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Water in the Solar System

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Contents

Abstract. **Over the past half century, numerous research space missions have been launched to explore various objects in the Solar System, primarily to find surface or subsurface water or water ice (in particular, to discover extraterrestrial oceans or their traces and to study their evolution in light of Earth's hydrospheric history). This paper briefly reviews the subject with an emphasis on the terrestrial planets to find out why it is that, while liquid water oceans once formed and still exist on Earth, the surfaces of other planets turned into arid deserts. Also reviewed are issues related to the origin and observation of water ice in the outer part of the Solar System. A list of important problems related to the water origin and spreading in the Solar System is presented.**

Keywords: water, water ice, oceans, Solar System, terrestrial planets, giant planets and their moons

1. Introduction

Water is spread widely throughout the Universe. It is present in the form of water vapor in the atmospheres of planets and their satellites, in a liquid form in the oceans, and in the form of water ice on the surface and in the interiors of large and small celestial bodies. In addition, chemically bound water is contained in various rock-forming minerals; this relates not only to Earth and its oceans, but also to other terrestrial planets, moons of giant planets, comets, asteroids, and other astronomic objects.

Water did not appear in our Universe from the beginning. For that to happen, the first generation of stars had to complete their life cycles, turning into supernovas. Heavy elements, including oxygen, appeared as a result of star nucleosynthesis in the Universe. Water could originate in the cold molecular clouds, where dust particles served as catalysts for water molecules forming on their surfaces (see, for example, Tielens' monograph [1]). Therefore, water already existed in the protoplanetary disc when the Solar System was being formed. Consequently, one may discuss that either objects of the Solar System could inherit 'star' water, or the water we observe now is a secondary product which appeared in the process of the Solar System's formation (see, for example, paper [2]). If the first hypothesis is true, then the formation of planets and small bodies enriched by water or water ice is not a unique event, and one may expect the proceeding of similar processes in other stellar systems (see, for example, Ref. [2]).

Liquid oceans are presumably present on Jupiter's and Saturn's moons (Europa, Ganymede, and Enceladus) and even on the dwarf planet Ceres, which is located in the asteroid belt [3–5]. All these celestial bodies were formed beyond the so-called *snow* (*frost*) *line* — the imaginary boundary which divides the Solar System into internal and external parts. Temperatures in the zone beyond that line were low enough for the water molecules of the protoplanet cloud to condense in the form of ice grains [6]. The snow line passed at a distance of approximately 3 astronomical units (AU) from the Sun through the asteroids belt [6]. The largest object which presumably has an ocean is Europa, a moon of Jupiter, which is the same size as the Moon. The surface of Europa consists of water ice which was frozen at extremely low temperatures (approximately 102 K) and mixed with dust, while the liquid water is located in the deep interior and maintained in the liquid phase due to the tidal forces of Jupiter [3]. The thickness of an ice shield may be up to approximately 10–30 km, and the liquid ocean below it may be up to 100 km deep. This makes it the largest ocean in the Solar System, exceeding Earth's oceans several-fold.

There are no such oceans on the terrestrial planets (excluding Earth), but deposits of surface and subsurface water ice have been discovered on Mars, Mercury, and the

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Moon. In general, it is considered that during the early stages of evolution, Earth, Mars, and Venus developed in a similar way and primordial oceans could be formed on each of them, and life could even have originated. Afterwards, Mars and Venus lost all subsurface liquid water, unlike Earth, and their surfaces turned into dry deserts, either very cold one, as on Mars, or very hot ones, as on Venus.

Below, we briefly discuss processes which led to the formation of oceans on Earth and the terrestrial planets, their subsequent evolution, and the current distribution of water/water ice over the surfaces of different planets and their satellites. In the Conclusion (Section 8), important problems which are to be solved in the near future are summarized.

2. Origin of Earth's hydrosphere

It is thought that the Solar System was formed in a giant cloud of molecular hydrogen 4.6 billion years ago. At the early stages of the Solar System's evolution, a fast rotating protoplanetary disc accreting to the young Sun in the center was formed. In the internal and hottest part of the protoplanetary disc (inside the snow line), where the temperatures were so hot that all volatiles, including water, could exist in the gas form only, dust grains consisting mainly of silicon, oxygen, and metals started to coalesce. Beyond the snow line, such grains could be formed not only from heavy chemical elements but from volatiles as well, if their condensation temperature allowed it. In the course of disc evolution, as a result of grain agglomeration, rather large objects (with characteristic sizes of 1–10 km) could be formed, which are called planetesimals. Thus, accretion of the planetesimals started in the protoplanetary disc, during which larger objects merged with smaller ones until several dozen protoplanetary embryos were formed with sizes corresponding to those of modern Mars or the Moon. At the last stage of evolution, as small planetesimals were exhausted, further growth was provided by the giant collisions of protoplanets during which a huge amount of energy was released (see, for example, paper [7]). It is believed that the Earth–Moon system could have formed in the process of such a giant impact.

Modern theories of the origin of water on the terrestrial planets, first and foremost Earth, may be divided into two categories corresponding to the two main scenarios, depending on the time from the beginning of the Solar System's formation right up until the moment when Earth's hydrosphere could appear. One may call these scenarios endogenic (Earth accreting wet scenario) and exogenic (Late-veneer hypothesis).

In the first case, it is believed that water could originally have been contained in the substance of which young Earth was formed or was delivered to Earth before the iron core of the planet was formed as a result of differentiation. The gas in protoplanetary disc consisted mainly of hydrogen, helium, and oxygen, and, hence, water vapor could have been present there, which is why a certain quantity of water could be adsorbed inside the planetesimals [9]. However, it is believed that the internal area of the protoplanetary disc, where Earth was formed, was very hot, which prevented the effective adsorption of water vapor from the protoplanetary cloud onto the surface of dust grains. By studying meteorites originally formed at different distances from the Sun, one may see that carbonaceous chondrites, formed in the outer asteroid belt at a distance of 2.5–4 AU, have the largest water content (10–20% by mass fraction). At the same time, for example, enstatite chondrites, (formed at a distance of ~ 2 AU) contain less than 0.1% of water (see, for example, paper [10]). Nevertheless, laboratory studies and numerical modeling show that water vapor adsorption could take place at temperatures of about 1000 °C, and at temperatures of around 500 °C several Earth oceans could be adsorbed from the protoplanetary cloud [11]. The mass of modern Earth's hydrosphere comprises only a small part of the total mass of the planet. By modern estimates, if all the water were homogeneously distributed in the mantle, we would get a content of about 250 ppm (parts per million) only. Such a small quantity (or even one several times larger) most likely could have originally been present in the composition of the primordial substance.

According to the most popular hypothesis in the framework of the endogenic scenario (Earth accreting wet), it is considered that most of the modern hydrosphere was delivered to the growing Earth at the late stages of its formation, when our planet had already passed through the growth stage of protoplanetary embryo (as big as Mars, or 1/10 of the current mass), but the giant impact, as a result of which the Moon was formed, had not yet occurred [10, 12–14]. Following this hypothesis, at the early stages, only 'dry' planetesimals formed nearby were accreting on Earth. During the later stages (>10 million years), as the planet mass was growing and the gravitational perturbations caused by Jupiter were increasing, the planet embryos enriched with water and formed in the more distant areas, first of all in the asteroid belt, came to reach Earth [10, 15]. They were formed beyond the snow line, where the temperatures were so low as to invoke condensation of volatiles (including water and the hydroxyl group OH) [6]. In this way, young Earth could get water in a volume of up to 10 Earth oceans [10].

The main problem with the endogenic scenario is not related to proving how water could be adsorbed by primordial planetary material from the heated part of the protoplanetary disc but to explaining how this water could be preserved during further evolution. Accreting planetesimals were probably heated so much due to the radioactive decay of a large number of short-lived isotopes (for example, ^{26}Al [16]), so that bound water could be expelled to the surface and evaporate. Moreover, all or almost all the mantle could melt due to the enormous energy release during giant collisions of the protoplanets, which led to the formation of a magma ocean and the disappearance of volatiles from the surface [17, 18]. Nevertheless, modern research shows that during fractional solidification of the magma ocean a differentiation of the vertical distribution of water occurred [13, 19–21]. Most of it was consolidated in the upper part of the mantle and could evaporate into the atmosphere, retaining there by gravity.

The discovery of a new class of minerals — detrital zircons — is considered to be indirect evidence of the existence of ancient oceans. The chemical and isotope compositions (first of all, the isotope composition of oxygen) indicate that they formed in a magmatic source interacting with a liquid hydrosphere. These are the most ancient formations, 4.3–4.4 billion years old [22, 23]. The isotopic ratio of xenon, ^{129}Xe/^{132}Xe, is another indirect evidence. It is believed that ^{129}Xe could be produced completely in 100 million years as a result of the decay of the short-lived isotope ^{129}I, which, in turn, was formed in the stellar nucleosynthesis. The isotopic ratio ^{129}Xe/^{132}Xe has different reservoirs in the atmosphere and in the mantle. It is believed that the water environment could play a key role in such a differentiation. The noble gas xenon easily evaporates from water into the atmosphere, while the halogen iodine is well dissolved in water. Thus, ^{132}Xe mainly evaporated into the atmosphere, and ^{129}Xe was mainly formed from ^{129}I on the ocean floor, increasing the ratio $^{129}\mathrm{Xe}/^{132}\mathrm{Xe}$. Due to the short decay period of ^{129}I, one may assume that the ancient ocean on Earth could have existed already 4.4 billion years ago [9].

On the other hand, the exogenic (Late-veneer) scenario postulates that most volatiles were delivered after differentiation was completed and Earth's core had formed. Comets and asteroids (carbonaceous chondrites) were the main sources in this process, and it covered a time period for several hundred million years, including the peak of late heavy bombardment [24] 3.8 billion years ago, resulting in a large number of craters appearing on the Moon and other Earth group planets.

To clarify and prove one of the presented hypotheses, an analysis of the isotope composition of volatiles is usually invoked (water, nitrogen, noble gases), first and foremost the isotopic ratio D/H. Thus, solar water, originating from the protoplanetary cloud, corresponds to the isotope composition of Jupiter and Saturn, and has a D/H ratio of about 2×10^{-5} (see, for example, Refs [25, 26] and also Fig. 1), while the D/H isotopic ratio in Earth's oceans is much higher — about 1.6×10^{-4}. About 12 values of the isotopic ratio have already been obtained for comets, and two of them from direct measurements aboard the ESA (European Space Agency) missions Giotto (1P Halley's comet which probably originates from the Oort cloud) and Rosetta (67P Churyumov–Gerasimenko (CG) belonging to the Jupiter family) [25–27]. All these measurements were made in cometary comas but not on the surface of their nuclei.

It was believed for a long period of time that Earth's water was delivered by comets from the Kuiper Belt (Jupiter family), as they have a similar D/H ratio as that of Earth, while for comets from the Oort cloud (Halley, Hyakutake, and Hale–Bopp) this value is twice as high (see Fig. 1). The latest measurements aboard the Rosetta mission, nevertheless, showed that the CG comet of the Jupiter family has a D/H ratio even higher than that of comets from the Oort cloud: $(5.3 \pm 0.7) \times 10^{-4}$ [26]. This means that the cometary hypothesis of the origin of Earth's oceans is experiencing serious difficulties now. The best explanation is that water was delivered to Earth by meteorites and asteroids consisting of carbonaceous chondrites, because it could account for the origin of the isotope composition of the volatiles on Earth, including the D/H ratio, which is close for them to the Earth values (see, for example, Refs [12, 28]).

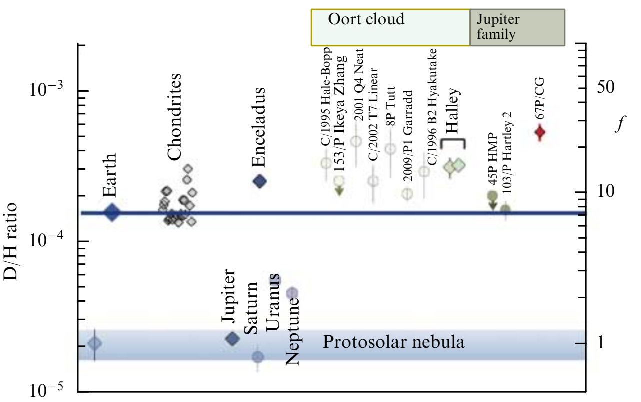

Figure 1. Isotopic D/H ratio measured for different objects of the Solar System; f — enrichment factor defined as the ratio between D/H for a given object and D/H for protosolar nebula (borrowed from Ref. [26]).

Regretfully, the situation is not that simple, and it is necessary to take into consideration that the D/H ratio could change during the numerous (sometimes catastrophic) processes of planet formation. Thus, the primordial low content of deuterium in the solar water, originally contained in the protoplanetary material, could increase. The observed D/H ratio in comets most likely shows us that we do not completely understand the processes influencing variations in deuterium content, because our measurements are referenced to the cometary comas and can fail to represent the true concentration of hydrogen isotopes in cometary nuclei.

Based on the aforesaid, one may speculate that several scenarios of the origin of Earth's oceans are possible. The first is accumulation of solar water in Earth's primordial material at the early stages of the evolution of our planet (i.e., Earth was wet almost all the time). Second, water was delivered by planetesimals and protoplanet embryos from the outer asteroid belt during the first 10 million years, when Earth's growth did not reach its final size. Finally, Earth's hydrosphere could have been formed in the late heavy bombardment epoch over several hundred million years as a result of collisions with comets and carbonaceous chondrite meteorites. Apparently, all the mentioned processes could have taken place, and the main problem for further studies is to find out which of them dominated.

For example, one of the latest studies [12] shows that, based on the results of isotope composition analysis of Earth's water and noble gases, one may consider a chondrite source of water. This leads us to the conclusion that most of Earth's hydrosphere was formed as a result of collisions of the forming Earth with water-rich planetesimals. Less than 10% remains for solar water, and only several percent for cometary water.

One possible option for studying this problem, as strange it may seem, may be the exploration of the Moon and a detailed analysis of its polar ice deposits, which could be preserved through previous epochs and may contain a geological record of the processes influencing the Moon's and Earth's formation, as well as their volatiles reservoirs.

3. The Moon as the closest-to-Earth reservoir of relict water ice

It is commonly believed that the Moon was formed as a result of a giant impact of Earth with a protoplanet as big as Mars, which is sometimes called Theia [8]. Most of Theia's fragments were blasted into orbit around Earth, and afterwards the Moon was formed from them. This hypothesis explains many observational facts, probably excluding the amazing similarity between the isotope composition of Earth and that of the Moon. Thus, Earth and the Moon have very close isotope compositions for oxygen, which are very different in magnitude from those in the meteorites delivered to Earth from Mars and the asteroid belt [29, 30]. Based on the heterogeneous distribution of oxygen in the Solar System, the good match of isotope compositions could take place only if one assumes that colliding bodies were formed in the same area of the protoplanetary cloud. Some researchers interpret this fact as an indication that, during formation, the Moon could have inherited much more material from Earth's mantle than was believed before [31], or after collision, but before the Moon accretion origin, a significant mixing of Earth's and the Moon's magma oceans occurred [32].

It was believed for a long time that the vast majority of volatiles (including water) remained on Earth after the giant impact. The analysis of Moon rock samples delivered to Earth as part of the Apollo program showed that the average content of water was very small — on average not more than 50 ppm by mass fraction [33], and it most likely appeared as a result of the interaction of solar wind protons with the lunar surface [34]. However, the study of volcanic glasses delivered to Earth by the Apollo-17 mission revealed significantly higher concentrations, reaching up to ≈ 750 ppm [35], which means that the Moon is not as poor in volatiles as once believed. According to the latest results of numerical modeling of giant impact and further accretion, as well as modern experimental observations, the Moon can contain a large amount of water [36].

Permanently shadowed polar craters have always been considered the main reservoirs of Moon water. The temperature there is so low that ice water can be preserved on the surface for several billion years. The first studies and discussions on this topic were published in papers [37–40]. Afterwards, the conclusion about cold polar traps and water ice preservation in them was confirmed in papers [41, 42].

Results of observations with bistatic radar aboard the NASA (NASA — National Aeronautics and Space Administration) Clementine mission at first confirmed this hypothesis [43], but afterwards it was put into doubt by radar observations from Earth [44] and by results of the reanalysis of Clementine data [45]. In 1998, the neutron spectrometer LNPS (Lunar Prospector Neutron Spectrometer) aboard the NASA orbiter Lunar Prospector discovered a significant decrease in epithermal neutron flux from the Moon's surface in the polar regions. These data were also interpreted as proof of the presence of water ice in the permanently shadowed craters [46–48]. The cometary origin of water ice [49–52] and the formation of hydrogen-rich compounds as a result of the bombardment of the lunar surface were also discussed [53, 54]. It was not possible to establish them precisely, because the spatial resolution of LPNS was too low to localize its findings with a resolution comparable to the sizes of Moon craters.

In 2009, another orbiter station was launched by NASA: the LRO (Lunar Reconnaissance Orbiter), with the Russian instrument LEND (Lunar Exploration Neutron Detector) as part of its payload. LEND is a collimated neutron spectrometer [55, 56]; its field of view was narrowed to 10–20 km, which allowed resolving many large Moon craters and establishing that water ice was contained in some of them [56, 57]. The average content of ice on the lunar surface turned out to be quite significant — from 1 to 10% by mass fraction, if one takes into account that ice can be deposited at depths of about 0.5 m [58]. This correlates with direct measurements in one such crater (Cabeus), performed by the LCROSS (Lunar Crater Observation and Sensing Satellite) mission for the artificial bombing of the Moon's surface, when the upper stage of the space launch vehicle was intentionally redirected from the Moon's orbit to hit this crater [59]. Orbital measurements of the raised plume and dust showed the presence of approximately 5% water vapor by mass fraction [59] in the ejected material [59].

It should be added that the LEND experiment presented an extraordinary view, having shown that not all permanently shadowed craters have ice water and, vice versa, that sunlit areas surrounding some of these craters could have an elevated content of water ice [57]. Presented in Fig. 2 is the most recent map of subsurface water ice distribution, prepared according to LEND data and showing that such large craters as Shoemaker, Faustini and Haworth, as well as their surroundings, can contain up to 0.5% water if a homogeneous depth distribution of water ice is assumed [58].

Mapping of the Moon's surface by other instruments [Diviner and LAMP (Lyman-Alpha Mapping Project)]

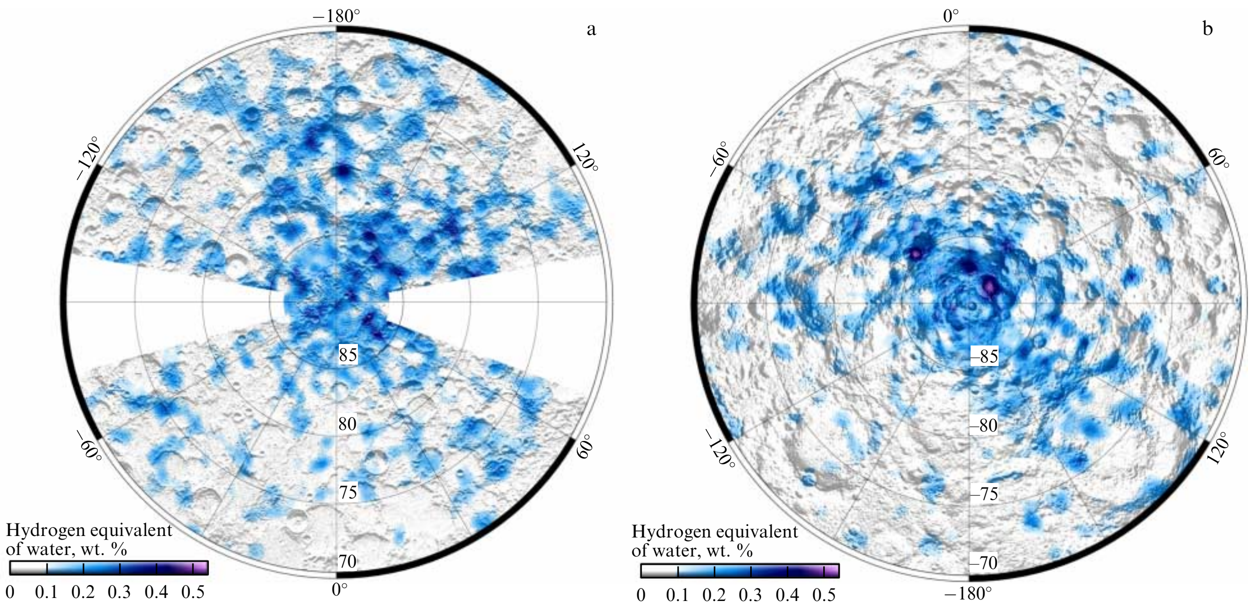

Figure 2. (Color online.) Water/water ice distribution (assuming homogeneous distribution by depth) in the north (a) and south (b) polar areas of the Moon according to the data from the Russian LEND experiment aboard the NASA spacecraft LRO (borrowed from paper [58]).

aboard the LRO spacecraft allowed an estimate of the surface temperature and the measurement of the surface reflection in the ultraviolet range. Based on these results, a possible depth where water ice could be deposited was estimated, and an indication of the existence of a thin layer of surface water ice in the areas surrounding some permanently shadowed craters was detected [60, 61]. Mini-RF (Miniature Radio-Frequency) radar was also aboard for this mission. Twenty years later, after measurements aboard the Clementine mission were performed, a special experiment was prepared, during which joint observations by a radar in orbit around the Moon and a radio telescope located in the Arecibo Observatory were conducted. These observations also showed that signatures of some polar craters may be interpreted as indicators of the existence of subsurface water ice [62].

Thus, on the one hand, there is a huge volume of observational data accumulated for 20 years by different lunar science missions, but, on the other hand, there are no self-consistent views about the distribution and origin of volatiles in the polar regions of the Moon. The main problem is a catastrophic absence of a good direct fit between different observations. Analyses of some experimental data have shown that ice water could be present in certain areas on the Moon, while other experiments have not discovered evidence to confirm this result. One may suppose that the nature of the observed phenomenon, formation mechanisms and distribution pattern of water ice are much more complex than was earlier expected.

Polar craters are cold traps which are able to capture and preserve for a geologically long time volatiles somehow delivered to the Moon. Three processes explaining 'polar' water may be distinguished. Solar wind protons bombarding the Moon's surface can interact with oxygen contained in lunar minerals and produce hydroxyl group OH and water molecules, which, in turn, can migrate to the poles [53, 54]. On the other hand, the bombardment by comets and asteroids at the early stages of evolution created a short-term atmosphere, enriched with water vapor, which was condensed on the cold poles, forming ice water deposits [37, 38, 41, 42]. Finally, volcanic activity, peaking approximately 3.5 billion years ago, could also have created a short-lived (dissipation in approximately 70 million years) and rather dense atmosphere (1–6% of the terrestrial atmosphere) saturated with water vapor from the young Moon's depths [36]. The total water quantity in such an atmosphere could reach 10^{17} g [36].

The possibility of the presence of water in the lunar depths is confirmed by recent observations of pyroclastic deposits by the infrared spectrometry method. Appropriate data were received by the M^3 (Moon Mineralogy Mapper) instrument aboard the Indian orbiter Chandrayaan-1 [63]. Absorption bands at the wavelength of 2.85 μm were discovered in the measured spectra. These findings identify minerals containing water molecules or the hydroxyl group OH. Data analysis showed that the relative proportion of water may comprise 300–400 ppm [63]. These data confirmed that the discovery of volcanic glasses with a rich water content is not unique but may characterize the true composition of volatiles in the depths of the Moon [63]. In addition, ten years ago, using a joint analysis of M^3 data [64], VIMS (Visible and Infrared Mapping Spectrometer) aboard the Cassini mission [65] and HRIIR (High Resolution Instrument–Infrared Spectrometer) aboard the Deep Impact spacecraft [66], it can be shown that water molecules and hydroxyl group OH could be present not only at polar but also at middle latitudes. Hence, the assumption that the Moon is not as dry as had been previously believed has been confirmed.

Returning to the polar cold traps, one possible hypothesis of their formation referenced polar wander, a shift in the lunar axis of rotation and change in the thermodynamic processes in the polar areas [67]. This phenomenon may be evidenced by the boundaries of possible ice water deposits observed in neutron spectrometer data [68, 69]. These areas are shifted aside from the south and north poles of the Moon, but are located along the same axis. Actually, we do not see a strong indication of the presence of water ice directly at the lunar poles (as, for example, in the Shackleton crater [70]), though the lunar poles are thought to be the most appropriate place for ice deposits. During the late heavy bombardment period 3.8 billion years ago (before the axis shift), the modern poles were not yet cold traps and could not capture and preserve volatiles from the atmosphere created by the plume and dust from collisions with comets and asteroids [67].

Thus, it may be stated that the Moon's polar areas are apparently large water ice reservoirs, but their origin (exogenic or endogenic processes) and factors influencing their distribution have not yet been explained. Future polar landing missions with the potential to acquire lunar samples from the depths and analyze them in detail may help to solve these questions. The ultimate goal of such missions is gathering polar samples (with the mandatory preservation of volatiles) and delivering them to Earth for more detailed research. Such projects, first of all, include the Russian missions Luna-Glob and Luna-Resurs with the active participation of ESA. Their launches are scheduled for 2019 and 2022, and their payloads comprise drilling and sample acquisition equipment and analytical laboratories which will allow subsurface lunar samples to be extracted from depths of up to 1.5 m and their chemical and isotope composition to be determined.

It should be noted that the presence of the cold polar traps is not a unique phenomenon only on the Moon. Similar features exist in the polar areas of Mercury as well, and large ice water deposits have recently been discovered there. In Section 4, we discuss the observed differences between these celestial bodies.

4. Paradox of the Moon and Mercury

Mercury is the closest planet to the Sun, and to expect the discovery of water on it, at first sight, seems to be a naive idea. The slow circumrotation of Mercury leads to the fact that its Sun-facing side can heat up to temperatures above 400 °C. Nevertheless, it is considered established that water ice not only exists on this planet but does so in significant quantities. What we expected to find on the Moon was discovered on Mercury. The circumrotation axis of both Mercury and the Moon has a small inclination, which is why some polar craters are never illuminated by sunlight, and thus all the necessary conditions are created for the preservation of water ice and other volatiles formed as a result of meteorite bombardment (see, for example, Refs [41, 42, 71, 72]).

More than 25 years ago, radar observations of the polar areas of Mercury were conducted from Earth, and bright areas were discovered which were interpreted as water ice deposits [73, 74]. In 2004, the robotic scientific mission NASA MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) [75] was launched to Mercury. Seven years later, the MESSENGER orbiter was

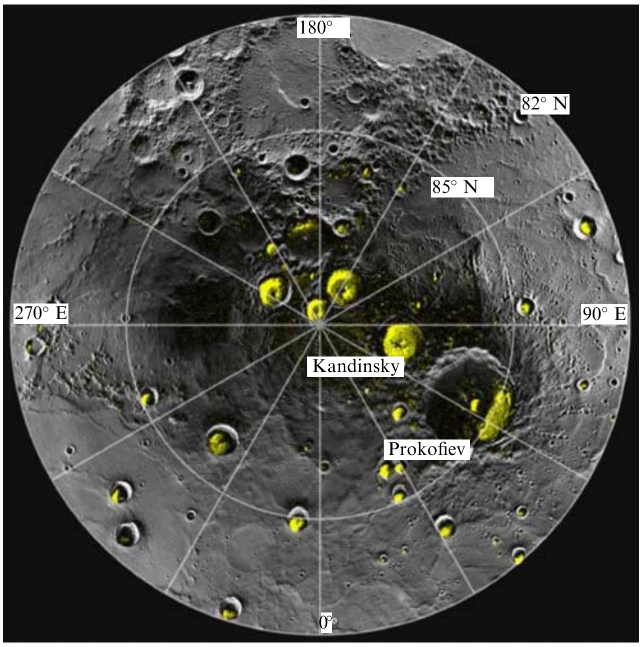

Figure 3. (Color online.) North pole of Mercury: superposition of terrain images (data from WAC aboard the NASA spacecraft MESSENGER) and the ice-rich bright areas (shown in yellow) identified in Earth's radar data. The locations of the Prokofiev and Kandinsky craters are shown (from Refs [76, 77]).

inserted into an elliptical orbit around Mercury and started continuous mapping of its surface. With cameras and a laser altimeter, detailed maps of the terrain were made, and polar craters which comprised cold traps were identified. It was discovered that bright areas identified in the course of radio observations from Earth (Fig. 3) coincide in a remarkable manner with such craters, confirming the discovery of water ice [78, 79]. There was also a neutron spectrometer on the MESSENGER space station, with the assistance of which a decrease in epithermal neutron flux was discovered and interpreted as an enhanced concentration of hydrogen (in the form of water ice) in the north polar area. Due to a wide field of view (from a 200-km altitude, the definitive size of the resolved areas exceeds 300 km), it was not possible to estimate directly a decrease in the surface neutron flux against the background of neutron flux from permanently shadowed craters, but numerical modeling taking into account the experimental data confirmed that the observed effect is explained by the presence of a large quantity of water ice in cold traps [80].

This significantly differs from the results of Moon explorations, as radar data obtained from Earth and from the Moon's orbit do not show a direct correlation with permanently shadowed craters, and the results of high-resolution neutron spectroscopy do not allow us to identify all cold traps as water ice deposits.

Before the end of its operations in 2015, MESSENGER stayed at the eccentric elliptical orbit with the pericenter 200 km above the north pole and the apocenter more than 10,000 km, which is why the primary part of the experimental data is related to the north pole only, and the detailed information on the south pole was not received as much. Nevertheless, with the help of cameras on the orbiter, an approximate map was made of cold traps on the south pole, showing that it also conforms with the results of repeated radar observations by the Goldstone and Arecibo radio telescopes. This research was conducted in 2005 and 2012 [76]. The obtained data confirm the overall picture, according to which 90% of the brightest radiolocation areas are found inside permanently shadowed craters, which agrees with the hypothesis on the presence of water ice [81]. It should be noted that not all detected permanently shadowed craters show such features, which, unquestionably, requires further research and the construction of more complex models [81].

Modern estimates show that the thickness of water ice deposits in the polar areas of Mercury can reach several dozen meters [82, 83], and asteroid and comet bombardment is usually considered an origin of water ice. Moreover, one must take into consideration the existence of a weak dipole magnetic field and the proximity to the Sun. This allows the assumption that solar wind proton implantation mainly in the polar regions could play a more significant part than on the Moon, and the discovered ice may be of solar origin.

The answer will probably be received based on the data of the next Mercury mission — BepiColombo, planned by ESA. Its launch is scheduled for 2018. Its orbit will be less eccentric, with the pericenter at the altitude of 400 km and the apocenter at the altitude of 1500 km [84]. The scientific payload of the mission includes Russian neutron and gamma spectrometer MGNS (Mercury Gamma and Neutron Spectrometer), which allows exploring in more detail and comparing elemental compositions on the south and north poles [85].

If water ice exists on Mercury and the Moon, what happened to the other terrestrial planets Venus and Mars? Sections 5 and 6 present results of observations of Venus and Mars, in particular: what water was discovered there and how could the hydrosphere evolve on these planets.

5. Venus — a 'dry' sister of Earth

Venus is a planet of the Earth group which is often called a twin-sister of Earth due to the approximately equal size, mass, average chemical composition, and proximity to the Sun. In addition, it is possible that at the early stages of the Solar System's evolution Earth and Venus followed similar scenarios. However, the similarity ends there. Thus, Venus's atmosphere is 92 times as thick as that of Earth and consists almost entirely of carbon dioxide. Moreover, Venus is the hottest planet in the Solar System. The average temperature on its surface is above 450 °C, even higher than the temperature on the surface of Mercury. Though in the past astronomers considered that, due to the thick atmosphere, it constantly rains and oceans exist on Venus, as a matter of fact, due to the extraordinarily high temperature, its surface is extremely dry and even its atmosphere contains several hundred times less water vapor compared to Earth.

It is considered that, due to the similarity of the formation processes of Earth and Venus, young Venus used to have oceans of liquid water. But evaporation from the ocean surface led to the saturation of the atmosphere by water vapor, which increased the greenhouse effect and caused further temperature growth and water evaporation, accordingly. Thus, an uncontrolled increase in the greenhouse effect led to the evaporation of all water from the Venusian surface into the atmosphere [86, 87]. Due to ultraviolet irradiation, water dissociated into hydrogen and oxygen, which later were blown away into space by the solar wind, as Venus does not have its own global magnetic field like Earth's. Observations aboard the ESA Venus Express mission showed that the loss of atmospheric hydrogen is still taking place and proceeds with the rate of more than 10^{24} atoms per second [88]. It must also be taken into account that the luminosity of the young Sun and the solar wind intensity could significantly differ from now (see, for example, papers [89–91]). Via photochemical reactions and photoionization, solar X-ray and hard ultraviolet irradiation could significantly influence the atmospheric evolution of the terrestrial planets [92]. This is all the more important because Venus is closer to the Sun than Earth is. By modern estimates, if one extrapolates losses of oxygen and hydrogen into the past and takes into account the young Sun's irradiation, the conclusion suggests itself that Venus could lose a quantity of water comparable to that of Earth's oceans [92].

An additional indication of the fact that young Venus could have oceans is the value of the isotopic ratio D/H. Measurements from Earth and aboard spacecraft have shown that it was 150 times as big as Earth values, meaning that a significant part of the lighter hydrogen (contained in water) evaporated into space [93–95]. Infrared scanning of the Venusian surface during a Galileo fly-by showed that highlands areas look darker in the infrared range, and they are probably composed of granite, which could not be formed without oceans [96].

Venus has not had the attention of space research missions in recent decades . This is due, first and foremost, to landing missions, the life period of which on the surface of Venus constitutes mere hours due to the extreme operational conditions. In the near future, it is planned to prepare several new landing missions, one of which is a Russian project, Venus-D. It is hoped these missions will provide a great deal of new information, as well as the answer to the question of what happened to oceans on Venus.

6. Was Mars ever warm and wet?

Modern Mars is dry and cold, and by all appearances, uninhabited. It has a thin atmosphere, which rules out the presence of liquid water on the surface. Nevertheless, at high north and south latitudes (above 50 – 60° north and south latitude), huge deposits of subsurface water ice were discovered at depths ranging from several centimeters up to half a meter. The ice is mixed with soil, but its mass fraction is more than 50% [97–101]. In the polar caps area, ice practically appears on the surface — thus, the residual north polar cap consists entirely of ice. Water ice deposits are so big that, if they were melted down, all the surface would be covered by several dozen meters of the global equivalent layer of water. That is why we usually speak not about a hydrosphere but about a cryolithosphere of Mars (see, for example, monograph [102]). Originally, ice deposits were discovered from the orbit of gamma and neutron spectrometers, including the Russian HEND (High Energy Neutron Detector) instrument [99]. Afterwards, these measurements were supplemented by radar observations aboard the ESA Mars Express and NASA MRO orbiters, which showed that the thickness of the subsurface ice shield can reach several kilometers (see, for example, paper [103]).

The inclination of the Mars axis significantly precessed during evolution and could occasionally increase up to 45–55° [104]. This means that during such periods ice could cover not only polar areas but also areas at moderate latitudes. An inclination decrease, on the contrary, caused the melting of glaciers. On modern Mars, according to data from high-resolution mapping (NASA MRO mission), traces of glacier retreats may still be observed (for example, at the bottom of Olympus Mons; see paper [105]). Despite the fact that now the inclination of the planet axis of rotation is approximately 25°, relict ice, buried under a thick layer of soil, could be preserved at moderate latitudes [106, 107].

Data from the Phoenix landing mission, which operated on the Martian surface in 2008, has also confirmed that water ice may be located close to the surface at high latitudes [108]. Its landing site was selected in the northern high-latitude area (about 70 degree north latitude) based on the gamma spectroscopy data from the Mars Odyssey mission, which showed a close disposition of subsurface ice deposits to the surface in the landing area [108]. The spacecraft's robotic arm excavated a small trench and observed on its bottom agglomerations of light-colored material which evaporated into the atmosphere within several days. Further research showed that it was water ice [109–111].

Mapping of the planet's surface (the orbital missions NASA MGS (Mars Global Surveyor), Odyssey, and MRO) showed that water in different forms can exist not only in polar and near-polar areas but also in the equatorial latitudes [99, 112, 113]. Exploration of the Martian surface with neutron and gamma spectrometers on board the orbiters detected elevated contents of water ranging 10–15% by mass fraction in the regolith of the Arabia and Memnonia areas [99, 112]. It is primarily physically and chemically (in the composition of minerals) bound water. An up-to-date map of water distribution over the surface of Mars is presented in Fig. 4 (according to HEND instrument data).

Through infrared spectrometers aboard the orbital missions MGS, Mars Express, Mars Odyssey and MRO deposits of various minerals were discovered, including phyllosilicates, which could be formed only by the long-term presence of rocks in a water environment under high-temperature conditions (see, for example, paper [114]). For many years, the Martian rovers Spirit and Opportunity explored the Gusev Crater and Meridiani Planum and also identified numerous features, proving the active hydrological history of Mars at the early stages of its evolution [115–118]. Finally, several times in the course of the exploration of Mars the

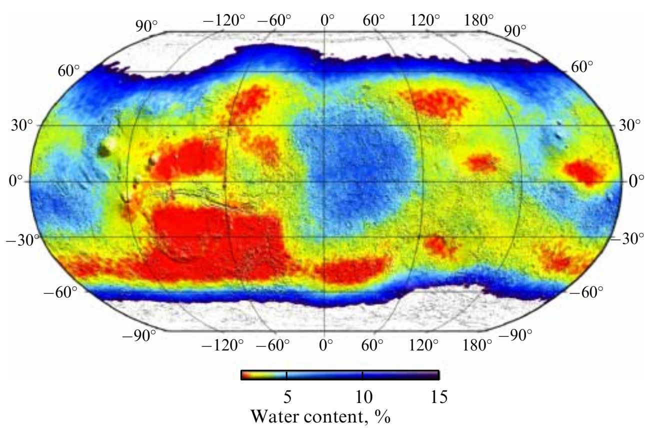

Figure 4. (Color online.) Map of subsurface water distribution on Mars according to data from the Russian instrument HEND aboard the NASA spacecraft Mars Odyssey. White color marks high-latitude areas, where water ice dominates in the subsurface. Color gradation shows variations of bound water.

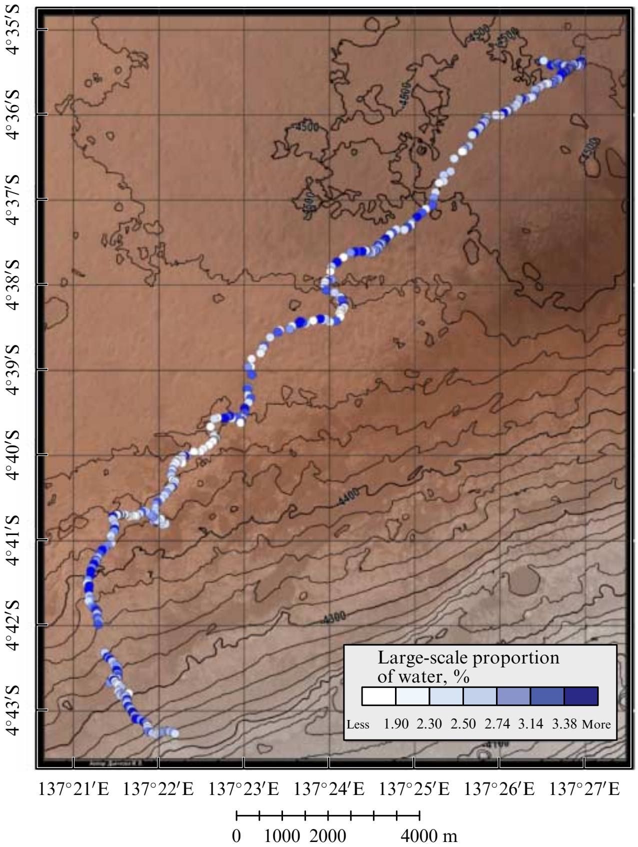

Figure 5. Content of subsurface water along Curiosity's trajectory according to data gathered by the Russian DAN instrument.

traces of liquid flows, which were interpreted as water or salty water flows from subsurface sources, were discovered on the slopes of hills and rims of craters [119, 120].

In 2012, the large NASA Mars rover Curiosity landed inside the Gale crater (5.37° south latitude, 137.81° east longitude). It was designed to search for traces of extraterrestrial life which could have originated on young Mars [121].

This Mars rover has continued its operations for more than five years, during which time it travelled about 20 km, exploring layered deposits inside the crater. Although the modern Gale crater looks rather dry even in comparison with other equatorial areas, it was shown that during the earlier stages of evolution it was filled several times with water, forming a lake in the basin of the crater [122–124]. Figure 5 shows the profile of subsurface bound water, measured by the Russian DAN (Dynamic Albedo of Neutrons) instrument along the rover path [125–129]. Layered sedimentary deposits inside the Gale crater represent a geological record of events connected with the evolution of Mars's hydrology and climate in the late Noachian and the early Hesperian periods. The hypotheses about the existence of a lake and, accordingly, the long-term presence of water on the surface is confirmed by the finding of clay minerals (phyllosilicates) and deltaic and sulfate-bearing deposits [122, 123, 131]. To explain the conditions for them to form and the distribution inside the crater, one can use models of the subsurface and surface hydrology, which show how soil waters and external sources of liquid water combined with each other at different stages of evolution [132]. Based on the observational data, a conclusion was made that during the lake's existence the Gale crater represented a favorable environment for habitability [122].

Many years of Mars explorations indicate that water had a significant influence on the course of its geological history. Using a laser altimetry of the surface aboard the MGS orbiter, detailed maps of the Martian surface terrain were prepared, on which one can easily see an extensive valley network, outflow channels, and deltaic and lacustrine deposits scattered on the vast territory of equatorial areas and the south Noachian highlands, which provide evidence of flowing the huge volumes of liquid water [123, 133, 134]. Moreover, analyzing the North lowlands, researchers identified ocean shoreline features covering approximately one third of the planet [135, 136].

Summarizing the above-mentioned facts, one may come to the conclusion that at the early stages of evolution (the Noachian and Hesperian periods), Mars presumably used to be warm and wet, and probably even an ocean existed on its surface. Afterwards, probably as a result of catastrophic events, Mars lost its global magnetic field, most of its atmosphere, and all liquid water.

Since September 2014, the NASA Maven (Mars Atmosphere and Volatile Evolution) mission has been operating in Mars's orbit. It is designed to explore the structure, composition, and variability of the top layers of the Martian atmosphere and is ultimately aimed at answering the question of what happened to Mars's atmosphere during its evolution [137]. One may extrapolate current atmospheric losses as a result of interactions with the solar wind to the past epoch and try accordingly to estimate the thickness of the young Mars atmosphere. Analyzing the isotopic ratio $^{38}Ar/^{36}Ar$, one may conclude how many volatiles were lost during several billion years of evolution. The noble gas argon may serve as a good indicator of the process governing disappearance of volatiles from the Martian atmosphere. Observational data received by the Maven mission show that about two thirds of atmospheric argon evaporated into space [138]. Taking into account many uncertainties due to data extrapolation to several billion years ago, it may be supposed that in the distant past Mars's atmosphere was as thick as that of Earth (approximately 1 bar or even more). And if one imagined all loses of oxygen and hydrogen in the form of water, this water could cover all the Martian surface with a global equivalent layer several meters thick.

Climate models of modern Mars try to use these data and establish accordingly what the average annual temperature used to be on the planet in the early epoch. In order to preserve liquid water on the surface, the average annual temperature must be increased to a value above 273 K. This is a rather difficult task, considering that currently the average annual temperature on the planet is only 225 K. The carbon dioxide atmosphere, similar to that of Earth, can create a greenhouse effect, but it is not sufficient to increase the temperature significantly, even if we set the surface albedo equal to zero. It is also important to take into account that the young Sun's luminosity 3–3.8 billion years ago (the appearance of a fluvial valley network is dated to this exact period) was only 70–80% of the modern values [91]. The addition of water vapor to the atmosphere increases the average temperature, but only up to ~ 240 K [139–143].

The latest research assumes the possibility of including in the consideration other greenhouse gases, hydrogen and methane in particular. In the case of hydrogen, one may construct an atmosphere model, according to which the average temperature will exceed the melting point of water ice, but this would require four Earth atmospheres of CO_2 and more than 5% hydrogen, which contradicts modern data (Mars's soil simply does not have such a quantity of carbonates which one might expect on the assumption of such a thick atmosphere). At the same time, the addition of methane to the consideration may solve this task. If hydrogen and methane are mixed in equal proportions ($\sim$ 3.5% each) in a CO_2 atmosphere with a pressure of 1.5 bar, the required conditions may be ensured [142]. The main problem here is the origin of sources for the necessary quantity of greenhouse gases. Volcanic activity (probable source of hydrogen), meteorite strikes, and the serpentinization of olivine rocks (a probable source of methane) may be considered. All these conditions limit the duration of such an atmosphere to a short period of several hundred thousand years, meaning that Mars could have been warm and wet only occasionally even at the early stages of its evolution.

From the majority of climate simulations, it may be supposed that in the Noachian era Mars was icy and cold, with average annual temperatures of 210–240 K. That is why it is necessary to explain how, under such conditions, different geomorphological signatures could appear, which modern science identifies as evidence of the existence and the flowing of liquid water on Mars's surface. In order to form the observed system of valleys and channels, to fill lakes, and to create river deltas, a global equivalent water layer from 3 to 100 m (water layer thickness in terms of the entire surface of the planet [144]) would be required. The time required to achieve it varies from 10^5 to 10^7 years [145], i.e., in the worst case, it is still less significant than the duration of the Noachian period (a little less than 1 billion years). If the maximum temperature during the summer season did not rise above 273 K, only occasional but catastrophic events, such as volcanic activity or meteorite strikes (which characterize the Noachian period) may explain it. But if we suppose that day temperatures during summer rose above 273 K on a regular basis, we may apply terrestrial analogues and consider, as an example, dry valleys in the Antarctic, where the average temperature is 253 K, and average day temperatures during the southern summer may rise above 0° Celsius for many weeks. This allows ice to melt and terrains and deposits to form, analogues of which we observe on Mars [146].

The latest research, incorporating results of numerical modelling of the Martian climate and analyses of existing forms of fluvial terrains, proves that conditions for such hypotheses could be met. For this, a rather large quantity of ice would have to be located in the equatorial valley network areas and seasonal temperatures would have to rise above zero to melt ice. The ice melting process must be repeated from time to time for 10^8 years in order to complete the formation of the entire observed valley network. It would be sufficient if young Mars had an atmospheric pressure of 1 bar, an axis inclination of 25°, a circular orbit around the Sun, and a small quantity of greenhouse gases (to increase the average annual temperature to $\sim$ 243 K). The last condition may be left out if orbit eccentricity is changed to 0.17 [147].

The hypothesis about a cold and icy Mars, but with seasonal ice melting, must explain not only different fluvial forms of terrain, but also a large variety of minerals which are found in the Martian soil and which, it is believed, were formed in a warm and wet environment in the presence of a large amount of water. Recent work shows that deposits of clay minerals were probably formed under the surface and on the surface of Mars as well, and can serve as an additional information source for how Mars's climate was changing. Mixes of smectites, chlorites, and carbonates most likely were formed under the surface, whereas the formation of pure Fe^{3+} smectites and sulfates was more influenced by conditions on the surface itself [148]. In order to ensure the forming of hydrated minerals in the cold climate, it is necessary to compensate for the effect of low temperatures with the large period of time which must be spent to complete the process of mineral formation. Numerical modeling shows that such minerals as smectites could be formed during the warm short seasons which occurred either periodically or sporadically all over cold and wet Mars [148].

Eventually, a plausible explanation of the experimental data appeared and does not require the constant presence of a warm and wet climate on Mars during the late Noachian and early Hesperian periods. Consequently, the following question still remains relevant — Was Mars at the early stages of its evolution warm and wet at all times? It was probably cold and icy at all times and rarely melted as a result of seasonal changes, sporadic volcanic activity, or collisions with large asteroids.

Studies of Mars are still being actively conducted. Currently, the ESA TGO orbiter (Trace Gas Orbiter) is in the aerobraking phase around Mars, and the Russian collimated neutron spectrometer FREND (Fine Resolution Epithermal Neutron Detector) is part of its payload. This instrument allows the spatial resolution to increase to $\sim$ 40 km for the mapping of subsurface ice and water deposits and ensures a direct comparison with data received from Martian rovers along their pathways (each of them has driven several dozen kilometers). Moreover, two more Martian rovers will be launched in 2020. One of them is being developed by the ESA — the joint European–Russian project ExoMars [149], the other one will be developed by NASA (similar to the Curiosity rover).

New science investigations on the surface will allow collecting and analyzing more soil samples and conducting the first deep-hole drilling (up to 2 m), which provides direct analyses of subsurface sedimentary deposits. The latter may help to confirm hypotheses of warm/wet or cold/icy Mars.

7. Water in the external part of the Solar System

In the modern Solar System, the snow line is situated at approximately 2.7 AU from the Sun, where the radiation equilibrium temperature descends below $\sim$ 150 K and water ice is stable on the surface of atmosphereless bodies on a geological time scale. The dwarf planet Ceres, the largest object in the main asteroid belt, is situated at a distance of $\approx$ 2.77 AU from the Sun, has a low volume density (2.16 g cm^{-3}), and probably contains up to 50% volatiles by mass [150]; water ice was discovered in several areas on its surface [151, 152].

Water may be contained, besides in ice, in phyllosilicates and other hydrated minerals. Other than water, Ceres contains notable quantities of ammonia and CO/CO_2. This is proved by a wide spread of ammonia compounds and carbonates on Ceres's surface [153, 154], discovered on the basis of terrestrial observations and confirmed by the NASA Dawn mission [155]. Several other objects in the asteroid belt have similar indicators of the presence of volatiles: a rather large asteroid 10 Hygiea and asteroids smaller in size

(< 200 km) demonstrate an absorption band at the wavelength of 3.15 μm, associated with ammonia compounds [156]. One may most likely imagine the formation of these objects on the external side of the Solar System, which is confirmed by modern dynamic models of the Solar System's formation, according to which at the early stages of development massive migrations of planetesimals took place in the range from 8 to 15 AU [157]. Alternative scenarios imply the forming of these asteroids in approximately the same place we observe them now, but planetesimal accretion on them took place, which migrated from the external parts of the Solar System [158, 159]. However, planetesimal migration through the space relatively cleared by Jupiter in the protoplanetary disc could have led to storage exhaustion of the most volatile compounds, ammonia specifically [160]. Consequently, the forming of Ceres and other large asteroids in the external part of the Solar System may be considered the most probable scenario.

At large heliocentric distances, water ice is the main component of the surface and internal parts of satellites orbiting the external planets; it also dominates in the composition of Kuiper belt objects. The presence of water in the depths of giant planets is considered established; however, its quantity is still poorly known. Water may exist not only in different hard phases of water ice, depending on temperature and pressure (crystalline or amorphous, polymorphous of low or high pressure), but also in a liquid form, at least in subsurface layers of several icy moons of Jupiter and Saturn, and at last in gas form, especially in the exospheres of small bodies and deep layers of giant planets' atmospheres.

It should be noted that water ice is rarely encountered in pure form. Water is easily mixed with other agents, transformed either into hydrated minerals or into the structure of clathrates-hydrates — compounds formed by the inclusion of water molecules into cavities of a crystal lattice composed of other types of molecules. Pressure, temperature, the nature of present volatiles, and their abundance relative to the amount of water influence the form in which water exists on one celestial body or another. Despite the fact that there are many uncertainties in our knowledge about giant planets and their internal and atmospheric structures, space missions and terrestrial observations have provided sufficient information to clarify their main properties.

Jupiter and Saturn consist mainly of hydrogen and helium, but they most likely contain more volatiles than all the other objects of the Solar System put together, except the Sun. It is supposed that Jupiter contains elements heavier than helium in the quantity of 10 to 40 Earth masses (M_{E}), and Saturn contains such elements in the quantity from 20 to 30 M_{E} [161–165]. Moreover, if their internal structure differs significantly from the adiabatic one, there will be even more heavy elements [166]. Some of these heavy elements are concentrated in the central core of the planet, and the rest is distributed in its shell. Results of experimental explorations of the gravitational fields of Jupiter and Saturn limit the mass of this core: less than 20 M_{E} [162, 164, 165, 167].

Currently, two alternative scenarios for the formation of giant planets are being discussed: the model of accretion on the central core, and the model of the development of gravitational instabilities in the protoplanetary disk (both described, for example, in book [168]). In both models, the central core described above is an important component for the formation of a giant planet. The accretion scenario assumes that a giant planet may be formed as a result of compression of a hydrogen–helium shell around a dense core with a mass estimated approximately at 10 M_{E} [169–172]. The other model implies gravitational instability of a protoplanetary disk with the formation of a dense core, which is followed by the capture of heavy elements [173, 174]. In both cases, presence of a large quantity of hard particles (in the form of dust grains or small stones) in the external part of the forming Solar System is evidently of huge importance for the formation of giant planets, because it helps to form the core fast [175–177].

Naturally, water, like other volatiles, is present in the giant planets' atmospheres. Water-containing clouds are situated lower than clouds with carbon, nitrogen, and sulfur compounds, which makes them very difficult to observe, but they are nevertheless the most important from the point of view of atmosphere dynamics and planet origin theories. Condensation of water ice clouds takes place at a pressure of approximately 5 bar on Jupiter, 10 bar on Saturn, and several hundred bar on the ice giants Uranus and Neptune. Identification of this cloud layer with remote sensing data is a difficult task due to a wide absorption spectral band by gases and aerosols above it. Only on Jupiter have clouds been identified at that altitude where H_2O ice clouds must be located [178–180]. Lightning activity associated with the separation of electric charges in water ice clouds were also directly observed on Jupiter [181, 182]. Water ice identified spectroscopically was observed by the Voyager spacecraft at the wavelength of about 44 μm [183].

Gasiform water situated above the cloud layer and following the pressure curve of saturated vapor was discovered on Jupiter by the Galileo and Cassini spacecraft based upon the presence of a feature at 5 μm in the measured spectra [184, 185]. However, it is very difficult to estimate precisely its concentration and vertical distribution. Taking into account that measurements made by the Galileo probe during its descent in the atmosphere showed an increase in water concentration until they stopped near a pressure of 22 bar [186–188], the question of water concentration distribution deep down in Jupiter remains unsolved. We may soon have new data, as a microwave radiometer aboard the Juno spacecraft aims to establish the distribution of H_2O and NH_3 at a depth up to 100 bar of pressure.

A violent storm on Saturn in 2010 allowed the detection of spectroscopic features which may correspond to a mix of water ice, ammonia ice the and ammonium hydrogen sulfate (NH_4SH) [189]. However, such an interpretation of observational data depends on the assumed optical properties of the particles. Signs of gaseous water in the upper troposphere were observed at the wavelength of 5 μm in the data from the ISO (Infrared Space Observatory) spacecraft [190], but the spectral resolution of instruments aboard the Cassini spacecraft is not high enough to make a map of the planet. Furthermore, terrestrial observations are highly 'contaminated' by water in Earth's atmosphere. Taking into account the difficulty of direct measurements of water on Saturn [191], the concentration of unstable compounds (CO, PH_3, etc.) which react with water may be used for indirect determination of water concentration [192]. However, this method involves many uncertainties.

Uranus and Neptune do not look like giant planets at all, with masses of 14 M_{E} and 17 M_{E} and densities of 1.2 and 1.7 g cm^{-3}, respectively. Despite the fact that Uranus and Neptune seem very much alike, the higher average density of Neptune than that of Uranus points to a somewhat different bulk composition: either to a higher quantity of elements heavier than hydrogen and helium, or to a higher ratio of the silicate component to the ice component. Measurements of gravitational field parameters show density distribution profiles close to those which 'ices' must have (i.e., a mix originally consisting of, for example, H_2O, CH_4, and NH_3 but fast transforming into a liquid with the average chemical composition inside the planet), with the exception of the most external layers, whose density is close to that of hydrogen and helium [193, 194]. The majority of models of these planets' structures assume the presence of three layers: a central core (rich in magnesium, silicates, and iron), an ice layer, and a hydrogen–helium gaseous shell (see, for example, Refs [195, 196]).

According to the models [196], Uranus contains as a minimum 1.8–2.2 M_E of hydrogen and helium, and Neptune 2.7–3.3 M_E of these gases. The average ratio of ice to silicates is very large: 19–36 for Uranus, and 3.6–14 for Neptune. These values are much higher than the ice-to-silicates ratio for the protosun, which is 2–3. Here, 'ice' means all elements condensated at low temperatures, and silicates are all the remaining elements that are harder to melt. The fact that one planet could accumulate much less a quantity of silicates than ice is mysterious and unexplainable from the point of view of modern models of planets formation. This probably means that the assumption that ices are situated in the shell around the core, while silicates and iron are in the core, is incorrect.

As a matter of fact, apparently all the above-considered models of Uranus and Neptune are inadequate due to the assumption of adiabatic temperature variations on the borders of layers with different compositions. It has been shown that a high abundance of methane prevents convection in the area where clouds form (pressure from 1 to 2 bar) and leads to a superadiabatic gradient of temperature, which was deduced from Voyager spacecraft data [197]. If water concentration exceeds that of the Sun by more than 10 times, a similar effect, albeit greater in magnitude, may occur, characterized by the presence of a deep zone of radiation energy transfer with a high increase in temperature with depth [198]. Deeper diffusion convection must take place in areas with chemical composition changes, which also leads to a superadiabatic gradient of temperature (see, for example, Ref. [199]). In the same way as for Jupiter and Saturn (see Ref. [200]), this will lead to higher temperatures in the internal parts of the planets and different restrictions on their chemical composition. In this case, the quantity of rocky material necessary for correspondence to average density and to the gravitational moments of inertia will, by all means, grow, which will probably allow the problem of the correlation between ice and rocky material to be solved.

Despite the fact that Uranus and Neptune are called icy giants, water on these planets is even more unavailable for direct observation than that on Jupiter and Saturn — liquid water and icy crystal clouds are formed at a pressure of several hundred bar and have not been discovered yet. Indirect estimates based on the CO concentration [201–203] allow the assumption that the O/H ratio for icy giants may reach several hundred. Microwave observations of Uranus allowed assuming the presence of a deep absorbing layer, which may be bound with water clouds [204, 205], whereas the analysis of microwave data gathered from Neptune [206] allowed only registering the presence of water. Method of water concentration measurement by microwave spectra has limited sensitivity to water in deep layers; however, estimating its concentration must be the main task of any future mission to the icy giants.

It may be summarized that in the upper clouds of gaseous and icy giant planets ammonia and methane dominate, whereas water clouds are deeply concealed from remote sensing. This leads to great difficulties in estimating the chemical composition of these planets, as neither orbital probes nor remote sensing from Earth penetrate into the deep layers of these planets. A comparison of average element compositions and isotope ratios of the four giant planets is useful from the viewpoint of clarifying the distribution of volatiles in the protoplanetary disc of the early Solar System, from which planets have formed. The volume distribution of oxygen contents has a decisive meaning due to its significance for water ice formation, when protoplanets were born in the external Solar System. Microwave spectroscopy in combination with *in situ* sample selection and analyses may give some new data on the four giant planets.

Hypotheses for the formation of numerous satellites of the giant planets now appear as follows. The piling up of material in the protoplanetary cloud in Jupiter's orbit led to the formation of a giant planet and its inner moons, similar to the process of the formation of planets and the Sun itself. The high temperature of the accretion disc in the area of Jupiter's formation could have prevented the condensation of volatiles at the distances of inner satellites orbits. Consequently, Ganymede and Callisto, the most remote of the eight inner moons, may be much richer in water and other volatiles than the moons which are closer to the planet.

Numerous small outer moons with their eccentric orbits and significant inclination to ecliptic have another origin. They are, most likely, captured objects. But the place of their formation still remains unclear. Embryos of these moons were probably originally formed in the outer part of the Jupiter nebula. Afterwards, they were thrown away from the giant planet system and later captured by it again into other orbits. They were probably formed independently in the protoplanetary disc of the solar nebula, and were captured by Jupiter afterwards. In any case, the process of capture presumably led to the destruction of original bodies and the formation of space debris which is now observed as outer moons. Continuous explorations of these objects and their possible relations among Trojan asteroids may shed light on their origin.

Water ice distribution on the surface of icy moons of giant planets was mapped with the aid of a combination of spectral features in the infrared spectra [wavelengths of 1.65, 1.5, 2.0, and 3.1 μm (see, for example, Ref. [207])].

Based on the data gathered in the wavelength range of 0.7–5.2 μm [208] by the infrared spectrometer NIMS (Near Infrared Mapping Spectrometer) operating aboard Galileo, it was discovered that the icy moons of Jupiter contain mainly crystalline ice, with some exceptions. The NIMS spectra showed that ice on Callisto is present in the crystalline form everywhere where its amount is sufficient for registration. On Ganymede, ice particles reach the cold polar areas along the lines of Ganymede's magnetic field, forming a thin layer of frost. The boundary between open and closed field lines is seen distinctly in color photos of the surface [209]. On Europa, cold temperatures and high radiation dosages enable the formation of amorphous ice [210].

Multispectral data received by the VIMD spectrometer aboard the orbital spacecraft Cassini, covering the spectral range of 0.35–5.1 μm [211], allowed conducting a thorough comparative analysis of icy Saturn satellites. It was shown that crystalline water ice dominates mainly on their surfaces [212].

The nature and distribution of volatile ices and their relation to water ice are the decisive factors for clarifying the origin and surface evolution of icy satellites, because surface material may be the link with the inner part of the moons and impose restrictions on the environment where these celestial bodies were formed and currently exist.

8. Conclusions

In conclusion, we would like to briefly highlight some global problems connected with the origin and distribution of water in the Solar System, which must be solved in the foreseeable future.

It is necessary to expand the list of Solar System objects (Moon poles, asteroids, small planets, comet nuclei, etc.) for which isotopic ratio D/H should be measured. It is also necessary to improve our knowledge of processes which may change the D/H value. This is one of the important indicators characterizing the distribution of different types of water inside the Solar System. As remote methods are not always effective, space missions, which may deliver samples from different objects in the Solar System, are considered the most interesting, although the most resource consuming. Some of these missions are already in the implementation phase.

The question of the origin of Earth's hydrosphere still remains unsolved. Was Earth's hydrosphere formed along with the planet itself starting from the early stages of evolution? Or was water delivered by asteroids and comets much later? If each of the sources made its own contribution, what process dominated, and what type of water prevails in Earth's oceans and subsurface — solar water or water delivered from distant areas of the Solar System?

If water absorbed directly from the protoplanet cloud played a significant role in the formation of the terrestrial oceans, then can one speculate about common principles in the evolution of other planet systems and assume that oceans, similar to those on Earth, could be formed on exoplanets?

How many volatiles were delivered to the Moon? Modern models of the Moon's formation as a result of a giant impact and the latest experimental data show that the interior of the Moon is not as 'dry' as had been considered before.

Huge deposits of relict water ice are observed in the polar areas of the Moon. By exploring them, we can gather new information on the evolution of the Earth–Moon system and, as a result, about the Solar System itself. The origin of water ice and its distribution on the Moon's surface still remain unexplored and unexplained in full detail. Did comets and asteroids make a major contribution, was ice formed as a result of interaction with the solar wind, or is it primordial water? To answer these questions, it is necessary to implement Moon landing polar missions, supplied with sample acquisition systems and instruments that can access great depths, allowing the analysis of chemical and isotope composition of the soil samples. In the ideal scenario, the most interesting soil samples must be delivered to laboratories on Earth for further detailed analyses.

The Moon and Mercury have common conditions for the formation and preservation of water ice deposits in the polar areas. So why is there such a great difference in the observed picture, where permanently shadowed craters on the Moon are not by default the places of the largest ice water deposits? What conditions were different from those of Mercury during the Moon's evolution?

How did Venus evolve and how did it lose all its water?

The latest experimental data show that Mars has lost more that 90% of its atmosphere and become a dry and cold desert. What was the trigger for this catastrophic process? And where did the water go: did it evaporate into space along with the atmosphere or go deep down inside the planet?

The statement that Mars used to be warm and wet at the early stages of its evolution is being questioned by modern science. This debate has been going on for several decades. Probably the Martian atmosphere was never dense enough and did not have a sufficient quantity of greenhouse gases to ensure an average annual temperature exceeding the freezing point of water. In this case, warming and the presence of liquid water on the surface were of a short-term and occasional nature. Further explorations of subsurface sedimentary rock in different areas of the planet will allow one of the alternatives to be chosen.

At the early stages of the Solar System's evolution, beyond the snow line a favorable environment developed for the condensation of water vapor from the protoplanet cloud onto the surface of the celestial bodies being formed. The moons of Jupiter and Saturn appear to be the most interesting objects for exploration, as they have oceans comparable in size to those on Earth. What is their chemical and mineral composition and biochemistry? Are they a birthplace of life? These questions will probably be answered by future missions to Europa, a moon of Jupiter.

There is insufficient observational data now for a quantitative consideration of the amount of water on the giant planets. It is necessary to conduct direct measurements of water or oxygen concentrations in the atmospheres of Jupiter, Saturn, Uranus, and Neptune.

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