

CONFERENCES AND SYMPOSIA

PACS numbers: **96.10.+i**, **96.30.–t**, **97.82.–j**

The Solar System: current understanding and future prospects*

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DOI: 10.3367/UFNe.0179.200910g.1118

Contents

Abstract. **The current concepts of the origin and evolution of the Solar System are discussed, and some notions about extrasolar planets are reviewed. The present status of and future prospects for space exploration in Russia and abroad are examined.**

1. Introduction

The exploration of the Solar System by spacecraft has allowed us to rediscover planets known since ancient times. At present, almost every planet has been studied by a robotic apparatus sent from Earth. The results of these studies have radically changed our knowledge about Solar System objects, including planets, their moons, asteroids, and comets. For example, the physical conditions on Venus, our nearby twin planet, turned out to be entirely different from terrestrial ones: the temperature near the surface amounts to about 500 Celsius degrees, and the pressure is nearly 100 times higher than on Earth. There is still the possibility of finding extraterrestrial life on Mars, despite negative, for the moment, results of intensive research, mostly by American automatic stations. The natural satellites of giant planets Jupiter and Saturn have turned out to be strange worlds with active volcanoes (Io) or with an ocean covered by an ice shield (Europa).

How were the planets formed, and how can the various conditions on them and their internal structure be explained? What was the origin of the Solar System? How do planets evolve? These and many other similar questions have been posed, not only by researchers of the Solar System but also by those who are interested in understanding the evolution of the natural conditions on Earth. Until recently, only the Solar System has been studied. In recent years, planetary systems have been discovered near other stars as well. The study of these new objects will allow a better understanding of our own planetary system.

The epoch of pioneer space explorations and studies of conditions on other planets is being replaced by the epoch of consecutive dedicated programs. Detailed studies and the search for life or its traces on Mars — the only Earth type planet where there is still hope to find life — is one of such programs. Until recently, such broad-scale space research programs have been elaborated only in the USA and Europe. Three years ago, the Russian Academy of Sciences approved a novel Russian Space Research Program that includes studies of Mars and its natural satellites, the Moon, and Venus, as well as a new avenue in Russian space research — a flight to the enigmatic Jovian satellite Europa and studying it with robots. This project can join the extensive international research program of the Galilean satellites of Jupiter, the 400th anniversary of the discovery of which will be celebrated in 2010.

Physical processes proceeding in the Solar System are controlled by many various factors which have determined its origin and evolution up to the present time. To understand how the Solar System came into existence and evolved, astronomers, physicists, chemists, and geologists consider different aspects of this general evolutionary process.

If one attempts to formulate the main problems of space research as broadly as possible, the following 'principal questions' emerge:

(1) How and from what did the Universe originate?

(2) Which fundamental physical laws govern its state?

(3) Which conditions are necessary for a planetary system to form? What is the origin and evolution of the Solar System?

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Received 24 August 2009
Uspekhi Fizicheskikh Nauk **179** (10) 1118 – 1140 (2009)
DOI: 10.3367/UFNr.0179.200910g.1118
Translated by K A Postnov; edited by A Radzig

* This paper is an extended version of the report "Prospects for the Russian research program on Solar System physical processes" by L M Zelenyi, presented at the scientific session Prospects for the Development of Fundamental Physics and Astronomy at the RAS Physical Sciences Division general meeting held on December 15, 2008.

(4) What conditions are necessary for the origin of life on the planets?

(5) How did the conditions for life on Earth as a space ecosystem form, and what is the impact of external factors (solar radiation, galactic cosmic rays, etc.) on it?

The last three questions relate to studies of the galactic provinces where the Solar System is located. In this paper we make an attempt to briefly present progress in the understanding of the physics of the Solar System, to give the state-of-the-art in different avenues of studies of the Solar System (including those with space vehicles), and to depict the possible role of Russia in these studies. The search for life on Solar System bodies is a special problem. Essentially, it has gone on since ancient times. Nowadays it is most often related to Mars. In the last third of the 20th century and the first decade of the 21st century, many unmanned expeditions have been sent to Mars with the aim of finding traces of life and studying possible sites for its existence. Today, 44 years after the first pictures of Mars were taken by spacecraft, the only definitive answer is that no signs of life have been found, although optimists continue to suggest new sites where life could exist and new methods of searching for it. The methods themselves are becoming more and more sophisticated, and instead of seeking life, they allow searching for traces of life that, perhaps, disappeared long ago or that perhaps never appeared at all.

2. Current understanding of the Solar System structure

Distance is measured in the Solar System using the astronomical unit (AU) which is equal to the distance from Earth to the Sun, 149.6 mln km. It takes 8.3 minutes for light to travel this distance. Orbital distances to bodies at the outer edge of the Solar System in the Edgeworth–Kuiper belt (or trans-Neptunian objects, of which Pluto is now one) is about 5 bln km, or 5 light hours (lh). The Oort Cloud, a tangle of many non-coplanar cometary orbits, is a more distant periphery. The Oort Cloud is located at a distance of approximately 20 thousand AU, or about 3000 bln km, or 0.31 light years (ly).

Eight planets orbit the Sun (Fig. 1): four terrestrial inner planets (Mercury, Venus, Earth, Mars), two gas giant planets (Jupiter and Saturn), and two so-called ice giants (remote Uranus and Neptune). The orbits of the planets are almost circular and coplanar. In turn, there are natural satellites (moons) around the planets. Their number is now 166 and continues increasing, due to the discovery of smaller and smaller bodies. Each of the four giant planets has a system of planetary rings.

Between the orbits of Mars and Jupiter, a belt of 'small bodies' — asteroids — is located. According to estimates, several hundred thousand asteroids with a diameter of more than 1 km are found in this belt. Smaller bodies are related to meteoroids.

The space between the orbits of Jupiter and Neptune, the most remote planet of the Solar System, is populated by another group of asteroids, the so-called centaur asteroids. Beyond the orbit of Neptune, at a distance of about 40–50 AU from the Sun, small bodies known as trans-Neptunian objects (TNOs), or the Edgeworth–Kuiper belt, are located. This region is similar to, but much larger than, the asteroid belt, by about 20 times in size and 20–200 times in mass. Here there are many small Solar System bodies (relics of the Solar

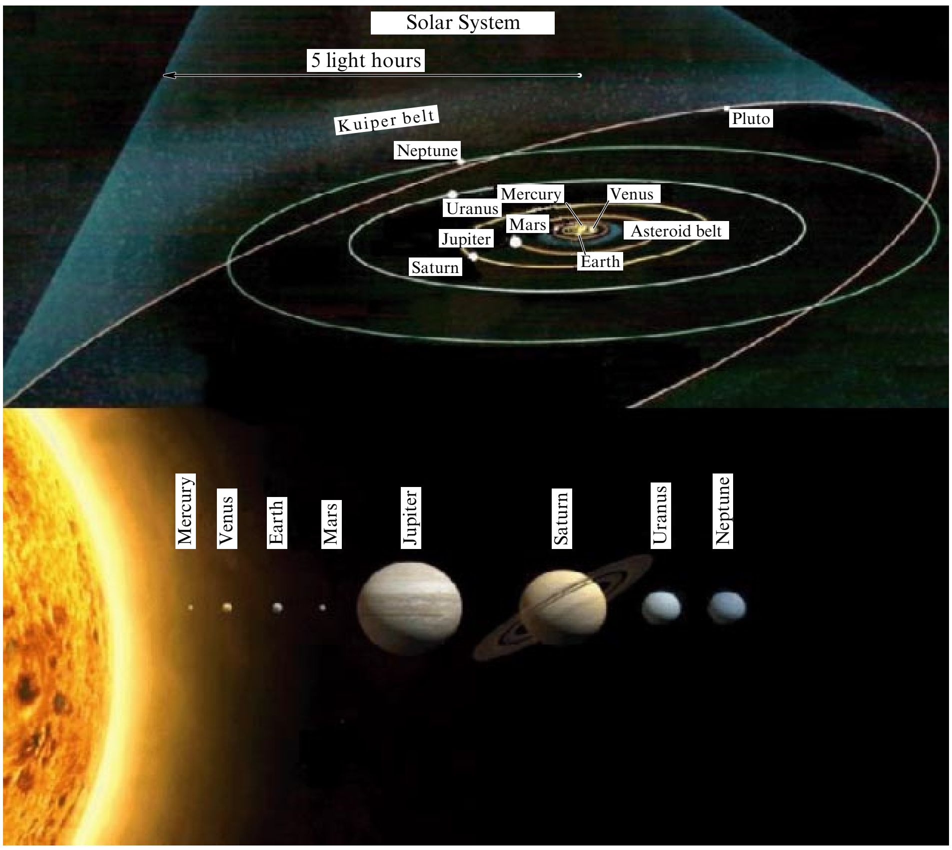

Figure 1. The Sun, the orbits of the planets, and the relative sizes of the planets.

System's formation), and at least three dwarf planets (Haumea, Makemake, and Pluto, which until 2006 was classified as the ninth planet of the Solar System).

The region of the Sun's gravitational attraction encompasses many thousands of astronomical units. Small objects having remained from the formation of the Solar System are preserved in its outskirts. It is possible to single out two such regions. The Oort Cloud is located much further away than the Edgeworth–Kuiper belt, at a distance of approximately 20 thousand AU from the Sun, in low-temperature conditions. Aphelions of cometary orbits are located there. Sometimes, TNOs leave this region due to gravitational perturbations and come to the inner regions of the Solar System, where they can reach the orbits of Earth and other planets.

Probably, the total mass of matter in the Edgeworth–Kuiper belt exceeds by many times that of the asteroid belt, but is apparently smaller than that of the Oort Cloud.

In contrast to planets, asteroids, and centaur asteroids, comets reside in very elongated orbits with high eccentricity. Short-period and long-period comets have their orbital aphelions either in the Edgeworth–Kuiper belt or in the Oort Cloud, respectively.

Besides these types of bodies, the dust component, solar electromagnetic radiation (extending from radio frequency band to hard X-ray range), solar wind (the flux of charged particles permanently propagating from the Sun), and solar and galactic cosmic rays (high-energy particles accelerating in the solar magnetic field or somewhere else in the Galaxy and reaching the Solar System) are very important factors for understanding the formation and the present state of the Solar System. Cosmic rays do not form plasma (i.e., a medium with collective properties) and follow the simpler laws of motion of individual charged particles. Finally, the Solar System is permanently refilled with interstellar matter, including neutral atoms, in addition to the galactic cosmic rays already mentioned. All these factors interact as a unique ensemble and must be considered as a whole to understand processes proceeding in the circumterrestrial space.

Solar plasma fills a smaller region (sometimes called the 'solar empire') known as the heliosphere (Fig. 2). This is a region of the circumsolar space where solar wind plasma outflows supersonically. When permeating the interstellar medium, the solar wind first brakes to become denser, hotter, and more turbulent. The surface where this transition occurs corresponds to the shock wave front and lies at a distance of 85–95 AU from the Sun. The American spacecraft Voyager 1 and Voyager 2, launched in 1977, crossed this boundary in December 2004 and August 2007, respectively. After passing about 40 AU beyond this boundary, the solar wind collides with interstellar matter and completely stops. This boundary separating interstellar medium from the matter of the Solar System is called the heliopause. Its location is determined by the balance between the ram pressure of the solar wind and the total pressure of interstellar gas and the magnetic field. The motion of the Solar System, with a velocity of 20–25 km s^{-1} relative to the interstellar medium, gives the heliosphere a nonspherical teardrop shape elongated in the direction opposite to the motion of the Sun. Outside the outer heliopause boundary, where the braking of upstreaming interstellar matter occurs, yet another collisionless shock wave (bow wave) is initiated.

Thus, the Solar System represents a complex conglomerate of solid matter, neutral gas, plasma, dust, energetic charged particles, and electromagnetic fields. The question as to how it formed 4.5 bln years ago inevitably emerges. New experimental data about extrasolar planets can be very useful in answering this question. The theory describing the formation of stars and planetary disks was elaborated fairly long ago, but now, due to the successes of astrophysics and observational astronomy, we are beginning to much better understand the details of the formation of this complex system, and the theory is becoming significantly more complicated.

3. Hypotheses for the Solar System's origin

O Yu Schmidt and his disciples from the United Institute of Physics of the Earth, RAS greatly contributed to the theory of star and planetary disk formation. Schmidt's main idea, which was based on the Kant–Laplace hypothesis (18th century), can be formulated as follows. Particles in the primordial extended interstellar gas–dust cloud start concentrating toward an arbitrary gravitating center to form a protoplanetary cloud (Fig. 3). The cloud starts rotating and

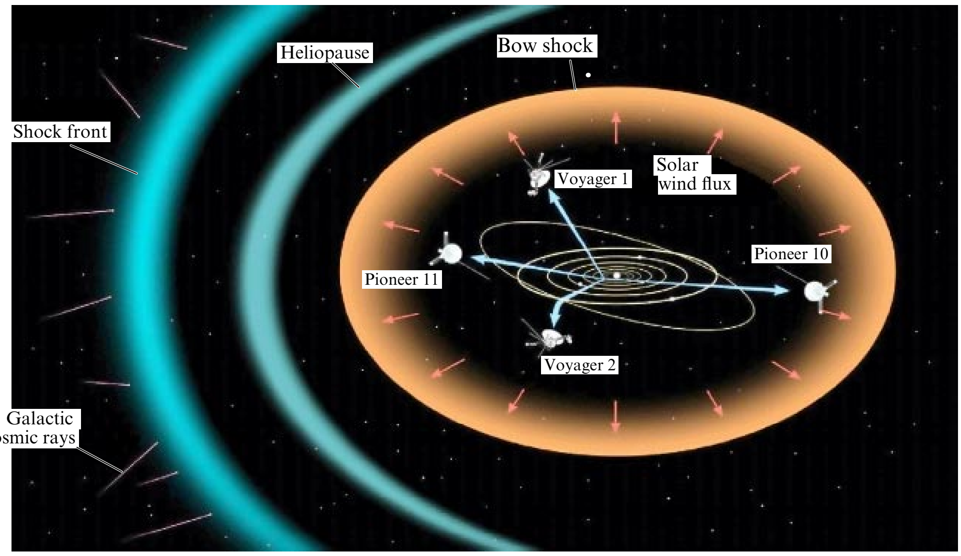

Figure 2. Plasma heliosphere. Shown are the trajectories of the Voyager 1, Voyager 2, and earlier Pioneer 10 and Pioneer 11 spacecraft.

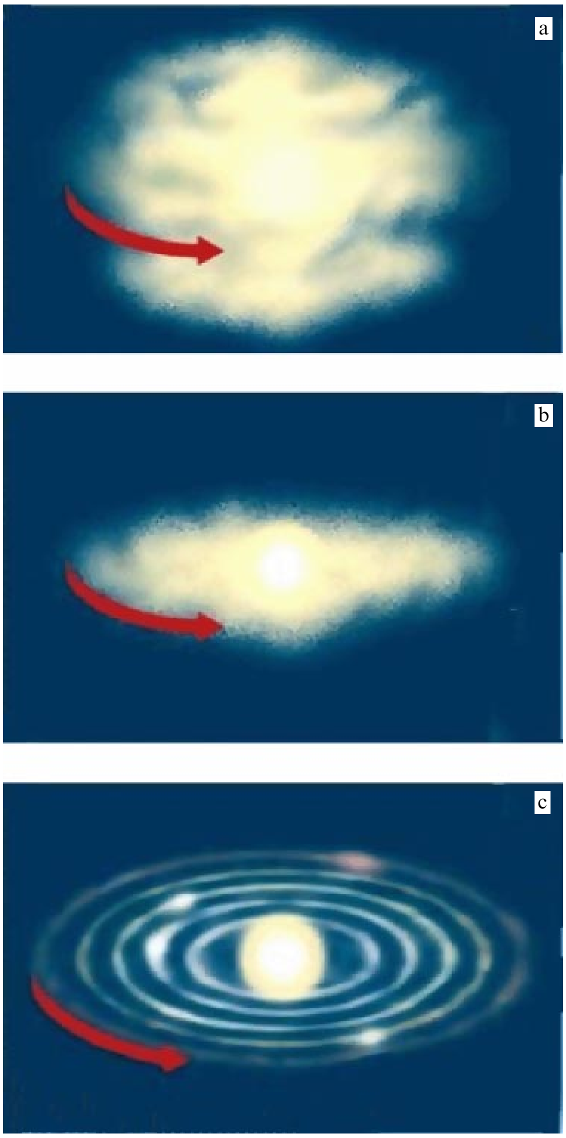

Figure 3. Three stages of the formation of the Solar System according to earlier concepts of the accretion theory (20th century). A gas–dust cloud rotates and gradually flattens (a) to become a thin disk (b) around the Sun forming in the center. In due course, rings appear (c), from which planets form.

by virtue of angular momentum conservation becomes flat. In this rotating disk fragmentation occurs, and much smaller sources of condensation — planetesimals — appear, and in turn collide and stick to become protoplanets. Then, after many collisions with the surrounding matter, the protoplanets form planets in the process of the accretion of matter from the gas–dust disk surrounding the young star. The masses of disks vary from one thousandth to one or two tenths of the star's mass, and their sizes lie in the range from several dozen to several hundred astronomical units. Early concepts of the protoplanetary disk were based on studies of our own planetary system, in which planets were commonly divided into two groups: terrestrial planets consisting of hard stony rocks, and giant gas–liquid planets. It was clear that the protoplanetary disk must be dominated by hydrogen and helium in addition to dust, since these elements dominate in Jupiter and Saturn which constitute 92% of the total mass of our planetary system and consist mostly of hydrogen and helium. All other elements and compounds could be in the condensed (solid) phase and were present in the composition of solid particles and bodies, depending on temperature which was mainly determined by the distance from the Sun.

The classical theory [1–3] assumes that the formation of giant planets occurred in several stages. Schematically, the first stage involves a prolonged accretion (up to 10^8 years) of dust grains onto a growing core of the first giant planet, until its mass reaches about 10–15 Earth masses [4]. Then, more rapid gas accretion onto the core occurs, increasing the mass of the giant planet up to the final value. However, observations of star–planet systems under formation, carried out in the last quarter of the 20th century, revealed a significant difficulty for this theory. The actual time it takes for the protoplanetary disk to lose its gaseous component, i.e., 98% of its mass, turns out to be very short — less than 10^7 years [5–8]. So there is no more material to form the planet. Many attempts have been made to improve the theory by accounting for the 'self-accelerating' growth of planetesimals and the core, which decreases the formation time of the core almost to the same 10^7 years (see, for example, Ref. [9]).

Ever increasing experimental data have made these theories more complicated. There is the 'standard' accretion model of planetary formation (in which, unfortunately, there are contradictions, especially in connection with the discovery of exoplanets, which we shall discuss in Section 7). But the accretion theory scheme is confirmed in general outline by observations, including those carried out with NASA's Hubble Space Telescope. About 150 protoplanetary disks have been discovered, providing us with images of the protosolar nebula back 5 bln years (Fig. 4). At the same time, further studies of protoplanetary disks have revealed serious contradictions in the accretion theory.

At the end of the 20th century, the hypothesis for gravitational instability was proposed [10, 11], the basic idea of which had first been published as early as 1951 [12]. According to this hypothesis, instabilities developing in the protoplanetary disk can initiate a gravitational collapse capable of forming a whole planet in just 10,000–50,000 years. This hypothesis is actively working up, but it is meeting difficulties and is being seriously criticized.

The accretion theory has been elaborated in more detail, but its radical revision appeared inevitable as well, mostly with respect to the time scale of events. The problem is that the gas component of protoplanetary disks (hydrogen with an admixture of helium) dissipates quite rapidly and is available for the formation of giant planets over not more than 3 mln years, and almost completely disappears in 10 mln years, while the accretion theory required approximately 100 mln years to form planets. Only after a serious revision of the accretion theory did it become clear that it is water, other volatiles, and the so-called 'water–ice line' or 'snow line' (see below in Section 4) that play the major role in the formation of a future planetary system.

4. Formation of planetary systems in the sequential-accretion theory

The new physics of planetary systems started with the discovery of the extrasolar giant planet 51 Peg b in 1995. Unique experimental material was obtained that enabled researchers to look at the accretion processes from a new point of view. The migration of exoplanets down to close circumstellar orbits was discovered, which made a strong

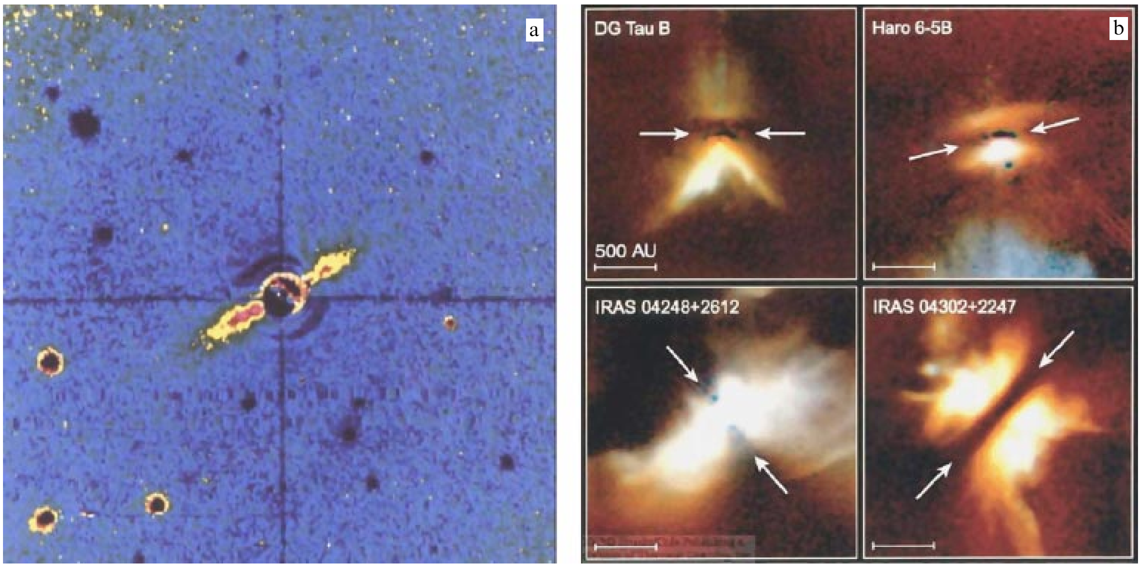

Figure 4. (a) The forming of a planetary system around the star Beta Pictoris (the distance is 63 light years) is an illustration of the 'standard' planetary formation model, according to which planets emerge due to accretion of dust–gas material from the disk surrounding a young star. The picture was obtained by the IRAS (InfraRed Astronomical Satellite) mission. The dust component is seen in ejections. (b) Examples of dust disks around young T Tauri type stars.

impact on the accretion theory. The planets of the Solar System apparently avoided such a migration. The radial velocity method enabled the discovery of many giant planets with masses comparable to that of Jupiter. The search for direct analogs to Earth-like planets still remains out of reach due to technical restrictions. The main signature of a planet orbiting the star is the detection of a Keplerian orbital sign-changing component in the radial velocity of the star. The Keplerian velocity of the Sun due to the motion of Earth is just 0.09 m s^{-1}, which is 20–30 times smaller than the currently measurable values. Instead, very important results have been obtained from observations of giant planets in unexpectedly close orbits. The statistical information about the orbital and mass characteristics of exoplanets serve as a reliable basis for testing the validity of the new theories being developed.

The modern, much more sophisticated accretion theory [13–17] pays more attention to the decisive role of a sequence of processes which had been partially known but under-estimated by researchers. It turned out that essentially the same process of sublimation, condensation, and phase transition of volatiles sequentially applied many times leads to radically different results that represent alternating stages of planetary system's formation. By and large, the process proved to be so complicated and sensitive to the external conditions that its results need to be considered as random. Apparently, this randomness explains why it is so difficult to find similar planets among the 350 extrasolar planets known so far.

According to the most advanced modern concepts, the so-called sequential accretion process has the following features [17, 18]. The condensation of a massive interstellar gas–dust disk quite rapidly (over a period from 150 thousand to several million years) results in the formation of a group of young stars; a protoplanetary nebula from the remaining material is formed around each of these stars and takes the disk-like form due to rotation. The dust component of the disk consists of submicron-sized particles of irregular form. The mass of the dust is about several percent of the total disk mass, which is mostly composed of hydrogen and helium. Collisions of particles sometimes lead to coalescence, sometimes to destruction. The increasing radiation from the young star gives rise to the stage of evaporation of volatiles, water, and gas occlusions in silicates from the inner part of the disk, but a significant part of the disk is screened by the dust from direct radiation heating. However, the heated medium re-emits the absorbed energy in the infrared range, and thus carries radiation flux to the shaded internal parts of the cloud, heating them up to a high temperature. At the periphery of the inner zone, the temperature is too low to evaporate volatiles, so a powerful stripping of volatiles occurs (the right side of Fig. 5) beyond the water–ice line. This line divides the planetary system into the inner region, almost deprived of volatiles and comprising solid bodies, and the outer region, rich in volatiles and containing icy bodies. At the water–ice line, the condensation of volatiles (first and foremost, water) occurs, and colossal masses of protoplane-tary material are concentrated beyond this boundary.

Inspection of images of protoplanetary disks suggests that the outer boundary of the condensation zone can extend to a distance of several hundred astronomical units from the central star. Gaseous volatiles condense on dust grains, thereby increasing their size by several hundred or thousand times. Almost all the mass of the young protoplanetary cloud orbiting the star falls on the gas. The gas density decreases with distance from the star. A selected gas volume is subjected to the complicated influence of gravity of the star and the cloud itself, ambient gas pressure, and centrifugal forces. As a result, the orbital velocity of gas becomes smaller than the Keplerian velocity. At the same time, once the velocity of solid particles is smaller than the Keplerian value, their orbits becomes lower. Just this occurs for sufficiently large particles with a size of more than 1 mm due to the drag in the gaseous medium. By migrating into the inner region relative to the water–ice line, they heat up, the condensates melt down, and particles become sticky and rapidly grow up to kilometer

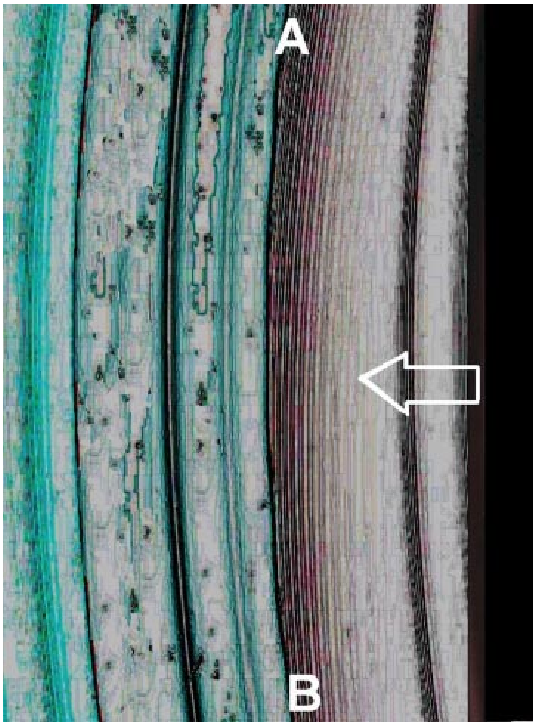

Figure 5. Stripping of volatiles from a star (the right side of the figure) beyond the water–ice line AB. Random contractions create short-lived rings, discontinuities, and waves in the gas–dust disk.

sizes. Such is the formation process of planetesimals — the building blocks of future planets. This stage takes around 1 mln years. First, the mass of planetesimals grows due to random collisions. But as their size increases, their gravitation becomes stronger, and they start absorbing their low-mass neighbors more efficiently [19]. Protoplanetary bodies form in this way. These bodies have relatively big masses and intercept remaining planetesimals from a narrow strip along their orbits. When most planetesimals are absorbed, the growth of the protoplanet stops.

At the same time, other important events occur at the water–ice line itself. Here, a pressure jump in the gas phase evaporated from the inner regions sets in; the orbital velocity of the gas reaches and exceeds the Keplerian velocity and now gas does not brake but accelerates solid particles. As a result, the migration of most particles in this region towards the central star ceases. Nevertheless, the migration from the far periphery of the disk continues, so a substantial mass of material piles up at the water–ice line to wait for the next stage of the planetary system formation.

Planetesimals are quite numerous: there are hundreds of millions or even billions of them. Multiple collisions between them result in the formation of moon-sized bodies or even larger ones, which capture the rest of the material and suppress the growth of neighbors [19]. After the mass of a protoplanet reaches several percent of the Earth mass, the protoplanet's further growth is limited by gravitational interactions with other bodies, and some bodies are completely expelled by gravitational interactions from the forming planetary system into the interstellar medium. A mass up to 0.1 Earth mass in its orbit can be accumulated over 100 thousand years, and is restricted by this value since no more material is available for the growth. The further a protoplanet is from a star, the slower its growth. To accumulate a mass of four Earth masses, a body in the modern orbit of Jupiter would require several million years. The process proceeded more rapidly fairly close to the water–ice line. As the protoplanetary cloud had not yet lost its main gas storage at that time, the gas accretion onto the core of the future planet started [20]. The gas capture rate is very sensitive to the core mass (at least 10 Earth masses is needed), the chemical composition of the gas, presence of heavy elements, and some other factors. There are many candidates for the role of the core of the future planet, but most of them do not survive. If they did survive and there were a sufficient gas supply, the gas accretion would release a significant amount of heat, which would hamper the formation of the planet. This restriction is well known in the theory of star formation. If the heat removal is inefficient and cooling is too slow, the gas could be lost and the giant planet would not form. The gas slowly accumulates over several million years, but then the other half of the gas is accreted in only 1000 years.

There are several further factors limiting the emergence of a giant planet. Migration is one of them [18, 21]. A migration of the first kind arises from gravitational interaction of the forming planet with the surrounding dispersed matter. The motion of the forming planet excites waves in the adjacent parts of the disk, as schematically shown in Fig. 6, with their effects in a homogeneous medium being mutually compensated. However, the medium is inhomogeneous and its dispersed mass beyond the planetary orbit (in the left part of Fig. 6) largely exceeds that inside the orbit (on the right side of Fig. 6), so some drag acts on the planet, slightly bringing the planetary orbit closer to the star. In 1 million years, the protoplanetary orbit can be lowered by a few astronomical units, down to the outer boundary of the water–ice line, where the migration is stopped under the action of the accelerating motion of gas (here, the orbital velocity of gas exceeds the Keplerian value). The matter is further complicated by approximately equal time scales of accompanying physical processes, which turn out to be close to the characteristic time of gas losses by the protoplanetary disk.

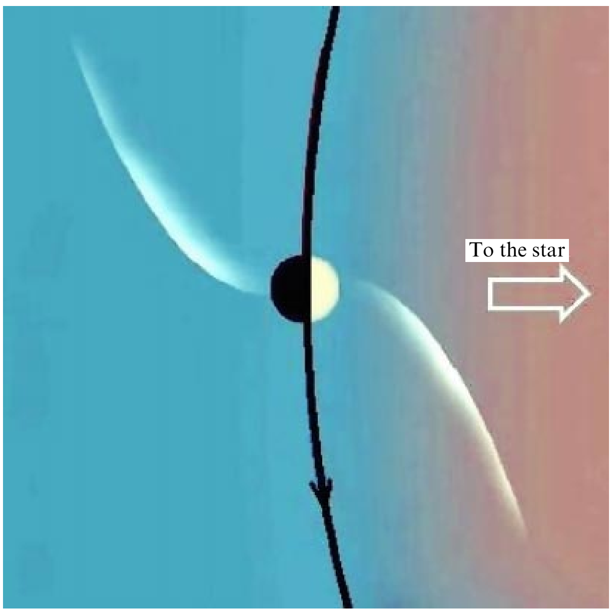

Figure 6. Planet migration arises from the interaction of a forming planet and waves in the surrounding medium.

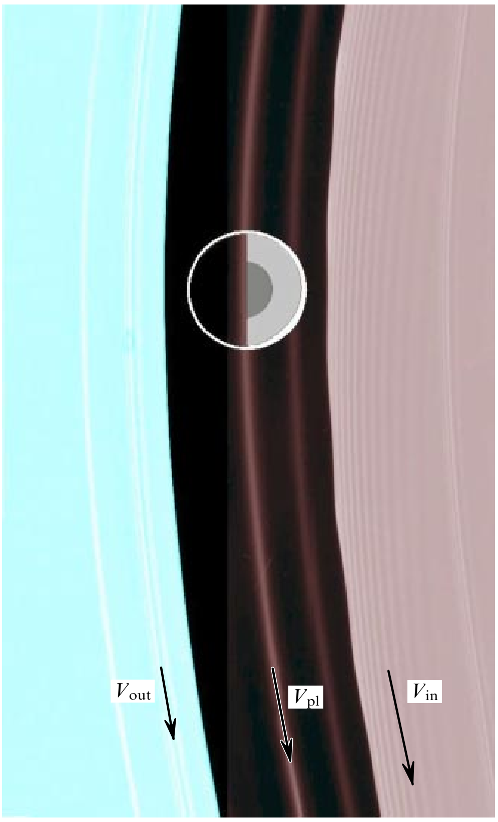

Figure 7. The mechanism limiting the growth of a giant planet.

The forming giant planet dredges material from the zone adjacent to its orbit and produces a break in the disk (Fig. 7). But at some instant of time the growth of the giant planet stops (in much the same way as for planetesimals). The process is again controlled by the gravitational interaction of the planet with the surrounding gas. However, at this stage the role of a planet that has already grown to the mass of Jupiter (0.001 times the mass of a solar type parent star) becomes crucial. The interaction of the planet with gas near the break inside the orbit (see the right side of Fig. 7) slows down the rotation of gaseous masses, while accelerating them on the outside of the break. It is easy to see that in both cases the gas starts avoiding the planet and its growth stops.

In some cases, a more complicated phenomenon occurs — migration of the second kind. In the adjacent regions of the disk, turbulent zones emerge from which turbulized gas can nevertheless enter the discontinuity zone. Its gravitational interaction with the planet leads to a very slow loss of the planet's angular momentum and to a correspondingly slow loss of height of the planet's orbit. This is a very broad concept of the migration of the second kind. Many features of this process still remain unclear.

By its gravitational interaction, the first-formed giant planet cleans the zone of the first generation asteroids [22] and speeds up significantly the formation of subsequent giant planets, if not all the gas has been lost. Apparently, the formation of Saturn was delayed by few million years relative to Jupiter, when a little amount of gas was available, so its mass is 3.3 times smaller than that of Jupiter. If there had been no influence from Jupiter, the formation of Saturn would have taken a longer time and its actual mass would have been even smaller. Probably, Uranus and Neptune were formed in similar conditions. However, it is not quite clear where this process took place, since these planets had most likely migrated from their initial orbits. Their formation took more time, the masses of the cores attained 10–20 Earth masses, and scanty gas supply turned out to be sufficient for only two Earth masses in each case. Clearly, Uranus and Neptune cannot be classified as giant planets: this is a special category of planets (ice giants) whose mass is insufficiently large to metallize hydrogen and to form the outer envelope of the core from it. It is such an envelope that determines many properties of Jupiter and Saturn. In total, the formation of these four planets took less than 10 mln years.

Further events in the zone of giant planets occurred more slowly. The formed Uranus and Neptune ejected the remaining planetesimals into the Edgeworth–Kuiper belt and partially toward the Sun, while Jupiter forwarded them into the Oort Cloud.

The sequential-accretion theory predicts that Earth-like planets in extrasolar planetary systems must be more abundant than giant planets. But before the discovery of extrasolar Earth-like planets, the theory can be based only on Solar System data. The formation conditions of the four Earth-group planets located in space inside the water–ice line, and of the four outer planets located beyond this line, are very different. The four Earth-like planets — Mercury, Venus, Earth, and Mars — formed in the inner part of the protoplanetary nebula mainly from materials with a high vaporization temperature, such as iron and silicate rocks. As noted above, closer to the Sun, where radiation intensity is very high (Fig. 8a), particles heated up, and the ice and other volatiles (substances with a low boiling temperature) evaporated to form a transparent zone almost free of dust with a radius of up to 5 AU, which is known from protoplanetary disk studies (Fig. 8b).

In the depleted zone inside the water–ice line, the mass of protoplanets could grow only up to 0.1 Earth masses, i.e., could only slightly exceed the mass of Mercury. To further increase mass, protoplanets had to have moved into elongated (noncircular) crossing orbits permitting collisions. The perturbation action of a giant planet could be the cause [22]. Therefore, the formation of the first giant planet during the initial 2–3 mln years should have preceded these processes. Then, the collision and merging of bodies moving in coplanar orbits not linked by resonant relations is only a question of time. According to some estimates of the sequential-accretion theory, the asteroid belt was formed during the first 4 mln years after the formation of Jupiter, Mars formed after 10 mln years, and then the Earth formed after30–50 mln years. It is much more difficult to explain the gradual circularization of orbits that followed the formation of the planets. The orbits of the Earth-like planets have not significantly changed since their formation, and the planets have not migrated. The formation of their orbits could have been affected by the remaining planetesimals and residual gas.

Planets can be considered as the final stage of accretion of matter surrounding the core of the protosolar nebula. Collisions of planets with small bodies, which rarely occur at present (such as the collision of the comet Shoemakers–Levy 9 with Jupiter in 1994), can be considered a fading echo of violent collisional processes that took place at the early stages of the formation of the Solar System. The planets survived the heaviest 'meteorite bombardments' in the early life of the Solar System, especially 3.9–3.8 bln years ago.

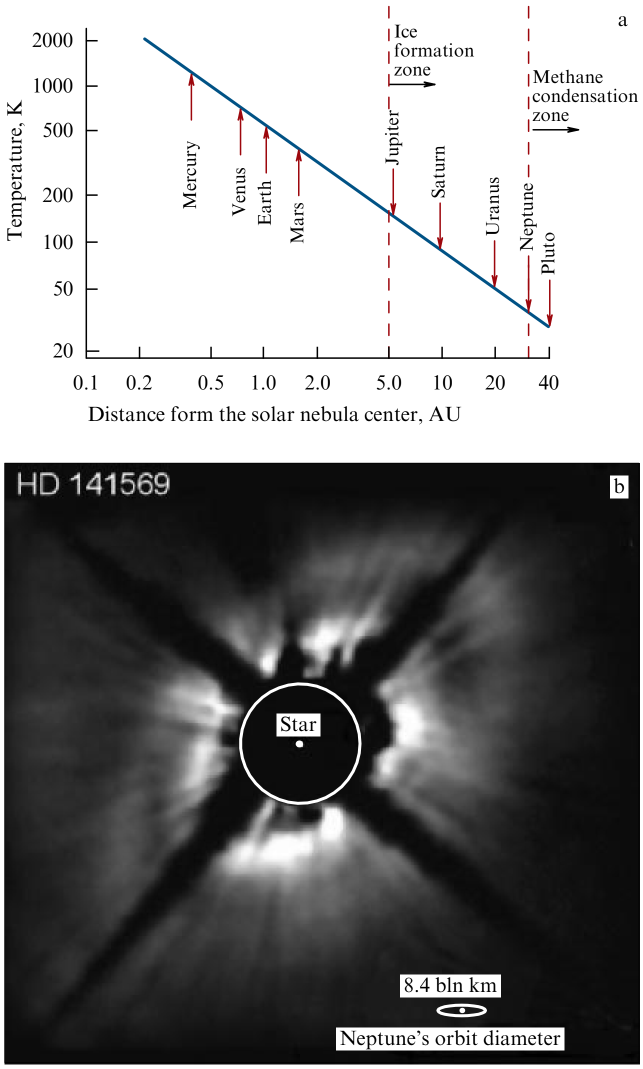

Figure 8. (a) The dependence of physical conditions (temperature) on the distance from the Sun. The star is surrounded by a volatile-free zone with a radius of 2–4 AU. Approximately at Jupiter orbit level (5 AU), the water–ice line is located, i.e., the boundary beyond which water (ice) and other volatiles are condensated. Near the orbit of Neptune (30 AU), another special zone is located, i.e., the condensation boundary of methane. (b) A virtually dust-free zone with a radius of 2–4 AU is typical for the protoplanetary cloud. The star is HD 141569 (observers B Schmidt and G Schneider, 1999). (The volatile-free zone in this picture is screened by the black circle, as is the star itself.)

Space research allows us to observe such processes even now. For example, the American space telescope Spitzer, launched by NASA in 2003, detected a possible collision of two planets near the star HD 172555 located at a distance of about 100 light years from the Solar System. The system HD 172555 is at the relatively early stage of planet formation, and being at the age of approximately 12 mln years it looks very young compared to the Solar System whose age is about 4.5 bln years. Numerical simulation showed that the smaller of two colliding astronomical bodies was apparently Moon-sized and was completely destroyed, while the second body comparable to Mercury in size survived, although was greatly damaged by the collision.

After the first protoplanets formed in the zone of Earth-like planets, the rest of the protoplanetary cloud material was gradually removed from the inner parts of the Solar System by several mechanisms, including scattering due to gravitational interaction with the already existing giant planet, exposure to solar radiation pressure, the Poynting–Robertson effect, and absorption by protoplanets in collisions. Manifestation of the Poynting–Robertson effect (the loss of angular momentum of a particle orbiting another body which is a source of electromagnetic radiation) in the Solar System results in the appearance of dust particles gradually migrating in a spiral toward the Sun.

The giant planets Jupiter and Saturn differ radically from the inner planets. The substance in the interiors of these planets is subjected to very high pressures and temperatures, and its behavior is dramatically different from what is known under moderate conditions inside Earth, whilst obeying the same physical laws. The first sounding space module has already been employed in the Jovian atmosphere and discovered many contradictions with common concepts about this gas–liquid planet. Jupiter and Saturn have turned out to be invaluable models in studies of extrasolar planets. For example, the multipole structure of the magnetic field, which should be observed in giant exoplanets, is also inherent in Jupiter and Saturn and is related to the level of metallization of hydrogen (Fig. 9). At the same time, the masses of the ice giants, the oceans-planets Uranus and Neptune, are insufficient for hydrogen to metallize, but there are signs of a multipole magnetic field in these planets, which may be related to the finite conductivity of substance in their interiors. Estimates show that most exoplanets can be ice giants, but it is more difficult to discover them as opposed to hot Jupiter type planets.

In a giant planet, the phase transition of hydrogen into a metallic state occurs under a pressure of about 1.4 Mbar [23], which in Jupiter is achieved at a depth of 0.8 times its radius R_J (see Fig. 9). Conduction electrons are released and sustain electric currents. So, extrasolar Jupiter-like giant planets must inevitably have strong magnetic fields with higher-order moments (quadrupoles, octupoles), similar to what is observed in Jupiter and Saturn. In principle, several experiments can be proposed, which would use this property as an additional signature for detection of exoplanets (for instance, the observation of Zeeman splitting of spectral lines, a change of polarization type from linear to circular, etc.).

Jupiter has a mass of 318 Earth masses and mainly consists of hydrogen (71% by mass in the atmosphere) and helium (25% by mass). Most models assume the mass of the small and very dense core of Jupiter to be from 5 to 10 Earth masses (Fig. 10). The central pressure is very high and attains 70 Mbar. But even at higher levels up to a depth of 0.8 of the planet's radius the pressure is high enough for hydrogen to be metallized.

The mass of Saturn is significantly lower, running to 95 Earth masses. It is mainly a hydrogen gas ball with an admixture of helium. The metallic hydrogen phase occurs at the level of about 0.6 of the planet's radius. The composition and structure of Uranus and Neptune are rather similar: the core consists mainly of 'ices', global ocean, and a comparatively thin gas envelope. The masses of Uranus and Neptune range up to 14.5 and 17.2 Earth masses.

All the outer planets have many natural satellites. The Galilean satellites of Jupiter (Io, Europa, Ganymede, and Callisto) (Fig. 11) are the biggest among them and show many distinctive properties.

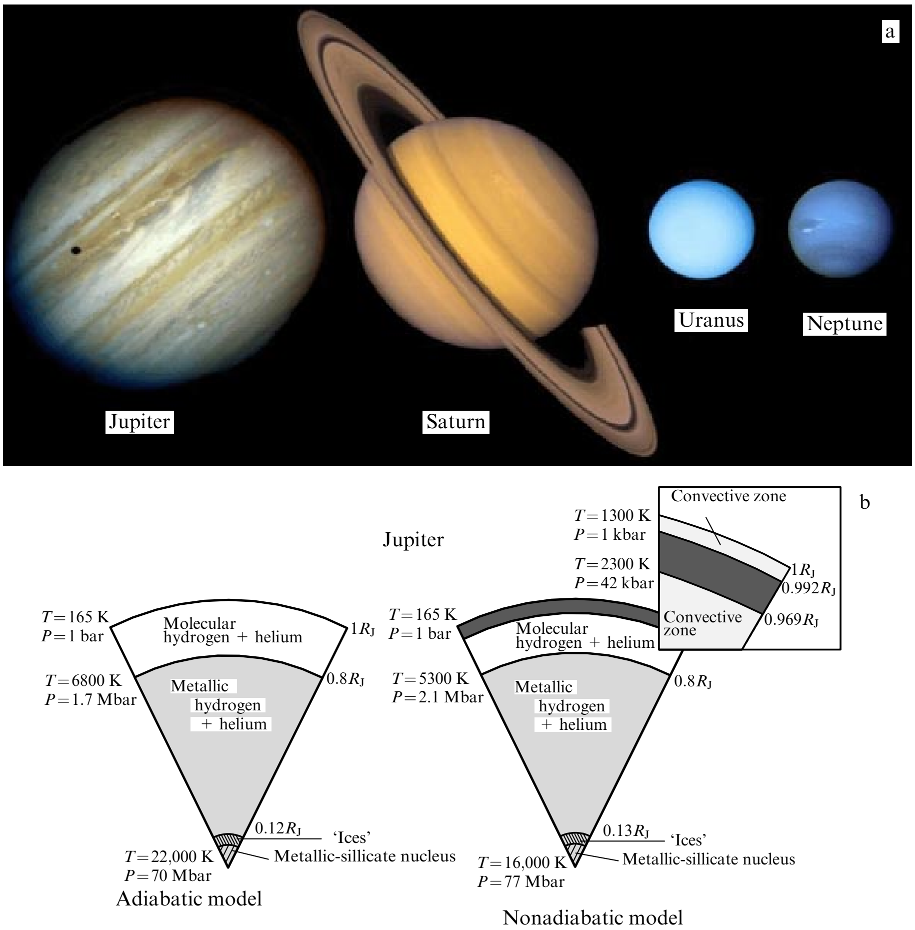

Figure 9. (a) The giant planets Jupiter and Saturn and the ice giants Uranus and Neptune. (b) Two theoretical models of the structure of Jupiter (Guillot et al. [23]).

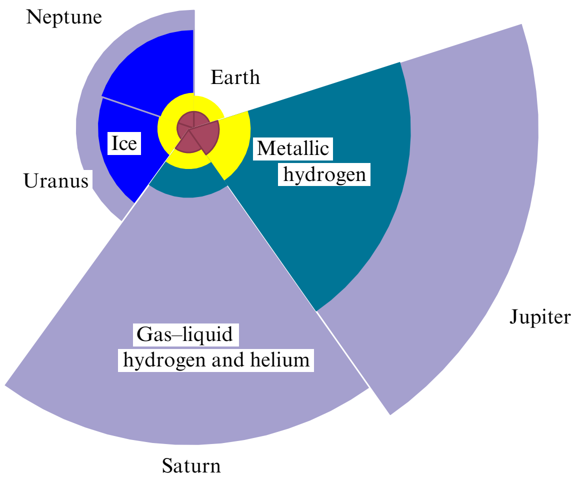

Figure 10. Structure and relative scales of the interiors of giant planets. Earth is shown for comparison.

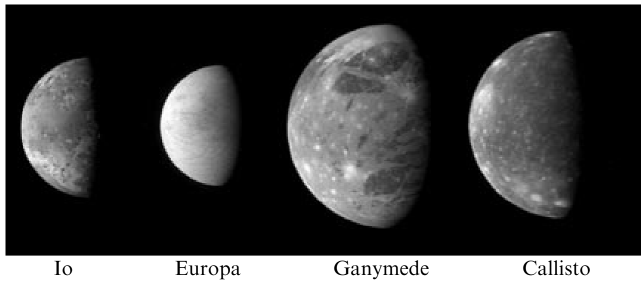

Figure 11. Galilean satellites of Jupiter (picture taken by the New Horizon spacecraft).

5. The Solar System as a scientific test site

The study of matter of Solar System bodies provides rich experimental material for progress in the theory of planet formation. Heavy elements played the key role in the evolution of the protoplanetary cloud. These elements are not very abundant — 98% of the protoplanetary cloud mass is accounted for by hydrogen and helium. But the remaining 2% includes heavier elements synthesized in thermonuclear reactions in stars older than the Sun and a small fraction of the interstellar dust which also contains heavy elements. This dust has been partially preserved until the present time (Fig. 12) and is also studied in space experiments. In particular, in 1999–2006 a dedicated experiment, Stardust (NASA), which attempted to collect the interplanetary dust grains and to bring them to Earth was carried out. Unfortunately, the clumsy landing damaged capsules with specimens in the impact with the ground, so the experiment has yielded few results so far. There is another option for studying primordial grains. Some of them make up meteorites. Some

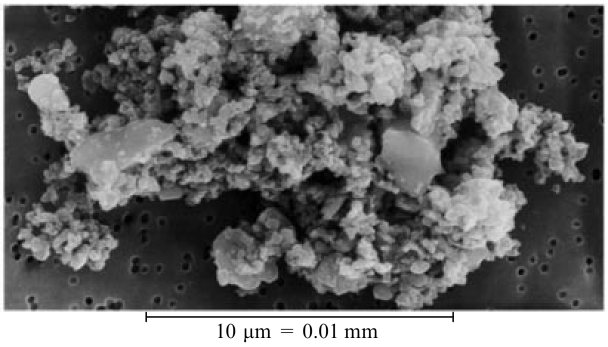

Figure 12. Interplanetary dust grains a micron in size.

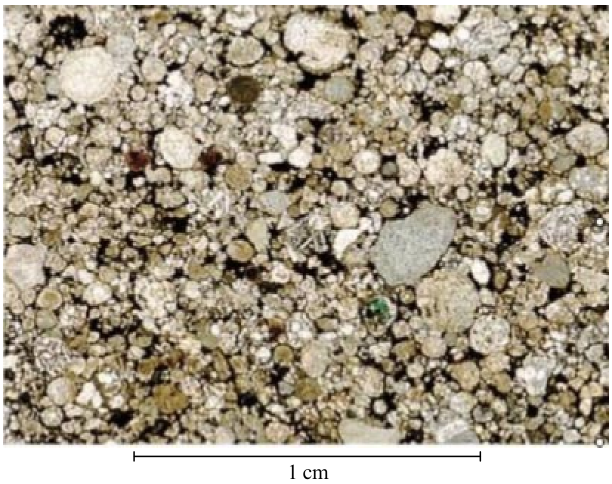

Figure 13. Chondrites are the most abundant type of meteorite. Chondrules comprise millimeter-sized grains that are partially formed from dust particles fused together and heated up in the inner parts of the protosolar nebula.

meteorites (chondrites) comprise so-called chondrules (Fig. 13), i.e., the grains older than the Solar System or objects of the same age. Chondrites have never been melted but can contain grains that had once been melted in the primordial gas–dust cloud heated up to several thousand degrees.

The Earth-like planets (Mercury, Venus, Earth, and Mars) consist of heavy elements. Their primordial atmospheres, which included hydrogen, helium, and volatiles, were 'swept out' by the stellar wind of the young Sun from the inner parts of the Solar System. The Earth-like planets have in general a similar structure and internal composition, including a metal nucleus surrounded by a mantle, but very different details (Fig. 14). Earth is often considered a double planet, since the ratios of the sizes (1:4) and masses (1:81) of the Moon and Earth are too high and are not found in other Solar System planets.

In contrast to Earth, the Moon has almost no metallic nucleus. Its main composition is similar to that of Earth's mantle where heavy elements are much less abundant. This is the key feature to understanding the origin of the Moon. There are two main models. According to the first hypothesis, which was recognized as almost 'classic', Earth and the Moon had been formed simultaneously in the inner part of the protoplanetary disk. However, there are numerous problems with this model. The three main contradictions are as follows: the composition of these two celestial bodies is significantly different; the model cannot explain the origin of the angular momentum of the Earth–Moon system, and the small size of the lunar nucleus (around 150 km) cannot be justified. The second hypothesis, which reconciles above contradictions and is confirmed by data on the structure of these bodies, assumes that the Moon originated from the impact of a giant celestial body (comparable to Mars in size and mass) with Earth, which stripped a substantial fraction of the outer envelope from proto-Earth. That is why the Moon has a low heavy element abundance and its structure is more similar to that of the intermediate envelope of Earth. The impact hypothesis appeared about 50 years ago and has moved from total obscurity to the appearance of relevant articles in modern encyclopedias.

The physical conditions on Mars, in contrast to other planets, are similar to those on Earth, but its atmosphere is very rarefied and there is no liquid water on its surface. At present, the mean temperature on Mars is about $-60\,^{\circ}$C. Only in the equatorial regions at noon in the summer can the temperature of the thin outer layer of the Martian soil become positive. The process of cooling on Mars was very long, lasting many hundreds of million of years. It is often noted that liquid water on Mars is absent not only because of low mean temperatures, but also because of the low atmospheric pressure. It is well known that in the mountains water boils at a lower temperature than in the plains. One could imagine such a high mountain peak on Earth, where water would boil at a temperature of $0\,^{\circ}$C. This would approximately correspond to conditions in the atmosphere of Mars. Water vapor

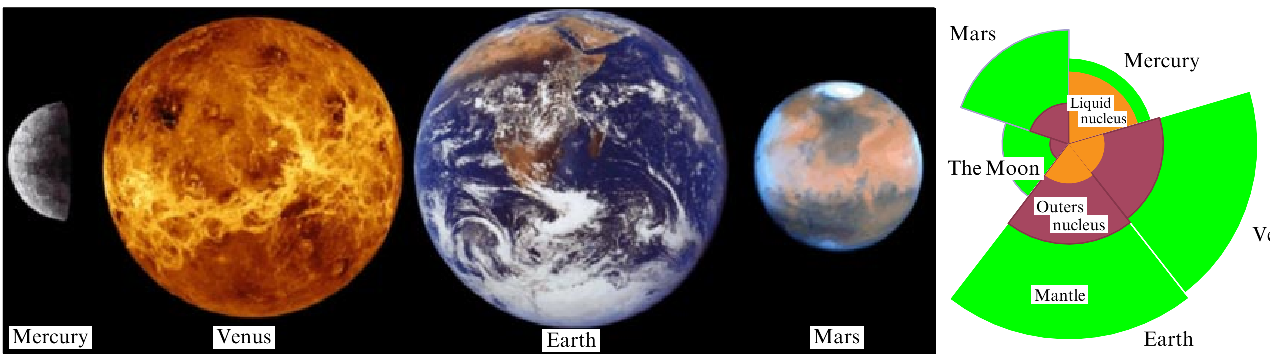

Figure 14. (a) Earth-like planets: Mercury, Venus (cloudy layer is not shown), Earth, and Mars. (b) Relative scales and structure of Earth-like planet interiors.

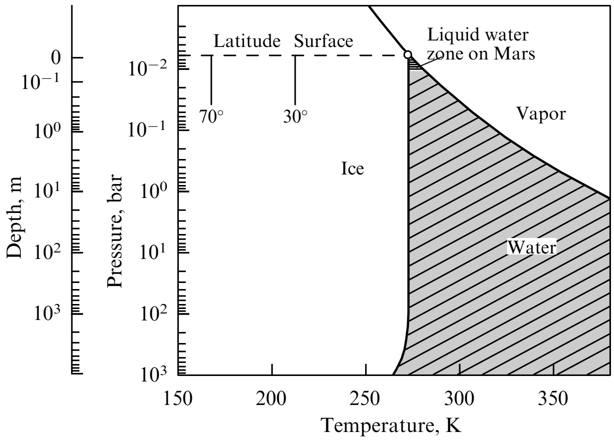

Figure 15. Water exists on Mars mainly in the form of ice; however, it is suggested that under certain conditions liquid water can be found, at least near the equator.

adds a negligible fraction of 1/10,000 to the atmospheric pressure on Mars. The atmospheric pressure on Mars of 6.1 mbar, which is adopted as the mean 'surface' value, corresponds to the triple point of the state of water at which ice, liquid water, and water vapor merge (Fig. 15). Real values of the atmospheric pressure near the surface of Mars lie in a wide range due to significant differences in surface altitudes. The pressure equals only 0.6 mbar on the peaks of giant old volcanoes of the Tharsis region that has an altitude of 24 km, 9 mbar in the deep parts (4 km) of the Condor Canyon (Mariner Valleys), and 10 mbar at the bottom of the deep Hellas impact basin. There, an open water surface could be preserved until the water freezes. Liquid water can well be present for some time in certain regions on the surface of Mars, and new pictures of Mars suggest such a possibility. On the other hand, water storage on Mars is very limited.

Figure 16 illustrates the movement of large portions of the soil, possibly sand, dust, and stones along slopes, which occurs in modern times. In the bottom part of the picture, one can see the smooth walls of crumbling material. The width of the area in the picture is about 3 km. Such a talus can be seen in other regions on Mars as well; they were discovered by the Viking mission. But in Fig. 16 one can see not only taluses, but also unusual formations. These are thin filamentary kilometer-length ravines or furrows along the slope. Their width in the narrow part is only several dozen meters or less. The ravines are very similar to gullies made by terrestrial mountain rivers or springs; but in contrast to terrestrial ravines, they do not widen, but narrow downhill. The medium that formed them either disappeared somehow halfway, or encounted certain obstacles in its motion. Flows of terrestrial mountain rivers usually widen downhill.

The narrowing of ravines on Mars could not result from a rockfall or large-scale mudflow. Nor could they be formed due to dust landslides that bury all ravines without a trace. It is liquid streams (of water or another liquid) that could easily form such strange gullies narrowing downhill. One can simply explain this paradox by low temperatures. If underground water really formed a spring issuing outward and flowing down a frozen slope, in the conditions on Mars the size of the emerging gully would mostly be determined by the surface temperature and the temperature of the flux itself. If the day temperature of the surface layer varies, depending on the latitude on Mars, from $-60\,^{\circ}\mathrm{C}$ to $-10\,^{\circ}\mathrm{C}$ or lower, then the

Figure 16. Ravines on the slopes of Martian craters are most likely formed by liquid water streams.

flux, streaming downhill, must gradually soak into the dry frozen soil and simultaneously freeze. Thus, in contrast to terrestrial mountain rivers, water fluxes on Mars narrow as they move downhill. When water with a temperature of $0\,^{\circ}\mathrm{C}$ executes a phase transition to ice, heat amounting to 80 kcal kg^{-1} is released. The heat capacity of the Martian soil is low, so the frozen base of the flux can be sufficiently thick, provided that the spring exists for a sufficiently long time. How the humidification of the ground on Mars occurs and how much heat is absorbed during this process is unknown precisely, but the balance of the released heat must include heat losses in the icy base of the channel formed, as well as a slower emission and rejection of heat into the atmosphere.

Recent studies carried out in the Mars orbit by the High Energy Neutron Detector (HEND), designed and constructed at the Space Research Institute of RAS, which was installed aboard the American spacecraft 2001 Mars Odyssey, for the first time allowed measuring the water abundance on Mars at depths of less than 1 m [24, 25]. Figure 17 shows a map of the permafrost area on Mars with a very high abundance of water ice, which was constructed based on the results of this experiment.

Ancient philosophers in their conjectures on the structure of the Universe tried to imagine the possible existence of living beings in other worlds. The habitability of other planets was almost obvious, and the great Isaac Newton allowed the habitability of even the Sun. Apparently, there is no more popular idea than the search for extraterrestrial life. In this respect, Mats is the most 'popular' Solar System planet, and the discovery of water ice and even liquid water on Mars clearly boosts interest in this eternal question.

Mercury has many specific features among the Earth-like planets. It has a disproportionately large metal core, a high

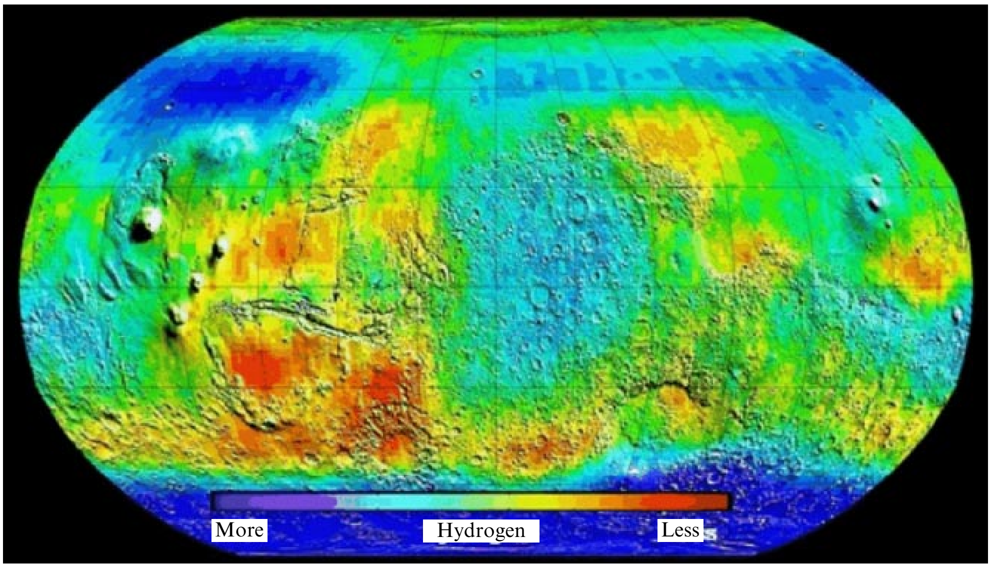

Figure 17. 'Permafrost' regions at high latitudes of Mars with a free water ice content of about 35% by mass, as well as regions with a high content of chemically bound water — about 5–10% by mass (see e-version of the figure at www.ufn.ru). (From measurements taken by the Russian high-energy neutron detector HEND constructed at the Space Research Institute of RAS and installed aboard the American satellite 2001 Mars Odyssey.)

mean density, and an unexpectedly strong magnetic field. Only traces of a magnetic field are known on Mars; there is no significant magnetic field on Venus. Earth, luckily for human beings, has a fairly strong magnetic field that occasionally changes its orientation. The lack of a magnetic field on Mars is puzzling; the lack of a field on Venus is most likely due to its slow rotation, but the puzzle of the origin of an appreciably strong magnetic field on slowly rotating Mercury has yet to be solved. The magnetic field of a planet is usually related to the liquid state of its core. But results of all calculations indicate that the core of Mercury must have been solidified when the planet was about 1.5 bln years old. There are interesting ideas on how to resolve this paradox.

In the evolution of Venus, which is most similar to Earth in size and composition, the history of its atmosphere and volatiles plays the key role: how did they form? how did they interact with the solid body? how were they lost? How did it become possible that two so similar planets are drastically different in their present-day properties? Where in their history was the bifurcation point met?

A 'basic' scheme of the Venusian atmosphere was constructed using the results obtained by Soviet spacecraft in the 1970s–1980s (Fig. 18). The main features include: a huge atmospheric pressure about a hundred times higher than that on the surface of Earth and a very high temperature of about 750 K near the surface. The atmosphere mostly consists of carbon dioxide with an admixture of nitrogen and traces of oxygen and water. At an altitude of 49–70 km, there are clouds consisting of concentrated sulfuric acid, which fully cover the surface of Venus. Interestingly, the ratio of deuterium-to-hydrogen content in the atmosphere of Venus is 150 times higher than in Earth's oceans. This likely evidences processes in the past by which the planet catastrophically lost light hydrogen, thus forfeiting possible oceans. The physical conditions on the planet are determined by a very strong greenhouse effect which increases the temperature in the vicinity of the surface by almost 500 °C. The greenhouse effect is produced by the planet's atmosphere. Some time ago

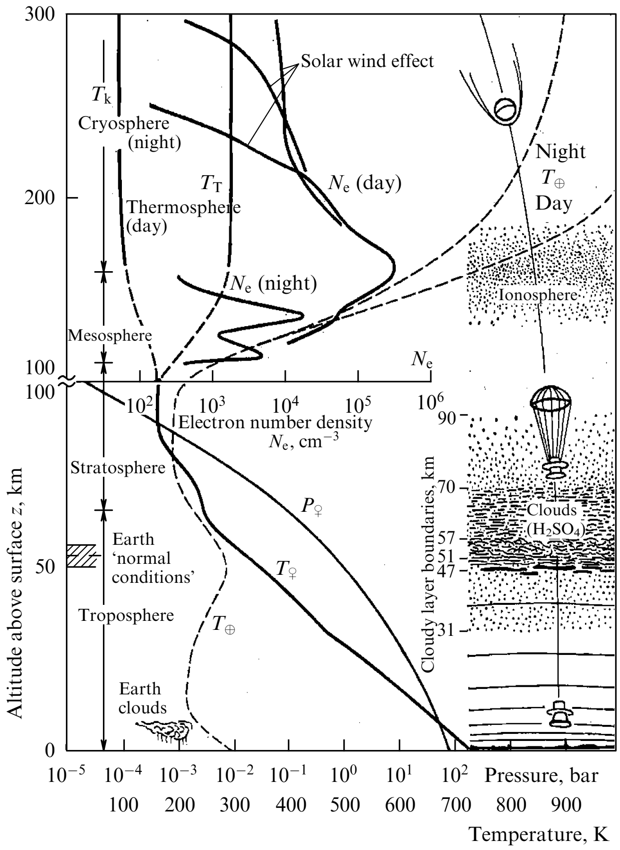

Figure 18. The structure of the Venusian atmosphere. The atmosphere model was constructed based on measurements by early Soviet and American missions to the planet. The properties of the terrestrial atmosphere are illustrated for comparison; the subscript $\oplus$ identifies the appropriate curves.

it was assumed that eternal night may reign on Venus due to its very dense atmosphere. In fact, the atmosphere of Venus, consisting of carbon dioxide with an admixture of water vapor, strongly absorbs violet, blue, and even light-blue rays, but generally is sufficiently transparent to light with wavelengths in the green to near-infrared spectrum (up to 2.5 μm). Solar rays quite easily penetrate the Venusian atmosphere, reach the dark surface, and are absorbed by the surface and atmosphere. The surface and nearby dense atmospheric layers are heated up in this way and re-emit the absorbed energy in another (infrared) region. However, the atmosphere of Venus is nearly opaque in this range and acts as a warm 'blanket'. To restore the thermal balance and for a sufficiently large portion of the energy to dissipate into space through the 'blanket', the brightness of an infrared source must be very high, with a radiation maximum at 4–6 μm; in other words, the temperature of the source must increase greatly. This is just the greenhouse effect. Notice that the greenhouse effect, although not so strong, is present in Earth's atmosphere, too. The ratio of the surface temperature of Earth to its effective temperature equals 1.15. Due to this effect, the terrestrial atmosphere increases the temperature of Earth's surface by 36 °C 'for free'. On Venus, this ratio reaches a value of 3.22, which corresponds to a difference of 160 times in absorption coefficients for the solar and planetary radiation.

In order to understand how this difference came about, we present a simple diagram illustrating the dependence of water vapor pressure on surface temperature, and show Venus, Earth, and Mars in this diagram (Fig. 19). The evolution of these Earth-like planets proceeded in three different ways. On Venus, a very strong greenhouse effect was beneficial for evaporating water into the atmosphere and the surface temperature started growing catastrophically. Despite water losses, the greenhouse effect was heightened due to the liberation of carbon dioxide. Earth went along the most favorable evolutionary path: oceans were formed. On Mars, water froze and exists nowadays in the form of ice and permafrost, although, as mentioned above, the latest data evidence the possibility of finding not only water ice but also liquid underground water in the near-equatorial zone.

As mentioned in Section 4, after the formation of Jupiter, planetesimals and protoplanets piled up in the orbit near the water–ice line. Part of this material was used to form a new asteroid belt instead of the primordial one, which had been destroyed during the period Jupiter was growing. As a result,

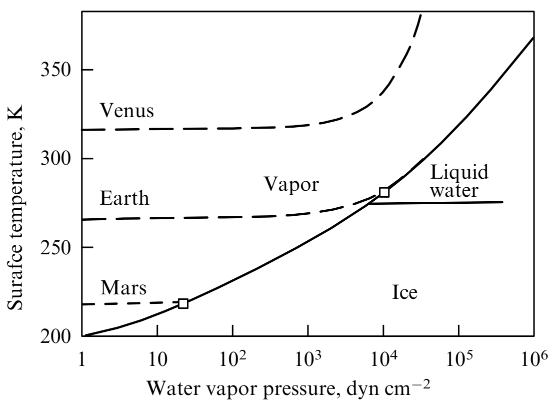

Figure 19. The simplest model of the early evolution of planetary atmospheres: gradual degassing with water storage. On Venus, the temperature grows catastrophically, and water remains in the atmosphere and is gradually lost in parallel with hydrogen losses. On Earth, part of the water condenses and forms oceans. On Mars, the temperature is very low, so water exists mainly in the form of ice and permafrost.

the asteroid belt presently exists between Mars and Jupiter. It consists of small bodies formed from the residual material of the early Solar System with masses of about only 0.001 Earth masses. The accretion of planetesimals first led to the appearance of 'embryos-planets', protoplanets, and then to the modern planets that form the planetary system around he central star — the Sun. But the rest of the primordial material, from which the planets had formed, was also preserved in the Solar System in asteroids and comets, where it was not transformed by endogenic processes. So, to understand the history of the Solar System it is very important to study the chemical and mineralogical composition of these materials, including studies of comets, asteroids, and other small bodies by direct contact methods in space.

Comets played a very important role in the origin of Earth's atmosphere. At the initial formation stages, our planet was too hot and lost a significant amount of volatiles, including water. It again acquired an atmosphere and ocean during gradual interaction with comets and icy planetesimals that joined its body. According to some estimates, the total mass of volatiles that came to Earth from the nutrition zone of giant planets rich in water is about 2×10^{24} g (the mass of Earth's oceans is about 1.45×10^{24} g). A significant portion of the water we use and which is responsible for life emerging on Earth was brought from the periphery of the Solar System.

6. Solar System studies and their main scientific goals

Fifty years of space research has radically enriched our concepts of planets, their natural satellites, and small Solar System bodies. During the first few decades of that period, pioneering expeditions to many planets, planetary satellites, several asteroids, and Halley's Comet were carried out. These expeditions gathered rich experimental data that allowed the diverse physical conditions on planets and their moons to be determined, the internal structure of planets and models of their origin from the protoplanetary gas–dust cloud to be specified, and the formation and evolution of the Solar System to be better understood. Nevertheless, in cosmogony (the science on the origin and evolution of the Solar System) there are still many unknowns that must be disclosed to understand the details of the evolutionary process which led to the formation of the unique and highly harmonized system of celestial bodies with different sizes, interior structures, and surface conditions. The study of the primordial material that Solar System bodies were made of is among the most relevant and interesting issues in modern planetary science. Samples of such material, as mentioned above, were preserved in small bodies: asteroids, comets, and dust components. Another, maybe the most intriguing question is the search for extraterrestrial life or traces of it. Presently, efforts of researchers are focused on objects with conditions favorable for life (at least, according to our present understanding), first and foremost those that have water.

To address these problems, space agencies work out long-term complex space programs. It is very sad, but over the last two decades our country has not realized any interplanetary projects, although Russian scientists have participated in American and European space research programs during that time. In 2006, the Russian Program of Scientific Space Explorations was adopted. The program was elaborated by the Space Council of the Russian Academy of Sciences. The realization of the program is now being carried out by the

Russian Federal Space Agency jointly with space industry enterprises and RAS institutes. The Federal space program includes complex studies of the Martian system — Mars itself, its natural satellites, and near-Martian space, as well as studies of the Moon, Venus, and Mercury. In addition, the possibility of space flight to the Galilean moon of Jupiter, Europa, is being considered for the first time. The last project could become a part of a joint international project of space flights to Jovian satellites, which is now being carried out by the Russian, American, European, and Japanese space agencies.

Below we shall consider several important short-term and long-term projects under development by Russian and foreign space agencies.

Mars and its satellites. Mars is one of the Earth-like planets and conditions on it most closely approach to those on Earth, in contrast to other planets. That is why Mars has always been the focus of interest of scientists. However, the Martian atmosphere is highly rarefied and there is virtually no liquid water on its surface. Why did conditions on Mars become so different from those on Earth and will Earth follow the same evolution as Mars? And, at last, the principal question: Is there any life on Mars and, if not, why did it not originate there? These and other questions have made Mars the most studied object by space methods. Presently, three NASA spacecraft are operating on the surface of Mars, and the European satellite Mars Express is orbiting Mars (two of these space vehicles include Russian instruments), and recently one more American spacecraft Mars Reconnaissance Orbiter was launched.

But in spite of intensive study, many principally important issues remain unsolved, including the already mentioned one of the abundance and role of liquid water on early Mars and the question of possible life or life that existed some time ago on this planet. Answering the second question most likely will require bringing specimens of Martian soil to Earth.

The natural satellites of Mars, Phobos and Deimos, are two small bodies of the Solar System that are found relatively close to Earth, and so they arouse great interest. Their origin remains puzzling: are they captured asteroids or do they represent remaining Martian proto-material? In addition, in their surface material (regolith), rock debris from Mars that was ejected during the impacts of asteroids with the planet itself could be present.

Interest in the Martian satellites appeared as early as the beginning of the 1970s, when the American spacecraft Mariner 9 obtained for the first time pictures of the surfaces of Phobos and Deimos from a relatively close distance. Then, at the end of the 1980s, a special mission Phobos-2 was launched by the Soviet Union to study this natural satellite of Mars. Not all the plans were realized in this expedition. Two months after entering the near-Mars orbit, the device went missing. Nevertheless, the results of scientific studies carried out by the spacecraft Phobos-2 during the 57 days of its orbital motion around Mars enabled unique scientific results to be realized, in particular, obtaining the thermal characteristics of the regolith of Phobos and its reflective characteristics in the infrared and optical spectra [26]. Plasma surrounding Mars and its interaction with the solar wind were studied in detail [27]. For example, using the oxygen ion flux escaping the atmosphere of Mars, as detected by an ion spectrometer aboard the Phobos-2 spacecraft, the rate of erosion of the Martian atmosphere due to interaction with the solar wind was estimated (see reviews [28, 29]). These measurements are very important for studies of the history of water and the atmosphere on Mars. Before the Phobos-2 mission, the near-Mars space was studied in less detail than that of Mercury or the much more remote Jupiter and Saturn.

Figure 20. Picture of Phobos against the background of Mars, taken by the TV camera aboard the Phobos-2 spacecraft.

Currently in Russia the project Phobos-Ground for a complex expedition to Phobos is under preparation; this project is aimed at bringing soil samples from Phobos to Earth.

What is Phobos and why is it so interesting? This is a small celestial body like an asteroid with a diameter of about 25 km (Fig. 20 [30]). The main goal of the project is to study the soil of Phobos, which most likely represents the primordial material of the Solar System. As a result, we hope to understand the history of Phobos: whether it originated simultaneously with Mars or is an autonomous small celestial body that was captured by Mars some time ago. The answer to this question can be arrived at from isotope analysis of samples brought to laboratories on Earth. It is also interesting that one can find on the surface of Phobos both the primordial matter and debris of matter from Mars that could have settled onto the Phobos surface after having been expelled from Mars by impacts with large meteorites.

Phobos-Ground constitutes a complex expedition that foresees exploration of the interplanetary space, distant studies of Phobos, and landing on its surface, as well as direct analysis of its soil by a complex of aboard devices. But the first and main task is the excavation of ground samples on the Phobos surface and their delivery to Earth. This will be the first times such a task has been posed since bringing back samples of lunar soil. The total mass of samples of soil from Phobos that is planned to be delivered to Earth is about 100 g, and there are many grounds to believe that they will also contain Martian fragments. The duration of the expedition will be about three years.

The next logical step should be delivery of soil samples from Mars itself. This task is included in the programs of all the major space agencies. Such an expedition will pursue

Figure 21. Mars research program elaborated by the S A Lavochkin Association: (a) Phobos-Ground goals: delivering samples of the soil of Phobos to Earth, exploring the near-Mars space, and studying variations in the atmosphere of Mars; (b) Mars-Net goals: creation of a network of small stations to study the climate and internal structure of Mars; (c) Mars-Ground goals: delivering samples of Martian soil to Earth.

several goals. It is motivated first of all by the search for traces of pre-biological processes, and relic or possibly existing life. However, even if traces of life itself are not found, studies of the chemical, mineralogical, and isotope composition of the regolith are extremely important for understanding the processes that could sustain life on Mars, whether relic or existing. In addition, analysis of Martian matter in laboratories on Earth would help in understanding the meaning of water in the history of the planet, ensuring exact dating of the principal geological processes. This study would allow us to impose the restrictions on the mechanism and time of accretion, and the differentiation and subsequent evolution of the crust, mantle, and the core. Finally, based on the analysis of a real sample of Martian soil, we should try to construct an engineering model of Mars and issue recommendations for the protection of future expeditions to this planet against interplanetary accidents.

The Mars exploration program being developed in Russia now includes three stages (Fig. 21). The first is to study and delivery samples of the soil from Phobos and to explore the Martian system (including natural satellites, the near-Mars space, and Mars itself). The second stage assumes the creation of a network of small stations on the Martian surface to study its climate and the interior structure. Collaboration with European colleagues is possible here. Finally, the third stage, which according to optimistic estimates can take place in 2020–2025, stipulates the delivery of Martian samples to Earth.

Further development inevitably leads to the question of a human piloted expedition to Mars. It is difficult to predict at present how this expedition would be realized. Probably, the plan suggested by engineers from S P Korolev's Rocket Space Corporation Energiya is worth considering. According to this scenario, before landing on Mars, which is a complex technical undertaking, it is necessary to construct an orbital station near Mars that could work as the coordination center for a network of spacecraft exploring the planet: Martian rovers, atmospheric probes, small meteorological and seismological stations, small orbital apparatuses, etc. Only after such a preliminary stage could an expedition with humans landing on the surface of Mars and its further exploration be realized. Of course, when preparing for such an expedition, many technical and other issues need to be solved. In Russia, the first experiments on modeling such a flight have already been started. At the Institute of Medical and Biological Problems of RAS, the Mars-500 experiment is being carried out, in which potential astronauts find themselves in conditions imitating those of a multimonth interplanetary flight.

It should be noted that research and exploration are quite different tasks. The exploration of Mars is, of course, not only an academic issue: it requires a special state program. But its realization would have both big political and scientific importance. With human participation, many unique experiments could be conducted on Mars, although most scientific tasks, of course, can be done by cheaper automated devices.

Venus. Venus has a special place in the Russian 'parade of planets', since the most important discoveries in the history of Soviet planetary science are related to this planet. The Soviet spacecraft launched to Venus in the 1970s measured for the first time the vertical profiles of the main characteristics of the Venusian atmosphere and obtained unique pictures of its surface (Fig. 22). The study of the evolution of the atmosphere of Venus continues to be one of the principal tasks of Venusian expeditions. At present, the European Venus Express satellite is orbiting Venus. Russian scientists are actively participating in studies carried out by this mission.

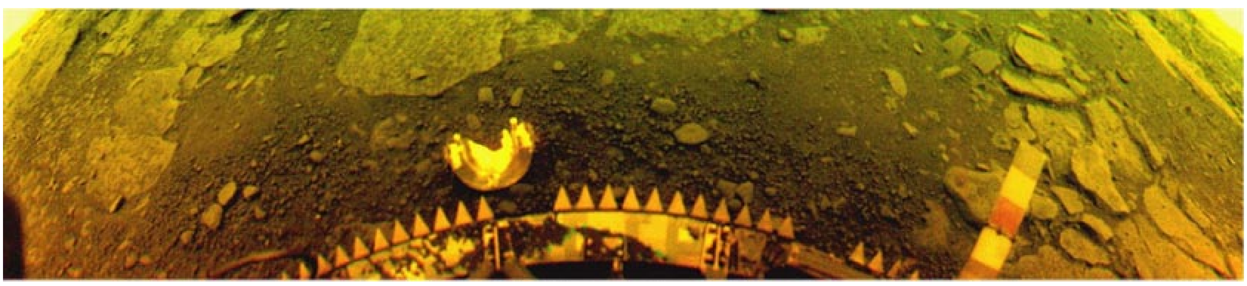

Figure 22. Picture of the surface of Venus taken by the landing module of the Venus-13 mission.

Venus is extremely interesting for geologists, too. In particular, it is unclear as yet whether tectonics of plates have ever shown its worth on this planet and whether volcanic and tectonic activity is currently under way there. How is the stability of the mountain relief of a very hot surface maintained? There are many other open questions.

The project Venera-D is currently under preparation in Russia. This mission is aimed at the multifaceted research of Venus. Its launch is planned for 2015–2016. The mission includes an orbiter to be set in a polar orbit around the planet, an aerostatic probe, and a sufficiently long-living (up to one day) landing module.

Mercury. Thirty-five years have passed since the American spacecraft Mariner 10 flew by Mercury in 1974. In 2008, the NASA Messenger mission approached the planet several times, and in 2011 should become the first artificial satellite of Mercury. The ballistic issue is extremely complicated, but soon another spacecraft will be sent to Mercury. This new mission, BepiColombo, is planned for 2014 by the European Space Agency (ESA). The mission will conduct several experiments with the participation of Russian scientists.

Europa (*satellite of Jupiter*). The outer part of the Solar System, comprising giant planets Jupiter and Saturn, has been actively researched by spacecraft, including the American missions Pioneer, Voyager, and Galileo, and the American–European mission Cassini-Huygens.

Now a new multifaceted international expedition to the Jovian system with the participation of Russia has started preparations. The launch is planned for the beginning of the 2020s. The mission includes launching of four spacecraft. The first one, Jupiter Europa Orbiter (NASA), is to orbit around Europa and will also study another Jovian satellite, Io. The second spacecraft, Jupiter Ganymede Orbiter (ESA), will be focused on studies of two other Galilean satellites of Jupiter, Ganymede and Callisto. In addition, the Japan Aerospace Exploration Agency (JAXA) makes plans to participate in this project with a magnetospheric apparatus, the Jupiter Magnetospheric Orbiter. The possible role of Russia is to continue research started by soft landing on the Moon and planned on Phobos in the framework of the Phobos-Ground project. It is expected that a Russian module will land on Europa and will perform a series of scientific experiments on its surface.

Special interest in Europa (Fig. 23) arose after the Galileo mission which took magnetic measurements during a fly-by Europa. According to this data, it was established that under a thick (about 10 km) ice layer covering the surface of Europa there is a liquid water ocean. As a consequence, life could exist or could have existed somewhere on this satellite of Jupiter.

The projected mission to Europa promises many interesting discoveries. The Jovian system itself is a unique natural plasma laboratory, offering rich possibilities to study cosmic plasma in natural conditions. At the same time, this fact represents one of the major threats for the mission, since a strong radiation background is very dangerous for both the electronics of the spacecraft itself and aboard scientific devices. In addition, it would be very interesting to study the dynamics, internal structure, and chemical composition of Europa's surface. The most important objective of the mission will be to search for possible outlets of liquid water on the surface.

The project for such a mission has been developed at the S A Lavochkin Research and Production Association (Fig. 24). Apparently, the launch will require the most powerful Proton carrier rocket which allows a scientific payload weighing 50 kg to be delivered toward the satellite to conduct some distant and contact scientific experiments.

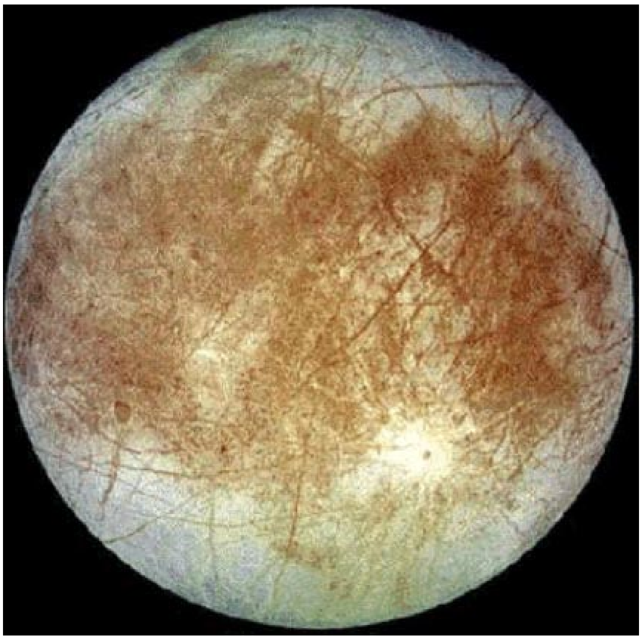

Figure 23. Jovian satellite Europa.

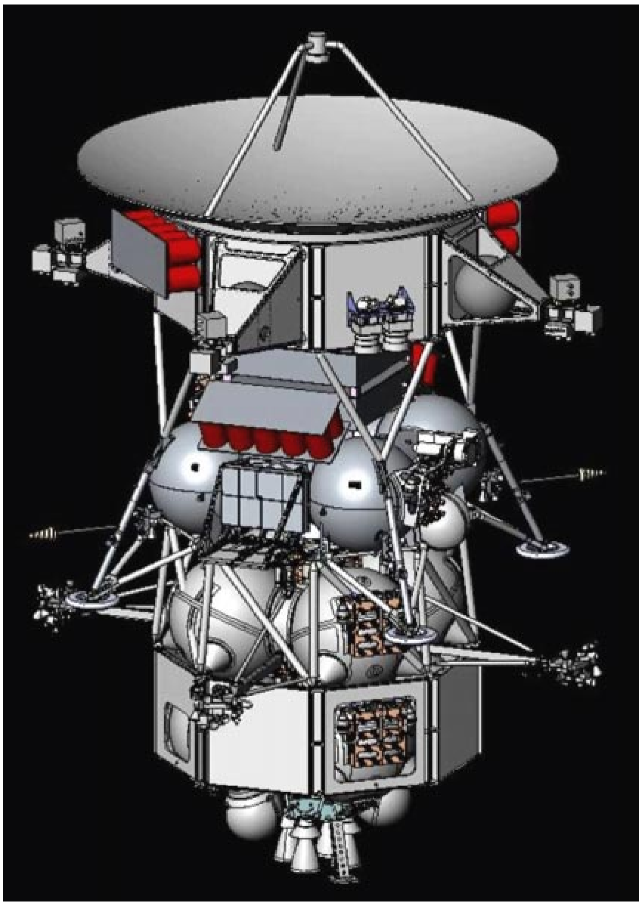

Figure 24. One of the possible spacecraft for the flight to Europa (designed by the Lavochkin Association).

Europa is the first remote object to be studied in the framework of the Russian Space Program, since Soviet and

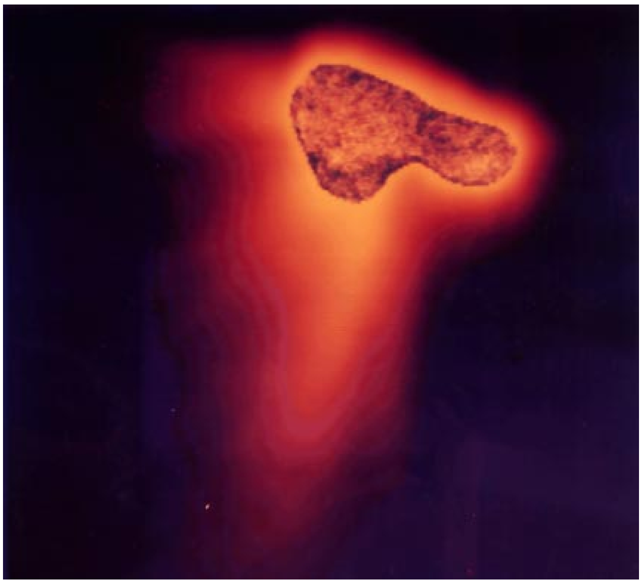

Figure 25. Image of the nucleus of Halley's Comet with emanating fluxes of gas and dust. (Obtained by the Vega-2 spacecraft.)

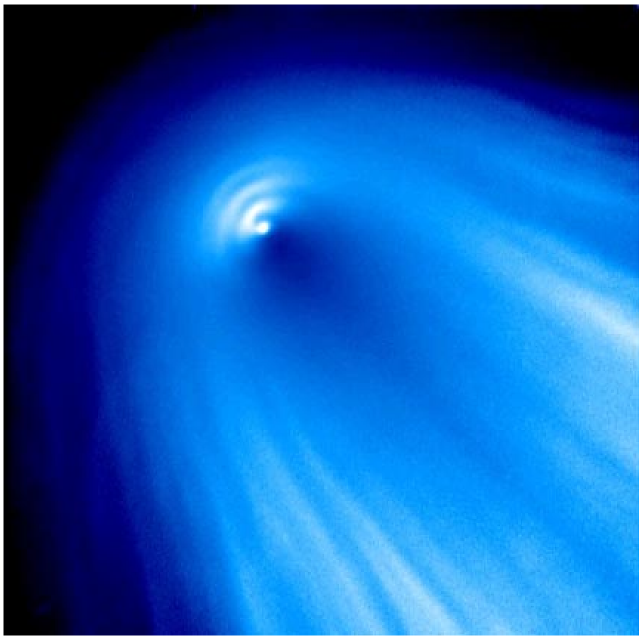

Figure 26. The Hale–Bopp comet. (Picture taken at the Peak Terskol Observatory.)

then Russian planetary research has been focused so far mainly on planets near Earth.

Comets. The first cometary research by direct methods began in the middle of the 1980s. In 1986, one of the most successful Soviet space projects, Vega, was carried out. This mission studied the short-period Halley's Comet (Fig. 25), which reaches the orbits of the inner planets once every 76 years in its perihelion. Two spacecraft, Vega-1 and Vega-2, that flew past the cometary nucleus were part of the international space flotilla studying Halley's Comet, including the European spacecraft Giotto and the small Japanese spacecraft Sakigake (Pioneer) and Suisei (Comet).

In 2014, a very involved experiment on studying the Churyumov–Gerassimenko comet by the Rosetta mission (ESA with the participation of Russian scientists) is set to begin. The mission promises to be very interesting, since an attempt will be made to make a soft landing onto the cometary nucleus to analyze its material. Other comets might appear more appropriate for such an experiment, for example, the recently observed Hale–Bopp comet, but this is not so (Fig. 26). A spacecraft can approach the cometary nucleus only if the location of the comet orbit permits it and if the velocity of comet relative to the spacecraft lies within technically admissible limits.

A new-generation project, such as the Triple F ('Fresh From the Fridge'), which has been lively discussed in recent years, can become the next stage in the development of the comet research program. The main objective of this mission is to deliver the material of the cometary nucleus to Earth. Schematically, the spacecraft must hover over the cometary nucleus and use a special robotic probe to extract a sample of its material, which will be brought to Earth. The task is extremely challenging, and not only because of the ballistic problem. The cometary nucleus consists of very volatile elements that would be difficult to preserve in their initial form until the analysis in terrestrial laboratories. The Triple F mission has been discussed by ESA jointly with the Russian Space Agency, but its fate is uncertain as yet.

Primordial material can be studied not only in comets. Recently, several missions have attempted to study its dust component in the Solar System, including Stardust (NASA) and the Deep Impact experiment (NASA), which was carried out during the flight to the 9P/Tempel 1 comet. The latter experiment foresaw the comet impact with a special probe ejected from the spacecraft. In order to study the structure of cometary matter, the products of the impact were captured by the spacecraft.

Meteorite hazard. There is one more aspect of small body research that has practical importance. Big meteorites do fall to Earth, although not so frequently as in earlier times of the Solar System formation. The meteorite hazard is evidenced by the presence of large craters on Earth, by the impact of the Tunguska meteorite only 100 years ago, and by the recent collision of the comet Shoemakers–Levy with Jupiter. It is important to try to predict what would happen if such a body collided with Earth. The consequences of such a collision have been evaluated mainly by specialists in nuclear explosions, and their experience leads to interesting conclusions (Fig. 27).

According to calculations, the largest damage can be produced in collisions with large-period high-velocity (several dozen kilometers per second) comets having the largest kinetic energy released during the collision. The damage from collisions with meteorites is smaller. Unfortunately, it is difficult to predict the precise trajectory of comets, since most of them reside in the far remote Oort Cloud ($\sim$ 20,000 AU from the Sun). For this reason, new celestial objects often appear quite unexpectedly for observers, and the timely prediction of their motion turns out to be a difficult task.

Apophis. The census of near-Earth asteroids and estimates of their danger in close encounters with Earth is now of great importance. In 2008, a special committee headed by B M Shustov was organized at RAS for studying the chances of a hazardous encounter of asteroids with Earth. The

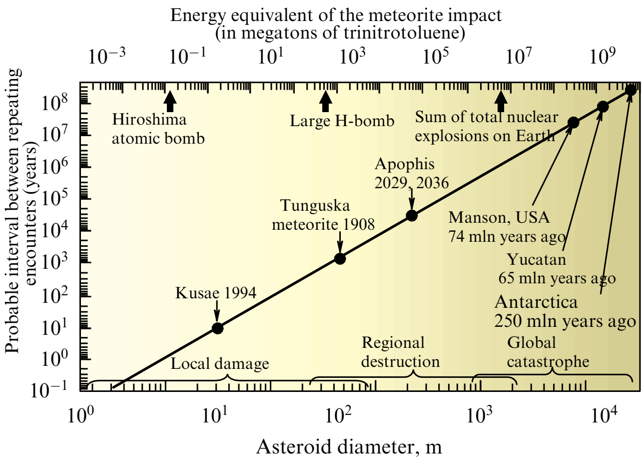

Figure 27. A diagram showing the time interval between encounters with an asteroid as a function of its size and the scale of possible damage.

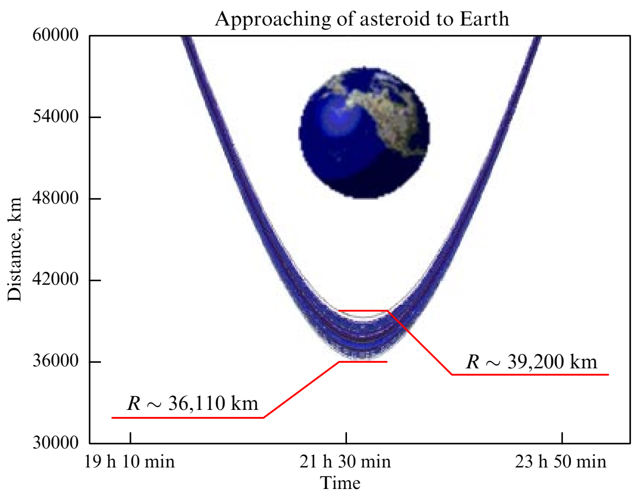

Figure 28. Encounter of asteroid Apophis 99942 with Earth in 2029.

problem is quite serious, although sometimes it is addressed ironically. In recent years, a new object was discovered that created much interest, among both Russian and foreign scientists: the Apophis asteroid. This small celestial body has a diameter of about 350 m. In 2029, the trajectory of the asteroid will pass quite near Earth (Fig. 28), and during the next cycle, in 2036, there is a nonzero probability of the asteroid collision with our planet. The destruction from such an impact could be several times larger than those caused by the Tunguska meteorite.

Clearly, the first question that arises is what we can do to prevent such a collision. To address this question, the asteroid is worth further scrutiny. To this end, the Lavochkin Association is designing a spacecraft to study Apophis. There are two main tasks for this mission. The first is to define the asteroid's orbit more precisely, which is a prerequisite to saying more definitely whether the collision will occur or the asteroid will fly nearby Earth without collision. The second equally important task is to determine the structure of this celestial body. This is necessary in order to choose methods of influencing the asteroid, to move it from the dangerous orbit, or to destroy it altogether. Some asteroids represent a weakly bound conglomerate of individual units. If, in contrast, this is a strongly bound consolidated structure, the problem is aggravated and can be solved only by a slow influence on the asteroid, for example, by using electrical jet-propulsion engines.

7. Beyond the Solar System: exoplanets

The projects considered above show how rapidly our knowledge of Solar System bodies progresses. It is very interesting to compare our planetary system with those discovered quite recently near other stars. Research on exoplanets is developing very fast; so far, about 350 planets have been discovered near other stars (Fig. 29). From the point of view of the theories of planetary system formation, which were earlier based entirely on data about our Solar System, the results of these studies can be called discouraging. All the planetary systems discovered so far are drastically different from the Solar System, and the evolutionary scenario suggested by the

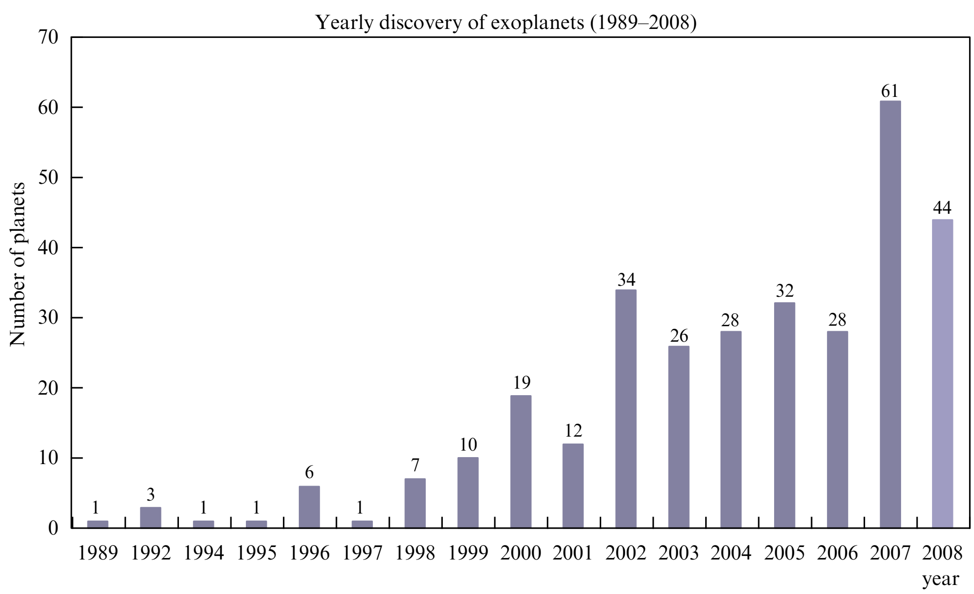

Figure 29. Number of exoplanets discovered from 1989 to 2008.

early accretion theory is not confirmed by these observations, as we mentioned above.

Most planets discovered so far have masses of about or larger than that of Jupiter. This fact in itself is not surprising, as the method presently used enables only giant planets to be detected, since they have a pronounced effect on the behavior of a parent star. Around 30% of these planets are in circular orbits at distances of less than 0.16 – 0.20 AU from the central star [31–37].

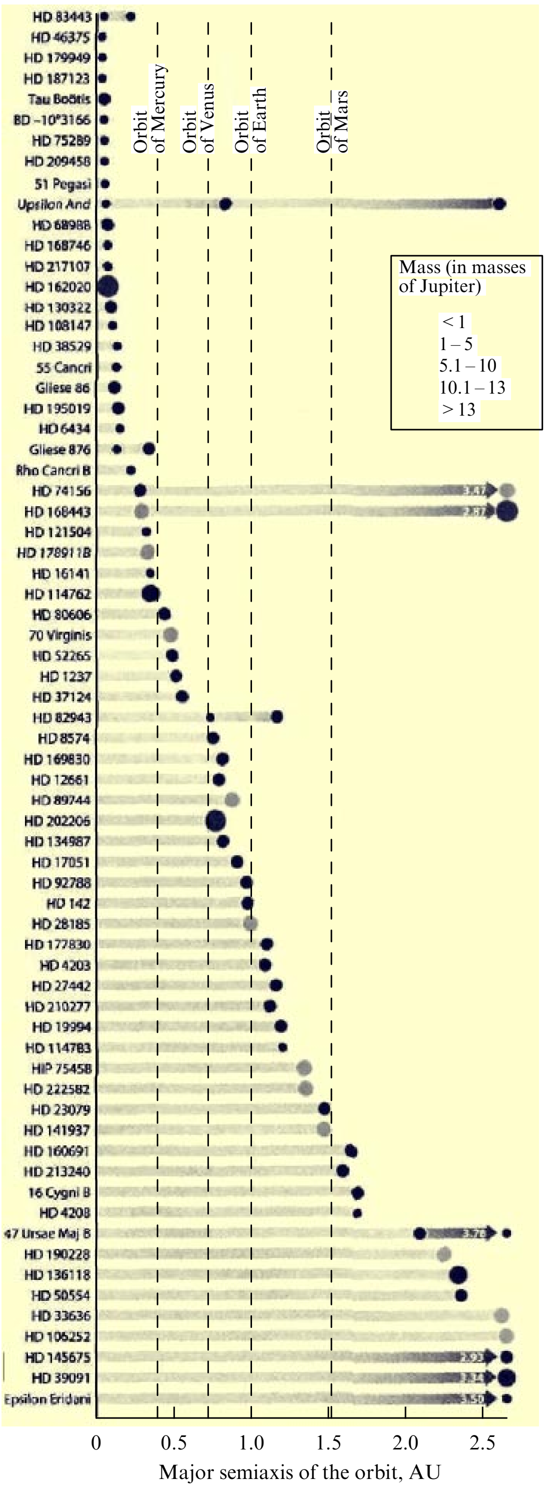

Figure 30. Around 30% of giant exoplanets reside in very low orbits.

These orbits are found much closer to the star than the distance of Mercury to the Sun (0.327 AU), although the stars themselves are not so different from our Sun. And the main problem, which we have already discussed above, is to understand how giant planets migrated to such low orbits (Fig. 30). The answer likely is that the migration of planets from outer to inner regions is the universal mechanism of planetary system formation. This mechanism is not observed in the present Solar System, but possibly operated at the stage of its formation.

The migration of giant planets toward the parent star can be a serious thread to the existence of Earth-like planets: on its way toward the star, a giant Jupiter-like planet leaves little chances for an Earth-like planet to survive due to inevitable catastrophic encounters with forming bodies (Fig. 31). Such a giant planet would absorb virtually all the material available for Earth-like planet formation. Another hazard could be the emergence of resonance orbits preventing coalescence of protoplanetary bodies, much like Jupiter did not allow a planet in orbit between Mars and Jupiter to be formed from the asteroid belt in our Solar System.

This problem is also related to our understanding where in the Universe life could emerge. The so-called 'habitation zones' of stellar systems are very narrow. For amino acid–nucleotide life (and the existence of other types of life is problematic), and moreover for the appearance of human-like civilizations, in the Solar System only Earth and, somewhat, Mars fall within this zone (Fig. 32).

What factors are decisive for life to exist in the form we know now? First of all, the gravitational force on the planet

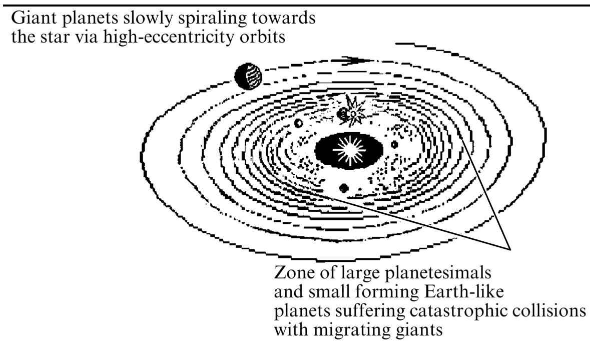

Figure 31. The scheme of migration of a giant exoplanet to a low orbit. Apparently, migration is the universal mechanism of planetary system formation.

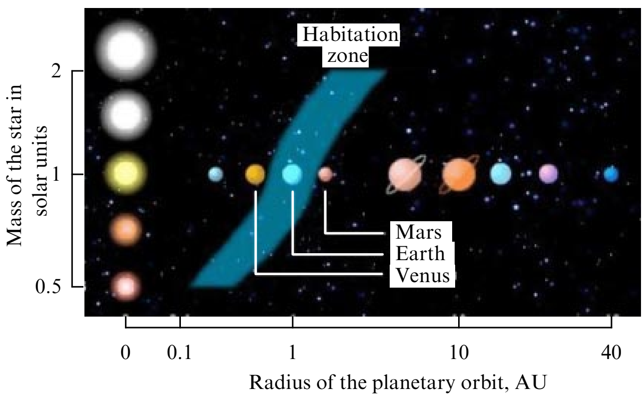

Figure 32. The location of the 'habitation zone' in planetary systems vs. the type of star and orbital distance.

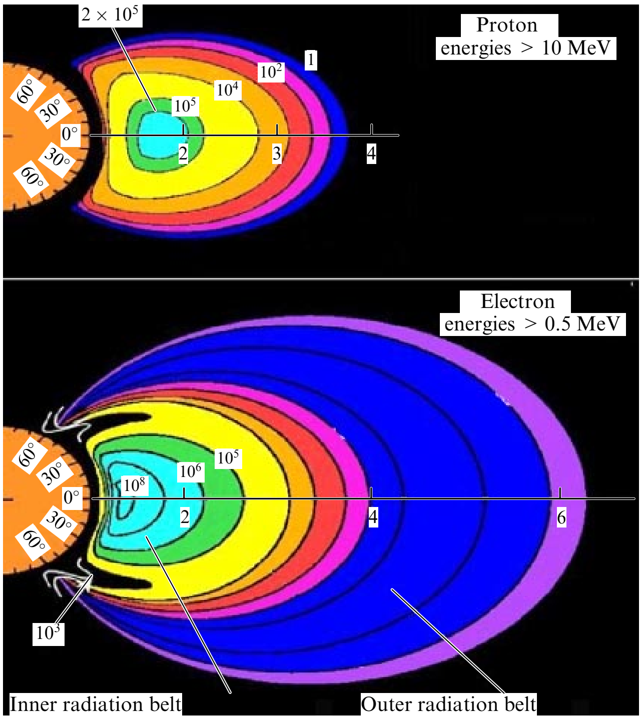

Figure 33. Most energetic particles are reflected by Earth's magnetic field. The penetrating part is kept inside the radiation belts. Top panel: proton distribution. Bottom panel: electron distribution.

must be moderate, and the period of rotation around the central star must not be too long. In addition, the planetary atmosphere must be capable of absorbing the external hard radiation. The density of radiation from the central star must be sufficiently large to maintain photosynthesis, and the planet must have internal sources of energy, such as volcanic activity and/or tectonics of plates. Finally, a sufficiently strong magnetic field is also a crucial factor. Hard cosmic radiation destroys big molecules which are necessary for life, and the magnetic field of Earth prevents such hard radiation from reaching the land (Fig. 33).

Magnetic fields of exoplanets can provide another method to test their habitability. Planets with a strong magnetic field are very powerful sources of radio emission. The surprising fact is that about 5% of the energy of particle fluxes striking Earth is converted in the magnetosphere to the energy of radio emission. It is a very high efficiency. Theoretically, it is expected that similarly strong radio emission could be observed from exoplanets with high proper magnetic fields. Unfortunately, it is impossible to detect it from the ground, since electromagnetic waves with a frequency below ~ 10 MHz are reflected by the ionosphere. It would be interesting to study exoplanets with an antenna array installed on the Moon. Such a project should be one of the objectives of constructing a habitable lunar base, which is being actively discussed now by different space agencies (NASA, ESA, India, China). A lunar base could be useful for radio astronomical studies (including the search for radio emissions from planets), especially from the far side of the Moon, where unique opportunities are opened for precise and sensitive measurements due to the absence of powerful anthropogenic electromagnetic background. The Moon also has many advantages for astronomical observations, including the absence of atmospheric disturbance, the possibility of long exposures, the weakness of spurious light pollution from Earth owing to its remoteness, and the possibility of observing weakest celestial objects due to the absence of atmosphere. Finally, weak gravity (0.16 of the terrestrial value) highly facilitates the installation of large instruments and detectors.

In our opinion, the creation of such an international observatory, which could both conduct lunar researches and study the most complex problems of the physics and astrophysics of planets, is now the only reasonable motivation for the extremely expensive construction of a lunar base.

8. Conclusions

To conclude, we can say that in spite of the delay that appeared in the 1990s, Russia is now trying to seek its niche in scientific space programs and to gradually gain back the trust in international collaboration that was seriously damaged due to many failures to meet the launch dates of our space projects. We can now look to the future with moderate optimism. In Russia, a modest (in comparison to Soviet and international projects) but quite interesting program of Solar System studies has been formulated.

Solar research remained beyond the scope of this paper. The last decade can be called the 'golden age' of solar physics in space, because an entire flotilla of spacecraft with the most modern detectors is observing and studying the Sun, both as an astrophysical object and the principal factor in space weather. The latter aspect is drawing more and more attention in connection with ever increasing human activity in the near-Earth space, which requires the prognosis of hazardous space factors (fluxes of high-energy particles, X-ray and gamma-ray emission) and the prevention of dangerous situations for spacecraft, astronauts, and other human activities in space. Such services in space and on Earth are becoming more and more necessary.

This is a huge separate topic. Russia has had serious successes here. Relatively recently, the space mission KORONAS-F was completed (2001–2005), which obtained very interesting results [38]. At the beginning of 2009, the third apparatus of the KORONAS (the Russian abbreviation of 'complex orbital near-Earth observations of solar activity') series, the KORONAS-Photon, began to detect hard radiation from solar flares in order to study energy storage and transformation processes in the solar atmosphere, and mechanisms of acceleration, propagation, and interaction of energetic particles. In addition, measurements made by KORONAS-Photon will enable the study of the possible correlation between physical and chemical processes in the upper atmosphere of Earth and solar activity. Due to an unexpectedly long delay in the beginning of the coming solar cycle, only several large solar flaring events have been detected so far, but it is already clear that the new cycle has started entering the active phase.

Another two promising solar projects are under discussion in the Space Council of RAS, including the Intergeliozond (Interhelioprobe) mission that foresees the flight of a spacecraft near the Sun at a distance of about 0.2 AU. This is a complicated task, but the study of the Sun from close distances can significantly increase the angular resolution of measurements and, in addition, will allow detailed investigation of the solar corona and mechanisms of the acceleration of the solar wind. Another original project of the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of RAS (IZMIRAN) is known as the Polar-ecliptic Patrol. It envisions the launch of two satellites in mutually consistent orbits lying outside the ecliptic plane at distances of about 0.5 AU from the Sun. These measurements will allow stereo-imaging of plasma coronal ejections, providing the possibility of seeing these phenomena as if from above the ecliptic plane, in contrast to measurements in recently started experiments using twin American satellites of the Sun, STEREO (Solar Terrestrial Relations Observatory). [1]

The Solar System is our home in which, as we hope, humankind is destined to live for the last billion years of its existence (this is, of course, an optimistic estimate that ignores the possibility of technical, natural, and, mainly, social catastrophes), so new knowledge on the past and current physical and chemical processes in the Solar System acquires a special practical meaning. The understanding of the uniqueness of our planet and the Solar System in general among other planetary systems can also have an outstanding philosophical sense in the explanation of fundamental issues of the organization and development of matter in the Universe.

The authors thank A T Bazilevskii, O V Zakutnjaja, O I Korablev, V S Kornilenko, V D Kuznetsov, M B Martynov, M M Mogilevskii, I N Tolstikhin, A M Finkelshtein, and B M Shustov for their help in preparing materials for this paper.

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[1] *Authors' note added in proof.* Many other important questions of the Solar System study, not covered in our paper, the reader will find in more detailed papers on small celestial bodies physics and processes of onset and evolution of our Solar System [39–42].