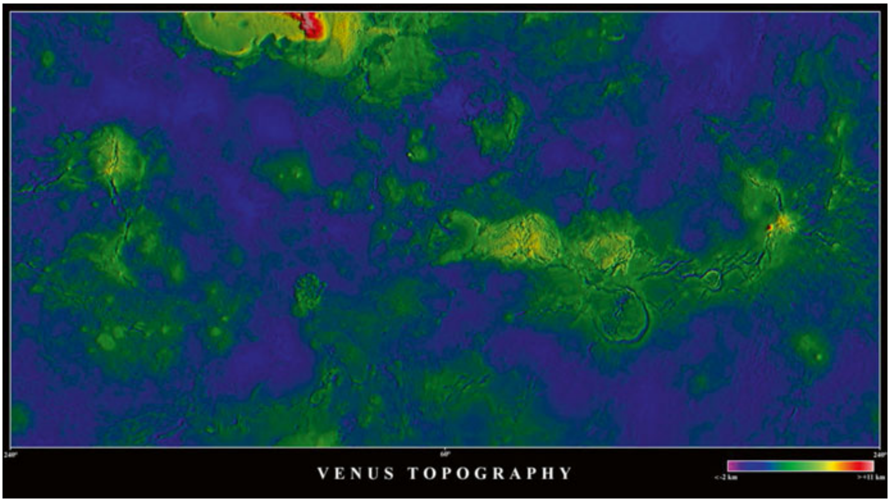

Fig. 2.18 Topographic map of the Venus surface in Mercator projection based on the Magellan radar mapping. *Green* color—elevated areas, *blue* color—low lands. The mostly high areas (*white* to *red*) are Ishtar Terra with Maxwell Mounts in high latitude (*upper left*) and Alta Regio—Aphrodite Terra and Beta Regio in the equatorial regions (Credit: NASA)

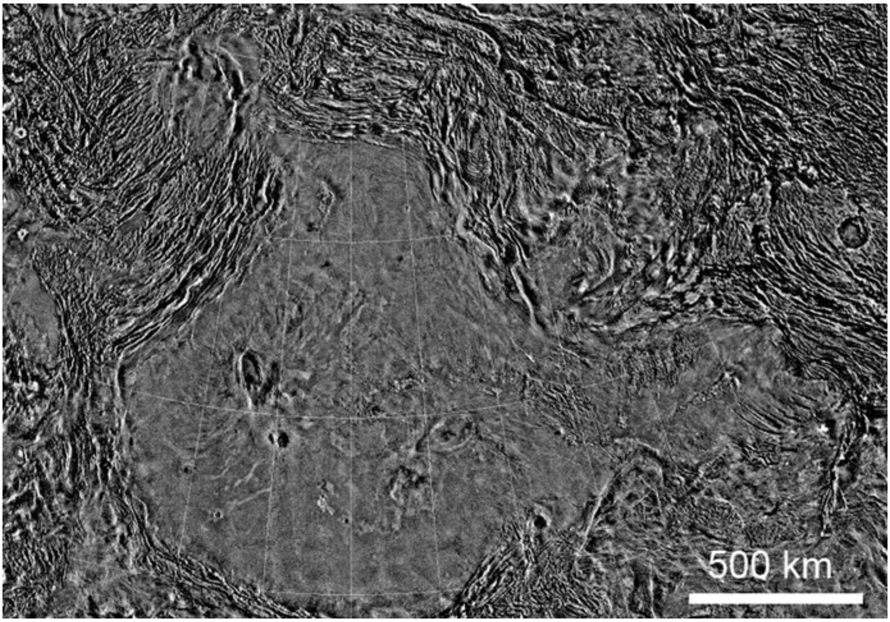

Fig. 2.19 Plateau Lakshmi in the near-equatorial region surrounded by numerous ridges (Venera 15/16 image) (Courtesy of Russian Academy of Sciences)

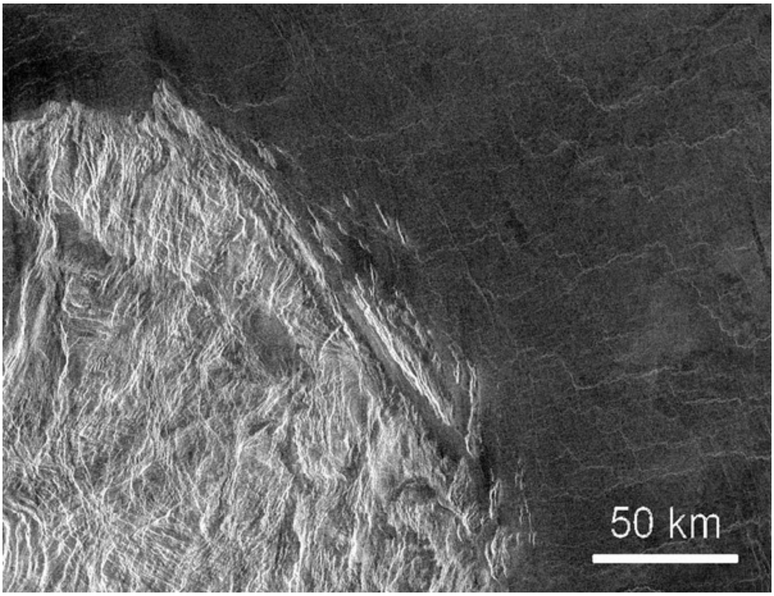

Fig. 2.20 These strongly deformed structures (ridges of compression and furrows of extension) called Tessera are typical for Venus plains (Courtesy of JPL, NASA)

of Venus are strongly deformed structures, ridges of compression and furrows of extension called tessera (Fig. 2.20). The largest highlands in the equatorial and middle latitudes are Aphrodite Terra and Ishtar Terra, which are comparable in size to the Earth's continents. The highest elevation is the mountain range Maxwell Montes at about 11 km in height and about 800 km in diameter (Fig. 2.21) on Ishtar Terra. Interestingly, Maxwell is one of three (historically preserved) male names on the planet, together with Beta Regio and Alpha Regio; by the decision of the International Astronomical Union, entirely female names are attributed for the surface features of Venus. Another elevation of presumably tectonic origin is Beta Regio (Fig. 2.22); however, unlike on Earth, there are no prominent tectonic structures that would dramatically modify the planet's surface.

However, there is strict evidence of widespread volcanism exhibited by large volcanic mountains (Fig. 2.23) and the surface outpouring of volcanic lava called "pancakes" (Fig. 2.24). There are also some local volcano-tectonic features represented by coronas—specific circular or oval-shaped structures of the Venusian surface morphology (Fig. 2.25). Similar to the coronas are arachnoids, peculiar ring structures left behind by ancient geologic processes of not quite clear nature. Volcanic activity apparently ceased on Venus relatively recently (~100 Myr ago). Although Venus possesses a very thick atmosphere, it has been bombarded throughout its history by large projectiles (a few kilometers across) capable of reaching the surface. Evidence of impact craters ranging between about 10 and 50 km in size with characteristic central dome and outbursts of soil of different

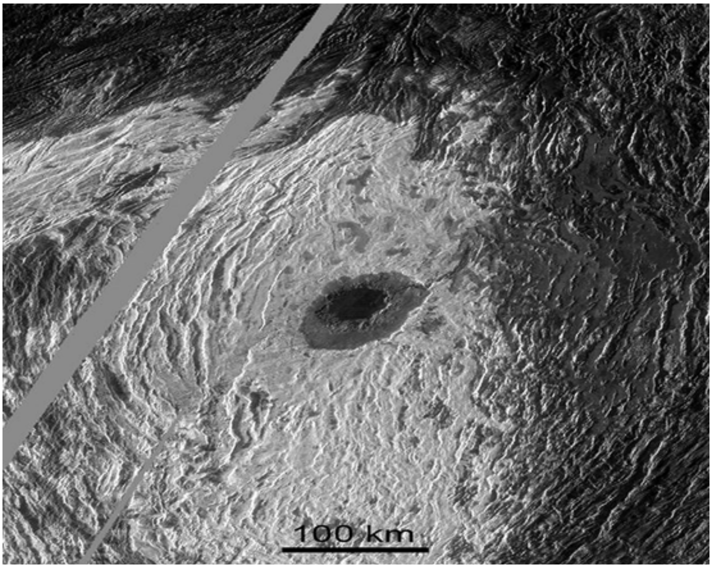

Fig. 2.21 Maxwell Mont of about 11 km in height, the highest on Venus. They have very bright surface above ~5 km in the radio wavelength (a sort of "snow line") that is probably caused of metallic type of substance the mountain is composed of (Courtesy of JPL, NASA)

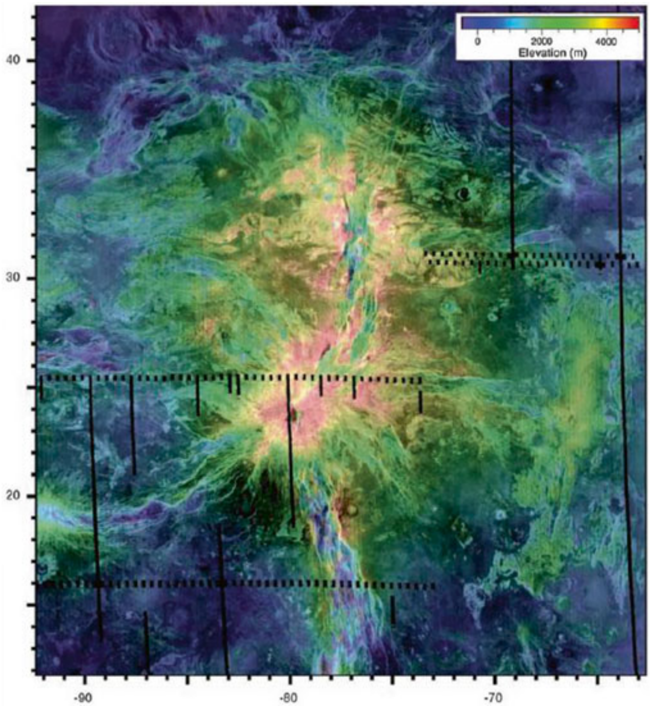

Fig. 2.22 Beta Regio—elevation of tectonic origin dissected by Devana canyon running from south-west to north-east. Scale of elevations is shown at the *upper right*. (Courtesy of NASA)

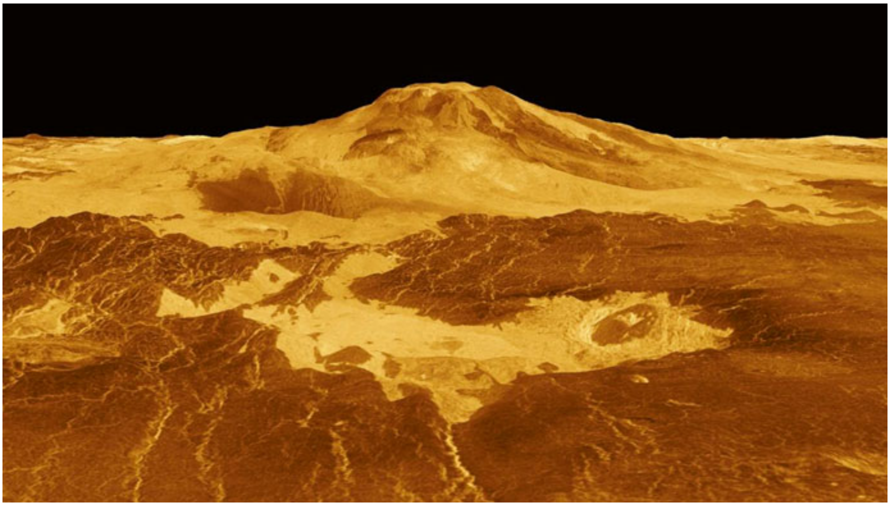

Fig. 2.23 Volcano Maat in Alta Regio—Aphrodite Terra on Venus in perspective projection. The height of the mountain is ~ 5 km; the traces of lava flows are clearly seen. The vertical scale is ten times enhanced for clarity. Surface brightness is also artificially exaggerated (Courtesy of NASA)

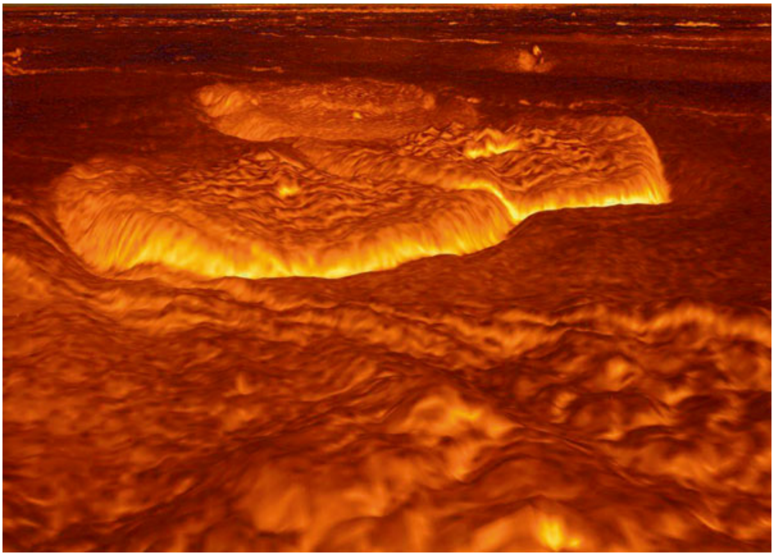

Fig. 2.24 An image of the surface outpouring of volcanic lava ("pancake") in perspective projection (Courtesy of NASA)

configurations formed in the dense atmosphere were revealed (Fig. 2.26). The most spectacular images are those of Venus's surface—color panoramas taken on the very hot surface by the Soviet landers Venera 13 and 14 and returned back to Earth (Fig. 2.27). An inhomogeneous relief of probably volcanic origin illuminated by the scattered reddish-orange solar light is clearly seen in the vicinity of both landers.

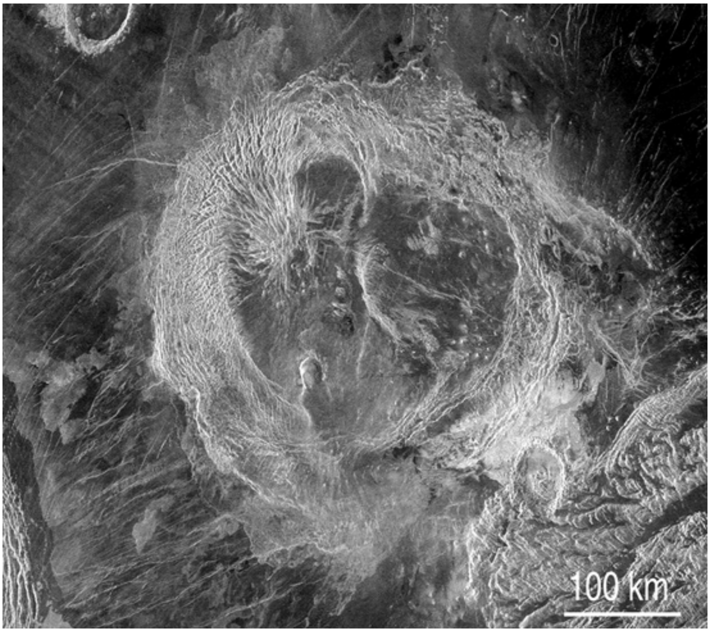

Fig. 2.25 Coronas—specific circle or oval shape volcano-tectonic structures of the Venus surface morphology (Courtesy of NASA)

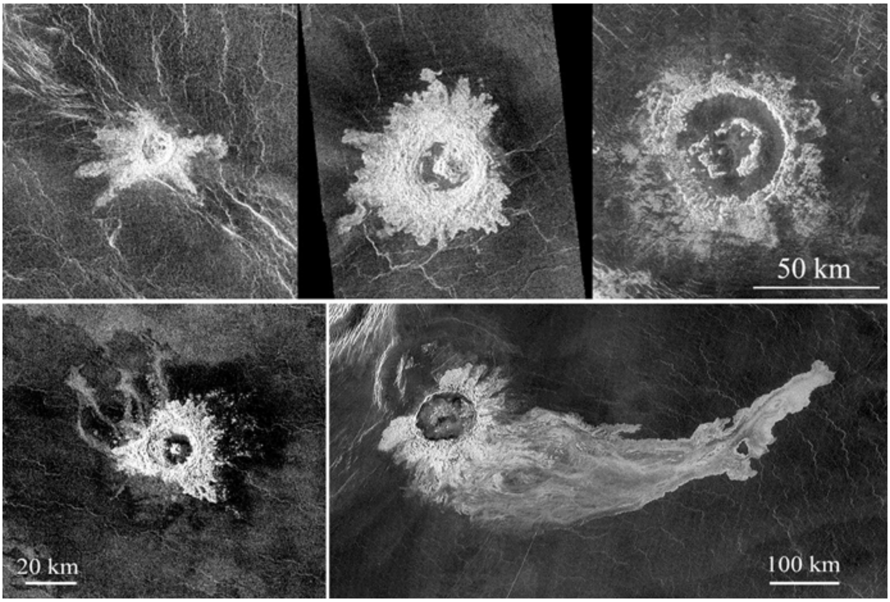

Fig. 2.26 Types of impact craters on the Venus surface with characteristic central dome and outbursts of soil of different configuration formed in the dense atmosphere. The size of craters varies between about 10 and 50 km and is indicative that projectiles of several km size penetrate the very thick Venus atmosphere and reach the surface (Courtesy of NASA)

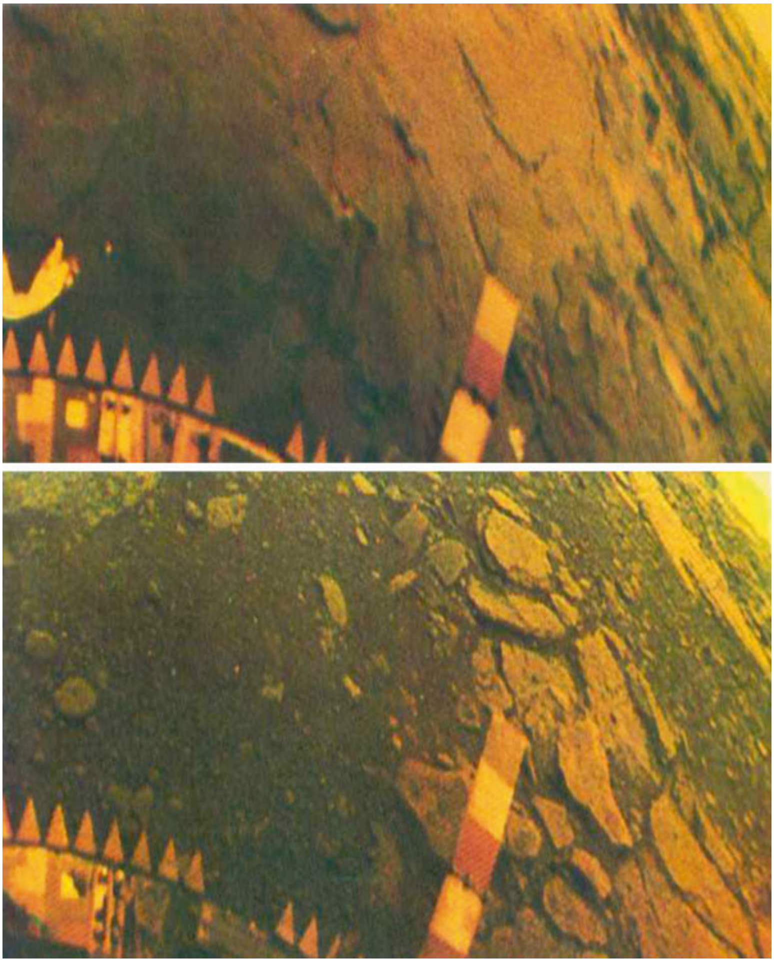

Fig. 2.27 Color panoramas of the Venus surface returned by Venera 13 (*up*) and Venera 14 (*bottom*) landers. Irregular relief is seen with heap of stones of presumably tuff composition. Horizon is at the *upper right* corner. At the *bottom left*—element of lander with tooth-shape aerodynamic ring and test-color plate. *Reddish-orange* color illuminating the surface corresponds to scattered light of the solar spectrum shifted to the longer wavelength (Courtesy of A. Selivanov)

A montage of the Venusian landscape at the Venera 13 lander site in perspective transformation is shown in Fig. 2.28. Note that unlike our blue sky, on Venus one would see skies orange in color.

The interior of Venus is still poorly known, and its model generally resembles that of the Earth. The same three main shells are assumed to exist: an upper crust of about 16 km thick, then a mantle extending to about 3,300 km in depth, and finally a massive central iron core comprising nearly a quarter of the overall mass of the planet (see Fig. 2.2a, b) Because of the very slow intrinsic rotation of Venus, the

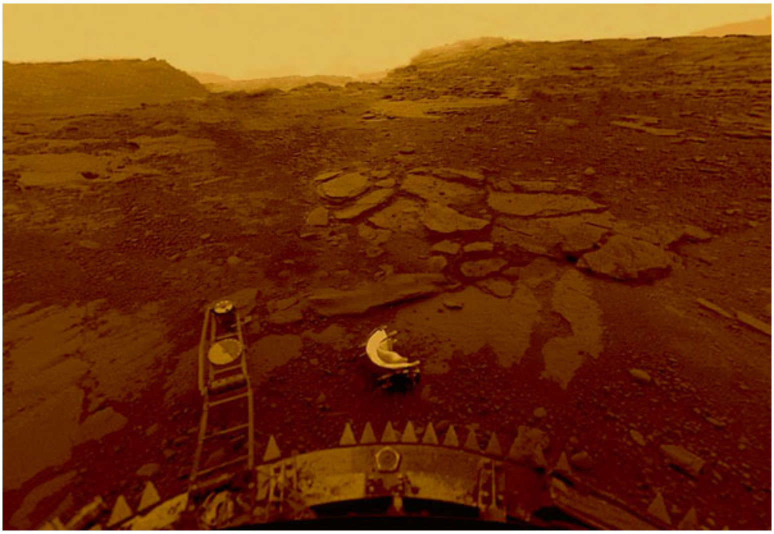

Fig. 2.28 Venus landscape at the Venera 13 lander site: montage and perspective transformation by Don Mitchell. The incident solar light penetrating to the surface (~3–5 %) is reflected by very low surface albedo (Courtesy of D. Mitchell)

dynamo mechanism is apparently damped and no electric current is generated in the core, which explains why Venus has no magnetic field.

Heat Regime and Dynamics. A fundamental question is: Why did a neighboring planet very similar to Earth and only 40 million km away take a completely different path in its evolution? This question is addressed in more detail in the last section of this chapter. Here we preliminarily touch upon only some basics.

One may assume that the unusual, in many respects exotic, climate of Venus was predetermined by many factors, primarily by the runaway greenhouse effect that probably resulted from a loss of water from the surface of the planet followed by decomposition of carbonates in surface rocks. We can hardly reproduce this process, but we can study in sufficient detail the physical mechanism of the formed stable thermal equilibrium state on the planet.

The problem of fundamental importance is how a thermal regime on a planet is formed. Let us note that, in contrast to stellar atmospheres, the influx of radiant energy absorbed by a planetary atmosphere, which is a permanently acting factor, leads to heat flux variability with altitude. The interaction of radiation with the gaseous medium characterizes the energy release. Thus, to understand the main features of the thermal regime in Venus's atmosphere, it is necessary to answer the questions of how the outgoing and incident radiation are balanced, in other words, how net heat flux is formed and what interrelationship occurs between the radiative and dynamical heat exchanges. To judge the patterns of radiative heat exchange, greenhouse effect formation, and the role of atmospheric dynamics, it is important first of all to compare the altitude profiles of solar and thermal radiation, each of which is the downflow-upflow difference (the net flux).

Evaluation of the radiative transfer involving optical properties of the main and minor atmospheric components, their abundance, and their height distribution is key for the greenhouse mechanism modeling. Thermal infrared radiation is absorbed by almost all gases of Venus's troposphere. Carbon dioxide release from the crust with involvement of positive feedback leading to irreversible increase of both temperature and pressure is mainly responsible for the runaway greenhouse setup and its escalation. The optical properties of CO_2 are determined by a number of strong vibration-rotation bands and several weaker bands produced by asymmetric isotopes. Because of the great CO_2 content in the path of ray propagation (~10^9 atm cm) and under high temperature, the contemporary atmosphere of Venus is opaque in the regions of intense absorption bands and radiation is transferred between them only in a few "windows of transparency." These windows become narrower, however, in the induced CO_2 absorption spectrum under high temperature and pressure because of the formation of far wings of strong bands. The weak bands falling into these windows also reinforce and contribute to the radiation absorption. Nonetheless, minor atmospheric species, primarily water vapor and sulfur-bearing compounds (SO_2 being the most important), whose bands fall in the CO_2 windows of transparency most efficiently influence the radiation transfer there, although their relative content (mixing ratio) amounts to only hundredths or even thousandths of a percent. Let us note that in a homogeneous medium, the mixing ratios are preserved as constant only for the components that are not subjected to chemical or phase transformations in the range of temperatures under consideration, whereas water vapor and sulfur dioxide contents change with altitude, especially in the cloud layer. The clouds themselves additionally contribute to the radiation transfer and net flux evaluation.

Calculations for more than 500 wavelength ranges with a high spectral resolution showed that almost all outgoing atmospheric radiation at the surface temperature of 735 K is concentrated in the infrared spectral range from 1.5 to 1,000 μm, with the intensity peak being at 4 μm and shifting to 8.2 μm near the lower cloud boundary at a temperature of 365 K in response to the Planck radiation law. It turns out that thermal balance is accomplished in the carbon dioxide atmosphere, provided the mixing ratio of water vapor is between 10^{-4} and 10^{-3} throughout the troposphere, which is in accord with the available measured data. The contribution to the opacity of sulfur dioxide is weak and is mostly pronounced in the upper troposphere region, above ~ 40 km.

In addition to the radiative transfer, an important role in the formation of the thermal balance of Venus is the atmospheric dynamics. Obviously, if there is a radiative equilibrium in the atmosphere (as in the terrestrial stratosphere), then the solar radiation energy is compensated for at each level by the outgoing radiation flux. In other words, the rates of solar energy input and atmospheric cooling through infrared radiation are equal in this case. If, alternatively, the radiative-convective equilibrium condition is met (as is usually the case in the troposphere), then the input of solar radiation is compensated for at each level in the atmosphere by the net heat flux through outgoing radiation and convective heat transport. In fact, these alternatives serve as a local approximation to the more complete picture of heat transport including dynamical processes of various spatial scales (e.g., planetary circulation, convection, turbulence).

While the condition for global-scale heat balance on the planet (characterized by the effective temperature near the upper boundary of clouds, $T_e = 228$ K for Venus) is rigorously met, an inequality between the input and output energies in different regions of the planet serves as the source of motions with various spatial scales. In other words, the emergence of thermal inhomogeneities (horizontal temperature gradients due to differential heating) is compensated for by the development of large-scale motions with a broad spectrum of spatial sizes, including the cascade fragmentation of turbulent vortices to sizes at which the dissipation of mechanical energy into heat takes place. This may explain the imbalance between the calculated heat fluxes and the measured altitude profile of the incoming solar radiation, as well as significant latitude dependence of the vertical temperature profiles revealed by microwave sounding of the Venusian stratosphere and difference in heat fluxes according to radiometric measurements from the Pioneer Venus probes.

The atmospheric dynamics results from transformation of a part of the incident energy flux from the Sun. Generally, we can say that planetary dynamics reflect the balance between the rate of potential energy generation through solar radiation and the rate of kinetic energy loss through dissipation. From this viewpoint, the planetary atmosphere is often compared with a heat engine in which the equatorial and polar regions serve as the heater and refrigerator, respectively. Note that the efficiency of such an engine is very low, no more than a few percent.

Thus, the obvious difference in heat influx from the Sun to the equator and poles on Venus is apparently not compensated for by the outgoing radiative heat flux due to the noted change in the contents of H_2O and SO_2 with latitude. In other words, at low latitudes influx of the solar radiation is larger and the radiative heat losses are smaller, while the reverse is true at high latitudes. If we take into account the earlier mentioned fact that the diurnal variations in the thermal regime of the lower atmosphere are negligible, then an explanation of this phenomenon can be found in the mechanism of planetary circulation through which a redistribution of heat and, accordingly, additional heating or cooling of the lower atmosphere occurs. Indeed, the imbalance of the latitude gradient of solar heating and infrared cooling in the lower atmosphere is an important energy factor in the planetary circulation mechanism.

The dynamical transport processes on Venus are very efficient. In contrast to the Earth, the influence of Coriolis forces on the slowly rotating Venus is insignificant, which means that the Rossby number $\boldsymbol{Ro} >> 1$. Therefore, the cyclostrophic rather than geostrophic balance condition is valid. This is characterized by the fact that a zonal velocity component increasing with altitude is superimposed on a Hadley circulation cell emerging due to the equator-pole temperature gradient. In this case, a significant heat efflux at high latitudes forms due to the existence of downward motions of atmospheric gas accompanied by backward flows in the lower atmosphere in the meridional direction and formation of huge vortex structures at the poles. The emergence of the well-known phenomenon of super-rotation (4-day circulation) in the Venusian atmosphere and the formation of vortices near the poles, with the angular momentum for atmospheric circulation being generally conserved, must be associated with the same mechanism.

Atmospheric super-rotation (also called carousel or merry-go-round circulation) causes the zonal wind velocity in the Venusian atmosphere to increase from ~ 0.5 m/s near the surface to ~100 m/s at an altitude of about 65 km and higher. The latter corresponds to the upper cloud boundary near the tropopause, where one observes characteristic ultraviolet contrasts of variable configurations (mosaics of white-and-black stripes), presumably attributable to the absorption of solar radiation by sulfur allotropes contained in the upper clouds and moving with this velocity. Let us note that one of the key elements of the atmospheric dynamics on Venus is turbulence. In particular, turbulence could play an important role in the early evolutionary stages of Venus if we consider the hypothesis about a primordial ocean that was subsequently lost due to the development of a runaway greenhouse effect.

Our current views on the structure of Venus's atmosphere with the most prominent regions at the different height levels and layers of the sulfuric acid cloud deck with lower and upper haze zones are summarized in the diagram of Fig. 2.29.

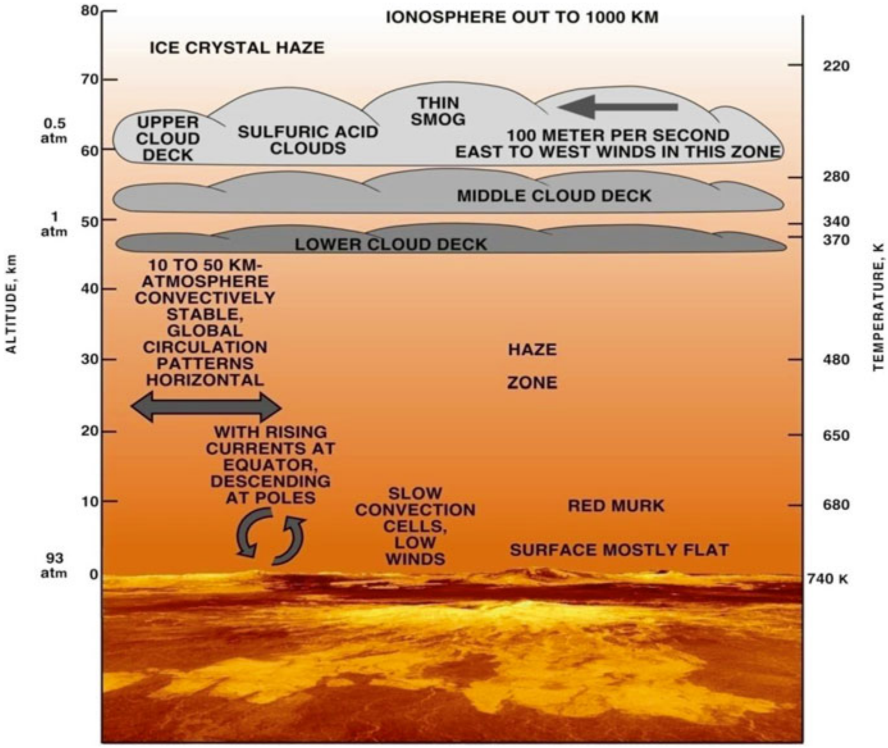

Fig. 2.29 Diagram of the Venus atmosphere structure with the most prominent zones at the different height levels. Temperature distribution along the *right* vertical axis is shown depending on altitude and respective pressure values along the *left* axis (Credit: T. Donahue & C. Russell)

The temperature distribution along the right vertical axis is shown depending on the altitude and respective pressure values along the left axis. The main mechanisms of atmospheric dynamics are indicated, including slow convection cells in the lower, mostly stable troposphere, rising currents at the equator and descending ones at the poles, and general horizontal global circulation patterns. Sustainable atmosphere-lithosphere interaction responsible for cloud formation is maintained by complicated geochemical mechanisms involving several cycles with the key role of sulfur-bearing compounds in the hot carbon dioxide atmosphere.

Mars

Main Properties. Mars is the fourth planet, located at 1.5 AU from the Sun and at a mean distance of about 0.5 AU from Earth, i.e., a bit further away than Venus but from the opposite side (Fig. 2.1). In ancient Roman mythology, Mars is the god of war (the Greek mythological equivalent is Ares), and the planet Mars was named for its reddish ("bloody") color when observed from Earth (see Fig. 2.1). Mars's visual stellar magnitude is rather high (maximum -2.88^m), though less than that of Venus and Jupiter. The semimajor axis of the Mars orbit $a = 1.52$ AU, and the eccentricity $e = 0.09$. This means that Mars orbits the Sun in a very elliptical orbit, approaching the Sun in perihelion by 206.65 million km (1.38 AU) and retreating at a maximum distance in aphelion by 249.23 million km (1.67 AU). The sidereal period of revolution (relative to the stars, or the Martian year) is 686.98 Earth days (1.88 Earth years) and the synodic period (relative to the Earth) is 779.94 Earth days. The period of rotation (which corresponds to an astronomical day) is $24^h\ 37^m\ 23^s$, while one solar day is a bit longer at $24^h\ 39^m\ 35^s$. The inclination of Mars's orbit to the ecliptic plane is 1.85°, and the inclination of the axis of intrinsic rotation (angular distance between the axis of rotation and perpendicular to the plane of its orbit) in the contemporary epoch is 25.19°. It is very close to that of the Earth's, and therefore, Mars experiences similar seasonal changes during the year. It is interesting to note that spring and summer in the Southern Hemisphere occurring near perihelion are shorter and hotter than in the Northern Hemisphere occurring near aphelion, and vice versa.

Mars approaches Earth at a minimal distance of 55.76 million km when the Sun and Mars are at opposite positions relative to Earth (they are in opposition repeating every 26 months at different points of the Mars orbit) and removes to 401 million km when the Sun is just between Mars and Earth (Fig. 2.30). Once every 15–17 years opposition occurs near to perihelion and is called the "great opposition," corresponding to the closest Mars approach to Earth when it reaches its maximum angular size (25.1″) and maximum brightness (-2.88^m). The last great opposition was on August 28, 2003, when Mars was at only 0.373 AU from Earth. The next one will occur on July 27, 2018.

Mars is approximately half Earth's size and nearly one-tenth its mass. Its equatorial radius equals 3,396.2 km and its polar radius is 3,376.2 km; hence, Mars' polar

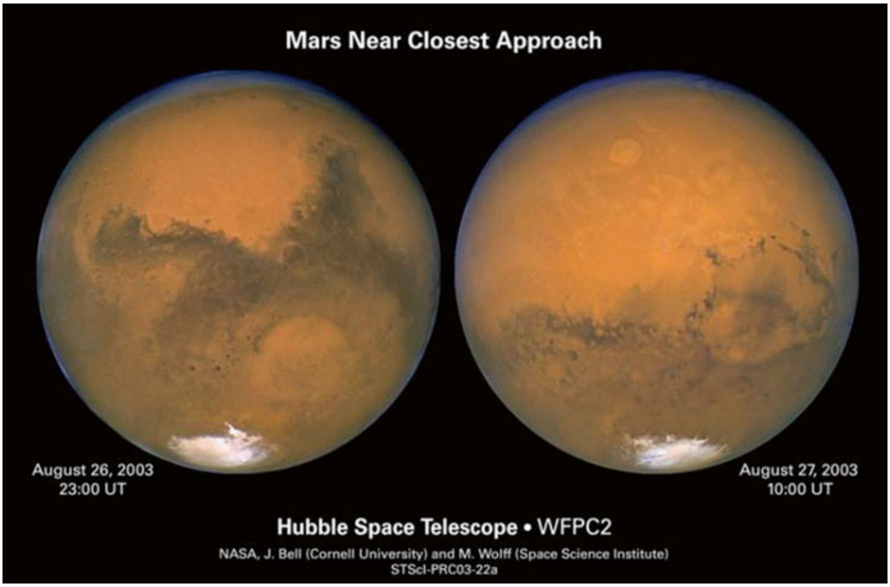

Fig. 2.30 Mars images near the closest approach in 2003 taken by Hubble Space Telescope (Credit: NASA and Dr. Tony Irving of the University of Washington)

oblateness is 0.006 (close to the Earth's). The mass of the planet is 6.42×10^{23} kg, its mean density is 3.93 g/cm^3 (0.71 of the Earth's), its acceleration due to gravity is 3.71 m/s^2, and the escape velocity is 5.03 km/s. The solar constant in the Mars orbit is 2.25 times less than that of Earth, and the mean annual surface temperature is ~220 K (−53 °C).

Historically, Mars was considered as a planet which could harbor life, even intellectual life. This is why the planet has attracted special attention since ancient times, but telescopic observation could reveal only the most prominent details. The distinguished large dark and bright areas, by analogy with the Moon, were called seas and continents, and it was found that more seas are located in the Southern Hemisphere. The concept of life's existence on the planet was supported by the observations of some surface features experiencing seasonal changes, and especially more or less regular linear structures associated with channels (Italian "canali"), thought to be built by Martian civilization. However, these canals turned out to be illusive because of the poor telescopic resolution available. The reality buried hopes of a civilization, but instead opened to our view an extremely interesting world that has evolved completely differently than our home planet. The present-day Mars is a cold desert with a plethora of craters, systems of mountain ridges, plateaus, uplands, and valleys that retained the traces of a paleomagnetic field, ancient widespread volcanism, destroyed igneous rocks, and the influence of atmospheric dynamics on the surface landscapes (weathering).

Enormous progress in the study of the nature of Mars has been achieved only in the last few decades due to space missions. The US Mariner 4 was the first spacecraft to fly by Mars, and it measured parameters of its atmosphere more accurately than was possible from the Earth. The following Mariner 6 and 7 flybys transmitted the first images of the Mars surface. Although the images were of rather poor resolution, the details were discouraging because they resembled those of the Moon's surface. However, images of much better quality from Mariner 9 and also from Mars 5 revealed a completely different planet with manifold landforms and traces of past geological activity, as well as unusual properties of its tenuous and very dynamic atmosphere. The Soviet Mars 3 was the first space vehicle to land on the Martian surface, though with a very short time of signal transmission, while Mars 6 made the first direct in situ measurements of the atmospheric parameters during its descent from about 60 km (well above the height of the Martian tropopause) to the surface. The most successful explorations were the US Viking 1 and 2 missions, both orbiters and landers, in the mid-1970s, which operated for more than one Martian year. They performed many important measurements, including a search for life on Mars, which was unsuccessful. This caused a loss of interest in Mars missions for more than 10 years; they were only resumed with the Soviet Phobos missions at the end of the 1980s. These missions were only partially successful. In the 1990s two new launches to Mars with NASA's Mars Observer and the ROSCOSMOS (RSA) Mars 96 were undertaken, and unfortunately both failed. Similarly, both the NASA Mars Polar Lander and RSA Phobos-Grunt missions launched later were also ill-fated.

Especially great advancements in the study of Mars began at the end of the last century and during the first decade of the 2000s with the successful flights of the US Mars Global Surveyor, Mars Reconnaissance Orbiter, Mars Odyssey, and Phoenix, and the European Mars Express. The first US Martian small rovers Pathfinder, and especially Spirit and Opportunity, significantly contributed to our knowledge about the planet. Recently, the large, much more capable, and well-equipped NASA Curiosity rover landed on Mars in 2012, with the goal of answering many intriguing questions about Mars, including those related to its geological/climate evolution and biology. Curiosity's operation provided important information, specifically about Martian soil composition and water content to highlight the planet's evolution, though no signs of life were detected.

From the viewpoint of evolution, Mars is the antipode of Venus and is another opposite of Earth, although it is more similar in its natural properties to our planet and may have been a close analog of the Earth at early evolutionary stages. The most topical problems that now face researchers of Mars include studying the short-term and long-period variations in climate, the geological and chemical composition of the rocks forming the planetary crust, the seasonal cycles of the water and carbon dioxide contents in the atmosphere, and searching for the distribution of various forms of water both at depth and in the subsurface layer—liquid, bound, and water ice. Basically, the research and development of various climatic, geological, and evolutionary models are focused on the problem of water in the geological past and present of Mars and are associated with the presence of possible traces of primitive extant or extinct life (bacterial fossils).

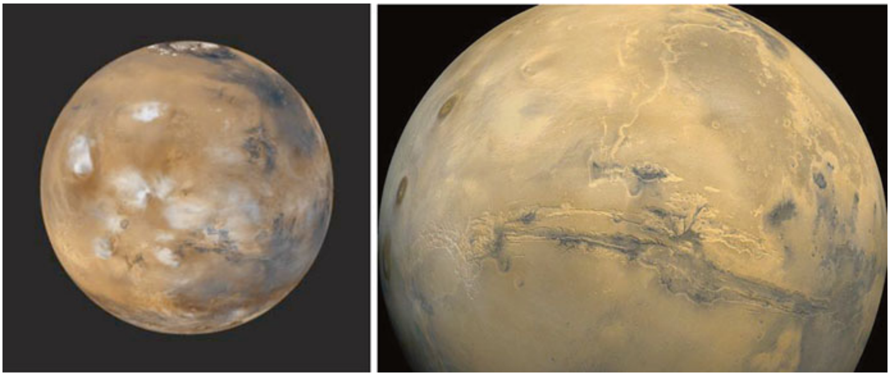

Fig. 2.31 Images of Mars from spacecraft. (*Left*) Clouds above the huge shield volcanoes in the Tharsis region, relief of the Northern polar region, and Valles Marineris rift zone are distinguished in this image. (*Right*) Mosaic of images in which the main features of the Martian relief, among the highest in the Solar system shield volcanoes with a height up to 26 km above the mean surface level in the northwest and the huge tectonic fracture Valles Marineris extending for more than 3,000 km nearly along the equator (Courtesy of NASA)

Surface, Relief, and Geology. The Mars relief is very complicated: different landforms dominate the Northern and Southern Hemispheres, the former being about 1–2 km lower than the mean level. There are heavily cratered terrains in the higher Southern Hemisphere, presumably 3–4 billion years old, in contrast to the obviously much younger lower plains and unique geological structures in the Northern Hemisphere. Here the most prominent features are the great rift zone Valles Marineris and the elevated regions Tharsis and Elysium with the giant shield volcanoes Olympus Mons, Arsia Mons, and Pavonis Mons. Olympus is the highest volcano in the solar system (Fig. 2.31). Its height is about 27 km above the Mars lowland level, the size of its base is nearly 600 km across, and its caldera is 70 km across and 3 km deep. It dwarfs the Earth's largest mountain, Everest, which is only 8.8 km high. Also, the largest known basin of suspected impact origin in the solar system, about 8,000–10,000 km in size, was discovered in the Northern Hemisphere and may be the cause of the north–south dichotomy. Rift zone Valles Marineris in the equatorial region is a great canyon, probably of tectonic origin, that extends more than 3,000 km and is about 600 km wide and 7–10 km deep with diverse geological structures located within it.

The most detailed mapping of Mars's very complicated relief was taken by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) orbiter (Fig. 2.32). The relief stretches from vast lowland plains in the Northern Hemisphere to heavily cratered terrains in the Southern Hemisphere. The Tharsis uplands with several huge shield volcanoes and steep slopes and the adjoining great rift zone Valles Marineris running nearly parallel to the equator southeast of Tharsis are clearly distinguished. They are shown in more detail in Figs. 2.33 and 2.34, respectively. Of special interest are the polar caps of Mars which are intrinsically related with its atmospheric circulation patterns and climate, the latter depending on Mars's

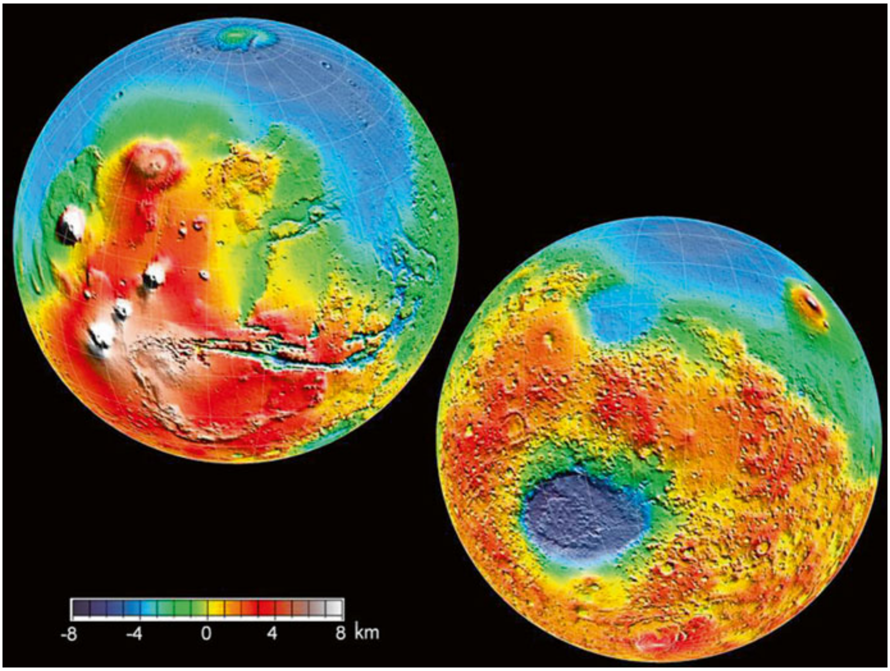

Fig. 2.32 Mars relief according to laser altimetry (MOLA) from Mars Global Surveyor (*MGS*) orbiter. Height scale (from *dark blue* basins to *red-white* elevations/mountains) is shown at the *bottom left*. Very complicated relief is revealed, from vast low land plains in the Northern hemisphere to heavily cratered terrains at the Southern hemisphere with the prominent transition regions. Tharsis upland with several huge shield volcanoes and steep slopes are clearly distinguished at *left* and adjoining great rift zone Valles Marineris running nearly parallel equator southeast of Tharsis (*upper* image). There are enormous basins Hellas of about 2,000 km across (*dark blue*) and Argir of about 900 km across (*white blue*) in the Southern hemisphere, (*bottom* image) (Credit: NASA)

obliquity. The perennial or permanent portion of the north polar cap consists almost entirely of water ice. Both polar caps contain water ice beneath the dry ice cover as much as about 3 km thick with a volume of ice of ~1.6 million km^3 (Fig. 2.35). There are enormous basins, Hellas, about 2,000 km across and Argyre. The northern polar cap accumulates condensed CO_2 as a thin layer of about 1 m thick in the northern winter only. The southern poar cap has a permanent dry ice cover about 8 m thick and much deeper water ice layer beneath it about 900 km across, in the Southern Hemisphere. Remarkably, there exist prominent transition regions between the Northern and Southern Hemispheres (Fig. 2.36).

There is no doubt that the surface and atmosphere of Mars changed dramatically over its geological history as a result of intense impact bombardment and volcanic, tectonic, and erosion processes closely related with water history and climate. Geologists distinguish three main epochs in the Mars evolution: Noachian, covering 4.6–3.7 billion years of Martian history, when the oldest crust formed, heavy impact

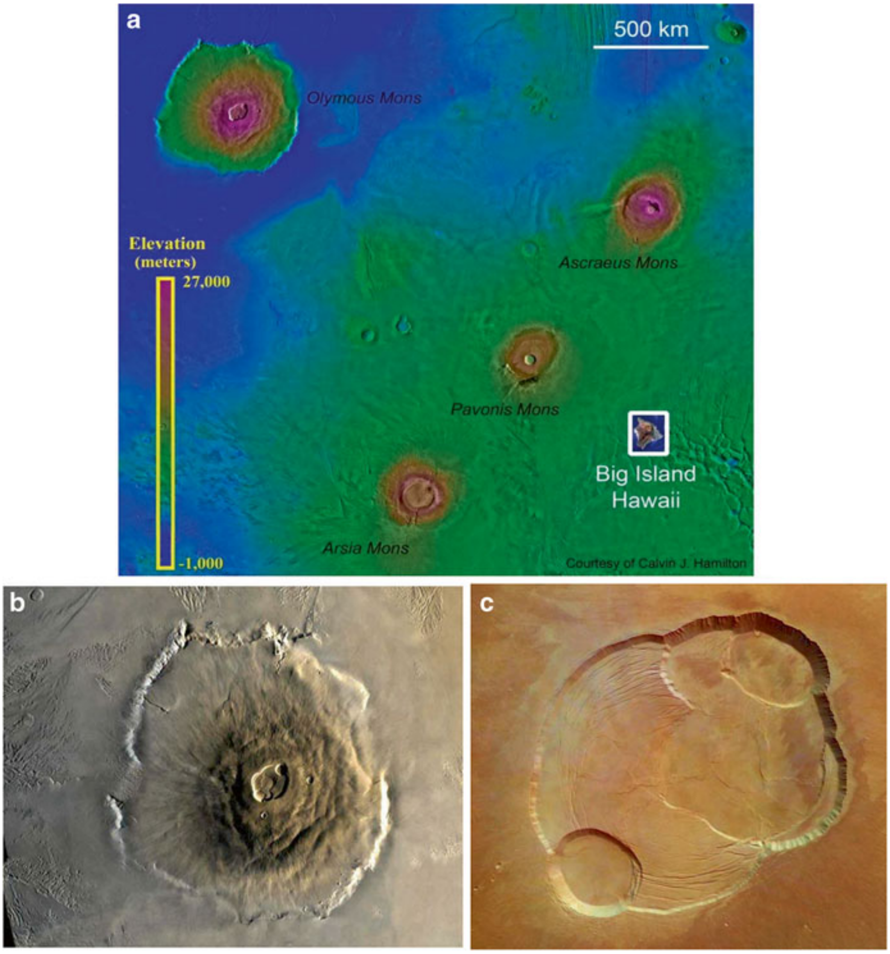

Fig. 2.33 Martian volcanoes. (**a**) Distribution of huge shield volcanoes in Tharsis region. Height is scaled in color at the *left*, horizontal size is shown and compared with Big Island Hawaii. (**b**) The largest Martian volcano Olympus Mons taken by Viking of about 500 km in foot. (**c**) An exquisite image of the 85 × 60 km summit nested caldera of Olympus Mons taken by Mars Express. Note how few impact craters are present (Credit: NASA)

bombardment ceased by the end of the period, early Mars was warm/wet, and a valley network formed; Hesperian, covering 3.7–2.9 billion years with volcanic activity, the great lava plains and outflow channels formation, as well as an assumed ocean existence; and Amazonian, 2.9 billion years ago to our time, attributed to a lower rate of impact crater formation and younger surface features appearance, in particular because of volcanic eruptions, including continuing Olympus Mons activity, as well as continuing outflow channels and late stage polar cap formation (Fig. 2.37). During this late period, the Martian climate dramatically changed, eventually becoming the contemporary cold, dry planet.

Fig. 2.34 Rift zone of tectonic origin running by more than 3,000 km along equator of maximum width 100 km and depth 8 km (Credit: NASA)

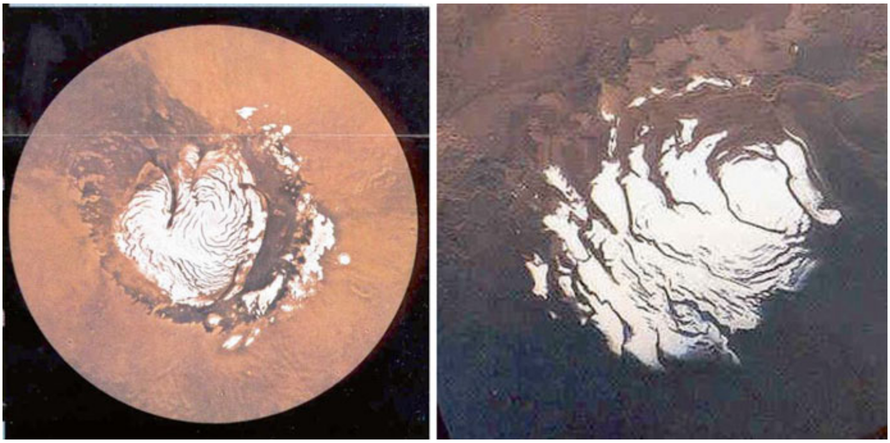

Fig. 2.35 Northern (*left*) and Southern (*right*) Polar Caps on Mars. In the Northern polar cap CO_2 accumulates as a thin layer about 1 m thick in the northern winter only. It has diameter of ~1,000 km during the northern Mars summer above perennial water ice layer having thickness 3 km and volume of ice ~1.6 million km^3. Southern Polar Cap maintains a permanent dry ice cover about 8 m thick. Its diameter ~350 km. (NASA Courtesy)

The surface features are intrinsically related to the interior structure. Obviously, Mars experienced differentiation resulting in the emergence of a liquid core, a partially melted mantle, and a solid crust in a very early epoch, soon after its origin, although differentiation was not as complete as on Earth (see Fig. 2.2a, b).

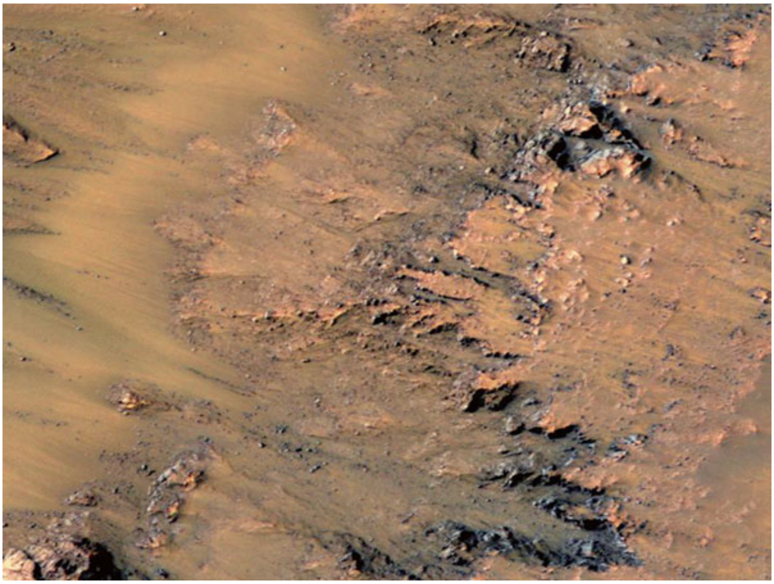

Fig. 2.36 Typical region of sharp transition between elevated terrain and plains at the Southern-Northern hemispheres boundary of Mars (Credit: NASA)

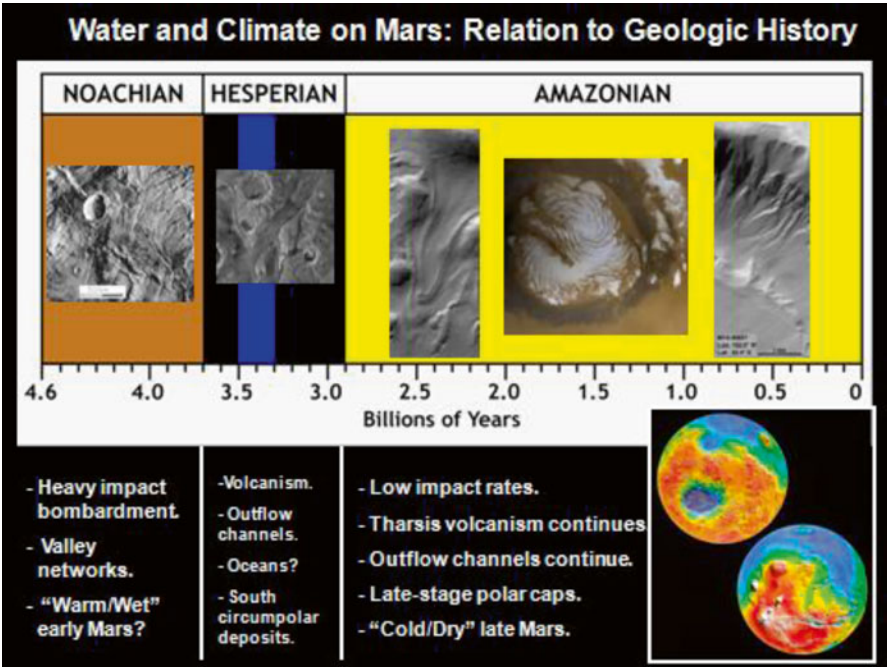

Fig. 2.37 Mars geologic history with implication to water and climate. The three main geologic periods Noachian, Hesperian, and Amazonian are fixed to time scale from 4.6 billion years to now. They are characterized by the most prominent processes which formed Mars' landforms and climate (Credit: J. Head/Brown University)

The widespread volcanism with formation of the great shield volcanoes is attributed to the first billion years. Mars cooled fast enough because of its relatively small size and limited storage of the radiogenic long-lived isotopes uranium, thorium, and potassium. According to the models developed, the contemporary Mars interior includes a thick (50–130 km) crust, a silicate mantle about 1,800 km thick, and a still partially liquid iron-sulfur core having a radius of 1,480 km and comprising 14–17 % of the planet's mass. The inner structure resembles that of Earth with the caveat that phase transitions and emergence of minerals forming under high pressure (for example, the transition of olivine to spinel) occurred in the Martian interior at much deeper levels because of the smaller acceleration due to gravity.

There are indications of an ancient liquid core existence that produced a magnetic field which eventually decayed, but left behind some remnant magnetic anomalies on the Mars surface, mostly in the Southern Hemisphere (paleomagnetism). The field is stripe-like and correlates with the most abundant hematite (iron oxide) contents on the surface (Fig. 2.38). The magnetic field strength at the Martian equator does not exceed 60 nanotesla, which is nearly 500 times weaker than the Earth's field. Because of the weak magnetic field, there are peculiar details of solar wind interaction with Mars's upper atmosphere–ionosphere involving formation of an irregular quasi-magnetosphere around the planet.

Tectonics (though probably unlike Earth's plate tectonics) strongly affected the evolution of ancient Mars. There is progressively growing support for the idea that early Mars during the Noachian-Hesperian epochs was quite different from what we see now. In particular, water can't be retained on the contemporary Mars surface, because it easily evaporates under very low atmospheric pressure. However, an ancient atmosphere comparable in density to the terrestrial one is assumed to have existed, which could provide a sufficiently high surface temperature capable of

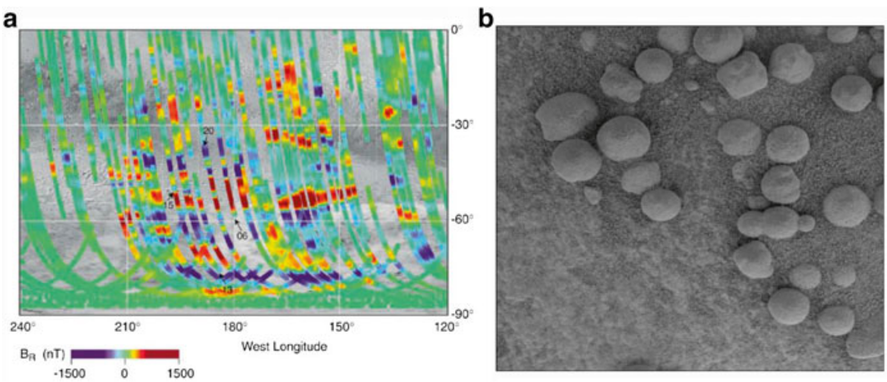

Fig. 2.38 Evidence of liquid core caused ancient magnetic field that decayed, however, later on leaving behind. (**a**) The stripe-like magnetic field remnants on the Mars surface in the Southern hemisphere (paleomagnetism). They correlate with the most abundant hematite (iron oxides) contents on the surface (Data obtained by Mars Global Surveyor). (**b**) Hematite spherules in the Martian soil. (Data of Mars Exploration Rover Opportunity. NASA Courtesy)

retaining liquid water and even its circulation between the surface and atmosphere. In any case, the appearance of a hydrological cycle and a secondary atmosphere 3.9–3.6 Gyr ago is to be associated with tectonic and volcanic processes. The mechanism of atmospheric weathering, involving combined hydrologic and glaciological processes on the surface and meteorological processes in the dense atmosphere (first of all, wind and water), was responsible for severe erosion of craters and modification of the Martian landscape. Obviously, the oldest craters were virtually wiped off the face of Mars. The present-day atmosphere could not generate such effects so destructively. We assume that this took place more than 3.5 Gyr ago, before the catastrophic collapse of the ancient atmosphere.

Water History. Many of the signatures that are an integral feature of Mars geology suggest that water furrowed its surface for several hundred million years of its history, probably most actively in the period from about 3.8 to 3.6 Gyr ago (Figs. 2.39 and 2.40). Numerous examples of geological features in support of this idea are preserved on the Martian surface from that epoch. These include primarily the systems of valleys and gullies resembling the beds of ancient dried-up rivers with numerous tributaries extending for hundreds of kilometers. Some of them can be associated with vigorous water flows produced by the melting of subsurface ice during the denudation of ice lenses, which can be likened to the motions of Antarctic glaciers. The region to the north of Elysium, where water could rise to the surface through faults in the Martian crust, is an example of such structures.

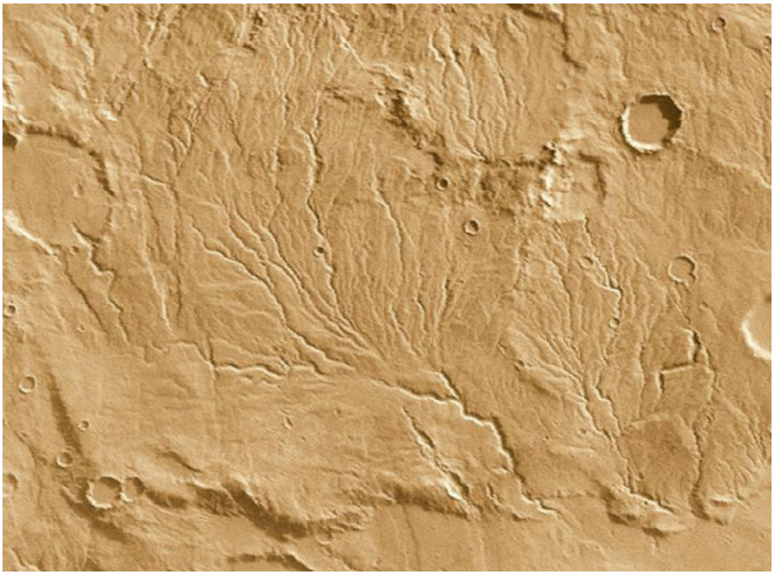

Fig. 2.39 Fluvial processes on the Mars surface—the beds of ancient dried-up rivers with numerous tributaries extending for hundreds of kilometers as a evidence of running water flows on the ancient Mars (Image returned by Viking. Credit: NASA)

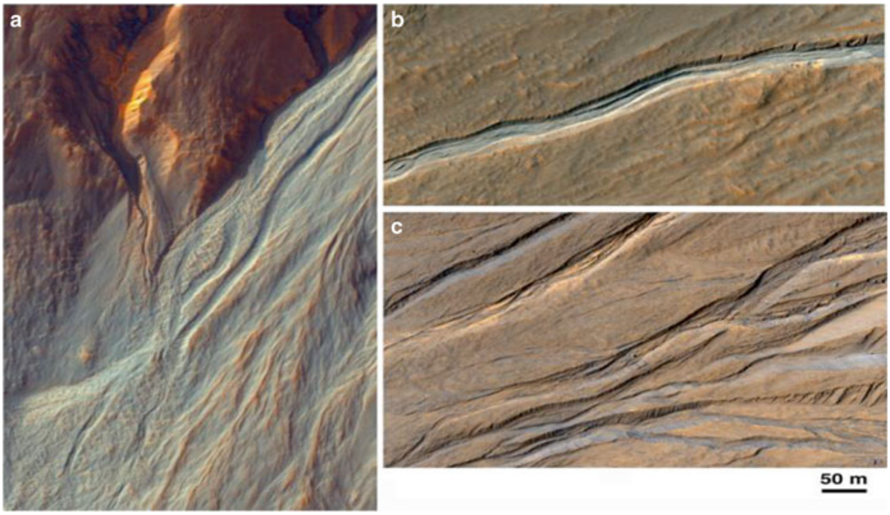

Fig. 2.40 Furrows on the Mars surface left behind by running water—ancient dry river beds (Credit: NASA/J. Green)

There are numerous examples of water erosion on Mars, some of which are shown in Fig. 2.41. These are the fissures—eroded traces of flows on steep slopes which could be produced by the fall of heavy rains or even torrents—or the spectacular Candor region in the central part of Valles Marineris. In some regions an ordered structure formed against a general chaotic background of the relief was detected in regions of ancient tectonic activity. Some regions of chaotic terrain formation are related to water channels, specifically those in river mouths. Of special interest are gullies that could be formed due to the emergence of water on the surface from below (seepage). A correlation was found between the ice-rich latitude-dependent mantle and related gully features including gully alcoves, channels, and fans (Fig. 2.42). These and some other morphological features argue for an occurrence of liquid water on the Martian surface. A close-up view of conglomerates from the Mars rovers indicates flowing water in the planet's history (Fig. 2.43). Surprisingly, a large ice lake inside one of the impact craters was detected on an image taken by the Mars Express spacecraft. This may serve as evidence of water's sporadic appearance even on the present-day planet (Fig. 2.44).

Rather young gullies were also detected on the inner slopes of impact craters or on the walls of deep troughs, mainly on their southern side, whose age is estimated to be not billions but less than millions of years old. These relief features may be associated with the challenging idea about short-term climatic variations owing to periodic changes in obliquity (the position of Mars's axis of rotation in space). They are attributed mainly to the short- and long-period variations of the Martian orbit due to the influence of the strong gravitational field of Jupiter, and are modulated by the periodic precession of the Martian rotation axis (Fig. 2.45). The total variation is in the range from 15° to 35° on a time scale of only a few million years (obliquity

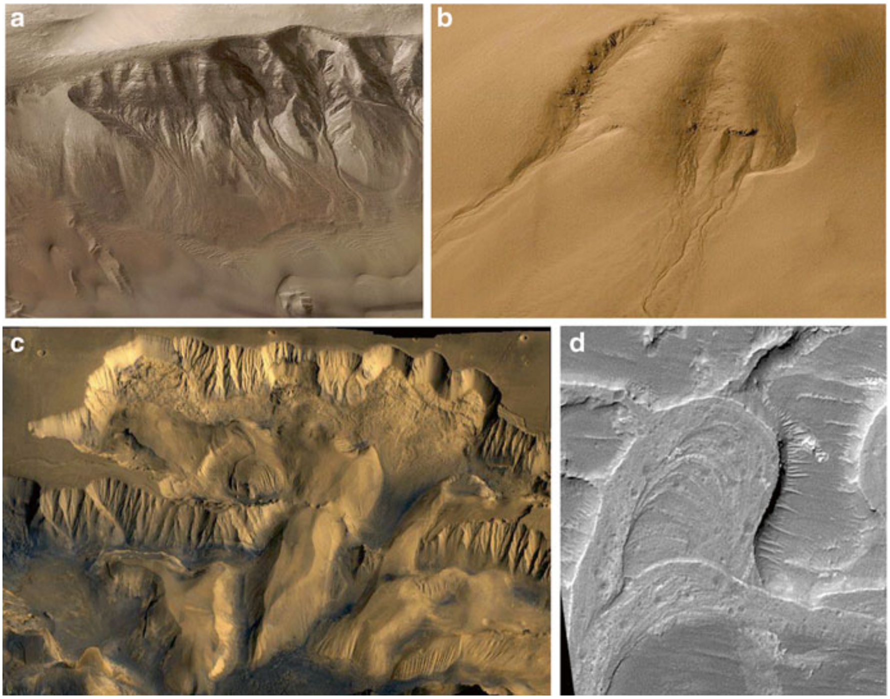

Fig. 2.41 Examples of water erosion on Mars. (**a**) The fissures that were most probably formed by water flows at steep slopes; (**b**) the gullies that could be formed due to the emergence of water on the surface (seepage); (**c**) the Candor region in the central part of Valles Marineris on Mars. Isolated more ordered structures whose formation can obviously be associated with giant water flows. They are distinguished against the background of chaotic morphology attributable to the early tectonic-volcanic processes; (**d**) Remnants of water erosion forming peculiar isolated ordered structures in chaotic terrain whose formation can obviously be associated with giant water flows (Courtesy of NASA)

cycle). Let us also note that Mars has no large satellite like our Moon that would be capable of stabilizing the position of the rotation axis in space (the two small asteroid-like satellites of Mars cannot perform this role). Theory predicts that on even longer time scales, the perturbations can become chaotic in nature, so that the inclination of the rotation axis may change from 0° to 60°. This creates the prerequisites for enormous climate changes due to a change in insolation at the poles (the warmth of polar summers) and in the intensity of the transfer of volatiles (mostly carbon dioxide and water) into the atmosphere from the polar caps, along with deposits of dust, and a change of permafrost boundaries in the summer and winter hemispheres (Fig. 2.46).

Basically, the relief of high-latitude regions is consistent with such a possibility. In particular, it was found that the surface between the poles and the equator is overlaid with sedimentary rocks with a thickness of 4–6 km in the north and 1–2 km in the south, while the surface itself is crisscrossed by cliffs and fractures that, as it

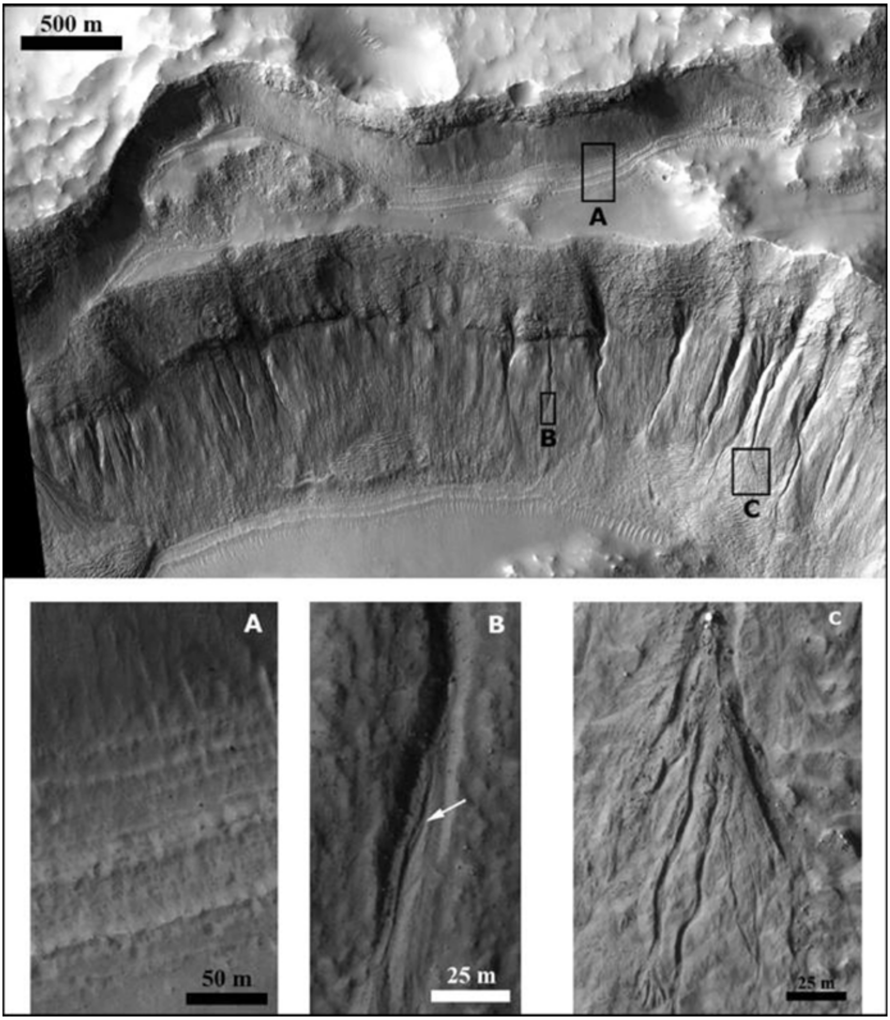

Fig. 2.42 Correlation of ice-rich latitude-dependent mantle and related gully features. (**a**) Exposed layerd mantle. (**b**) Galey alcoves and channels. (**c**) Gally channels and fans (Credit: J. Dickson; S. Schon and J. Head)

were, are wound around the poles. The sedimentary cover itself has a layered structure, backing the assumption about periodic climate changes.

Unfortunately, the huge layers of dust-sand material on the Martian surface hide many of the original structures, including large deposits of subsurface water ice formed after the supposed climate change on ancient Mars. The presence of such deposits at a depth of about 1 m predominantly at high latitudes was confirmed by neutron spectrometry measurements during monitoring from the Mars Odyssey satellite orbit and later from the Mars rovers. The ice content in rocks reaches 50 % by mass.

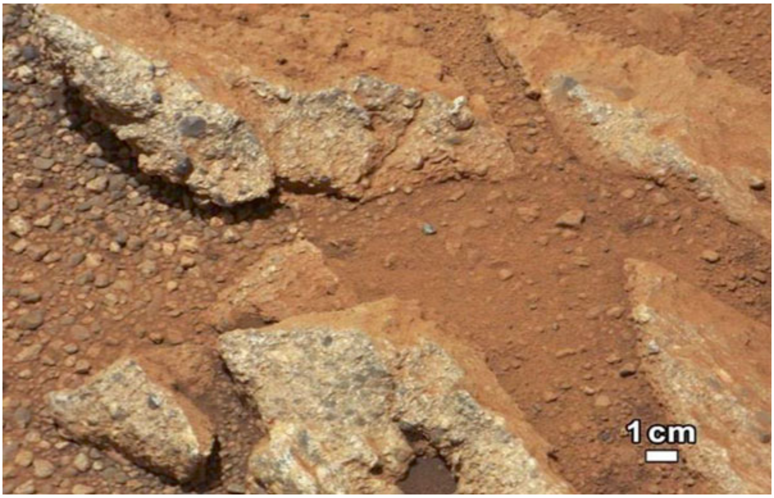

Fig. 2.43 Conglomerates: Indication of flowing water. Close up view of Curiosity rover (Credit: NASA/J. Green)

The individual relief features, especially those on slopes, were probably formed by the involvement of water flows, and features that are tempting to associate with periodic seepage of subsurface water in the recent past are detected on a number of surface structures. One may assume that it is salt water, which is capable of surviving more easily under Martian conditions. With a high probability, one might expect even larger reserves of water in the form of ice lenses and inter-layers to have been preserved at a depth of several hundred meters, and the possibility that liquid water can be near the lower surface of a thawing ice lens due to the accumulation of heat through the internal heat flux under the very low thermal conductivity of ice cannot be ruled out. General ideas about the contemporary hydrological system on Mars covering both Northern and Southern Hemispheres are shown in Fig. 2.47. The system spans the subsurface region (basement) to megaregolith and permanently frozen (cryosphere) layers below and above the water freezing point with the involvement of the polar caps and troposphere. Obviously, climatic changes due to obliquity variations exert only a small influence on the diagram.

Therefore, it is unlikely that water in rivers could appear on the Mars surface in periods of comparatively short-term climatic warming. This is evidenced by the age of the craters near these relief shapes, which most likely date from the first billion years of the planet's evolution. At the same time, it is hard to reconcile the above data on the layered structure of sedimentary rocks at mid-latitudes with these views, so certain contradictions are retained. Also, they by no means rule out an episodic hydrologic activity on the present-day Mars, along with preserved residual volcanism. The lake appearance within an impact crater (Fig. 2.44) could be connected with such activity. To resolve the problem, mapping of the planet's mineralogy could help, specifically the search for minerals forming only in the presence of water.

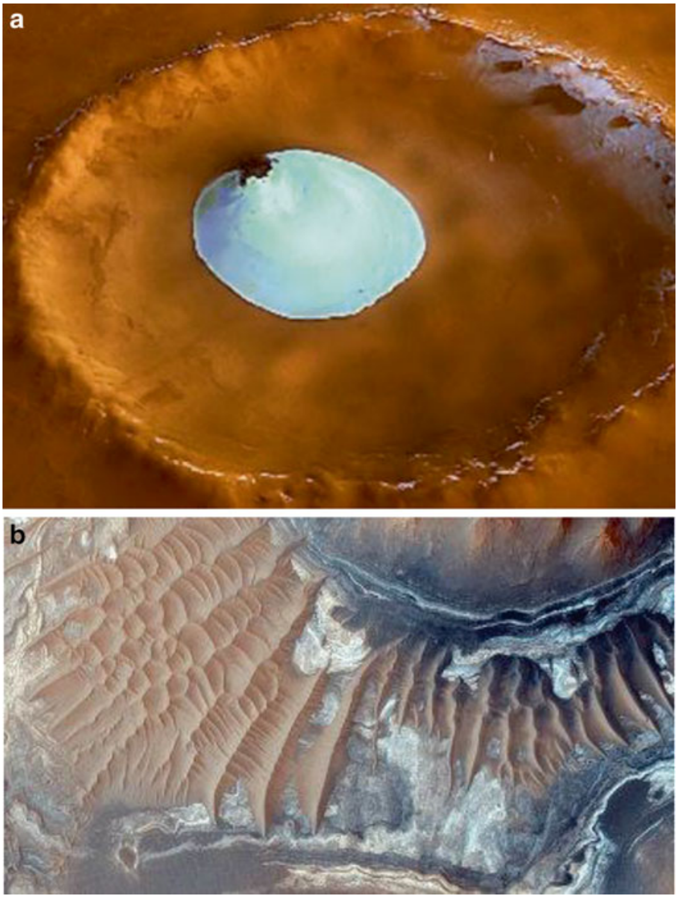

Fig. 2.44 (**a**) Icy lake at the *bottom* of a Martian crater (An image from the Mars Express spacecraft Credit: ESA). (**b**) Evidence of filling up Endeavor crater with water, possibly twice in geologic history (Credit: R. Arvidson, Saint Lewis University)

We know that generally basalts form the Martian surface. Our more detailed knowledge of the Martian soil is based mostly on the landers' measurements, which discovered some variations in the surface mineral composition containing silicon, magnesium, aluminum, calcium, sodium, and sulfur compounds. Martian soil is enriched with iron oxides (up to 15–18 %), which is compatible with the basaltic composition of its crust and, as we mentioned, was apparently caused by the less complete Mars differentiation compared to that of Earth. The NASA Viking landers supported the conjecture that the distinctive overall reddish color of Mars was caused by surface dust deposits that strongly resembled mixtures of clay and ferric oxides, like those produced by weathering of terrestrial lavas. Of special interest was the finding by the Opportunity lander of rock samples composed of clay and enriched by aluminum, such as montmorillonite, which could form on ancient Mars

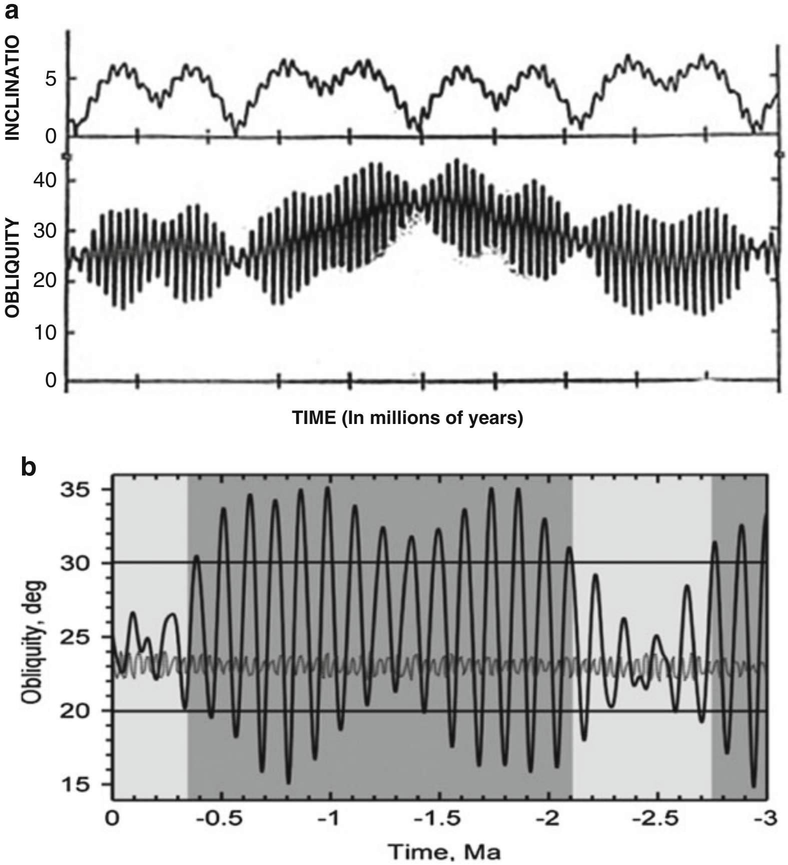

Fig. 2.45 (**a**) Periodic variations of the Mars obliquity caused by combined effect of the changes in the inclination of Martian orbit and precession of the axis of intrinsic rotation. (**b**) Obliquity changes during the last three million years. The current value fits 24° (Credit: J. Laskar)

only in the presence of fresh rather than oceanic salt water. Interestingly, the alkalinity of the Mars surface is close to that of Earth and theoretically could be suitable for cultivation.

The most intriguing idea concerns the existence of an ocean on ancient Mars. Indeed, the relief structures in the Martian northern regions, as revealed by observations from the Mars Global Surveyor satellite, resemble the coastlines of an ancient ocean bounding regions of constant surface height. This can be explained by the uniform precipitation accumulated in large volumes of water on the Martian northern plains. Moreover, there was reported a detection of layered structures (resembling sedimentary rocks on the Earth's ocean bed) with a high concentration of chlorine and bromine salts at Meridiani Planum by the Martian rover Opportunity. Figure 2.48 helps confirm the idea of the existence of an ancient ocean on Mars.

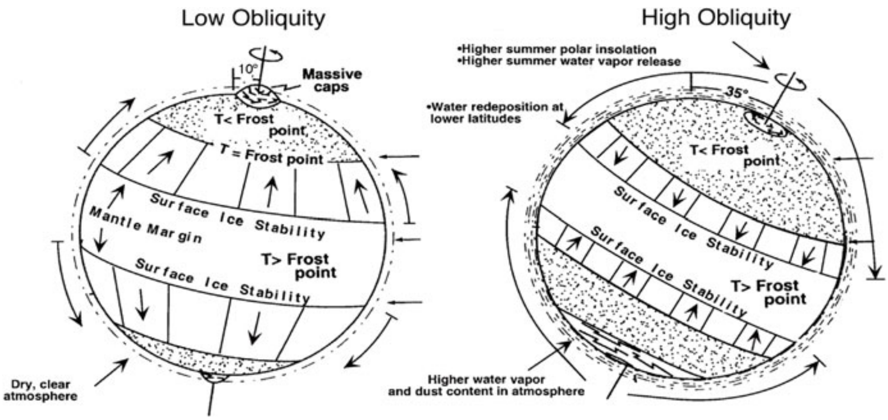

Fig. 2.46 Mars obliquity variations between low and high and consequences. The surface features and Mars climate dramatically change. At very low obliquity (<20°) collapse of CO_2 atmosphere, deposition near poles and perennial accumulation of CO_2 on steep slopes seems occur. At the high obliquity (35–40°) the mean temperature increases because of higher summer polar insolation resulting to a higher summer water vapor/dust release from the pole transited to the atmosphere and higher water deposition at lower latitudes occur. Surface ice stability zone becomes narrower, atmosphere thicker (more opaque) because of higher water and dust content (Credit: M. Kreslavsky and J. Head, Vernadsky Institute and Brown University.)

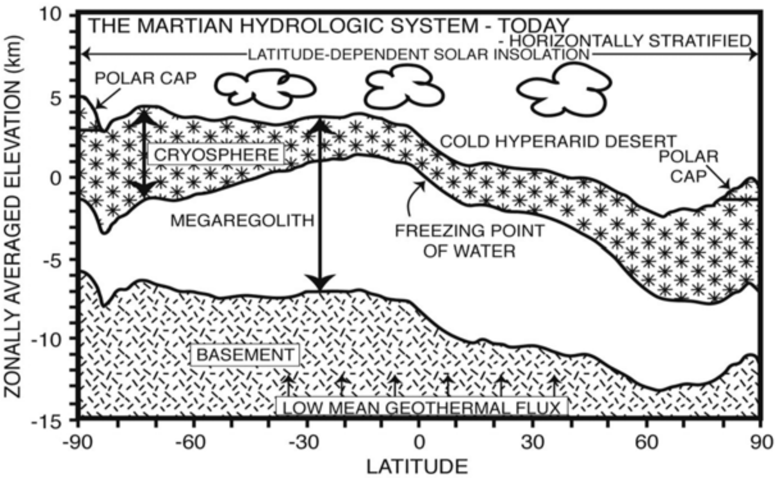

Fig. 2.47 Schematic view of the contemporary hygrological system on Mars covering both Northern and Southern hemispheres and spanning from subsurface region (basement) to megaregolith and cryosphere layers below and higher water freezing point with the involvement of the polar caps and troposphere (Credit: J. Head/Brown University)

Fig. 2.48 These rocks at the Martian Meridiani Planum resemble those on the Earth's ocean floor. High concentrations of chlorine and bromine salts detected in them also relate their emergence with the Mars ancient oceans. The region in the images may be associated with a coastline where cyclic evaporation and/or freezing occurred on shallow water (Images from the Opportunity Mars rover. Credit: NASA)

These deposits can actually be associated with the coastline of an ancient ocean where the cyclic processes of evaporation and/or freezing took place on shallow water, leaving behind layered sedimentary rocks rich in chlorine and bromine salts which are common to the Earth's oceans. The search for such terrains is one of the goals of the rover Curiosity currently operating on Mars, which is capable of tracing water abundance in Mars minerals using the technique of neutron monitoring with a better resolution than that from an orbiter. Of particular interest is the discovery of the rock's enrichment in sodium, giving it a feldspar-rich mineral content, which makes it very similar to some rocks erupted on ocean islands on Earth.

In any case, there is little doubt that Mars had a water ocean in the past. According to estimates by geologists, the total mean depth of the ocean (if it were poured uniformly over the surface) could reach 0.5 km. This value apparently restricts the maximal reserves of water that could be preserved on Mars, minus the losses (~30 %) due to aeronomic processes, as was shown by calculations of the nonthermal escape of hydrogen and oxygen atoms from the planetary atmosphere. As we discussed above, the challenge is to find out not only what caused dramatic climate change but also the mechanism of water loss. A possible aeronomic mechanism involving superthermal atmospheric particle escape is depicted schematically in Fig. 2.49.

A significant breakthrough in the space research of Mars was accomplished with the launch in 2011 of the NASA Curiosity (Mars Science Laboratory) rover (Fig. 2.50), which has been operating at the bottom of large Gale Crater (Fig. 2.51) since August 2012. It advanced both surface and atmospheric studies of the planet, and we will address the main results here in more detail.

The analysis of volcanic rocks, in particular the pyramid-shaped stone called "Jake Matijevic," obtained more insight into the problem of Mars's geologic evolution and the rate of differentiation of its interior. Soil samples were taken and analyzed with the onboard Sample Analysis at Mars (SAM) instrument including a gas chromatograph and a mass spectrometer. The rover's scoop was used to collect dust, dirt, and finely grained soil from a sandy patch known as Rocknest. Some authors

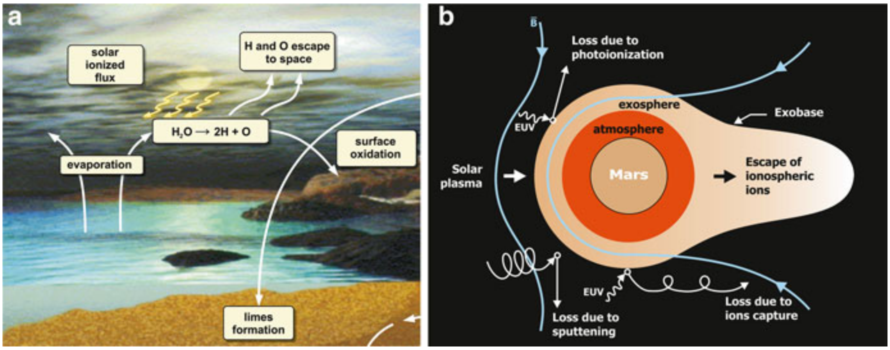

Fig. 2.49 (**a**) Model for the loss of water from the Martian atmosphere caused by the aeronomy processes (superthermal particles formation and escape). This mechanism could be responsible for loss of approximately a third of the Mars ancient ocean over the geological time. (**b**) Diagram of the mechanisms of hydrogen and oxygen dissipation from the atmosphere (as a consequence of the photolysis of water molecules and deactivation of the excited O atoms), with the formation of super-thermal oxygen atoms with an energy sufficient for their escape from Mars (Credit: V. Shematovich and M. Marov)

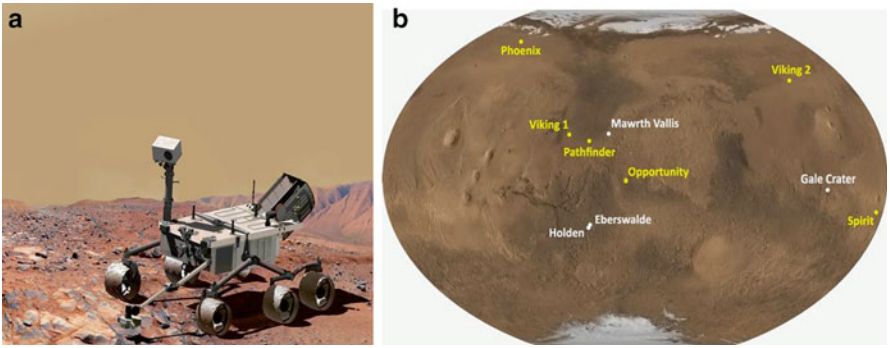

Fig. 2.50 (**a**) Mars Curiosity rover (sketch). (**b**) Landing sites of Mars landers on the Mars surface (marked in *yellow*). Curiosity landing site is in Gale crater (*right edge* on the map) (Credit: NASA)

have said that the grains in the samples, a "garden variety of Martian soil," are "finer than sugar but coarser than something like flour." Gases from a sample taken inside the instrument were released after the soil was heated to 835 °C, and the composition was measured. Besides a significant abundance of carbon dioxide, oxygen, sulfur-bearing compounds, chlorinated methane compounds, and water were found. The chlorine was probably of Martian origin and together with oxygen came from perchlorate, which has previously been detected on Mars. The water abundance turned out to be quite high, about two weight percent, the water molecules being bound to fine-grained soil particles. Because a similar water abundance was detected in several samples taken along the rover route, one may argue for water distribution over the whole planet rather than mostly in high latitudes, as was earlier shown by neutron monitoring. Martian water was found to be enriched with the heavy

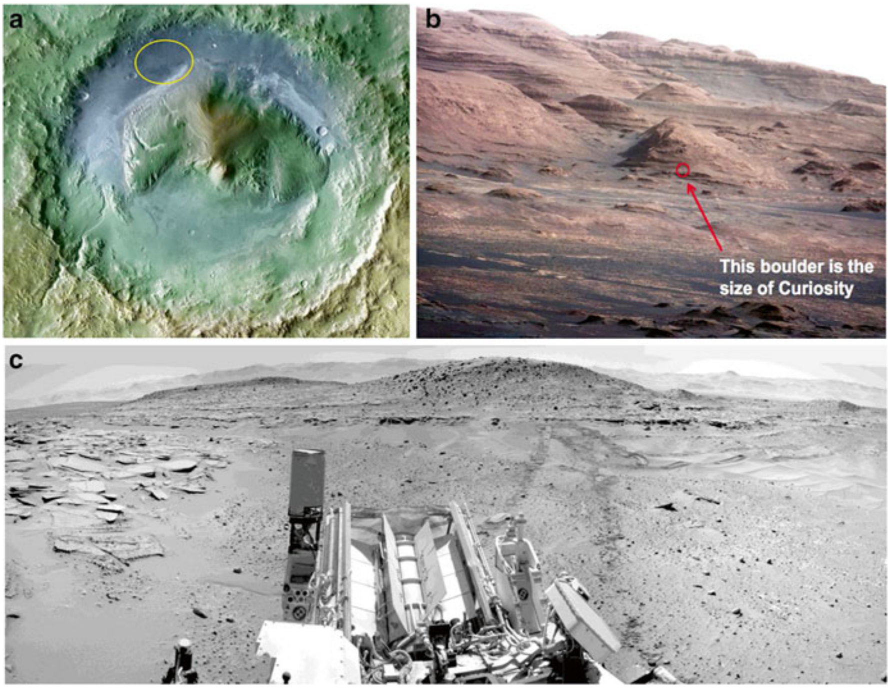

Fig. 2.51 (**a**) Gale crater (4.5°S, 137°E, −4.5 km) contains a 5-km sequence of layers that vary from clay-rich materials near the *bottom* to sulfates at higher elevations. Curiosity landing site is shown with a *yellow circle*. (**b**) Curiosity landing site—quite hummocky local terrain—in a perspective view (Credit: NASA/J. Green) (**c**) Picture taken by Curiosity as it departed the latest sample site on April 14, 2014 (Courtesy NASA/W. Huntress)

hydrogen isotope[4] deuterium in proportions analogous to that of the thin atmosphere. Atmospheric origin water in the soil has been assumed.

More complicated is the problem of organic compounds, which are not likely to be preserved in surface soils exposed to harsh radiation and oxidants. Trace levels of organic compounds containing both carbon and chlorine were detected in the experiments with the SAM instrument as well. The results are not clear, because organic compounds could likely be formed during the samples' heating and reaction with terrestrial organics already present in the SAM instrument background. This means that the measured organics are not clearly Martian in origin. Another possibility is that they formed in the processes of interaction of exogenous organics due to comet/asteroid bombardment of early Mars (see Chap. 4) with atomic chlorine released from toxic perchlorates found in Mars's polar regions as early as in 2008 and now discovered in the equatorial region as well. Notice that the general extension of toxic substances on the planet's surface not only prevents us from determining

[4] Isotopes are variants of the same chemical element with different numbers of neutrons and therefore different atomic weights.

whether organics are indigenous to Mars, but also seems to complicate prerequisites for the origin of life and may pose a problem for the future crew of the Mars human mission.

Curiosity also has made a comprehensive mineralogical analysis on the Martian surface using a standard laboratory method for identifying minerals on Earth: X-ray analysis. This allowed us to identify 10 distinct minerals, but also to find an unexpectedly large amount of amorphous ingredients, rather than crystalline minerals, in the Rocknest composition. Amorphous materials, similar to glassy substances, are a component of some volcanic deposits on Earth. The results on both crystalline and noncrystalline components in the soil and the chemical compositions of the rocks provide clues to the planet's volcanic history and, in particular, can be used to infer the thermal, pressure, and chemical conditions under which they crystallized.

Atmosphere. Mars has a very thin atmosphere. The average surface pressure (corresponding to the triple point of water) is 6.1 mbar, which is a factor of 160 lower than the Earth's. The pressure varies depending on relief, increasing to 12.4 mbar at the bottom of Hellas basin and dropping to 0.5 mbar at the top of Olympus Mons. The atmosphere is composed mainly of carbon dioxide (95 % by volume). Other components are nitrogen (2.7 %) and argon (1.6 %). Minor species are oxygen (0.13 %), carbon monoxide (0.02 %), and water vapor (0.01 %). This water abundance, confirmed by exploring the water signature found by Curiosity in the ubiquitous Martian dust, is in coincidence with the tiny amount of ambient humidity in the planet's arid atmosphere. The atmospheric water content is negligible (it corresponds to tens or hundreds of micrometers of precipitated water). However, this abundance turns out to be near saturation in the very rarefied atmosphere and may condense out on the surface as hoarfrost. Of special interest in terms of potential Mars biology is the minor species methane. There were reports about finding methane at the upper level of only one hundred million's abundance, though no traces were detected. But one should be aware that principally it could be either organic or inorganic (volcanic) in origin and that its presence would not be key in determining potential Martian biology.

In contrast to Venus, there is no noticeable greenhouse effect on Mars, although even a tenuous atmosphere raises the surface temperature, however by only a few degrees. Seasonal-diurnal temperature variations exceed 150°C, from +20°C in some regions near the equator in summer to –130°C on the winter polar cap, where dry ice (CO_2) condenses. The temperature lapse rate in the troposphere is about –2.5°/km, and above the tropopause (in the stratosphere) the temperature reaches a nearly constant value of –129°C. Because the atmosphere of Mars is so rarefied and permanently contains suspended dust, the colors of Martian skies are different from those on Earth. In contrast to our blue sky, for which Rayleigh scattering is responsible, the daytime sky on Mars is orange-red and becomes dark violet at the horizon. Interestingly, the SAM instrument on the Curiosity rover found that the ratios of isotopes in the soil, including the above-mentioned hydrogen-to-deuterium ratio and carbon isotopic ratios, are similar to those found in the atmosphere, indicating that the surface soil has interacted heavily with the atmosphere. This tends to support the idea that as the dust is moving around the planet, it is reacting with some of the gases from the atmosphere.

The dynamics of the Martian rarefied atmosphere with its low thermal inertia differs significantly from the terrestrial one primarily by the absence of oceans, which are heat accumulators and damp the diurnal-seasonal temperature inhomogeneities. For the fast-rotating Mars ($\boldsymbol{Ro} << 1$) the geostrophic balance condition is met. The global circulation model (GCM) predicts a topology of motions in the troposphere and stratosphere generally similar to that of Earth, with a predominance of winds blowing eastward at high latitudes in winter, near the subtropics in summer, and westward at other latitudes. The polar caps also play an important role in planetary circulation. As we said above the polar caps are composed of water ice (a secular component) overlaid by carbon dioxide ice with a lower temperature of phase transition, and so there is freezing (CO_2 collapse over the cap) in winter and melting in summer. The thickness of the permanent north polar cap of water ice amounts to a few km, while the layer of freezing carbon dioxide does not exceed a few meters but may expand to 50° latitude in each hemisphere. The seasonal carbon dioxide exchange between the atmosphere and cryosphere in the polar caps serves as the main driving mechanism of air transport in the meridional direction, as illustrated by the diagram in Fig. 2.52. This gives rise to Hadley cell configurations with upflows and downflows, rearranging the system of winds near the surface and at high altitudes in the summer and winter hemispheres and causing seasonal changes of the cloud cover.

Convection compensates for the high static instability of the Martian atmosphere close to saturation even at a very low relative content of water vapor. Nonetheless, even under conditions of low moisture and the dry adiabatic gradient, massive clouds form. The convection excitation efficiency during daytime hours is approximately an order of magnitude higher than that in the Earth's atmosphere, while during the night it is completely blocked due to the formation of an inversion layer with a positive temperature gradient near the surface. Convection also maintains a

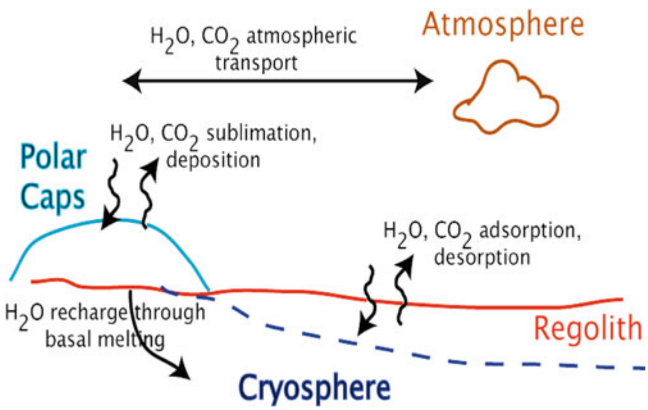

Fig. 2.52 Cryosphere-atmosphere volatiles exchange driving global atmospheric circulation on Mars (Credit: J. Head/Brown University)

constant high content of dust in the Martian troposphere and produces an additional dynamical effect superimposed on the global system of winds and the formation process of a windblown drift of sand and dust. This effect arises from a positive feedback between the dust content and the degree of atmospheric gas heating, which manifests itself as thermally generated diurnal and semidiurnal tides. This peculiar feature of the Martian atmosphere is most pronounced during periodically emerging global dust storms when fine dust rises to an altitude above 30–40 km because of turbulent mixing. Since the troposphere is highly opaque, a reverse greenhouse effect strongly damping circulation transport is produced near the surface. (The discovery of this unique natural phenomenon during a global dust storm on Mars in 1971 served as the impetus for drawing an analogy between it and the possibility of "nuclear winter" on Earth as an inevitable consequence of using atomic weapons and helped to cool down some political ambitions.)

Note also that the circulation in the Martian atmosphere is strongly affected by the surface relief (areography) on which both the observed wind patterns and generation of horizontal waves with various spatial scales depend. In turn, the planetary waves attributable to the baroclinic instability of the atmosphere and also internal gravity waves manifest themselves as irregularities in the temperature and vertical motion profiles in the stratosphere. The observed wave motions in the structure of clouds from the leeward side when flowing around obstacles, suggesting the existence of strong shear flows in the Martian atmosphere, are associated with them as well. The entire near-surface atmosphere turns out to be turbulent due to shear flows, even under conditions of relatively stable stratification.

The turbulence of a dispersed medium whose pattern depends significantly on the dynamical and energetic interaction of the gas and dust phases undoubtedly plays an important role in the complex of processes responsible for the formation, maintenance, and decay of a Martian dust storm, although the details of these mechanisms are not yet completely clear. Nonetheless, some estimates can be made based on the turbulent momentum and heat fluxes deduced from the measured altitude profiles of the mean velocity and temperature at the surface boundary layer, which are, however, modified in the case of turbulent flows with a heavy admixture. This approach allowed the conclusion that the presence of relatively small dust particles in the near-surface flow gives rise to the growing velocity gradient and increases the effect of saltation, transporting much larger amounts of dust particles into the atmosphere. This mechanism could be responsible not only for global dust storms lifting billions of tons of dust into the atmosphere but also for the formation of local eddies (dust devils) one thousand times in excess of what forms on Earth.

Moons. Mars has two small satellites of irregular shape: Phobos ($27 \times 22 \times 18$ km) and Deimos ($15 \times 12 \times 10$ km); see Fig. 2.53. In Greek mythology the names mean "fear" and "horror," acknowledging two sons of Ares who accompanied him in battle. Both satellites are locked in a synchronous rotation that results in their facing Mars with the same side. Their orbits lie close to the plane of the Martian equator. Interestingly, the period of Phobos's revolution around Mars is nearly two times shorter than the period of Mars's intrinsic rotation around its axis; therefore, an

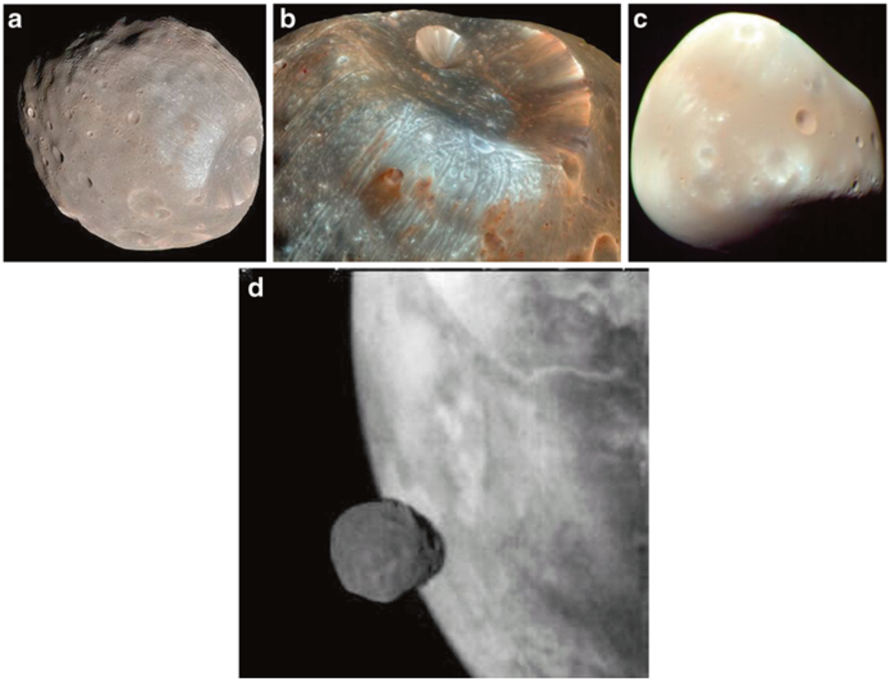

Fig. 2.53 The Martian moons Phobos (**a**, **b**) and Deimos (**c**) (NASA Courtesy). Image of Phobos at the background of Mars taken from the Russian Phobos 88 (**d**) (Credit: the Author). Phobos has accumulated dust and debris from the surface of Mars, knocked into its orbital path by projectiles colliding with the planet. A sample-return mission to Phobos would thus return material both from Phobos and from Mars

observer on the surface of Mars would see Phobos rise and set two times every day, crossing the sky quite quickly during the night. The period of Deimos's revolution is much longer, and both moons can often be observed simultaneously.

The problem of the origin of both Martian satellites remains unresolved. They could be either remnants of primordial bodies from which the planet formed and preserved since then, or asteroids captured by Mars much later. The latter scenario seems more plausible, although it is not clear how asteroid orbits eventually evolved from originally elliptical to nearly circular. Phobos experiences a significant tidal influence from Mars that results in a slow contraction of its orbit, and it will ultimately fall to the planet in a hundred of million years. Changes of the Phobos orbital parameters were already noticed in the middle of the last century, and as an explanation of this fact, the speculative idea was put forward that the satellite is hollow inside and artificial in origin, designed and launched by Martians. This intriguing idea died soon after perturbations from the irregular gravity field of Mars (strong gravity anomalies) were found. Images of both satellites transmitted by space vehicles brought evidence of the numerous impact craters on their surfaces, some of them comparable in size with the moons themselves (e.g., Stickney on Phobos). The bulk density of these satellites is low enough to testify to a rather porous structure of their interiors. Another possibility is that they had ice in their interiors or were once completely fragmented and assembled back like a loose rubble pile. There is a dust torus along the Phobos orbit produced by the meteorite bombardment including that erupted from Mars and eventually gathered as sediment on Phobos. Moreover, Phobos probably has accumulated soil, debris, and rock from the surface of Mars, knocked into its orbital path by projectiles colliding with the planet. This means that the tiny moon has been gathering Martian castoffs for millions of years, and thus a sample return mission to Phobos would be a twofer, returning material both from Phobos and from Mars. Unfortunately, the Russian Phobos-Grunt sample return mission in 2011 was ill-fated, and it is planned to be repeated in collaboration with the European Space Agency (ESA) in the early 2020s.

We see that historically predetermined interest in Mars has been maintained and has even increased in the last decades. The bottom line includes not only the wish to disclose why the nearby planet took a path of evolution different from Earth's but also the still-remaining hope of finding life signatures on past or present Mars, extinct or extant life features. One possibility is that abiotic primitive life origins could be related with groundwater cycles in volcanic regions, schematically shown in Fig. 2.54, similar to the supposed abode of ancient life on Earth. In the last decade of the last century, there was great excitement related to the in-depth study of meteorites collected in the Antarctic, some of them coming from Mars as the result of catastrophic asteroid impacts and blowing out matter from the Martian surface into space millions of years ago. Scattered debris traveled for millions of years in interplanetary space before some of it reached other planets, in particular Earth, and

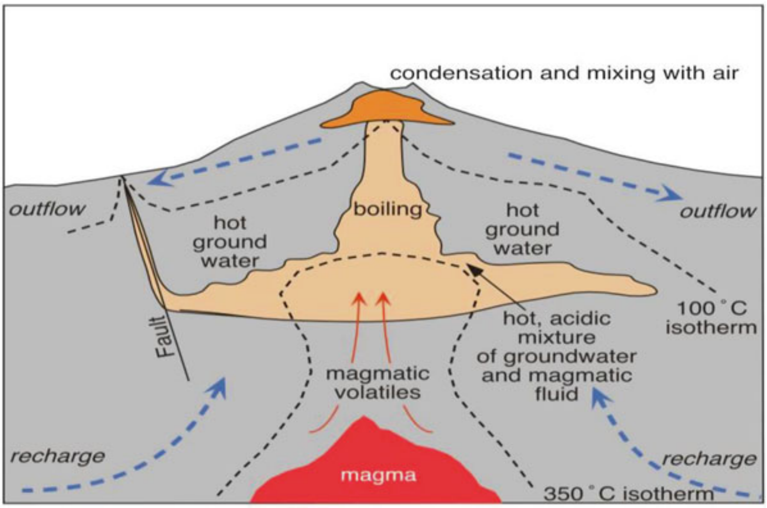

Fig. 2.54 Schematic representation of ground water cycle in volcanic region as abode of abiotic life origin (Credit: J. Head/Brown University)

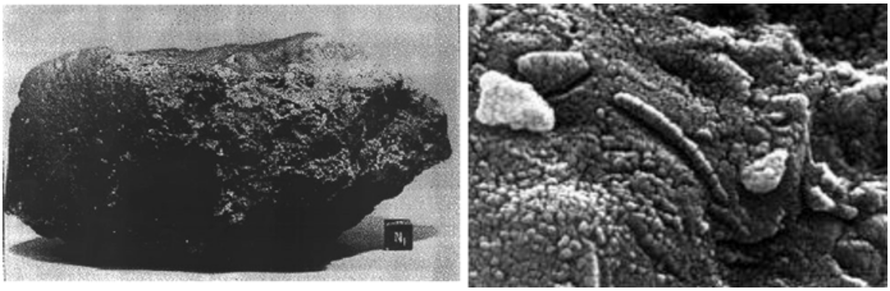

Fig. 2.55 Antarctic meteorite of achondrites class ALH 84001 (mass 1,931 kg) found on Dec. 27, 1984 in Alan Hills mountains in Antarctic (*left*), where traces of bacterial fossils of worm-shape were announced to be found. Later study showed these structures are rather of inorganic origin (Credit: D. McKay)

impacted the surface. The Antarctic ice cover is the best area for meteorites to be preserved and found. Many meteorites came from the Moon, but some were identified as being of Martian origin because of the unique composition and isotopic ratios of trapped gases, similar to those of the Martian atmosphere. They were distinguished by mineral composition as the class of shergottite-nakhlite-chassignite (SNC) meteorites (see Chap. 4 for more details). Note that recently another meteorite also associated by gas composition with Mars origin was found, this time in Morocco, and was called Tissint for the name of the town near the fall site. Of specific interest is the Antarctic meteorite ALH84001 (Fig. 2.55), where traces of bacterial fossils were thought to be found. Unfortunately, the follow-up studies did not confirm this discovery and related it rather with structures of inorganic origin.

Mars not only attracts progressively growing interest from scientists, it also draws public interest. The attention could be increased by the virtual presence of people on Mars. An interesting proposal was made some time ago by the Planetary Society to set up a robotic Mars outpost network with access to the transmitted real-time information/images and data collected through the Internet. The basic idea is to select a few of the most intriguing sites on the Martian surface and to deploy there (quasi) permanent robotic stations including both stationary platforms equipped with communication, navigation, and other supportive systems, and rovers. Balloons could also be launched and controlled from a stationary stations network. All these facilities would comprehensively investigate the surrounding terrain and different patterns of planetary geology, geochemistry, atmosphere-surface interactions, atmospheric dynamics, and weather. Researchers from various countries, college/university students, school children, amateur astronomers, and even the general public could participate in this endeavor, getting real-time access to data acquisition and analysis. Students could be a part of special teams and participate not only in the study of Martian landforms but also in operation planning including rover maneuvering through craters, dry river beds, and basins suspected to be ancient lakes of biological interest. Several rovers could operate in parallel, for example, for the study of geological history at a denudated steep wall of cliffs. Another challenge is the deployment from a stationary station drilling facility to excavate soil patterns from different horizons. All this would imply a nice integration of the basic science and public interest/involvement, because people from all over the world could collaborate and have a virtual presence on the planet, thus ensuring much better public/taxpayer support for planetary exploration.

Outlook. Summarizing this brief overview, we may conclude that, among the terrestrial planets, Mars with its satellites continues to draw great attention as a neighbor world which evolved differently than Earth but is nonetheless still close enough to the home planet by its natural conditions to warrant inspection. The outlook for further Mars study is as follows:

– History of the planet's seemingly once-volcanic and aquatic history, its water and climate, relationships with geological structures in support of evidence of an earlier wet and warm Mars; what caused transitions from global warming to global cooling;
– Role of abundant liquid water and pluvial activity in pervasive alteration of crust: water inflow, rainfall, filling and outflow, open-basin lakes; valley origin and history; ancient ocean at shallows; subsurface permafrost as uppermost of the surface, seasonal changes in hydration, polar caps, glaciers;
– Topology of hydrological system and its alteration throughout the Noachian/Hesperian/Amazonian periods in Mars history;
– Evolution of the Martian crust and deeper regions, surface morphology in relation with the volcanic diversity, mineralogy, loose rocks, sand and dust; search for punctuated volcanism and hydrothermal sources to alter crust composition; elemental composition of the surface, including hydrogen-bearing compounds, sulfates, chlorides, and metal-bearing clays; search for carbonates;
– History of magnetic field in conjunction with the interior, paleomagnetism;
– Thermal regime/dynamics of the atmosphere (specifically the role of CO_2, H_2O, SO_2, and chlorine compounds) thermal balance near the surface, role of aerosols; minor constituents (in particular, methane) and noble gases, isotopic ratios; estimates of dissipation to outer space of an earlier denser atmosphere;
– Search for organics and biosignatures/life features, extinct/extant biosphere in close proximity to ancient water environment. Of special attention should be search for life signatures beneath the surface shielded from harmful UV solar radiation and based on metabolic processes similar to those of deep-seated biosphere on Earth.

New missions to Mars are on the agenda of the different national space agencies, which stimulates continuing activity in planetary exploration. An important step forward is the most recently launched NASA Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft focused on the Martian aeronomy-upper atmosphere study with the goal to reveal atmospheric formation and loss history. ESA announced its planning of INSPIRE—a future Mars network science mission with deployment of several coherently operated landers on the Mars surface—which was earlier preliminarily designed at the NASA Mars Mission Research Center. ESA and ROSCOSMOS joined efforts around the two challenging ExoMars missions (Fig. 2.56) including a

Fig. 2.56 Joint ROSCOSMOS-ESA project of Mars study ExoMars (Courtesy of ROSCOSMOS and ESA)

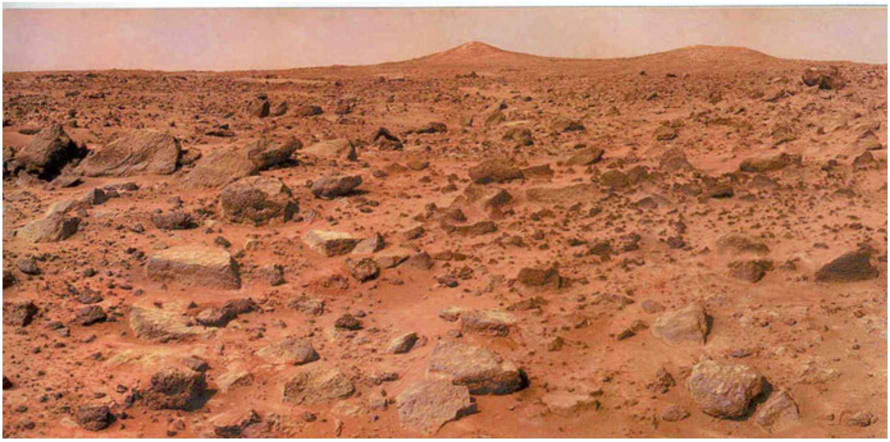

Fig. 2.57 Panorama of the Martian surface at the Pathfinder landing site in Ares Vallis. Note the *gray* rocks covered by *red-brown* dust (Courtesy of NASA)

Mars rover to be followed by the above-mentioned new Phobos-Grunt (preliminarily called Boomerang) and Mars Sample Return (MSR) missions.

In the contemporary epoch, Mars with its hostile natural conditions is an inhospitable desert world that would not be easy for humans to adapt to (Fig. 2.57). It is, however, the most suitable place among other solar system planets to visit and possibly to habitat. Robotic missions have returned to Earth invaluable information on Mars. New ambitious missions of progressively growing complexity and capabilities will further improve our knowledge on the present and past of this intriguing world. They are also regarded as precursors of future human flights and the long-term goal of Mars exploration and utilization. Different mission profiles and scenarios have been suggested for flying to Mars with humans before the middle of this century. Are they realistic? The bottom line is that such a mission can be undertaken when new technologies become available, first of all, new propulsion systems involving nuclear engines and/or electric plasma jets. Needless to say, we should ensure minimum risk for astronauts in terms of safe return flights and protection from a hazardous radiation environment. Also, a human flight to Mars will require the investment of enormous financial resources, which are currently estimated as at least 600 billion dollars. Can we afford this ourselves now when humanity faces so many serious problems on the home planet? Would it be justified in terms of promoting future technology development and potential trade-offs? The first goal is, therefore, to examine how to pool financial and technological resources most efficiently to undertake such a mission internationally.

Nonetheless, the purpose of the coming decades is to develop foundations at a program level architecture for robotic exploration of Mars that is consistent with the challenge of human missions. It would incrementally develop an infrastructure on the Mars surface that would be needed for the future human flight. This would involve not only detailed studies of the selected sites and their natural conditions throughout several years to ensure that future astronauts could avoid unexpected situations, but also the organization of a reliable navigation/beacon system, preparation for some necessary logistics deployment, and preliminary study of the potential for production and storage of breathable oxygen and propellant from atmospheric carbon dioxide and soil to facilitate safety and reduce the cost of the human expedition. A well-developed robotic infrastructure on Mars would be extremely supportive and valuable for humans and it would advance human-machine symbiosis in general.

Undoubtedly, sooner or later the human flight to Mars will be implemented. It should be undertaken as an international endeavor and the common target of our civilization manifesting the next step in its evolution (Fig. 2.58). Projects of Mars terraforming are also discussed for the very far future.

Some Problems of Our Neighbor Planets' Evolution

Let us now return to the key questions intrinsically related with the formation of natural conditions on our neighbor planets. Why did Venus and Mars take different evolutionary paths than Earth? What formed the peculiar thermal regime of Venus, and what catastrophic event caused the dramatic change of an assumed originally clement climate on Mars?

Earth is located in a comparatively narrow zone of circumsolar space where the development of favorable (for life's existence) climatic conditions is possible. This is called the habitable zone in the solar system. Its inner boundary is located 10–15 million km closer to the Sun than the Earth's orbit, while its outer boundary extends

Fig. 2.58 First astronauts on Mars. Artists concept (Credit: NASA)

to approximately the orbit of Mars. The orbit of Venus is outside this zone, at a distance that is almost triple the critical value. Obviously, if the Earth were moved to the location of Venus (actually, even not as far), then it would probably evolve according to the Venusian scenario. Let us also recall that the whole solar system is fortunate to be located in a quite limited zone of our Galaxy where conditions suitable for biota appearance could be principally developed (see Chap. 10).

Indeed, let us assume that the initial albedo of early Earth was mainly determined by surface and corresponded to the lunar one ($A = 0.07$). Then based on the average annual balance between the solar radiation absorbed by the terrestrial surface and the thermal (bolometric) radiation emitted by Earth (at the reduced luminosity of the young Sun) the effective (equilibrium) temperature would be ~255 K, which is even below the freezing point of salt water. We therefore need to assume that a greenhouse effect developed in the original atmosphere and substantially contributed to the early stages of our planet's evolution (currently, the greenhouse effect raises the mean temperature near the ground to 288 K). This means that even under reasonably low atmospheric pressure (~0.01 atm) Earth could retain its water that was concentrated in the primordial water reservoirs and atmosphere. In turn, carbon dioxide would accumulate in the terrestrial hydrosphere and carbonates of sedimentary rocks through its binding with metal oxides incorporated into the ocean crust and upper mantle (with the formation of aqueous silicates) and, biogenically, through the deposits of lime skeletons of sea organisms.

Venus. Now, addressing Venus, one must be aware that at the same postulated initial albedo, the equilibrium temperature turns out to be at least 325 K, which is above the water boiling temperature down to a pressure of 0.2 atm. To retain water on the surface, Venus should have an initial atmosphere denser than that of Earth by about an order of magnitude. At equal rates of mantle material degassing and atmospheric dissipation into outer space, this is unlikely. More likely, carbon dioxide gradually accumulated in the atmosphere together with water vapor. This, in turn, contributed to a further rise in surface temperature and eventually the runaway greenhouse effect developed, resulting in the transport of increasingly large amounts of CO_2 and H_2O into the atmosphere, up to some equilibrium state. The latter is characterized by the relationships between mineral phases and volatiles on the surface, carbonate-silicate interaction in the upper layer of the planetary crust being the most important.

Let us emphasize that the above scenario is characteristic of a system with positive feedback and internal instability when initial perturbation is not suppressed but, on the contrary, fairly rapidly enhanced. Therefore, it is not coincidental that such an effect on Venus is called a runaway greenhouse effect leading ultimately to the high surface temperature. At this temperature, carbon dioxide turned out to be not bound in carbonates of sedimentary rocks, as on Earth (and, probably, on Mars), but was released into the atmosphere, giving rise to very high pressure. According to the model estimates, the amount of carbon dioxide locked in the Earth's sedimentary cover is comparable to the content of CO_2 in Venus's atmosphere.

Whereas the abundance of carbon dioxide on Venus can be explained in terms of a fairly simple equilibrium model (though the real geochemical processes involving sulfur-bearing and other compounds are much more complex), the situation with water is even more difficult to understand. Assuming "geochemical similarity" in evolution scenarios with the involvement of both endogenous and exogenous processes, the volumes of volatiles and, accordingly, the reserves of water on Venus, must have corresponded to the volume of the terrestrial hydrosphere, which is approximately 1,370 million km^3 or more than 1.37×10^{24} g. Meanwhile, water could not be preserved on the surface of Venus at a temperature above the critical one (647 K). The same is valid for aqueous solutions (brines) with a slightly higher critical temperature (675–700 K). Regarding the atmosphere, the amount of water it contains at an average relative water vapor content of 5×10^{-4} does not exceed 3.5×10^{20} g. This is considerably greater than the total water content in the terrestrial atmosphere (because of the much higher gas volume) but is less than the reserves of water in the hydrosphere by almost four orders of magnitude.

Thus, the key problem of evolution we address for Venus is whether the early Venus had water, if so, how and where it was stored, and when and how it was lost. We may reasonably assume that Earth and Venus received approximately the same reserves of volatiles, including water, through degassing from the mantle that accompanied the interior differentiation process. Heterogeneous accretion due to migration of planetesimals from the formation zone of the giant planets and their fall to inner planets as comets and asteroids of the carbonaceous chondrite class could contribute significantly to this process as well. Then one might expect Venus to have possessed an ocean at the initial phase of its evolution comparable in volume to the terrestrial one—an ocean that was somehow lost. The deuterium-to-hydrogen

D/H ratio measured in the Venusian atmosphere, which turned out to be larger than that in the Earth's atmosphere by two orders of magnitude, confirms this concept. This high deuterium enrichment can be explained by an efficient thermal escape of the lighter hydrogen isotope during the evaporation of the primordial ocean followed by dissociation of water molecules by solar UV radiation and its dissipation from the atmosphere. However, adoption of this mechanism requires an assumption that enormous masses of liberated hydrogen and oxygen were evacuated from the atmosphere and bound by surface rocks, which seems hardly realistic though, in order to accommodate a huge amount of hydrogen evacuation, the very efficient hydrodynamic blow off assist mechanism was suggested.

There is also a different viewpoint that Venus was initially formed as a "dry" planet, though the introduction of volatiles through the mechanism of heterogeneous accretion is assumed to play an important role as well. In this scenario, the water content was essentially constant throughout the geological history of Venus, remaining approximately at the current level while the efficiencies of heterogeneous accretion and hydrogen dissipation from the atmosphere were considerably lower. In such a case, the observed enrichment of the Venusian atmosphere with deuterium during the separation of isotopes in the process of their dissipation from the atmosphere can also be explained.

As we see, at present, it is difficult to answer the question of whether Venus had a primordial ocean and, thus, to choose between the above scenarios for its evolution due to limited experimental data to back the models. Both scenarios basically lead to the development of a runaway greenhouse effect and the present-day climatic conditions. At the same time, the possibility that Venus possessed a more clement climate at the earliest stages of its evolution must not be ruled out. The model postulates an existence of negative feedback stabilizing some equilibrium state rather than positive feedback enhancing temperature growth and being responsible for the runaway greenhouse effect. The negative feedback may be attributable to the atmosphere-lithosphere interaction pattern controlled by the carbonate-silicate cycle and, in principle, could exist on Venus in a certain period, before the luminosity of the Sun rose by about 30 % (when it passed to the main sequence on the Hertzsprung-Russell diagram, see Chap. 6) and the atmospheric humidity threshold had been overcome. The mechanism underlying this scenario was called the "wet" greenhouse effect. As calculations showed, the transition from the wet greenhouse effect to the runaway one might not happen if the increase in the planet's albedo to its current value occurred earlier than the rise in solar luminosity and, thus, compensated for the increase in the influx of solar energy. Venus would then possibly possess a wet carbon dioxide atmosphere with a pressure near the surface of only several atmospheres and a temperature of less than 100 °C. Such a planet could be suitable for the emergence of at least primitive life forms.

This consideration leads us to the idea that marginal possibilities containing both deterministic and stochastic components existed in the evolution of Venus, which eventually led to the runaway greenhouse scenario. The processes responsible for this scenario included the planet's formation at a certain distance from the Sun, orientation of its rotation axis in space, geological evolution and lithosphere-atmosphere interaction involving decomposition of carbonates and the loss of water, the retention of major and minor components in the atmosphere maintained by volcanic activity which provided high opacity, the circulation of sulfur-bearing compounds and halogens between the surface, atmosphere, and clouds, formation of the peculiar features of the planetary circulation, etc. Altogether, these processes led ultimately to the existing unusual nature of Venus. We cannot exclude, however, that a different evolutionary scenario of the planet as a nonlinear dissipative system could happen, provided that the essence and sequence of the above processes would somehow break and then the planet would pass to a stable state with different natural conditions.

Unfortunately, the current state of Venus seems more stable than the climatic state of Earth. Our main concerns are focused on mankind's invasion of the environment which eventually becomes comparable with the natural processes. Climatic changes could lead to uncontrolled heating involving carbonate decomposition, water evaporation, and, accordingly, a sharp rise in the atmospheric temperature and pressure. The case for Venus thus serves as a warning for Earth to avoid such unfavorable processes and dangerous scenarios. In this connection, it is pertinent to recall the statement quoted by Nobel Prize winner Ilya Prigogine in the book *The End of Certainty (2001)* that human existence consists of the continuous creation of unpredictable innovations. We hope that the innovations of our civilization will not dramatically impact the nature of our home planet.

Mars. Let us now address the problem of Mars evolution. As we saw, Mars took a completely different path of evolution from that of Venus. First of all, it is necessary to answer the question about mechanisms that exerted a critical impact on the pleasant natural conditions that presumably were on Mars at an early epoch, which is backed by the morphological features preserved on the planet, in particular, the ancient cratered terrain of the southern highlands which are thought to hold clues to the planet's early differentiation. Important geochemical clues to the early geological history of Mars have been provided by the SNC meteorite quite reliably associated with the Mars origin. Some clasts (e.g., NWA7533 found in northwest Africa) were identified with a Martian regolith breccia of unique composition (different from that of the Moon) containing zircon crystals[5] for which an age of 4,428,625 million years was measured. This confirms early crustal differentiation with contribution from impact melts and chondritic (CI) input. In addition, it implies that the Martian crust and its volatile inventory, formed during the first 100 million years of Martian history, coeval with the earliest crust formation on the Moon and the Earth. This allows us to unravel the geologic history of early Mars.

Assuming the integral albedo of early Mars was similar to what we postulated for early Earth and Venus, its equilibrium temperature would not exceed 220 K. At this temperature Mars would be able to retain only frozen rather than liquid water on its surface. However, there is widespread evidence of the presence of liquid water flows, meaning a considerably denser atmosphere and much more favorable climate

[5] Zircon crystals typically form during magma crystallization, and they are impervious to the impact melting processes influencing the composition of their host rocks.

than the one today. The hypothesis about the favorable climate of ancient Mars immediately poses the following fundamental question: Were its present-day natural conditions formed as a result of long and complex evolution, or did these changes occur suddenly on the geological time scale? The composition of SNC meteorites (in particular, the measured D/H ratio) imposes certain constraints on the standard model of the planet's thermal evolution. The model suggests the separation of an iron sulfide core shortly after the end of accretion, the differentiation of constituent material into shells (though less complete than that on Earth), convective heat transport in the mantle that provided early volcanism, generation of the magnetic field through the dynamo mechanism in the core, as long as it remained liquid, and collapse of the dense atmosphere. However, it is not clear whether this model is in accord with the formation of Mars from the most ancient primordial matter, similar to other terrestrial planets. The primordial matter is assumed to constitute chondrite meteorites for which the iron and silicon contents equal 1.7 which, in particular, corresponds to the terrestrial value. There is some evidence that this is not the case for Mars, which probably experienced disturbance 1,712,685 million years after formation, an evidence brought by SNC study. The original difference of evolution of Mars from that of Venus and the Earth was probably predetermined by its formation in a ring clump of a turbulent gas-dust cloud closer to Jupiter, which could influence the composition of its original matter. Answering this question would have important implications for resolving the problem of the solar system's origin.

Let us note that the nature of the present-day dry Mars cannot be explained by the fact that it is 0.5 AU further away from the Sun than Earth. More likely it should be associated with Mars's size, which is approximately half the Earth's. Accordingly, the mass of Mars is almost an order of magnitude lower than that of the Earth. As we said, this should have led to early depletion of radiogenic isotopes, which served as energy sources, and this would have determined its thermal history and geology, and eventually the collapse of the atmosphere. Mars began to cool, volcanism ceased, and the atmosphere reduced. In other words, a limited reserve of radiogenic isotopes rather than distance from the Sun dramatically impacted the Mars evolution.

This model seems fairly justified. At the same time, it is also hypothesized that Mars experienced a great catastrophe in its history: collision with a large asteroid that produced the Hellas basin of about 2,100 km across—the region in the Southern Hemisphere antipodal to the Tharsis upland, on which the largest shield volcanoes in the solar system originated. The hypothesis suggests that the release of magmatic rocks through the young Martian crust and volcanism on Mars were triggered by such a catastrophic event. In turn, this led to a radical change of the relief in the Northern Hemisphere and may have contributed to the formation of an atmosphere. The follow-up loss of the atmosphere and the transition of Mars from an evolutionary path similar to the Earth's in the first billion years to a completely different scenario of the follow-up evolution are associated with another, more recent, global catastrophe that was also produced by the collision with a large asteroid. Both these hypotheses are largely speculative. Nonetheless, the possibility of catastrophic events, likewise in the case of the Moon, should not be ruled out, especially bearing in mind the higher efficiency of impact bombardment near Jupiter.

We conclude this section by addressing, once again, the importance of extending geophysics studies focusing on Earth to all terrestrial planets. Turning to our immediate cosmic environment, we naturally wish not just to understand how the solar system came into being, but what is responsible for its stable configuration, as we state in Chap. 1. We should also understand what sets the Earth, with its unique natural conditions, apart from other terrestrial planets, primarily its nearest neighbors Venus and Mars, and what the limits are for the existing regulation mechanisms for the feedback on Earth to prevent unfavorable scenarios for its subsequent evolution. In other words, we want to know whether, for example, the accumulation of negative anthropogenic impacts on the surrounding natural medium will lead to a radical change of conditions associated with the bifurcation of the state of an open nonlinear dissipative system. An integration of Earth and planetary sciences aimed at a better understanding of the present, past, and future of the Earth based on a comparative planetology approach is called for to answer this key question. Concurrently, this must help to solve the cardinal problems of planetary cosmogony and, in particular, to impose much more stringent constraints on the range of parameters used in developing models for the origin and evolution of Earth and solar system as a whole.

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