A Brief History of the Early Solar System

Leonid E. Grinin

The issue of formation of the Sun, Earth, other planets and their satellites has long been a matter of great concern to people. Over the past few decades astronomers and cosmologists have considerably advanced in the perception of the architecture, history, and evolution of the Solar System. In particular, we understand the mechanism of the origin of the Solar system much better due to direct observations of the emerging young stars and discovery of numerous exoplanets. However, one can hardly speak about the history of the Solar system in a proper sense of the word; rather we hypothese. The present article presents the investigation into the evolution of our Solar system in the first few hundred million years of its existence when it experienced the most dramatic changes. The article is written in a rather popular manner, at the same time it is based on rigorous scientific research.

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The Protosun System Formation from a Gas-Dust Cloud

Our Solar system was mainly formed during the first few dozen million years, its current order was developed during the first hundreds of million years (up to 1 billion), but the actual narrative of this early stage is extremely fragmentary and unreliable. That is why we cannot speak of a history of the Solar system in a strict sense of the word; rather we hypothese on the matter. Yet, with respect to some events, in particular, the formation of a protosolar system from the gas-dust cloud, the hypotheses are gradually corroborated by data from observations of the emergence of new stars and the discovery of numerous exoplanets (Gillon *et al*. 2016, 2017; Vibe 2016; Bochkarev 2010).

The age of the Solar system, determined by applying radioactive dating techniques from the study of the oldest meteorites, is about 4.57 billion years, but the estimates generally fluctuate within the interval from 4.57 to 4.66 bln years (Pfalzner *et al*. 2015; Shukolyukov and Lugmair 2003; Vityazev and Pechernikova 2010: 168; Hazen 2015; Lin 2008; Johnson and Melosh 2012).

Over the past two to three decades, the so-called standard scenario of the planetary system formation has been elaborated, gained from the protoplanetary gas-dust disk surrounding of the protosun as well as from numerous computer models of planetary formations from asteroids. This allows defining the general outlines of the process, especially in the context of formation of the Sun and planets. As to the history of the Solar system after the formation of protoplanets during the first hundreds of million years, it was full of migrations, collisions, mergers and bombardments with ancient meteorites (see, *e.g.*, Gomes *et al*. 2005; Alven and Arrhenius 1979: 50–51; Batygin *et al*. 2016; Bottke *et al.* 2012; Surdin 2012; Morbidelli 2013).

To reconstruct the origin of the protosun, the model of star formation, supported by numerous direct observations, is commonly used. The stars are usually formed in the densest parts of molecular gas-dust clouds, the latter composed mainly of hydrogen and helium and having a temperature approaching to absolute zero. Under these conditions in a cloud with a solar mass there emerge contractions unstable against gravitational collapse and the star formation becomes possible. The gas clouds can preserve equilibrium for many millions and tens of millions years. There is a need for a certain impulse (a trigger) to launch the condensation process (and subsequent collapse). For the birth of the Sun such trigger may have been the shockwave from a nearby supernova about two million years before its collapse started. There is also an opinion that approximately a million years after the start of the solar system formation another supernova exploded (Adushkin *et al*. 2008: 276; Bizzarro *et al*. 2007). These explosions significantly enriched the chemical composition of the future planets of the Solar System (Marakushev *et al*. 2013: 133).

Along with condensation of the gas-dust cloud, a contraction commences – we may also speak of a free fall controlled by self-gravity. The contraction is uneven: the central parts contract faster and turn denser than the outer ones. This process may last for ten thousand years (Marov *et al.* 2008: 225; Motoyama Kazutaka and Tatsuo Yoshida 2003). In the course of the collapse the initial fragment of the nebula breaks into smaller clumps so that it can generate an array of stars. The continuing condensation within the clump makes its matter gradually concentrate thus preparing a transformation into a proto-star. When the density increases by about a hundred of times the cloud becomes opaque to its own infrared radiation (Bochkarev 2010: 13). Consequently, the ongoing contraction generates a great quantity of heat. Heating would slow down compression and stop fragmentation. The interiors of the cloud become hotter than its exterior so there starts convection that is moving of matter. The ceased heat exchange with the environment and the centripetal forces supported by gravity form the structure of the future star consisting of core and envelopes (for more details see Grinin 2013: Ch. 5).

At first the core has a mass of about 0.01 solar masses with the central temperature reaching 2100 Kelvin; meanwhile, the radius of the core is about 6,000 solar radiuses. But the gas falling on the core continues to heat it up. When temperature reaches 10,000 Kelvin, the matter starts to change its structure. As a result of further heating and changing of the structure of matter, the central part of the core contracts sharply again. One can observe the formation of a denser and hotter inner core and of a compound periphery. The pressure increases by more than a thousand times as compared with the initial phase. Gradually, the temperature in the core of the protostar rises.

After the outer and inner cores of the protosun had been formed, the rest of peripheral matter partially flew on the core, adding to the mass of the formation of the star. This process of falling of matter (in the case of a protosun of gas) onto the surface of a body is called accretion. After the accretion shell falls essentially onto the protostar, the latter turns into a new star. Meanwhile, its inner temperature reaches several million Kelvin and thermonuclear fusion starts. The formation of the Sun as a star is supposed to take about a million years, but there are different estimations, some suggesting a longer, others a shorter time span.

The Formation of Protoplanetary Bodies

The protoplanetary disk and its evolution. In the course of the formation of a new star its circumstellar disk often becomes optically visible at visual and shorter wave-lengths. The leftover matter of the accretion disk (of stars including the protosun) is partially scattered into space as well as used in the formation of a protoplanetary disk, also called a preplanetary disk or a cloud. The concept of a 'disk' also reflects the axisymmetric and flattened form of that object whose thickness increases with the distance from the star. Naturally, the mass of this disk amounts to only a small part of the accretion disk.

According to relevant observations, such disk around the stars exists for 5 to 25 million years (Makalkin and Dorofeeva 1995; Zabrodin *et al.* 2008; Marov *et al.* 2008: 225; Kuskov *et al*. 2009: 57; Adushkin and Vityazev 2007: 397).

The difficulties with the reconstruction of planetary formation for the Solar System are connected with the fact that this process is mainly hypothetical, at best modeled by computer simulations, while the data confirmed by direct observations or analysis of the matter from different planets are scarce. The complexity of the problem and the lack of data are commonly compensated by a vast number of hypotheses and theories which have been developed over the last two centuries. But none of the hypotheses can explain the whole range of the facts related to the planets so far.

However, the vast majority of cosmologists believe that the Sun and planets were formed from a single cloud (the protosolar nebula) whose matter differentiated into the Sun and protoplanetary envelope, the latter evolving into a disk as a result of rotation (see, *e.g*., Tlatov 2010: 175). The rotation and fragmentation of this proto-planetary disk formed the planets in the course of a new cycle of accumulation of matter in protoplanetary bodies. The duration of the protoplanetary disk formation is considered within the interval from one to several million years.

At present, the Sun contains 99 per cent of all the matter in the Solar system. We can only guess what part the proto-sun has accumulated, but, apparently, no less than 90 per cent, and the mass of the protoplanetary disk is estimated between 3 and 10 per cent of the solar mass. Even though the protoplanetary disk was not too massive in comparison with the gas-dust cloud from which the Solar system originated, it was nevertheless spatially distributed and rather heterogeneous. The dimensions of the accretion disks of the young stars are in the range from 100 to 1000 astronomical units.

The long-debated question is whether the protoplanetary disk was hot or cold. Most cosmologists proceed from the idea that the planets were formed from cold material, which was later heated by shock wave, radioactivity and other impacts. The disk was more heated in its inward parts while its external regions remained relatively cool. Some contractions occurred there, which contributed to the emergence of separate gravitational centers of planetary formation. Still the mechanism of this process is extremely controversial.

The formation of the dust subdisk. Apparently, the protoplanetary disk was composed of ~98 per cent gas from the proto-solar cloud. Meanwhile, the molecular hydrogen of the latter is about 71per cent by mass and helium about 28 per cent with all other elements constituting about 1 per cent. The dust particles, though accounting from ~0.5 to ~1.5 per cent of mass, might play a prominent role in the evolution. This dust contained microscopic solid grains (water ice, sticky molecules and atoms, in particular iron and other solid matters of micron size). The formation of the protosun that accumulated most part of gas increased the dust concentration in the protoplanetary disk at the later stage of its evolution. But it began to increase even more as a result of the accretion of dust onto the middle plane of the disk.

Some cosmologists (yet, not all of them) believe that the most probable way of formation of planet embryos is the accretion of dust particles (influenced by physical factors and disk rotation) onto the equatorial plane of the pre-planetary disk (Zasov and Postnov 2011: 199). As a result, a dust-gas subdisk was formed in the center of the disk; meanwhile, its 'dust-gas' ratio already differed by 10–1000 times as compared with the surrounding space. In the course of subdisk formation the dust grains can also increase in size (due to sticking and pulling). Thus, the potential planetary system passed a very important transition involving the concentration of solid matter (so far in the form of dust), which played an essential role in the growth of pre-planetary bodies, and later planets. According to some models, the near-solar protoplanetary disk would evolve for one to two million years before a dust-enriched subdisk was formed.

Actually, the dust subdisk was comparatively thin and its thickness was by 10^3–10^4 times smaller than its radius. It must have been opaque to the sun rays, and therefore, they did not reach the periphery of the disk. Among other things, this determined the varying conditions for the formation of planets, depending on the proximity to the protosun.

The started formation of pre-planetary bodies. As some cosmologists suppose, for some time (for about hundred thousand years) due to the gravity and turbulence the subdisk may have contracted while the dust and gas condensations and then clusters may have been formed within it. But the debating point is whether the planets have been formed from these dust and gas clumps (as the condensation theory maintains) or already from solid matter.

The theory of formation of planets from solid matter is called the theory of successive accretion (or accumulation). Many, if not most cosmologists, consider it the most probable scenario. According to it, tiny dust particles would stick together, first forming small particles of solid matter and then larger objects which gradually grew into planetary embryos. The particles of solid matter (from small to large, kilometer or even thousand kilometer size) are called planetesimals.

Another condensation theory (widely used by Russian scientists) is based on the fact that fragmentation of the dust subdisk took place due to the gravitational instability of the dense dust layer in a turbulent environment, and then the pre-planetary dust condensations would be formed. As a result, first there were formed large condensations – preplanetesimals, which then were transformed into large planetesimals, and even immediately into the embryos of the planets according to some alternative approaches within this theory.

The most important stage in the process of planetary embryos formation is the formation of large solid bodies-planetesimals. All theories and hypotheses agree on this point. However, with respect to the number, size and other dimensions of these large objects, there are considerable discrepancies. There are different estimations of the boundary size (critical for the process) planetesimals. The proponents of the theory of successive accretion of matter by planetesimals hypothetically consider the formation of millions and billions of kilometer-sized bodies, which gradually increase while swarming. According to the condensation theory, the largest objects could reach a thousand-kilometer size.

Chaos and the emergence of prerequisites for the formation of order. The role of gas and ice. The particle motion in the proto-cloud (and subdisk) was very chaotic, although basically the movement was directed towards the Sun as the main gravitational center. In this chaos, gas and dust particles move at different speed. Among many forces that influenced the concentration and accumulation of matter, transformation of the protocloud matter into solid objects, determination of orbits and, in general, the protoplanetary formation, two forces are recognized to play a fundamental role in planet formation: gravity and solar radiation. And both of them directly depend on the distance of the object from the Sun. At the distance between 2 and 4 AU from the Sun, between the orbits of Mars and Jupiter, there is a theoretical boundary called an ice line, or a snow line. Water molecules accumulate on this very line as they boil off grains. The ice line turns into an ice cluster which promotes the origin of planetesimals (Lin 2008).

Formation of large planetesimals. When the masses of planetesimals increase, their gravity allows them to attract closely located particles. Thus, there appear numerous kilometer-size planetesimals which start to actively pick up primary dust. Their growth generated the so-called protoplanetary swarm of bodies, where planetesimals of various sizes were swarming. Gradually, there emerged a small-numbered 'elite' consisting of bodies of the size of the Moon or even Mercury. There are many hypotheses concerning their origin. Over time, the orbits of the largest bodies became circular which made them centers of attraction for surrounding matter and thus, transformed into planetary embryos.

While describing the processes in the period from the formation of the objects swarm, including both small and large planetesimals, to the formation of planetary embryos, the proponents of different approaches become better visible. But the discrepancies are still considerable. According to various assumptions on the number of large planetary embryos, it might have been from a few to hundreds of them. As to the timescale of the formation of planetesimals, the assessments vary between tens and hundreds thousand years, while the formation of protoplanetary bodies from planetesimals might have taken several million years.

Planetary Embryos and Protoplanetary Formation

About the matter from which planetesimals and planetary embryos were formed. To understand the processes of protoplanetary formation, it is important to consider the issue of the pristine matter from which planetesimals were formed. From this perspective, of paramount importance are the data on meteorites, many of which were formed during the first million years of the existence of the Solar system, and their composition.

Meteorites, called chondrites, consist of small, millimeter-size grains called chondrules, some of which have a glassy texture (Lin 2008; Shklovsky 1987). This is the oldest and the most common type of meteorites, accounting for 85 per cent of all meteorites. There are extensive discussions and controversial statements concerning meteorites: some would argue that the oldest meteorites have never been melted and incorporated into the primary planetesimals. Still others believe that meteorites were free molten drops, formed as result of fragmentation and distribution of matter, and subsequent aggregation of recondensations formed by the high-speed collisions of objects. In the latter case, it turns out that they were not primary, but secondary rocks.

Chondritic meteorites are similar to most asteroids by their physical properties. So the asteroid belt is also called the chondrite belt. Chondritic meteorites are the samples of planetesimals that originated from the protosolar cloud whose accretion formed the planets of the terrestrial group. Thus, chondrites can reveal the nature of planetesimals and help understand the mechanisms of the formation of planets; they are material evidence of the origin of planets.

The data on meteorites (Connolly 2005) prove that the formation of chondrules took from 2 to 5 million years. According to R. Hazen's figurative expression (2015: 17), when the Sun's nuclear reactor had been switched on, the emerged 'blast furnace' melted the dusty disk into clots of small sticky rock pebbles called chondrules. The grains of stardust and mineral fragments cemented together the clusters of these ancient chondrules to form primitive chondrites, millions of which settled down on the surface of the Earth and other planets.

The emergence of a spherical shape and intensifying geological processes. Some proto-geological processes started already during the protoplanetary formation; in particular, the heat from impacts (collisions) together with the heat from radioactive elements heated and partially melted the matter so that the iron-nickel heavy particles accumulated on the mass-center of future planets while lighter silicate particles were ejected to the surface. Thus, the primary cores, mantles and future planets' crusts were formed (Yazev 2011: 357).

The important formative processes also occurred when the planetary embryos accumulated matter and grew in size and mass. The preliminary calculations show that the emerging objects – planetary embryos – have an oblong shape which would gradually transform so that the protoplanets became spherical. The spherical shape typical of most cosmic objects with diameter exceeding 250–300 km is determined by gravity emerging from heating and softening of the interior. Thus, if the mass of a cosmic body is large enough for its own gravity to cause them to become spherical, it means that geological evolution takes place within its interior. As a result, the matter is differentiated according to the density (light matter floats while heavy matter sinks), heat is released, and chemical reactions take place, *etc*. (Gromov 2012: 47).

Hypotheses about the growing planetesimals and the struggle for resources. The planetesimals would grow due to accretion of matter, including gas, as well as to mutual attraction and accidental collisions. But the larger a planetesimal is, the stronger is its gravity, and the more intensively it sweeps up its low-mass neighbors. Thus, the larger planetesimals would grow through absorbing the smaller ones. When individual planetesimals' masses become comparable to the mass of the Moon, the gravity significantly increases so they can bounce off the surrounding bodies thus escaping collisions. As result of struggles, clashes and mergers, a small number of large cosmic bodies are formed ('oligarchs', planetary embryos, protoplanets), which would dominate in their orbital zones and fight for the leftover matter. At the same time, the growing planetesimals constantly collide and, sometimes merge or on the contrary, split after blows. The numerous splits allowed the larger bodies to capture more and more resources. The already large enough objects would continue to grow. Gradually, the processes of self-organization started to dominate in this chaos.

Depending on their location, the options of growth for planetary embryos differ from each other. The feeding zone for each embryo is a narrow band along its orbit. As soon as the embryo absorbs the most part of planetesimals from its zone, its growth stops. The size of the zone as well as the duration of absorption increases with the distance from the star. At the distance of about 1 A.U. embryos can reach about ~0.1 Earth mass within 100,000 years while at 5 A.U. they can reach four Earth masses within a few million years.

Formation of the Protoplanetary System

Issues and hypotheses about the formation of planetary groups. Most researchers believe that the period prior to the formation of the first planets lasted for at least several million years. But the discrepancies in determining its duration are rather considerable, ranging from a hundred thousand up to a hundred million years.

Since the planets of the Solar system are divided into two categories (terrestrial and gas giants), the problem of their different patterns of formation becomes essential. Was this formation fundamentally the same in both groups, and the differences were determined by the distance from the Sun, or was the process of formation of different groups of planets essentially distinctive, or were there other alternatives? Still some researchers believe that the planets might have been formed almost simultaneously, while others consider them to originate at different times (see below).

No doubt that the distance from the Sun defined the peculiarities of the planetary formation models. Different orbital periods of planetary embryos (the farther the planet from the Sun, the longer the orbit) provided opportunities to capture surrounding planetesimals and, respectively, defined the radius and mass of a protoplanet. The snow line defined a higher concentration of planetesimals and matter in certain regions of the Solar System which could also impact the size of planets in different regions.

However, all these factors are clearly not enough to explain some important phenomena in the Solar system. The first question is looking for the peculiarity of the composition of the terrestrial planets, also asking why these planets have small amounts of hydrogen, helium, and other gases? Questions are furher whether they used to contain gases in their composition or not and in case they did, then how, when, and why they lost the main part of the volatile substance? The second point is why Neptune and Uranus have less hydrogen and more ice than Jupiter and Saturn? And finally, why are Jupiter and Saturn closer to the Sun by their composition than other planets?

There are three main approaches to the issue of formation of terrestrial planets.

1) A planet's mass reaches its present size via accumulation of planetesimals (and meteorites) which results in a gradual differentiation of the planet's interior into core, mantle and crust.

2) The formation of terrestrial planets followed the giant-planet pattern. However, later the terrestrial planets would lose gases into space and only their inner iron-nickel and silicate core would remain. Thus, the iron-silicate nuclei of those protoplanet giants have turned into small independent planets. The differentiation into an iron core and silicate-rock shells would prevent their explosive disintegration (Marakushev *et al*. 2013: 135–137).

3) Jupiter and Saturn affected the formation of terrestrial planets since they accreted all gas from the surrounding disk and pushed planetesimals closer to the Sun, as a result the terrestrial planets managed to increase in mass.

However, the explanatory approach to the formation of terrestrial planets strongly depends on whether the researchers consider the formation of all the Solar-system planets as a simultaneous process or not.

Hypotheses and theories about the outer planets. Many aspects of the formation of giant planets still remain unclear. However, the theory of planetary formation pays special attention to two gas giants which account for 92 per cent of the mass of the whole planetary system (*i.e.*, Jupiter and Saturn, but especially Jupiter). The low temperatures in this zone play a peculiar role since they prevent gas dissipation.

There are two major hypotheses describing the possible formation models of Jupiter and Saturn composed mainly of hydrogen and helium (Vidmachenko and Morozhenko

2014: 22; Kuskov *et al.* 2009: 129–30). The first (contraction) hypothesis explains the fact that gas giants have the same composition as the Sun by the massive gas-dust condensations – protoplanets – that were formed within a massive protoplanetary disk, which later due to gravitational compression would transform into giant planets. According to this hypothesis, the temperature of giant planets was high at the early stage. However, this hypothesis does not explain the disappearance of a considerable amount of matter, not accreted by the planets, as well as the reasons why the composition of Jupiter and Saturn differs from that of the Sun.

According to the second hypothesis of accretion, the formation of Jupiter and Saturn proceeded through two stages. At the first stage, the solid bodies were accumulated similar to the processes with terrestrial planets, and after the mass of the largest bodies reached a critical value (two to ten and more earth masses), the second stage would start – the accretion of gas onto these already quite massive bodies which took place on a time scale of 105–106 years. First, some gas from the Jupiter region dissipated that is why its composition differs from the solar one, and this was even more evident in case of the formation of Saturn. At the stage of accretion, the highest temperature of the Jupiter outer layers reached 5000 Kelvin, and of Saturn – about 2000 Kelvin. The much stronger heating of Jupiter's outer layers determined the silicate composition of its close satellites.

The description of the dynamics of processes proved to be more reasonable in the framework of the accretion hypothesis. The formation of Uranus and Neptune, which contain less hydrogen and helium, is also better explained by the hypothesis of accretion, since most of the gas has already left the Solar System after reaching critical mass.

However, the planet formation via the core-accretion is rather slow and may take several million years. Some researchers (see *e.g*., Lin 2008; Dudorov *et al*. 2015: 11), along with the core-accretion model also account for the gravitational instability in dense and cool regions of the disk that may lead to the formation of planets. The planetary formation due to gravitational instability may take much less time than the core-accretion may require. There is also a hypothesis suggesting that gas giants are formed through a sudden collapse destroying the primary gas-dust cloud. But most cosmologists deny the possibility of gravitational collapse for planets because of their relatively small masses (recognizing it only for stars).

The sequence of the planetary formation. Most scientists suppose that the planets were formed more or less simultaneously. Still a number of scholars believe that some planets were formed before others. Thus, some think that it was Jupiter that came first, then Saturn, while the terrestrial planets were formed much later (within 50 million years), (see, *e.g*., Lin 2008; Savchenko and Smaghin 2013); still others believe that the Earth group planets emerged first (see, *e.g*., Marakushev *et al.* 2013; Vityazev *et al.* 1990). Moreover, there exist grounded opinions (see, *e.g.,* Batygin *et al.* 2016) that the present-day planets (or some of them) are not the first-generation planets since the first protoplanets either fell into the Sun or were ejected beyond the solar orbit, or collapsed.

Some scholars think that at first the terrestrial planets were similar to the giant planets, but later they would lose their fluid envelopes. This is explained by the fact that when close to the Sun most part of light gases from the planetary atmospheres would be blown away by solar radiation to the farther regions and into the open outer space.

Still other researchers believe that it was Jupiter that came first only 2 million years after the started transformation of the protosolar cloud. According to this viewpoint, the formation of this giant was not just the most important moment in the history of the planetary system. When such a planet is formed, it begins to control the whole system. On the one hand, the gas giant stimulates the formation of other giants and terrestrial planets, but on the other, having emerged earlier, Jupiter accreted most part of the gas from the disk, and moreover, it 'swept up' the first-generation asteroids, that is, it accumulated masses of planetesimals and asteroids. The mass of Saturn is smaller than that of Jupiter just because it was formed several million years later. During the following 8 million years after its formation Jupiter would 'help' form other giant planets. According to this hypothesis, the planets of the terrestrial group were the latest to come within the period from 10 to 100 million years. These planets 'were late' for the gas distribution so they accreted small amounts both of gas and solid matter. In brief, 'first come, first served', the distribution of resources in cosmic world is just as unfair as in the biological and social realms (on the 'struggle for resources' in cosmic world see Grinin L. E. 2013: Ch. 5; Grinin A. L. 2016).

The current views on the sequence as well as on the mechanisms of planetary formation in the Solar system make us deal with numerous coexisting competing and contradictory hypotheses. Nevertheless, the whole range of hypotheses allows defining the main contours of this interesting and unique process.

Analogues of planets. Naturally, not all matter could be accumulated into large objects. The planetesimals, which failed to stick into large bodies, as well as fragments after collisions of protoplanets are found within the Solar system as asteroids, meteoroids and comets (Zasov and Postnov 2011: 279). Asteroids and meteorites, found in the Solar system in large quantities, are generally the leftover matter from which the planets were formed. Asteroids have survived due to the fact that the overwhelming majority of them move in a wide interspace between the orbits of Mars and Jupiter. Thus, the asteroid belt is probably a failed planet, whose formation was prevented by Jupiter's gravitational impact.

The Planets' Changing Positions

Did the position of the planets in the Solar system change? As was previously thought, planets remain in the original orbits since their formation. But recently the opinion became popular that it took the planets about a billion years to occupy the current orbits. Thus, the system of planets and satellites emerged within the first few hundred million years. According to V. G. Surdin (2012: 62), the planets formed and moved out to their current orbits about four billion years ago. It is accepted that after this the Solar system has not changed significantly. Great changes occurred on the planets themselves, in their geology, climatology, atmospheric composition and so on.

However, in its early history the Solar system was different. In particular, it is quite probable that the outer Solar system was much more compact in size than now while the Kuiper belt was located closer to the Sun. Migrations of the planets effected their location and orbits as well as the collisions with planetesimals and various other factors, such as meteorite bombardments, catastrophes, collisions, *etc*., which were especially numerous during the first billion years of the history of the Solar system. All alternatives of changing orbits below are still hypotheses, there are hardly any evidence confirming them; moreover, none of them can be considered dominant.

About orbits and changing location of the terrestrial planets. Earlier we have already mentioned that the planets of the terrestrial group were formed not simultaneously under the influence of Jupiter which was the first to be formed. The long-time influence of its gravity caused migration of the emerging planets of terrestrial group, moving them closer to the Sun. If the wave instigated by Jupiter had gone unchecked, it would have pushed all the terrestrial planets to the orbit of Mercury (Lin 2008). According to some assumptions the Earth and other terrestrial planets, existing nowadays, have merged from the scarce debris, leaving almost empty space inside the system.

We emphasize again, that there is also an idea that there were not one but two or more generations of primary planets which Jupiter and Saturn would push onto the Sun or knocked out of the Solar system. Thus, the space within the Solar system has become mostly empty, and the planetary orbits became circular. Thus, the current order required two or more attempts before it was established.

The change of the orbit of Jupiter and other planets. There are many suggestions concerning the migrations of the largest planet in the Solar system. According to one of them, this gas giant must have formed within the inner part of the planetary system, near the snow line, when there was still a considerable amount of gas and solid matter in the disk. Thus, it had to move to its present orbit (Lin 2008). When Jupiter drifted to the Sun dragging Saturn, it functioned as a gravitational bulldozer, 'pulling' several earth masses of ice matter into the system (Batygin *et al*. 2016).

There is a hypothesis that about 600–700 million years after the formation of the Solar system Jupiter began drifting and came into orbital resonance with Saturn. The resonance changed the orbits of both planets since it slowed down their migration inside and sent them back to the outer part of the Solar System. The resonance greatly affected the whole Solar System. In particular, Neptune and Uranus exchanged the orbits since Uranus used to occupy a farther position from the Sun than Neptune (*Ibid*.; see also Batygin and Brown 2016).

It took some time for the planets to come out of resonance. Over a few million years the chaotic interaction between unstable giants 'pushed' Jupiter inward to its present place, while other planets 'moved away'. Moreover, according to one of the exotic hypothesis in the course of such reconfiguration one of the giants may have been expelled to the interstellar space. Here we mean the hypothetical ninth planet which may have existed in the distant past. The rest of the planets gradually stabilized their orbits interacting with the external icy debris (which we now call the Kuiper belt). About 3.8 billion years ago, the giants settled in their current position (Batygin *et al*. 2016: 23).

Further Formation of the Solar System and the Role of Catastrophes

The main landmarks of the completion and arrangement of the Solar system during the first billion years after the formation of the planetary system. As we have already pointed out, the formation of the current architecture of the planetary system took hundreds of millions of years. And this period of 'fixing' and 'arranging' would be quite turbulent and witness numerous catastrophes, as well as various migrations, some of which we have already described above. At the same time, this was the period of enormous geological changes on the planets and their satellites, as a result of which their structure and envelopes were generally formed.

According to some cosmologists when Jupiter and Saturn came into resonance 600 to 700 million years after the formation of the Solar system, this brought about many consequences. In addition to the described above events, they have made the asteroid belt and the Kuiper belt less dense and as a consequence the number of planetesimals decreased by several times (it is believed to decrease by a hundred times but this seems an exaggeration). Anyway, it must have been a dramatic 'cleaning', although the destruction and redirection of planetesimals continued both before and after it.

In addition, the so-called late era of heavy bombardment, or, more precisely, a certain part of this epoch is probably associated with this event (see Bottke *et al*. 2012; Gomes *et al.* 2005). The early era occurred at the beginning of the formation of the planetary system in the first millions or tens of millions years. An immense amount of meteorite precipitation fell on rocky planets during this period. Some scholars used to suppose that it had lasted for 300 million years (from 4.1 bln to 3.8 bln years ago). Yet, the relatively recent studies have shown that this was a long era, which ended not 3.8 but 3.2 billion years ago, that is, it lasted for almost a billion years and was caused by the aforementioned change in Jupiter's and Saturn's orbits after the formation of Neptune and Uranus. Recently it was also suggested that in the past the asteroid belt used to lie at the distance of 1.7 A. U. from the Sun instead of current 2.1 A. U., that is, it has moved away from the sun under gravity impact (see Bottke *et al.* 2012). As a result, catastrophic collisions with asteroids and their powerful impacts on the terrestrial planets continued for a long time.

Formation of satellites. The proponents of cosmogonic hypotheses usually explain the origin of regular satellites (whose orbits are nearly circular and close to the equatorial planes of their planets) by the reproduction on a small scale of the same process that they suggest for explanation of the planetary formation of the Solar system. Jupiter, Saturn, and Uranus have such satellites. However, they explain the origin of irregular satellites (which follow a distant, inclined, and often retrograde orbit) in terms of capture. Since satellites have a gravitational impact on planets, the system 'planet-satellite(s)' evolves over time. In this sense, the systems Earth – Moon and Neptune – Triton evolved due to tidal phenomena.

Collisions and catastrophes in the early history of the Solar system. The most debated are the two supposed catastrophes that occurred during the first hundred million years. The first one was the collision of Venus with Mercury. Venus has a retrograde rotation (counter the rotation of the Sun around its axis) while most other large bodies in the Solar system rotate in the same direction with the Sun. Mercury has a non-proportional nickel-iron core, since its metallic core amounts to 60 or more per cent of its total mass (Solomon 2003). There are several possible explanations here. The first one is that this may be the result of a collision of Mercury with a large asteroid and as a result of this tangent blow Mercury lost most of its mantle and shell (Yazev 2011: 48). There is also a more exotic alternative that Mercury was initially farther from the Sun and moreover, it was not a planet but a satellite of Venus from which it later 'escaped'. This explains both Mercury's small size, more appropriate for a satellite, and the retrograde rotation of Venus. The mainstream theory here is the tidal effect of a large satellite (*i.e.*, of Mercury) which long ago both retarded the planet's orbital motion and even made it rotate in the retrograde direction (*Ibid*.: 57–58).

Another famous hypothesis associated with catastrophes states that between 30 and 100 million years after the formation of the Sun, a Mars-sized planet embryo collided with the proto-Earth ejecting a huge amount of debris that later would coalesce to form the Moon. Naturally, such a powerful blow scattered an enormous amount of matter within the Solar system. This giant impact should have swept away the Earth's primitive atmosphere. The Earth's present-day atmosphere mostly came from the gas trapped in the planetesimals that formed it. Later this gas was vented by volcanoes (Lin 2008). This assumption has several alternatives. There exists a fascinating hypothesis, suggested by William K. Hartmann and Donald R. Davis in 1975, that for millions years a protoplanet Theia may have orbited close to the proto-Earth and finally collided with it. The collision is thought to occur almost tangentially and at a relatively slow velocity. That is why some of the Earth's and Theia's mantles were ejected to the low earth orbit and from these debris the Moon would be formed which started to rotate along circular orbit.

More hypotheses about collisions. We have mentioned above that about 600–700 million years after the collapse of the protosolar nebula Neptune migrated into a new orbit. Recently, a hypothesis has been put forward by David Nesvorn, the astronomer from the Southwest Research Institute in Boulder, that there used to be not four but five giant planets in the Solar System, and that the fifth planet collided with migrating Neptune and pulled it to the current orbit while the fifth giant planet had collapsed into a cluster of debris which Neptune threw out into the Kuiper belt, that is, to the outskirts of the Solar System (it was generally believed that during its migration Neptune threw out planetesimals, but not the debris of the planet which it had destroyed).

On the whole, a number of impressive catastrophes, changes and losses occurred before the Solar system reached a more or less stable state: two of the nine planets (Theia and the fifth giant planet) were destroyed and disappeared, while Mercury became an independent planet (or was strongly crumpled and reduced in size while being settled in its current position); Venus started to rotate in the retrograde direction; Neptune distanced itself from the Sun significantly, throwing the debris of the broken planet to its outskirt into the Kuiper belt; the resonance between Jupiter and Saturn caused a powerful bombardment of the terrestrial planets and sharply cleared the asteroid belt and the Kuiper belt.

Whether these catastrophes happened in reality or not, anyway, one can rightly expect that the formation of such a compicated and powerful system as the Solar system should have been accompanied by certain disasters and great headwinds (see Grinin 2017 for a detailed and systematic narration of the history and evolution of the Solar system, and the literature on this issue).

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