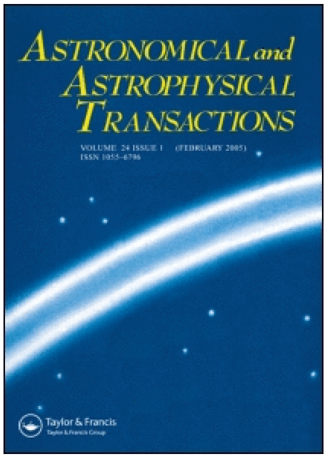

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A. A. Marakushev [a]
[a] Institute of Experimental Mineralogy, Russian Academy of Sciences, Moscow oblast, Russia

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Cosmic petrology and the planetary evolution of the Solar System

A. A. MARAKUSHEV*

Institute of Experimental Mineralogy, Russian Academy of Sciences,
Chernogolovka, Moscow oblast 142432, Russia

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Cosmic petrology, whose origin was triggered by astronomic discoveries at the turn of the twenty-first century, now plays a pivotal role in the 'compositional' interpretation of the results of extraterrestrial observations. Cosmic petrology is able to play this role owing to the experience gained in studying meteorites and, in particular, chondrites, which display preserved traces of their two-stage evolution. The latter relates these meteorites to the planetary evolutions of the Solar System. This evolution started with the origin of the giant planets via the accretion of water–hydrogen icy ('cometary') planetesimals simultaneously with the accumulation of the Sun's mass. They underwent contraction with the release of energy sufficient for their complete melting and subsequent differentiation into giant fluid envelopes and chondritic cores. The iron–silicate differentiation of the latter brought about the magnetic fields of the giant planets. The Sun evolved even further and, upon reaching its stellar state, began actively to affect the surrounding planetary system and induced the dissipation of the dense interplanetary nebula in space. This process gave rise to the rapid rotation of the giant planets. The influence of the Sun on the giant planets caused the surface migration of hydrogen, a process accompanied by the acceleration of the rotation and, as a consequence, the separation of satellites under the effect of centrifugal forces. This glaringly manifests the deceleration of the planetary evolution with increasing distance from the Sun. This effect was at a maximum on the near-Sun giant planets, which have lost their fluid envelopes, so that their cores were transformed into independent terrestrial planets simultaneously with the loss of their satellite systems. The preserved relics of these systems are the Moon of the Earth, and Phobos and Deimos of Mars. They provide evidence of the very old age of the near-Sun terrestrial protoplanets, in contrast with the relatively young ages of satellites of the giant planets belonging to the Jovian group. The Moon is one of the oldest known satellites in the Solar System. Volcanic activity on the Moon has an age of 4.6–3.2 Gyears, whereas its analogue Io (a satellite of Jupiter) is now characterized by the culmination of its volcanic activity. Volcanic events on the satellites of the giant planets and on the terrestrial planets are some of the most conspicuous manifestations of their endogenic activity, which is caused by the fluid state of these molten cores, generating magnetic fields. This activity was lost by planets when their consolidation was completed. The duration of the endogenic activity of planets was predetermined by their protoplanetary evolution in the form of the cores of their parent giant planets. In this sense, the Earth is a unique planet, whose endogenic activity has already lasted for 4.6 Gyears, whereas the Earth's core is now less than 50% consolidated. This makes the Earth different in a major way from the rest of the terrestrial planets (Mercury, Venus and Mars), whose endogenic evolution terminated at a primitive stage because of the loss of their fluid components as a result of complete consolidation, which was coupled with the loss of their magnetic fields. There are good reasons to believe that the Earth had completely differentiated under the tremendous pressure of the fluid shell of its parental planet (Proto-Earth), and this predetermined the huge reserves of fluid components stored in its liquid core. At the same time, the differentiation of the other terrestrial planets was associated with the loss of the fluid shells of their parental protoplanets. The effect of parent protoplanets was

*Email: marakush@igem.ru

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even weaker in the states of the satellite planets, which lost their fluid shells and differentiated in space vacuum, a process that was responsible for the low reserves of fluid components in their molten iron cores and, correspondingly, their relatively short-lived endogenic activity (1.4 Gyears). The endogenic activity of iron–stony planets is caused by their protoplanetary evolution, which was associated with the concentration of fluid components in their molten cores, whereas the planetary stage itself was accompanied only by the loss of fluid components coupled with endogenic activity up to the complete consolidation of the planets. Traces of these two evolutionary stages can also be discerned in more primitive chondritic planets, whose orbits are situated around the terrestrial planets and lie between the orbits of Mars and Jupiter. Because of the greater distances between these planets and the Sun, they did not have sufficient time to differentiate and develop their rigid silicate shells. Because of this, these planets underwent explosive break-up and gave rise to the asteroid belt ('chondritic belt'), the source of meteorites. The two-stage character of the evolution of the planets can also be definitely inferred for chondrites. During the early protoplanetary stage, the isotopically anomalous evolution of chondritic melts proceeded as chondrites differentiated into chondrules and matrices, in which diamond nuclei with abundant inclusions of fluid components were formed. This testifies that they were produced under the huge pressures of the fluid shells of the giant planets. Chondrites crystallized mostly later, during the planetary stage proper, under a relatively low pressure. In contrast with the protoplanetary stage, this was not associated with the anomalous fractionation of isotopes.

Keywords: Cosmic petrology; Planetary evolution; Giant planets; Terrestrial planets; Satellites of giant planets

1. Introduction

Cosmic petrology [1] deals with the solid material of the Solar System, which can be provisionally classified into two groups: icy (cometary) and iron–stony (meteoritic).

The cometary material is inaccessible for petrographic examination, although it is known to be dominated by water ice with particles of iron–silicate dust. The latter is introduced into the Solar System by comets and brings about meteor showers in the Earth's atmosphere. The meteoritic iron–stony material has been studied on the Earth since ancient times, and the world's meteorite collection (about 2000 samples) includes 86% chondrites (iron–stony meteorites) and 14% other types, with roughly equal percentages of iron-rich (iron meteorites and pallasites) and silicate (achondrites) meteorites. After finding meteorites in the ice of Antarctica, the overall number of meteorites found increased more than tenfold, but the aforementioned proportions of their major types did not change. Chondrites remain the predominant type and are subdivided into ordinary (93%), carbonaceous (5%) and enstatite (2%). Ordinary chondrites are further classified according to their iron contents into very rich in iron (HH), rich in iron (H), poor in iron (L) and very poor in iron (LL). The composition of ordinary HH chondrites corresponds to the average composition of the Earth. These meteorites are also comparable with terrestrial and lunar rocks in terms of oxygen isotopic composition [1]. They are analogues of the material composing the Earth. The chondritic model of the Earth has long been used in cosmochemistry but, in our opinion, it erroneously refers to carbonaceous chondrites (C1) as the primary material of the Earth, although these meteorites have an oxygen isotopic composition quite different from those of terrestrial rocks. Also, we consider invalid the cosmochemical interpretation of chondrites as the direct condensates of the protoplanetary nebula that were later metamorphosed and accreted to produce the terrestrial planets, which served as planetesimals [2]. This model is at variance with the results of petrographic examination of chondrites, which indicate that chondrites are, in essence, magmatic rocks with characteristic textural features of liquid immiscibility, a process responsible for their differentiation into an iron-rich matrix and chondrules (tiny silicate droplets). Chondrules are obviously replaced by the matrix melt. Overprinted low-temperature metamorphism is widespread only in carbonaceous chondrites (C1), in which clinozoisite, serpentine and other secondary minerals contain only relics of magmatic minerals (olivine, pyroxenes and plagioclase). The genesis of chondrites and their role in the origin of the terrestrial iron–stony planets will be considered below, in compliance with the chondrite model, together with the simultaneous general evolution of the solid material of the Solar System.

2. Cometary suite of the Solar System

The icy material is primary, formed by the direct condensation and solidification of the gas nebula, which had been produced by the explosion of a giant star, the precursor of the Solar System. The Solar System inherited from this giant star its chemical elements, up to the heaviest elements (uranium, thorium and others), which were produced by the final explosions of giant stars [3]. The Sun itself (a yellow dwarf) is able to synthesize only relatively light elements, which are not available for examination.

The icy material is now preserved only in the surroundings of the Solar System, where the most remote Oort cloud and the Hills and Kuiper belts, from which comets originate, are composed of it. Comets consist mostly of water ice impregnated with iron–silicate dust particles and contain numerous carbon-bearing compounds. Their surface evapouration produces black polymer coatings on the nuclei of comets. These coatings are distorted by the explosion of water vapour in the form of jets. The latter create white stains on the black surface. Consequently, cometary nuclei acquire their typical appearance, which is also characteristic of larger accretionary objects of water ice, which possess the proper names Ixion, Varuna, Quaoar, Chaos and others. Another object of this group is Pluto, whose diameter is 2320 km and which is compared with the nucleus of comet Halley in figure 1. These objects display combinations of black backgrounds and paler stains, although the background of cometary nuclei is darker, which determined them as objects darker than Pluto. As is also typical of cometary bodies, the albedo of Pluto should increase on approaching the Sun. The surface evaporation of Pluto over a very long period caused the rounded shape of this body, which is often mistaken for a planet, although its orbital plane does not coincide with the ecliptic plane but is inclined to it at an angle of 17°. Owing to the significant offsetting of its orbit, Pluto comes into the Solar System from the Kuiper belt and runs along part of its circumsolar trajectory within Neptune's orbit.

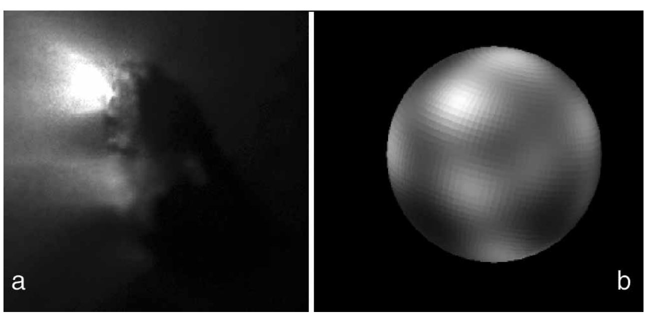

Figure 1. (a) Image of the nucleus of comet Halley (16 km × 8 km) (the image was taken by the Giotto space probe in 1986) in comparison with (b) an image of Pluto (2320 km in diameter; computer-processed data obtained by the Hubble Space Telescope). The dark colours of the objects are caused by refractory polymeric compounds accumulated on the surface during ice evapouration. Pale stains resulted from explosive jets of water vapour.

3. Giant planets

The principal difference of Pluto from other planets is clearly demonstrated in figure 2, in which Pluto is compared with Uranus (51 800 km in diameter). The latter is differentiated into an iron – silicate core and a giant fluid shell and is orbited by a satellite system. Pluto forms a rotary system with Charon (diameter, 1270 km), both having similar geneses and produced by the direct accretion of icy material. Because of this, Pluto and Charon are hierarchically equal in the genetic sense, and neither of these was derived from the other. In contrast with Pluto, planets (Uranus in this example) are parental for their satellites, which were separated from their vast fluid shells under the effect of centrifugal forces on rapid rotation and now revolve around the planets in their equatorial planes. Simultaneously the giant planets developed their iron-richer iron – silicate chondritic cores. The giant planets were the only systems in which the iron – stony (meteoritic) material was generated and underwent its subsequent chondrite – achondrite differentiation. The abundance of fluids in the melts that separated into satellites and planetary rings is reflected in their silicate – ice compositions. The separation was coupled with the migration of the most volatile components (hydrogen, helium and others) and the enrichment of the icy phase in relatively refractory components (water, hydrocarbons and others), *e.g.* according to the disproportionation reaction of components during cooling:

$$3H_2 + CO = H_2O + CH_4.$$

Uranus and Neptune are the outer planets and the most distant from the Sun, whose bulk composition is close to the average composition of comets and is dominated by water. This characterizes the composition of planetesimals, whose accretion produced Uranus and Neptune. They differed from small cometary accumulations (Pluto, Charon and others) in having huge masses, which were sufficient for gravitational contraction, energy release and complete melting, a process that produced the giant planets. The onset of liquid immiscibility in these planetesimals resulted in their differentiation into iron – silicate (chondritic) cores, fluid – silicate (achondritic) satellites and vast fluid shells. The molten masses of the satellites were segregated under the effect of the rapid rotation of the giant planets and became concentrated in the equatorial planes of these planets. The proportions of the gravity and centrifugal forces controlled the distributions of components between the chondritic cores and achondritic satellites. Iron was preferentially concentrated in the chondritic cores, which differentiated during the subsequent evolution of the giant planets and formed molten subcores (which generated the strong magnetic fields of these giant planets). The satellites acquired much less iron, which nevertheless formed the molten cores of massive satellites. These cores generated the magnetic fields of the satellites, with these fields surviving until complete consolidation of the satellites. Because of this, the presence of magnetic fields of satellites is correlated with their endogenic activity. This can be illustrated by the examples of Ganymede,

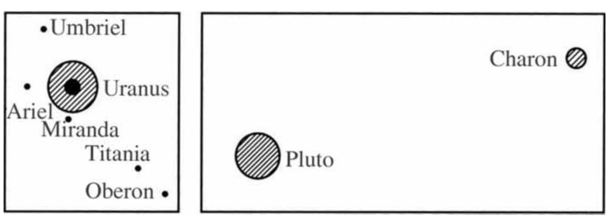

Figure 2. Structure of Uranus (51 800 km in diameter), which is differentiated into a molten iron – stony core and a fluid shell, and the system of its satellites (Miranda, 235 km; Ariel, 580 km; Umbriel, 585 km; Titania, 799 km; Oberon, 770 km) in comparison with the double-cometary system Pluto (2320 km) and Charon (1270 km).

Io and Europa, Jupiter's satellites, whereas another of its satellites, Callisto, has lost both its endogenic activity and the magnetic field because of complete consolidation. The Moon, the oldest analogue of Io, lost its volcanic activity at approximately 3.2 Gyears, simultaneously with the loss of the magnetic field, whose traces can now be identified in the form of the remanent magnetization of lunar rocks. Satellites are incomparably smaller than their parent planets and could acquire fast orbital velocities only owing to the rapid rotation of the giant planets from which these satellites were separating.

With the transition from the peripheral planets (Neptune and Uranus), which are similar in composition to the cometary surroundings of the Solar System, to its inner planets, the sizes of the planets increased and their compositions approached that of the Sun, because the planetesimals acquired composition containing predominantly hydrogen (figure 3) owing to the temperature decrease toward the centre of the solar disc. The example of Jupiter in figure 3 clearly illustrates the tremendous temperature increase as a result of gravitational contraction during the origin of giant planets. This temperature increase was responsible for the thermal radiation of the planets and makes them look like stars (the so-called wandering stars).

Although the Sun and its planetary and cometary suites now occur in space vacuum, they were produced in a huge gas – dust disc, which was generated by the explosion of the precursor star of the Solar System. The latter inherited from this protostar not only its chemical composition but also the kinetic energy, which is predominantly concentrated in the giant planets. The latter were 'spun' by the disc around the slowly rotating Sun.

The rapid and mutually consistent revolution of planets, which was far from adequate for the slow rotation of the Sun, was created by the dense interplanetary environment (protosolar disc in which they were produced), as has been hypothesized already by Immanuel Kant (1755). However, the mass of this environment was assumed by Kant to be equal to the mass of the Solar System that created the basis for the currently existing revolution of space bodies, after which gravity cleaned this space, and the interplanetary material concentrated in planets, comets and the Sun itself. However, the mass of the modern Solar System is obviously insufficient for the observed 'revolution of the bodies'. This was convincingly demonstrated by Shmidt [2, 4], who emphasized that the dynamics of the Solar System are characterized by 98% of its

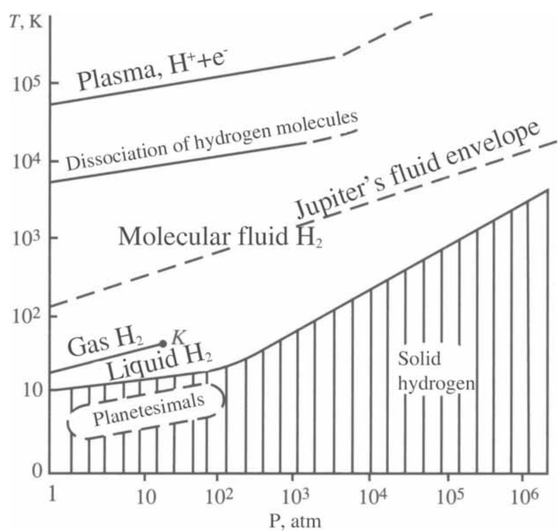

Figure 3. *P–T* diagram for the state of hydrogen (K is the critical point). The outlined area corresponds to the origin of hydrogen icy planetesimals whose accretion produced the masses of the Sun and its nearest planets (Saturn, Jupiter and the terrestrial protoplanets). The diagram also shows the modern state of the giant fluid shell of Jupiter.

kinetic momentum caused by planets, which accounted for as little as 1/700 of the mass of the system. According to Shmidt, this fundamental state can be explained if '. . . we cease to consider the Solar System separately from the greater system whose part is our Solar System' (p. 81 of [4]). As a variant of the dynamic expansion of the Solar System, Shmidt proposed 'the hypothesis that the Sun captured the interstellar material, gas – dust nebulae that participated in the galactic revolution' (p. 82 of [4]).

In fact, this greater system 'whose part was the Solar System' was a gas nebula that had been produced by a supernova and eventually transformed into a very rapidly rotating vast disc of dense gas – dust mixture, whose mass increased from its internal to its peripheral parts. The giant planets and cometary accumulations that developed in this disc inherited not only its chemistry but also the kinetic energy and its typical distribution between the central and peripheral parts. Upon reaching its stellar state, the Sun began actively to affect its surroundings and induced, first of all, the migration of the dense material of the protosolar disc into space. This process predetermined the mutually consistent revolutions of the giant planets and surrounding cometary accumulations. Upon the dissipation of the disc under the effect of the solar wind, both the Sun itself and the surrounding giant planets and comets occurred in space vacuum.

An analogue of the Solar System during this evolutionary stage seems to be the modern structures of the numerous star – planetary systems that were recently discovered by astronomers (see, for example, [5–7]) and whose stars are surrounded by near-Sun giant planets and brown dwarfs (figure 4). Now they exist in space vacuum, but the fact that they are surrounded by dynamic planetary systems provides evidence of vast nebular discs that at some time encompassed these stars. The masses of the giant planets first increase toward the stars (arrow), with

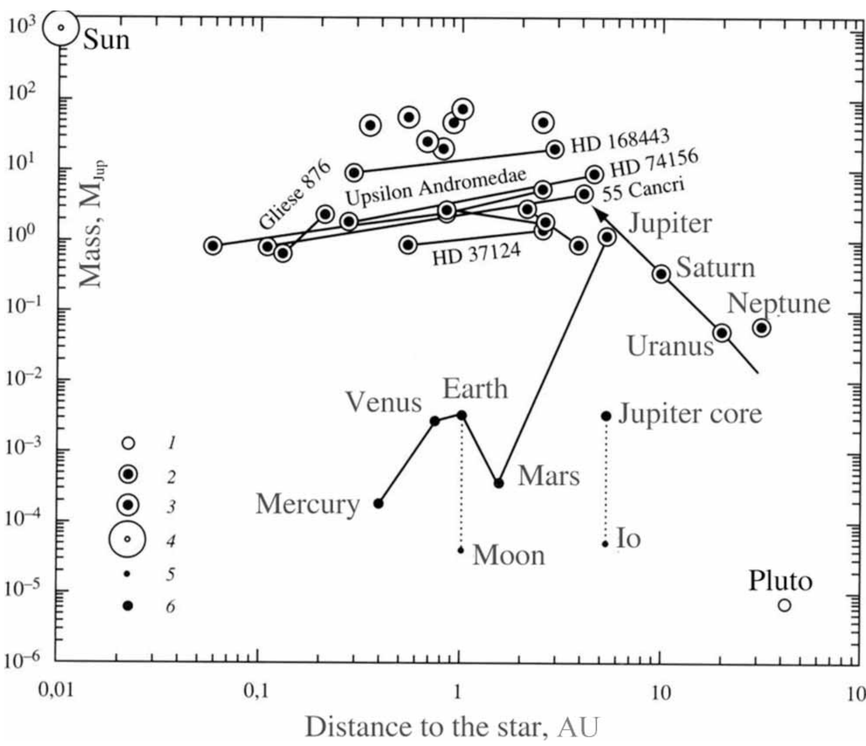

Figure 4. Solar and analogous stellar – planetary systems: 1, icy planetesimals; 2, giant planets; 3, brown dwarfs; 4, stars; 5, satellites; 6, terrestrial planets, which are comparable with the iron – silicate core of Jupiter.

these planets giving way to brown dwarfs near the stars, and then decrease as a result of their surface degassing under the effect of the star wind (tie lines in the diagram). This reflects the prograde and retrograde (destructive) evolution of planetary systems. The prograde evolution of planetary systems ends with the origin of central stars (the Sun and others), after which the opposite retrograde (destructive) evolution of the planetary systems begins under the effect of the stellar (solar) wind. In the overwhelming majority of planetary systems, stars analogous to the Sun (yellow dwarfs) have not been produced at all, and the evolution of these systems was limited to the development of brown dwarfs that occupied central positions analogous to those of stars. They float through the galaxy independently (as stars do) and thus differ from brown dwarfs, which inhabit orbits around stars (as planets do).

Brown dwarfs 'span a mass range of 12 to 75 Jupiters: too light to attain high central temperatures required to fuse ordinary hydrogen nuclei but heavy enough to fuse deuterium. Newly formed brown dwarfs shine like feeble stars but quickly exhaust their deuterium supply and start to cool down like planets' (p. 26 of [8]).

The origin of brown dwarfs, which are intermediate between stars and planets, reflects the uniformity of the genesis of planets and dwarf stars, which is predetermined by a systematic temperature decrease towards the central parts of their parent discs to the level at which hydrogen becomes involved in the accretion of their material (figure 3).

4. Surface degassing of giant planets and the origin of terrestrial planets

In the Sun and analogous stars that developed in the central parts of the gas–dust discs that were produced by giant stars, hydrogen fusion proceeded, which determined their star states as yellow dwarfs. In the overall evolution of the stellar world, the generation of heavy metals in giant stars with relatively short lifetimes results in their replacement by long-lived yellow dwarfs surrounded by planetary and cometary systems [9]. The calculated lifetime of the Sun is close to 10 Gyears. For about half of this time, the Sun actively affected its rapidly revolving surroundings and induced the dissipation of the nebula matrix of cometary and planetary bodies and the surface degassing of near-Sun giant planets. The primary state is now preserved in the inner zone only by Saturn, the lightest planet of the Solar System, whereas the giant planets, which are closer to the Sun, underwent significant transformations.

Astronomical observations [7, 10] detected the degassing of the giant planets, a process accompanied by the loss of the mass of these planets (figure 5) due to the surface migration of hydrogen (figure 6).

It is reasonable to believe that the complete loss of the huge fluid shell of planet HD 209458b should result in the transformation of its dense core into an iron–stony planet, whose position relative to its parent star (HD 209458) resembles that of Mercury relative to the Sun in the Solar System. The near-solar giant planets have completely lost their fluid shells, and their dense cores were transformed into individual terrestrial iron–stony planets.

Their analogues were recently discovered near small stars [11]. These discoveries provide reason to hope that these systems can include analogues of the Earth, some of which possibly not only have analogous sizes but also occur at the optimal distances from their stars, in the so-called continuous inhabited zones, which makes it possible for the planets to develop hydrospheres. The latter is, in turn, necessary for the origin and evolution of life.

The retrograde evolution of planetary systems is the most active in near-star planets and manifests itself in the complete loss of their fluid shells. This evolutionary stage in the Solar System has progressed up to the development of terrestrial planets.

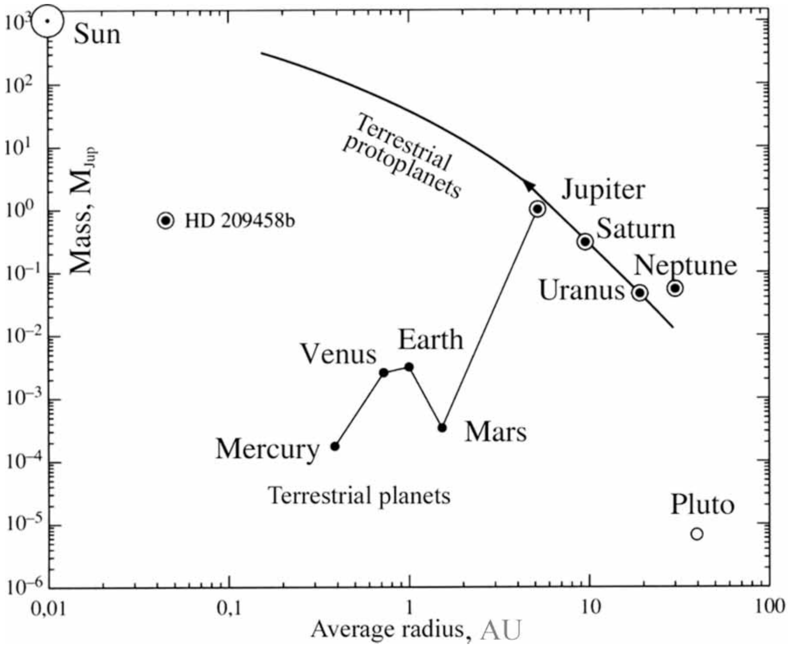

Figure 5. Model for the origin of the terrestrial planets via the loss of helium – hydrogen shells by the giant parent protoplanets under the effect of the Sun. For comparison the position of the giant planet HD 209458b, which is now losing its hydrogen shell under the effect of the star HD 209458, is shown.

The early stages of the influence of the Sun on the masses of the giant planets can be traced using data on Jupiter, a planet of anomalously high density (1.3 g cm^{-3}), which is almost twice that of Saturn (0.7 g cm^{-3}). This reflects the significant loss of hydrogen by this planet as a result of its surface degassing, a process that was associated with the weakening of the gravitational field and the loss of some of Jupiter's satellites. The lost satellites inherited Jupiter's orbit and formed the Trojans asteroid family on it [12]. The Trojans are dark asteroids. According to [13], the largest of these asteroids have radii of 25–120 km and an albedo of 0.03–0.09;

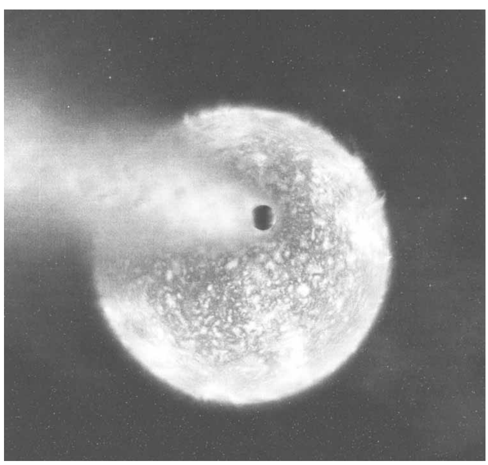

Figure 6. Giant fluid shell of the planet HD 209458b. Because of the orbiting star HD 209458, the planet leaves behind a vast hydrogen trace.

only a few of these asteroids (Ennomos) have an albedo as high as 0.13–0.18. Judging from these values, the Trojans consist of ferrous olivine, pyroxene and insignificant amounts of plagioclase. The variations in the albedo of the Trojans are caused by their irregular shapes and revolution, and also by the development of double rotational systems (Patroclus), which are typical of asteroids.

The Trojans provide relatively young SNC meteorites (ferrous olivine and pyroxene melanocratic achondrites with ages of approximately 1.3 Gyears, which reflect the young ages of the Jovian-group giant planets). Io, a massive satellite of Jupiter that is the closest to it, is now characterized by highly explosive high-temperature (approximately 1500 °C) volcanic activity [14, 15]. Io separated from Jupiter in the form of a molten fluid – silicate mass. An important discovery was the detection of a vast elongated hydrogen cloud accompanied by a torus of hot plasma ($T = 10^5$ K) that revolved together with Io around Jupiter at a distance of 422 000 km from it (p. 154 of [16]). This furnishes direct evidence in support of the recent origin of Io and provides insight into the mechanism of its origin in the system of Jupiter differentiation into an iron – stony core (which generates the magnetic field of this planet), a satellite system (which separated owing to the rapid rotation in the past) and a hydrogen shell. Figure 7 demonstrates the analogies between the sizes of the Earth and the core of Jupiter and between the Moon and Io (the nearest and the densest of Jupiter's satellites).

Achondritic satellites, which separated from giant planets, were formed synchronously with the heavy chondritic cores of these planets. The distribution of the iron and silicate material between them was controlled by the ratios of the gravitational forces, which formed the cores, and the centrifugal forces, which were determined by the rotation velocities of the planets and controlled the separation of the satellites.

The degassing of near-Sun planets was accompanied by the loss of their satellite systems, whose only preserved relics are now the Moon (the satellite of the Earth) and Phobos and Deimos (fragments of Martian satellites). The loss of the satellites was associated with their explosive destruction, the partial inheritance of orbits from the terrestrial protoplanets, and the development of asteroid families: the Amors, Apollos and Athens. The destruction of the satellites of the Proto-Earth also caused the origin of so-called lunar meteorites. Figure 8

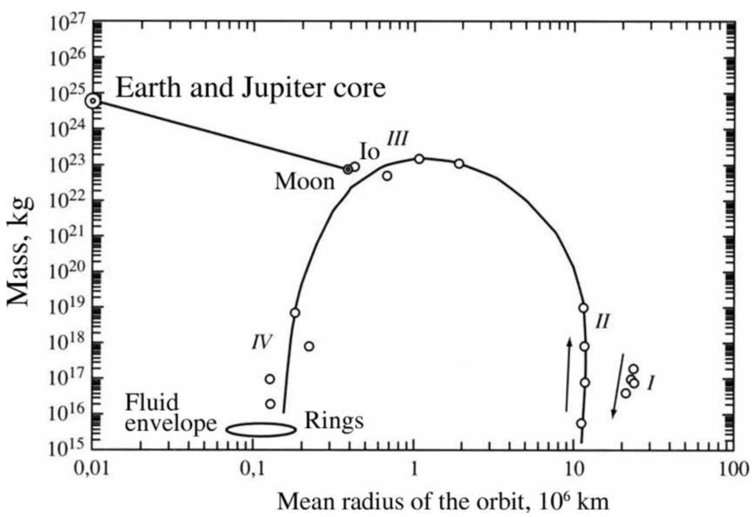

Figure 7. Jovian satellite system in comparison with the Earth – Moon system: I, remote satellites of early opposite revolution around Jupiter; II, light remote satellites of normal evolution; III, massive near-planet satellites of normal evolution; IV, near-planet light fragmentary satellite related to the origin of the rings. The arrows indicate the opposite revolution (I) and direct revolution (II) of the satellites.

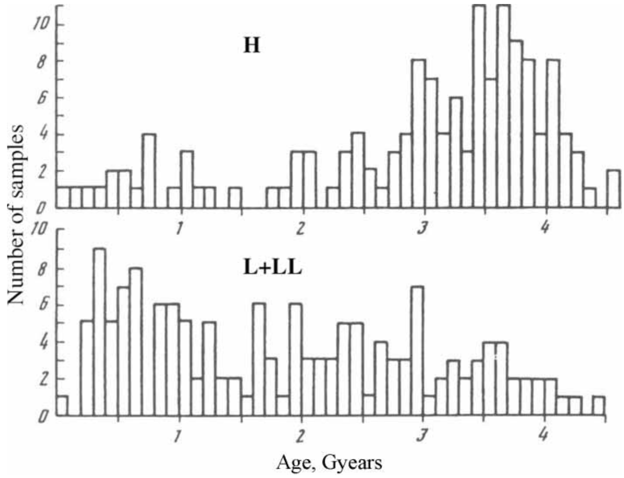

Figure 8. Histograms for the absolute ages of ordinary chondrites, which are classified into iron-rich (H) and iron-poor (L + LL) types [17, 18].

demonstrates the orbital correspondence between the Moon and Io (which have similar sizes), because of which the Moon fits the Jovian satellite system. It is reasonable to hypothesize that this system is analogous to the satellite system of the Proto-Earth, which lost its satellite system simultaneously with the loss of its giant fluid shell.

5. Satellite – planetary evolution of the Solar System with time

Although the systems of the Earth and Moon and of the core of Jupiter and Io display several similarities, they are principally different in age. The Moon is the oldest of the currently preserved satellites in the Solar System. Volcanism occurred at the Moon within the age interval 4.6–3.2 Gyears, whereas volcanic activity on Io is modern. This is correlated with the occurrence of modern volcanic activity on several other satellites of the giant planets of the Jovian group, including Triton, a satellite of Neptune (a planet that is the most distant from the Sun), on which active ammonia geysers have been identified [19]. The occurrence of the latter suggests the following disproportionation reaction that takes place in hydrogen fluid flows coming from the core:

$$H_2 + NO = H_2O + 0.5\,N_2.$$

The differences between the ages of satellite systems situated near the Sun and away from it reflect the different rates of the evolution of their parent giant planets. The effect of the Sun on the giant planets induced the loss of hydrogen from their surfaces, a process that accelerated their revolution and thus facilitated the separation of satellites.

It was emphasized above that the origin of the satellites of the giant planets and their chondritic cores are coupled processes, and this suggests their simultaneousness. This can also be extended to the age of the terrestrial planets, which were produced by the differentiation of the chondritic cores of the protoplanets. From this standpoint, the oldest and most evolved satellite system of near-Sun planets was the lost system of Proto-Mercury. It had captured much of the silicate material, and this has predetermined the anomalous richness of Mercury in the nickel – iron phase. In this respect, Mars evolved in the opposite direction to that of Mercury, and Venus and the Earth occupied an intermediate position. The giant planets situated far away from the Sun are characterized by degrees of their planetary evolutionary maturity decreasing in succession from Jupiter to Saturn, Uranus and Neptune, which is correlated with a decrease in the number of their satellites.

The above materials and speculations concerning the coupled character of the separation of satellites and the development of chondritic cores of the giant planets make it possible to attack the age problems of the planetary evolution using data on the asteroid belt from which chondrites originated. The asteroid belt, in which planets that were completely degassed on their surface underwent explosive break-up, is, in a sense, transitional from the terrestrial planets to the giant planets of the Jovian group. Correspondingly, the age of meteorites predominant in this belt (ordinary chondrites) broadly varies (figure 8), with H chondrites predominantly having ages within the range 3–4 Gyears, and L + LL chondrite possessing ages of about 1 Gyear, *i.e.* close to those of SNC meteorites.

The asteroid belt consists of fragments of planets at very primitive (chondritic) evolutionary stages. Nevertheless, Vesta, an asteroid 516 km in diameter, was found to bear basaltic flows [20], a fact suggesting a higher evolutionary level of the planet whose break-up produced this asteroid.

A very important distinctive feature of the terrestrial planets is their long-lived endogenic activity, which was predetermined by their protoplanetary evolution in the interiors of the respective parent planets. In this sense, the Earth is a unique planet, which has completely differentiated under the huge pressure of the fluid shell of the Proto-Earth. As a result, the molten nickel – iron core of the Earth contains tremendous amounts of fluid components, which have maintained and controlled the endogenic activity of the planet for 4.6 Gyears [21]. In contrast with the Earth, all the other terrestrial planets differentiated during their transition to the planetary evolutionary stages; thus, they have limited reserves of fluid components stored in their cores and are characterized by briefer periods of endogenic activity (about 2–3 Gyears). This activity died off as the planets consolidated and simultaneously lost their magnetic fields. Still briefer time periods of active evolution were characteristic of massive satellite planets, which separated from their giant parent planets in the form of fluid – silicate (achondritic) masses, differentiated and consolidated in space vacuum. Correspondingly, the relatively small nickel – iron cores of these planets contain limited reserves of fluids and, hence, the volcanic activity of these planets was relatively short lived (no longer than 1.4 Gyears (*e.g.* within the time span of 4.6–3.2 Gyears for the Moon)).

6. Conclusion

It is expedient to consider the current state of the Solar System (figure 9). The slowly rotating Sun (25 days at the equator and 35 days at high latitudes) is surrounded by giant planets, which rapidly revolve around the Sun along almost circular orbits, and by small objects, which inherited their circular orbital movements from larger bodies; these are the terrestrial planets, asteroids, the lost satellites of planets, and cometary accumulations, which compose the Kuiper and Hills belts and the distant Oort cloud. The planets are, in turn, orbited by their satellites; binary rotational systems with smaller bodies are composed of asteroids and cometary accumulations. The largest of the known cometary bodies is Pluto, which forms a rotational system with Charon. The break-ups (which were mostly explosive) of the large bodies into smaller fragments modified the circular orbits into elliptic, parabolic and hyperbolic. They control meteorite falls onto planets (planet-centric or heliocentric) and the invasions of comets into planetary systems. Over the huge time spans during which they fell, the asteroid belt and

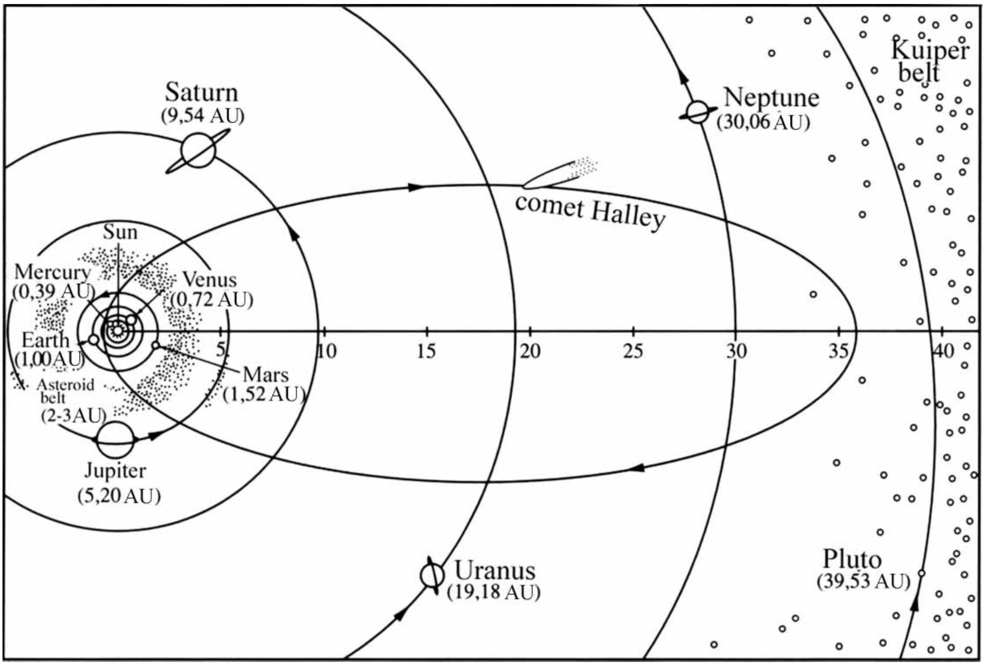

Figure 9. Structure of the Solar System and the orbit of comet Halley in it (the numerals correspond to the distances in astronomical units (AU)). The comet revolves around the Sun with a period of 75–76 years and was first observed in 240 BC. It was recently seen in 1986 and is expected to appear in 2061. As can be seen, the comet (similarly to Pluto) originates from the Kuiper belt.

cometary suite of the Solar System were significantly exhausted, so that it is virtually impossible to assay their original sizes. Now more than 2300 asteroids have been detected between the orbits of Mars and Jupiter. These asteroids revolve around the Sun in the same direction as the Earth and other planets do, *i.e.* from west to east. This was predetermined by the compatibility of the revolution of all giant planets around the Sun. The same also pertains to the parent planets of the terrestrial planets and asteroids, which are classified into ten families according to their affiliation (in addition to the family of the lost and decomposed satellites of planet) and inherited orbits (the Trojans, Amors, Apollos and Athens). The system of the giant planets that at some time surrounded the Sun was then much more grandiose than now. Nevertheless, the only four giant planets that have been preserved provide evidence of the origin of this system in the temperature gradient of the giant protosolar disc. Because of this, the near-Sun giant planets acquired their hydrogen composition, similar to that of the Sun itself, whereas the remote planets have an aqueous composition, which is close to that of comets. This leads to the conclusion of a very low temperature (close to the absolute zero) in the central part of the protosolar disc, because otherwise the Sun and its nearest planets could not condense hydrogen (figure 3) and helium. The temperature in the peripheral parts of the disc was not as low, and none of these two elements could be incorporated in the compositions of the peripheral planets and cometary accumulations, whose compositions are aqueous. The temperature distribution assumed in cosmochemical hypotheses is the opposite; the solar nebula is thought to have been hot near its centre, cold in its intermediate zone, and very cold in the peripheries (p. 36 of [22]). This erroneous assumption resulted in a misleading conclusion about the early origin of chondrites in the immediate protosolar nebula itself, and similarly to the origin of cosmic dust; samples of more refractory starting material from the inner parts of the solar nebula are preserved as the meteorites referred to as chondrites [22]. In fact, chondrites correspond to a higher degree of evolution of the cosmic material. They produced the molten cores of the parent giant planets and differentiated into chondrules under the huge pressures of the fluid shells. The latter were responsible for the isotopic anomalies and tiny diamond crystals with abundant fluid inclusions. However, chondrites crystallized mostly after the loss of the fluid shells of the giant parent planets, under the effect of the Sun, within relatively small chondritic iron – stony planets, at low pressures. These conditions were characterized by the normal mass fractionation of isotopes between minerals (without isotopic anomalies), the crystallization of low-pressure minerals (such as pigeonite) and the origin of volcanic glass. The extremely contrasting nature of chondrite in terms of fluid pressure (chondrites displays combinations of extremely high- and low-pressure features, including isotopic and mineralogical characteristics) was misinterpreted when the genesis of chondrites was deciphered in the course of cosmochemical studies. The petrological approach [1] is advantageous in this sense, because it was developed for studying volcanic rocks, including their diamondiferous varieties, which bear traces of several facies of the genetic conditions of these rocks (although these facies are not as contrasting as those in chondrites). The rocks started to crystallize in the mantle's magmatic chambers but completely solidified in the crust, under much lower pressures.

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