5. Conclusions

As stressed in the introduction, we are still in the early days of analyzing the data that we have in hand from Cassini–Huygens and we anticipate much more data to be coming in as the mission progresses over the next three years. Yet we can already see that Titan is a fascinating world in its own right, with the potential to provide some valuable perspectives on the origin and evolution of our own planet's atmosphere.

Any attempt to extend these perspectives to the problem of the origin of life on Earth must confront the intense cold on Titan and the consequent absence of water in both the liquid and vapor states. Thus, not only is there no chance for aqueous solution chemistry (Darwin's famous 'warm little pond') but there is no readily available reservoir of oxygen, a key element in terrestrial biochemistry. Nevertheless, our ability to understand the organic chemistry that does exist on Titan will surely help us to unravel some of the reactions that took place on the early Earth before life began.

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Small bodies in the solar system and some problems in cosmogony

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1. Introduction

The solar system is our nearby cosmic surroundings, and hence its study is of primary scientific and practical interest. Enormous progress in solar system studies has been made over the last several 'cosmic' decades, and the avalanche of discoveries grows steadily. Television and radio imaging of planets and their satellites, observations of their surfaces and atmospheres at various wavelengths, and studies of circumplanetary space, and studies of comets, asteroids, and meteors have provided rich experimental material. This has led to the revision of many previous concepts. To a large extent, this was made possible because of the elaboration of much more advanced models of natural phenomena using modern computation facilities. The mechanics of cosmic media has developed greatly. Comparative planetology has opened new possibilities in studies of the entire family of celestial bodies. Complex studies of terrestrial planets, Venus and Mars first of all (as the limiting evolutionary models of Earth), in combination with the dynamics of processes in the entire solar system, have founded the basis for a deeper understanding of properties of both our planet and various natural mechanisms [1].

In recent years, planetary cosmogony has been put on a more rigorous scientific foundation. Its impressive successes have been achieved due to the discovery of extrasolar protoplanetary discs and planetary systems. The next important step on this path must be direct studies of extraterrestrial matter, the primordial matter of small celestial bodies first of all, with its transport to Earth. The design of new highly effective space tools is aimed at solving this problem in the nearest future.

Achievements in researching the solar system required a new outlook on many unsolved problems. These include, first and foremost:

(1) the origin and early evolution of the solar system;

(2) revealing reasons for the uniqueness of the solar system, with the properties of the formation of extrasolar planets taken into account;

(3) the study of the properties of Earth's evolution that made it peculiar among the other terrestrial planets;

(4) the origin of volatiles on terrestrial planets, which allowed the formation of an atmosphere, hydrosphere, and, ultimately, a favorable climatic environment for the emergence and development of the terrestrial biosphere.

Clearly, the question of the origin of life, which remains disputable, is connected with the most intriguing directions in studies of the nature of planets, their satellites, and small bodies, including the problem of transportation (migration) of matter in the solar system and its prebiotic evolution. Of primary interest in this respect are Mars, the Jovian satellite Europa, and the Saturnian satellite Titan. In January 2005, a spacecraft landed on Titan under the joint American–European project Cassini–Huygens.

2. Small bodies. Definitions and main characteristics

Small bodies of the solar system include asteroids (minor planets), comets, meteoroids, and interplanetary dust. An asteroid is a celestial body of irregular form with a size from ~ 1000 km to several meters. They mostly reside in the Main asteroid belt located between the orbits of Mars and Jupiter at distances from 2.2. to 3.2 a.u. Comets are icy bodies $\sim 10-20$ km in size, usually in highly eccentric orbits. Short-period comets inside Pluto's orbit periodically approach the Sun. Meanwhile, the main cometary families, which also include much bigger bodies, reside outside Neptune's orbit in the Edgeworth–Kuiper belt (one distinguishes the belt itself ($\sim 30-50$ a.u.) and an extended disk reaching $\sim 10^3$ a.u.) and in the Oort cloud located at the boundary of the solar system ($\sim 10^4-10^5$ a.u.). Only some

bodies from the Oort cloud can enter inside; then they are observed as long-periodic comets.

Stony bodies of smaller sizes, which are fragments of numerous collisions of asteroids, are related to meteoroids. Usually, these are pieces of rock with a diameter ranging from several meters to several centimeters. They populate a wide variety of orbits in the interplanetary space. When entering the Earth's atmosphere, they brake and are observed as light flashes (meteors), and their unburned solid fragments falling on the terrestrial surface are known as meteorites. Finally, the smallest particles, with sizes below ~ 1 mm, constitute the interplanetary dust. It is largely formed by consecutive fragmentations of asteroids and meteoroids and is also ejected from cometary nuclei destroyed by insolation when approaching the Sun.

Regions occupied by asteroids in the inner part of the solar system are shown in Fig. 1. The total number of asteroids in the Main belt with sizes exceeding 1 km is $\sim 10^5$. Nearly 50,000 of them have been discovered by now, but only 25% have been cataloged because an accurate determination of the orbit is required from several observations. The total mass of the Main belt asteroids is about 1/2000 the Earth's mass. Numerous results of ground-based observations revealed important differences in the reflection albedos, and spectral and color characteristics of asteroids, which are mainly determined by the position of an asteroid inside the belt. According to their properties, asteroids are subdivided into 18 classes. The most famous classes are C, S, and M. The mineral composition of these classes of asteroids is most close to stone, iron–stone, and iron (metallic) meteorites, respectively. The nature of the last is apparently connected to the largest bodies' interiors having had partial differentiation due to retaining radiogenic isotopes. This, as in the giant planets, led to the formation of a silicate mantle and an iron core [1]. Accordingly, stony and metallic asteroids were formed during subsequent collisional fragmentation of these bodies. They mainly occupy the inner regions of the Main belt closer to the Sun. In turn, the most primitive carbon chondrites, which have virtually not evolved and have preserved the primordial composition (apparently close to the composition of the protoplanetary disk), are located in the outer regions close to Jupiter's orbit. Here, in addition to class C, one distinguishes classes Q, K, P, D, and Z with a pronounced abundance of clay minerals, carbon, and organics [2]. Such a difference in the composition classes is consistent with the condensation model. According to this model, a successive condensation of the high- and low-temperature elements and compounds in the protoplanetary disk occurred depending on the distance to the Sun.

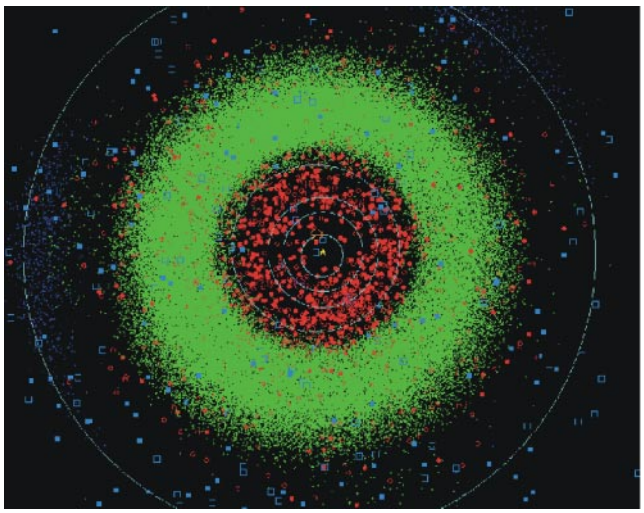

Figure 1. Location of asteroids in the solar system. The main family lies inside the Main belt between the orbits of Mars and Jupiter (orbits of the planets are shown by thin lines, asteroids are marked with dots). Asteroids approaching Earth (NEO) — the groups Amour, Apollo, Aton — are located inside the inner region.

In the beginning of the 1990s, the first television images of asteroids were taken from spacecraft flying nearby. They clearly demonstrated that the surface of asteroids has many craters formed from numerous collisions. Some asteroids have satellites, which is likely due to the capture of a fragment collisionally separated from the main body, even for a weak gravitational field of a comparatively small body [3].

Simple estimates show that strong tidal perturbations from Jupiter on asteroids in the Main belt prevent them from coalescing, or in other terms, from planet formation. In addition to the differences in the composition classes and the comparatively small masses of asteroids, this fact contradicts early suggestions that an ancient planet Phaeton existed and that the bodies from the Main belt are remnants of this planet. The strong tidal influence of Jupiter manifests itself in orbital resonances (Kirkwood gaps), which are multiple of the orbital period of this biggest planet around the Sun: inside these gaps, no asteroids with periods of the corresponding multiplicity (2:1; 3:1; 5:2, etc.) are found. Orbital parameters of asteroids lie within a wide range: eccentricities are $\leqslant 0.3$, inclinations are $\leqslant 20^\circ$, and spin periods span from several to several dozen hours.

There are three separate groups of asteroids approaching Earth or even regularly crossing Earth's orbit; they are called NEOs (Near Earth Objects). These include Amour — a group of asteroids crossing Mars's orbit, approaching Earth, and evolving into NEOs on a time scale of 100 – 1000 years; Apollo — a group of asteroids crossing Earth's orbit; and Aton — a group of asteroids entering inside Earth's orbit (see Fig. 1). Clearly, as regards a possible encounter with Earth, the most dangerous is the Apollo group, although, as mentioned above, model calculations show that the orbits of asteroids from different groups evolve. It is easy to see that our planet is inside a huge swarm of bodies with different sizes. According to present estimates, there are more than 1500 asteroids with a diameter exceeding 1 km, although orbits have been determined only for two thirds of them [4]. We also note that the orbits of the NEO asteroids are rather chaotic, which significantly complicates any forecast of their motion.

Starting from the 1980s, high-quality images of some NEO asteroids with a size of several kilometers were obtained by radio location. These images revealed bodies of an irregular form, which is due to their insignificant proper gravity. In February 2001, the spacecraft NEAR (Near Earth Asteroid Rendezvous) landed for the first time on Eros, a large asteroid ($33 \times 13 \times 13$ km) of the Amour group. Numerous craters from several meters to several kilometers in size were found on the surface of the asteroid, which indicates intensive collisional bombardment. Some craters show traces of erosion and the presence of a regolith layer. The surface is literally spotted with stone blocks up to several dozen meters in size; their total number is estimated to be several thousand. Obviously, they were ejected during impacts of asteroids (meteoroids) and then settled on the surface of Eros.

Some large craters on the surface of asteroids have a size similar to that of the asteroids, which indicates that the energy of the impact would be sufficient to destroy the entire solid body. That it was not the case implies a very inhomogeneous or porous structure. This conclusion is supported by the value of the mean density that for most asteroids lies within the range from 1.2 g cm^{-3} (class C) to 2.5 g cm^{-3} (class S). In addition, the spin period of an asteroid was clearly found to depend on its size: the spin period for all studied asteroids with size above 200 m turned out to be less than 2.2 h. This threshold value corresponds to the limiting rotation velocity at which a nonmonolith body is destroyed by centrifugal force. All this suggests that the structure of most bodies with sizes exceeding 200 m is a conglomerate of smaller bodies ('fragments') formed by energetic encounters (see, e.g., [5]). As a result, fragments at the escape velocity flew away from the primary body, and those at smaller velocities joined into a new body due to mutual attraction; this body is not monolithic and probably has voids or niches. We note that such a structure is supported by the catastrophic event observed in the summer of 1984, when the nucleus of the comet Schumaker – Levy 9, captured by Jupiter into a close orbit, was destroyed by its powerful tidal forces into more than 20 fragments. They successively impacted with the planet with an enormous release of energy.

We now consider the physical nature and models of comets. Comets are special among small bodies for being 'stores' of primordial matter. Hence, they bear important information on the dawn of the solar system's formation (Fig. 2). Comets can be associated with planetesimals expelled by tidal perturbations from formation regions of giant planets into the periphery of the solar system. The Edgeworth – Kuiper belt and the Oort cloud were formed there. It is estimated that the Edgeworth – Kuiper belt, which has a disk-like form beyond Neptune's orbit, contains $\sim 10^5$ bodies ('ice dwarfs') with sizes 10 – 500 km and $\sim 10^9$ comets with a size about 20 km [6, 7] and the total mass $0.1 M_E$ (where M_E is the Earth's mass). Pluto and its satellite Charon belong to this family together with other recently discovered bodies of a comparable size (Quaorar and Sedna), and hence it is essentially a convention that Pluto historically retains its name of a planet. But the main family of comets ($\sim 10^{12} - 10^{13}$) resides in the spherical Oort cloud at the solar system's periphery. Their total mass does not exceed $(1 - 3) \times M_E$. It should be noted that there is no strict boundary between asteroids and short-period comets: after multiple approaches to the Sun, some comets are covered with a thick dust layer prohibiting ice sublimation and stop demonstrating comet activity. Sometimes, the reverse process is observed: an asteroid can be suddenly covered with an atmosphere, which is apparently explained by cracking or expelling the mantle around the body, which was formerly a comet, due to its intense heating.

Figure 2. The icy satellite of Saturn Feba with the size ~ 230 km, whose surface structure and mean density correspond to a comet nucleus apparently captured by Saturn (picture taken by the Cassini spacecraft).

Study of the structure and properties of comets and their migration into the inner regions of the solar system is of primary interest for planet cosmogony. In addition, because of the diversity and complexity of physical processes accompanying the evolution of these bodies at different heliocentric distances, comets are extremely interesting subjects for mathematical modeling by means of the methods of fluid mechanics and gas dynamics [8]. Of main interest are studies of the structure of the porous comet nucleus and the processes of thermal and mass transfer inside it, which are connected with features of the near-surface Knudsen layer, the sublimation of ice conglomerates of different chemical composition, and the formation of a gas – dust coma. For this, we suggested and, in specific cases, successfully applied a modified method of stochastic modeling (a physical – probabilistic analog of the original kinetic phenomenon and spatially homogeneous evolution of the state of gas in Markov's form) that can model such media and numerically solve the corresponding model problems [9, 10]. Effective methods for solving such systems, which are based on analog Monte-Carlo algorithms, allowed us to develop a class of structural stochastic models for relaxational systems with a complex structure of kinetic scales determining the local kinetics of the processes. In particular, these models were applied in the Vega space project.

The models include the kinetics of transport processes in heterogenic media, the analysis of phase transition, and the study of the evolution of the sublimating multi-component gas for different insolation conditions. As an example, Fig. 3a shows profiles of the temperature, density, and velocity of particles sublimating from the ice nucleus surface within around ten free path lengths inside the Knudsen layer; at the outer boundary of this layer, particles acquire the speed of sound. The structure of this layer is sufficiently complicated (which, in particular, is reflected in the temperature divergence of particles and their reverse flux on the nucleus surface), and kinetic methods are needed to model it. The profiles of neutral atoms and molecules (water, hydrogen, hydroxyl) in the inner coma of Halley's comet at a distance of several thousand km from the nucleus calculated using such methods [10] are shown in Fig. 3b. Similar calculations have been performed for ionized components. We have successfully developed methods of stochastic modeling using highly effective parallel algorithms, which increases the reliability of the interpretation of experimental data obtained by ground-based observations and during space flights to comets.

3. Migration-collisional processes and heterogenic accretion

The migration of small bodies reflects dynamics of regular and chaotic processes in the solar system. One of the consequences of the migration is the impact of comets and

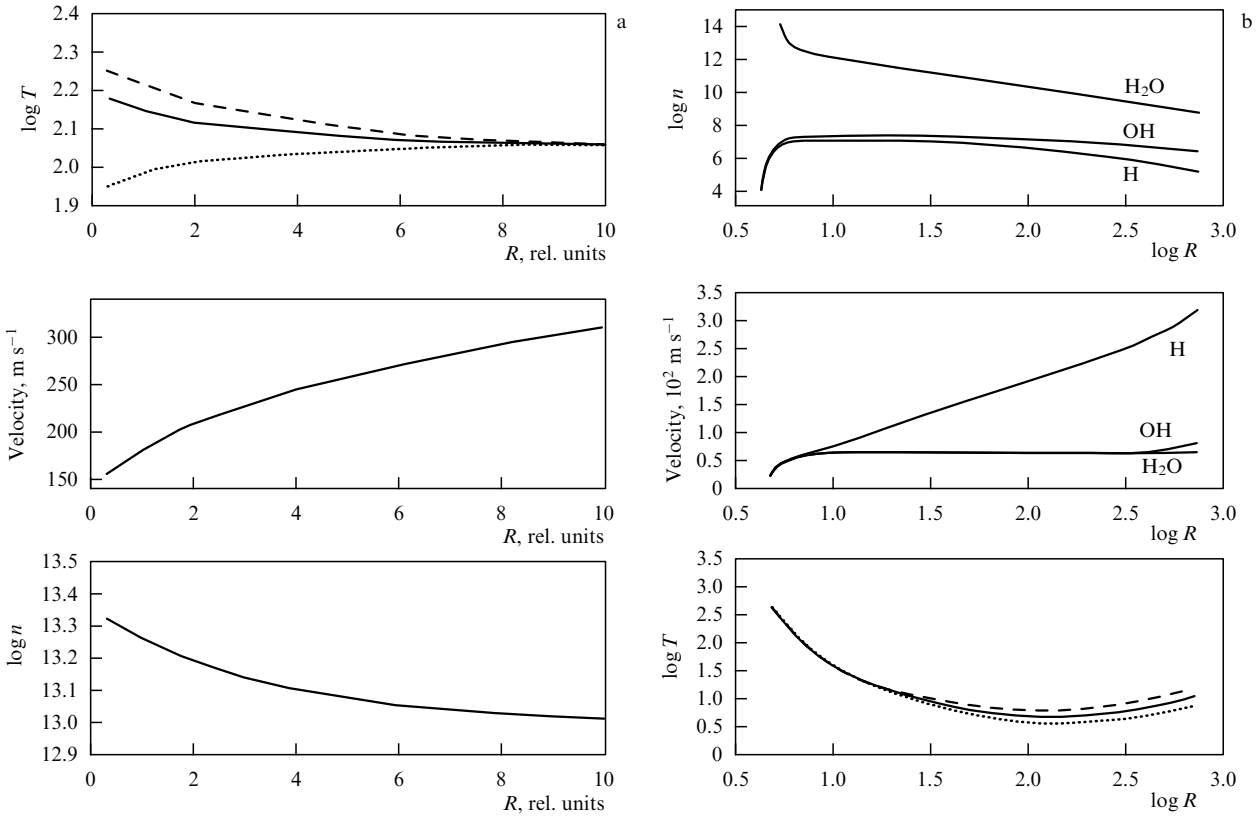

Figure 3. Results of modeling of the dust and gas sublimation from the surface of the nucleus and the formation of a coma. Shown are radial profiles: (a) of macroparameters in the Knudsen layer, (b) of macroparameters of neutral gas in a gaseous shell around Halley's comet at the distance 1 a.u. R is the radial distance (units: in Fig. a, relative units; in Fig. b, 1 km), n is the density [cm^{-3}], T is the temperature [K].

asteroids with planets. They lead to catastrophic events and the transport of matter, which is of paramount importance for the evolution of planets and their atmospheres.

According to modern ideas, volatiles could not have been retained in the formation zone of terrestrial planets due to the high temperature in this part of the protoplanetary disk ($\sim$ 1000 K) and the swiping out of the primordial atmospheres by the solar wind from the young Sun. Nevertheless, a relatively high abundance of volatiles on these planets can be explained by the mechanism of heterogenic accretion due to an intense bombardment by comets and asteroids from outer parts of the solar system at early evolutionary stages. Studies of the orbital dynamics of small bodies (comets, the main-belt asteroids, and bodies from the Edgeworth – Kuiper belt) allow qualitatively estimating their migration in the zone of terrestrial planets and thus finding arguments supporting this mechanism. The relative contribution of ice comets and carbon – chondrite asteroids to the transport of water and other atmophile elements on these planets can be constrained from studies of the abundance of noble gases and isotope composition of planetary atmospheres [11]. Modeling of the migration of small bodies is also directly connected with the analysis of the role of collisional processes in the solar system and the evaluation of the efficiency of transitions of asteroids on orbits intersecting Earth's, which contributes to the study of the actual asteroid threat problem [12].

In the framework of the N-body problem, we [13 – 15] performed direct integration of the migration of 2×10^4 bodies from the extra-Neptune belt transited to Jupiter-crossing orbits (JCOs) and partially migrating inside the solar system. It was shown that the mean probability of their collision with Earth is $P = 6.65 \times 10^{-6}$. This means that an object with the diameter $\sim$ 1 km can collide once per $\sim 10^6$ years. The probability for Venus was found to be approximately the same, while for Mars it was three times smaller. On average, one in 300 JCOs falls on the Sun. Figure 4 shows sample calculations of the migration of JCOs originally found in virtual orbits with parameters similar to comets from Jupiter's family. These calculations are presented as temporal variations of their perihelion distance q, aphelion distance Q, major semiaxis a, and eccentricity e. They illustrate the complex evolution when migrating inward through the solar system. At the same time, the fraction of NEOs migrating toward Earth from the 5:2 resonance region of the Main belt was found to be four times as large as from the 3:1 resonance region.

The migration of planetesimals and their remnants (comets and asteroids) from the extra-Neptune belt is regarded by us as an effective mechanism that provides volatile compounds from external to internal regions of the solar system and compensates for the initial deficit of volatiles on the terrestrial planets, as they are very likely to have lost their atmospheres originally captured from the protoplanetary cloud at the accumulation stage. Compelling evidence for such a loss is the fact that the abundance and isotope composition of noble gases in the actual secondary atmospheres is different from the Solar one [16]. Undoubtedly, the degasation from the interiors during the subsequent evolution, which accompanied mantle stratification of the planets, greatly contributed to the formation of the secondary hydro-

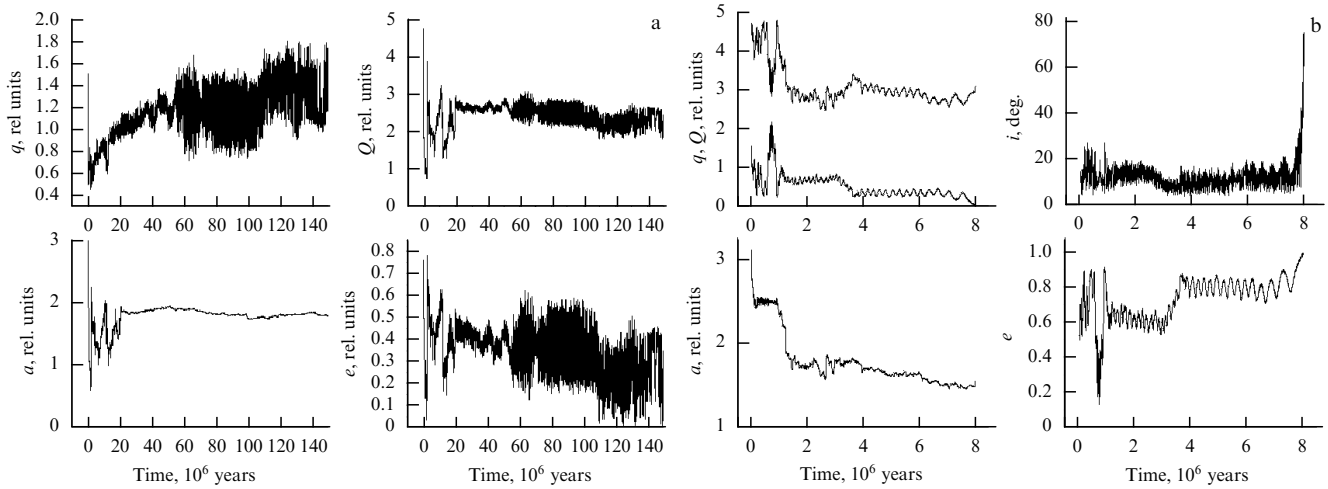

Figure 4. Examples of calculations of the migration of trans-Neptune bodies captured on JCO orbits. Shown are variations of the perihelion q and aphelion Q distances, the major semiaxis a, the inclination i, and the eccentricity e as functions of time for virtual JCOs located in Jovian comet-like orbits 9P Tempel 1 (a) and 10P (b).

sphere and atmosphere. Was such a source unique and sufficient to compensate the loss of low-temperature volatiles (water, nitrogen, carbon, sulfur, etc.) in the formation zone of the terrestrial planets due to the Jeans dissipation mechanism? In addition to the high temperature, the small mass of these planets also helped the lightest atmophile elements to escape. In any case, the assumption about the additional source of volatiles in the presence of the initial temperature stratification of elements and compounds in the framework of the condensation model greatly contributes to the planetary atmospheric genesis problem.

Unfortunately, it is difficult to estimate the relative contribution of the interior degasation (endogen mechanism) and the transportation of volatiles by comet (asteroid) migration and their fall on the terrestrial planets (exogen mechanism) to the formation of the secondary atmosphere. Nonetheless, small bodies could provide a supply of volatiles at least comparable to that from the endogen source during heterogenic accretion, i.e., after the main phase of planetary formation has been completed. According to our model of extra-Neptune bodies' migration into the region of terrestrial planets, the total mass of bodies falling on Earth due to heterogenic accretion is estimated as $6 \times 10^{-4} M_{\mathrm{E}}$. Assuming that half of this mass was in the form of water ice, the total mass of volatiles transported from the feeding zone of the giant planets was $\sim 2 \times 10^{24}$ g, which is 1.5 times larger than the water content of Earth's oceans ($\sim 1.4 \times 10^{24}$ g) [17]. We note that the peak of the heterogenic accretion was ~ 4 bln. years ago, which corresponds to the maximum bombardment of the planets. This is confirmed by analysis of the number and age of craters on their surfaces. The mass of fallen volatiles was less than 0.1%.

As we see, the heterogenic accretion could be crucial for the formation of a hydrosphere and atmosphere on Earth and other planets. According to the migration – collisional model, Venus gained a somewhat smaller and Mars a somewhat larger amount of exogen water than Earth (per mass of the planet). This allows us to draw an important conclusion about the presence of ancient oceans on Venus and Mars and to strengthen ideas on different ways these planets neighboring Earth subsequently evolved. According to these ideas, the primordial Venusian hydrosphere was lost due to the irreversible green-house effect, while the Martian one was preserved in the form of the cryosphere after the atmosphere collapsed [1, 18]. Additionally, the interplanetary transport of matter from the periphery of the solar system by comets consisting almost entirely of volatiles could also be responsible for organic and even biogenic matter supply on the planet, and hence could notably affect the emergence and evolution of life on Earth. The fall of interplanetary dust on planets could even more strongly contribute to this process. The point is that although the amount of dust falling on planets is about three times smaller than the amount falling on small bodies [19, 20], the short-time heating of a dust particle entering the atmosphere is much smaller due to a high ratio of the surface area to the mass of the particle. Therefore, the particle temperature does not exceed $\sim 100-150\,^{\circ}$C. Laboratory experiments have demonstrated that the survival probability of bacteria or a spore under such conditions is quite high for an exposure time of the order of several seconds [21]. As a result, such a method of bioorganic matter supply on the planet could be quite effective.

4. Some problems of cosmogony

The study of the nature of small bodies that almost preserved the primordial composition during evolution is of primary interest for solving the fundamental problem of the origin of the Solar system.

The basic problems of cosmogony are directly related to the appearance and evolution of the protoplanetery nebula. According to modern views, planets are formed from this nebula during accretion of gas – dust matter on the middle plane and the formation of the protoplanetary disk. The theory of accretion disks around young stars has many common features with accretion disks in binary stars produced due to the transfer of matter to the secondary massive component. In both cases, we deal with a turbulent multi-component gas – dust medium, in which kinetic processes, i.e., various chemical transformations, generally occur. New astrophysical data allow more complex studies, both theoretical and numerical, of the physical structure and evolution of the gas – dust protoplanetary disk around the young Sun and many other similar disks that are observed

around young low-mass stars (T Tauri stars). Modern data on planets, comets, and asteroids obtained by spacecrafts and laboratory studies of meteorites are of comparable importance here.

In contrast to previous decades, observational data on the protoplanetary disks around many stars and the discovery of extra-solar planets, combined with data on the composition and properties of bodies in the solar system, put important constraints on modern cosmogonical models. It became clear that the formation of stars, as a rule, is accompanied by the formation of gas – dust protoplanetary disks. Disks comparable with the solar system's size were discovered around nearby stars. By now, more than 130 planets with a mass from about 0.3 to 15 times that of Jupiter's, including planetary systems with several planets [22], have been discovered. It should be emphasized that planets have been found only around high-metallicity stars (with a high ratio of Fe/H), i.e., around stars from the late stellar population.

Up to 20% of G – K stars are thought to have planetary systems, or giant planets at least. Most likely, the number of planets increases with decreasing their mass, and the absence of Earth-like planets around other stars is explained by restrictions imposed by the Doppler spectrometry used, i.e., by effects of the observational selection. It can be assumed that a strong gravitational instability operates inside gas – dust accretion disks. The drift of giant planets toward the central star is likely to occur. This decreases the probability of the existence of planets with much smaller masses inside the 'habitation zone' due to strong tidal perturbations. From the observational data, one can conclude that a stable configuration of planetary systems like the solar system is apparently a rare, maybe even unique, case. Of course, one should then take the selection effect mentioned above into account, because giant planets like Jupiter and Saturn at 5 a.u. from the central star can be detected by modern facilities only on a time scale longer than 12 years, which has not been achieved so far (see, e.g., [23]). Yet despite observational difficulties, one planetary system (around 47 UMa) similar to our solar system has already been found.

In turn, the study of the structure and composition of small bodies puts certain bounds on scenarios of the evolution of accretion disks and the formation of gas – dust clusters and the solid proto-planetary component [24 – 27]. These data are especially important in modeling the thermal structure of the proto-planetary disk, with its chemical abundance, the aggregate state of the main components of the proto-planetary matter, the location of the condensation – sublimation fronts, and the space distribution of dust taken into account. We note that many unsolved problems of planet cosmogony are related to the dynamics of dust particles and plausible mechanisms of their aggregation to the size of planetesimals. Apparently, unrealistic notions, which are not supported either experimentally or theoretically, on the successive growth of particles in a gas – dust medium due to relatively high-velocity collisions [28 – 30] should be rejected. Nevertheless, we note that the behavior of such particles in a turbulized heterogenic medium, in particular during the formation of regular structures, and the efficiency of coagulation in such a medium are poorly known [31]. Another mechanism based on the assumption of the formation of extended (filling the entire Hill's sphere or a significant part of it) self-gravitating dust clots from which planetesimals subsequently grow also encounters certain difficulties [32, 33]. An attempt was made to confirm such a scenario and to bring it into agreement with geochemical data using the formation of the Earth – Moon system as an example [34, 35].

As we can see, searches for mechanisms providing for the growth of particles and formation of bodies with diameters up to kilometer-size planetesimals remain very topical. It is natural to suppose that a rotating disk becomes thinner and denser (i.e., a dust subdisk forms) when dust particles accrete along the z coordinates toward its mean plane. At some critical density, $\sim 10^{-7}$ g cm^{-3}, corresponding to the dust – gas density ratio $\rho_{\rm d}/\rho_{\rm g} > 10^2$, conditions inside the disk become favorable for the gravitational instability to develop due to fluctuations on different space-time scales, which leads to the formation of gas – dust clots (clusters). With self-gravitation and viscous effects taken into account, the resonance excitation of a density wave may play a certain role in disk evolution. They can strongly affect the morphology and behavior (dynamics) of nonlinear chaotic systems, which is supported by numerical simulations [36, 37].

The subdisk formation with subsequent agglomeration of primordial clusters and solid bodies on a time scale of about 10^7 years is shown schematically in Fig. 5 [29]. To analyze the formation of self-gravitating clusters and to estimate the probability of protoplanet formation in further evolution, one can use the local criterion for gravitational instability with respect to radial perturbations in thin disk [37, 38], which can be written as

$$\frac{c_{\rm s}\Omega}{kG\Sigma} < 1\,,$$

where $c_{\rm s}$ is the speed of sound for a gas (or in the first approximation, for a dust – gas medium), Ω is the epicyclic rotational frequency at a given distance from the Sun (which is close to $\Omega = 2 \times 10^{-7}$ s^{-1} at 1 a.u. when the rotation is close to the Keplerian one), G is the universal gravity constant, Σ is the disk surface density (the mass comprised inside a column of unit cross section in the direction parallel to the rotational axis), and k is a numerical coefficient ($k \approx 1$). Apparently, at a given distance from the Sun, this criterion is mainly determined by the ratio of the critical surface density, i.e., the dust content, to the speed of sound $c_{\rm s}$. For example, it is easy to estimate that a gas – dust cluster with cosmic abundance at ~ 1 a.u. must have the initial surface density $\Sigma > 10^5$ g cm^{-2}, because $c_{\rm s} \approx 1$ km s^{-1} in the gas, and hence, for this condition to be satisfied for an initial mass of the order of that of Earth, the cluster must consist of $\sim 99\%$ of dust and only $\sim 1\%$ of gas; for the inverse dust – gas mass ratio, the initial mass of the cluster should have been about 10^{30} g ($100M_{\rm E}$). In that case, the problem arises as to how to 'eliminate' such an excessive mass when forming the Earth – Moon system, for example.

Analysis of evolutionary processes in disks is tightly connected with problems of turbulence, which have not been properly considered until recently. The effects of turbulence, turbulent viscosity in an inhomogeneous medium first of all, have been treated by introducing different parameters. Meanwhile, the shear turbulence has enormous effects on surface properties and the internal structure of the forming dust layer and its subsequent evolution, including the stability of the disk and gas – dust clusters inside it. Indeed, ring-like clots forming in the subdisk due to gravitational instability should disintegrate into separate gas – dust clusters, in which much more favorable conditions arise for subsequent density and size growth of particles, leading to the formation of initially fluffy structures. Considering that the definition of

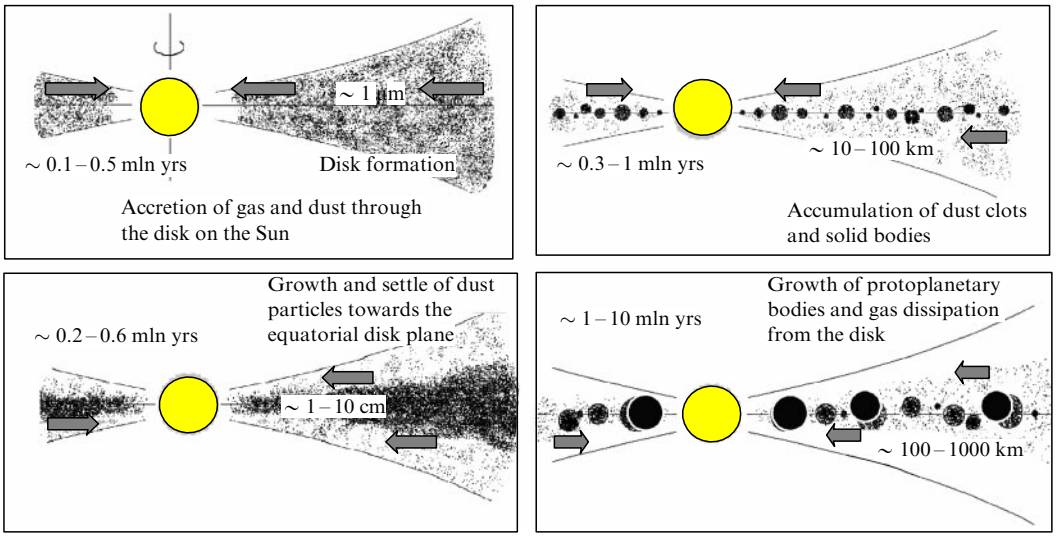

Figure 5. The formation scenario for a protoplanetary disk — the model of gravitational instability developing due to fluctuations in the gas – dust subdisk when particles are settled toward the middle plane and increase the density. When the critical condition for the instability is reached, the primordial gas – dust clots (clusters) are formed in which further density increase and particle growth occur with the formation of solid bodies and planetesimals accompanied by gas dissipation from the disk.

such clusters is etymologically consistent with the notion of a medium in which both the particle agglomeration by collisions and coagulation and self-gravity are effective, the alternative formation mechanisms of planetesimals considered above could turn out to be rather similar. It should be noted that spectral observations of disks around young T Tau stars suggest the presence of small dust grains ($\leqslant 1$ μm) over a period of 1 – 10 mln. years. At the same time, theoretical arguments imply that large-size bodies ($\sim 100 - 1000$ km) or even larger clots of the equivalent mass could emerge in the inner parts of the disk ($r < 10$ a.u.) over this time interval (see Fig. 5).

We see that problems concerning the modeling of gas-dust complexes and the formation of protoplanetary (small) bodies during their evolution are very tightly related to the study of processes of heat and mass exchange in a turbulent compressible shear flux of interacting gases. The development of a theory of inhomogeneous turbulence using the thermodynamic approach to the closure of hydrodynamic equations for averaged motion is an essential step in modifying the mathematical theory of turbulence of inhomogeneous media [30, 31, 41]. Using nonequilibrium thermodynamics and Onsager's reciprocity relations, we could thus obtain the main relations for inhomogeneous turbulent thermodynamic fluxes. These relations generalize the results of the hydrodynamics of homogeneous fluids in the case of a multi-component chemically active continuum and most completely describe the mass and heat transfer in a multi-component turbulent medium. The obtained system of equations of a high-order closure forms the basis of the invariant theory of turbulence. In the local approximation, it reduces to the K-theory of turbulence (see [31, 41]), which allows obtaining a system of algebraic relations and calculating turbulence transport coefficients (turbulent viscosity and heat conductivity) in a stratified multi-component gas stream with perpendicular velocity shear.

Extending this theory to heterogeneous media has allowed us to apply it to the most adequate modeling of the gas – dust accretion disks. The problem reduces to studying, in the hydrodynamic approximation, the joint occurrence of the heat and mass transfer and coagulation in a two-component medium with shear velocity in a differentially rotating gas – dust disk and polydispersion solid particles suspended in the flow. The use of the K-theory has allowed calculating semi-empirical coefficients of turbulent transport for gas – dust disks, which are a generalization of the turbulent viscosity coefficient in gas α-disks [42], and studying the mutual interaction of turbulent mixing and the kinetics of coagulation when a gas – dust subdisk is formed. The parametric method of moments suggested by us [31] to solve the integro-differential Smoluchowski coagulation equation, in the framework of the model of a two-phase dispersive turbulent compressible medium with different volume content of suspended dust grains and their size distribution functions, opens the possibility of performing numerical modeling of the grain settling on the subdisk in the regime of limit saturation of the gas flow with dust particles.

Successful applications of this method enable us on a new basis to construct models of the structure of the protoplanetary accretion disk forming around a young solar-type star. In these models, radiative and turbulent thermal energy transfer, the change of matter opacity, and the efficiency of evaporation and condensation of the main dust components and their chemical composition are taken into account. Calculations of the (r, z)-distribution of $T - \rho - P$ parameters and the location of the emitting disk surface, of the region of partial evaporation of magnesium silicates and iron inside the disk corresponding to the inner boundary of the planet formation zone, and the water ice sublimation – condensation front coordinates determining the internal boundary of the formation zone of giant planets and comets [43], allow us to consistently treat mechanical and geochemical aspects of the problem. It is then necessary to self-consistently take into account the disk heating by turbulent energy dissipation inside it and by the central star illumination outside the disk by varying the mass accretion rate through the disk on the Sun, the turbulent viscosity, the density ratio of the dust and gas components, the sizes and spatial distribution of dust

grains, and the contribution of the heat convection to the turbulence and heat transfer in the disk. As a result, we can more fully justify the appearance of the gravitational Jeans instability in the dust subdisk and calculate the dynamical model of the disk interaction with the surrounding accretion shell, including the structure and mass flows on the disk surface, in the Eckman surface layer, and in the inner region. Models of dynamical interaction of dust grains between themselves inside a turbulent medium of gas – dust clusters and with larger bodies forming there — gravitating planetesimals — provide further progress in this approach.

5. Prospects of space studies

The elaboration of models is directly related to detailed experimental studies of small bodies as carriers of primordial cosmogonic information. Space missions toward small bodies to study the structure and composition of asteroids in the different zones of the Main belt, of asteroids approaching Earth, and of course direct studies of comet material are of primary importance. At the same time, a complex understanding of all experimental data underlying modern concepts of the solar system is needed.

Presently, cosmic studies of planets and minor bodies are undergoing a real boom world-wide, which is unfortunately in strong contrast with the situation in Russia. In the background of sharp financial cuts to cosmic research, the importance of scientific cosmic research is generally underestimated. The Mars-96 space mission failure in 1996 had a huge negative impact on planetary studies, which strongly encouraged the search for principally new approaches in the exploration of remote space.

The space mission Phobos-Ground (Fig. 6) included in the Federal space program [44, 45] is aimed at reviving the national program of planetary explorations, which has beautiful traditions and big achievements. This project stipulates the transportation of samples of material from the Martian satellite Phobos to Earth. It is of great scientific importance and simultaneously serves as a necessary step in solving other topical problems. It is much cheaper than the previous missions due to the use of advanced technologies and breakthrough technical ideas. These include: the module-block principle in constructing the spacecraft with the use of composite materials, a significant reduction in mass and large-scale unification of onboard systems, large operational autonomy at different stages of the flight, and a high degree of reliability of functioning of individual systems and the mission as a whole. If necessary, the spacecraft can be equipped with low-traction electro-reactive engines (ERE) on the basis of highly effective solar batteries and can function utilizing the SEP (solar energy propulsion) principle, which increases the energy resource of the apparatus.

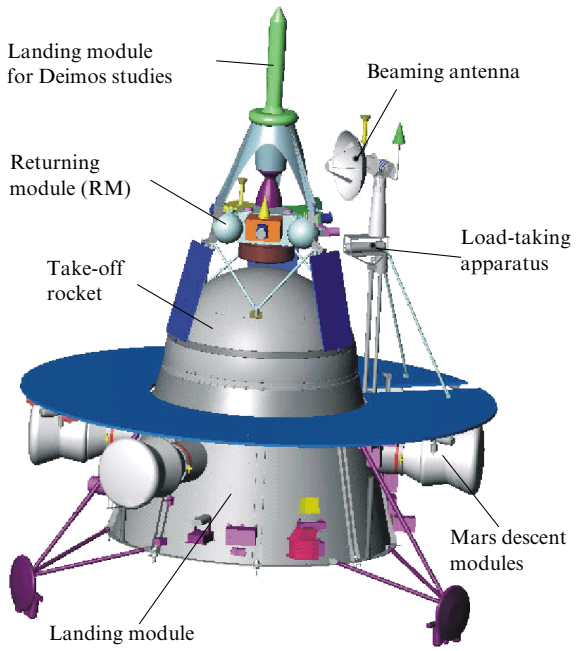

Figure 6. The project of a new-generation spacecraft Phobos-Ground, which is the basic spacecraft for flights to other small bodies in the solar system.

The choice of a mission to one of the minor bodies — Phobos — as a topical scientific goal of planetary studies is not accidental. Samples of rocks from Phobos are of special interest due to the as yet unsolved problem of its origin as a planetary satellite: is it a relic body surviving from the accretion stage or an asteroid captured by Mars's gravitational field? In any case, the samples would be the first from such a small asteroid-like body. In addition, thorough studies performed by various devices near Phobos and on its surface would provide invaluable data on the nature, internal structure, and proper motion of this body and on physical conditions of the interplanetary medium near Mars and Phobos. New data on Mars will also be obtained both in the course of long-term distant observations and by small space modules separated from the spacecraft approaching a circum-Martian orbit; these modules are planned to smoothly land on the surface of Mars.

The project perfectly fits the international strategy of solar system explorations and at the same time does not duplicate projects proposed by other countries, in particular, the ambitious NASA program of Mars exploration. Other topical studies of planets and small bodies can be performed on the basis of the multi-function basic module. The planned missions to comets and asteroids meet the existing energetic constraints if medium-class carriers like Soyuz-Fregat and ERE are used, which satisfies the required decrease in costs of space missions. At the same time, lunar studies remain very topical, including their cosmogonic aspect. These studies can be considered one branch of the general strategy of planetary explorations, including the use of the conversion carriers.

6. Conclusion

The solar system is a unique natural laboratory with a huge variety of celestial bodies, natural phenomena, and interactions. Small bodies — asteroids, comets, meteoroids, interplanetary dust — are important ingredients of the solar system. They physically and evolutionaily interact with large planets. The composition of these bodies has only minimally changed during the evolution. This allows relating their studies to the fundamental problem of the origin and evolution of the solar system and the origin of life. Therefore, studies of small bodies and the elaboration of their physical-chemical models play the key role in solving cosmogonic problems and in astrobiology.

Migration and collision processes reflect the dynamic character of interactions in the solar system, which is manifested in the permanent transport of matter, in the

material exchange between various bodies. At an early epoch ($\sim$ 4 bln years ago), this mechanism, called the heterogenic accretion, was probably responsible for the supply of volatiles due to the falling of comets and asteroids with composition close to carbon chondrites onto the terrestrial planets, and thereby for the formation (at least partial) of their atmospheres and hydrospheres. Thus, the heterogenic accretion could have been important in the evolution of Earth, Venus, and Mars. Studies of migration – collision processes are directly related to the asteroid threat problem and projects of its prevention.

Studies of small bodies put certain bounds on the existing scenarios of the accretion disk evolution, and of the formation of gas – dust clusters and the solid pre-planetary component. Many key unsolved problems of planetary cosmogony are related to the dynamics of dust grains and plausible mechanisms of their growth to planetesimal sizes. The most plausible scenario is the formation of a dense dust subdisk in the middle plane of the accretion disk and the emerging at some critical density of a gravitational instability responsible for the formation of gas – dust clusters in a wide range of space scales. Primordial hard bodies — planetesimals preceding the formation of planets — are probably formed from these clusters during subsequent evolution.

Analysis of evolutionary processes in disks is tightly related to problems of turbulence that mostly affects the properties, structure, and stability of the disk and gas – dust clots. Problems of modeling gas – dust complexes and of the formation of proto-planetary (small) bodies during their evolution require a detailed study of the heat and mass exchange in a turbulent compressible shear flow. A significant contribution is here provided by the theory of turbulence of inhomogeneous media. The extension of this theory to heterogenic media opens possibilities of its applications to the most adequate modeling of differentially rotating accretion gas – dust disks around young solar-type stars. Of key importance is the development of a model that could provide the gravitational instability development mechanism in the dust subdisk. This model should additionally account for the radiative and turbulent thermal energy transport, the change in matter opacity, and the efficiency of the evaporation and condensation of the principal gas and dust components of different chemical composition.

The problems of modeling are tightly connected with direct explorations of small bodies as carriers of primordial cosmogonic information. Launches of spacecrafts to asteroids and comets have been started; these studies become more and more important. Our lag in this field can be partly compensated by the launch of a new-generation spacecraft (Phobos-Ground) and by flights to small bodies of modules constructed on its basis. Such projects are under development and their realization is planned beginning from 2009.

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