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Delivery of water from beyond the Jupiter's orbit to the terrestrial planets and the Moon

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Abstract

We calculated the migration of planetesimals from beyond the Jupiter's orbit and the probabilities of their collisions with planets, the Moon, and their embryos. Our studies show that the total mass of water delivered to the Earth from beyond the Jupiter's orbit could exceed a half of the mass of Earth's oceans. The fraction of such planetesimals delivered to the Moon was estimated to be by a factor of 16 or 17 smaller than that for the Earth. The mass of the material delivered to a planet to the mass of the planet for Mars was about two times greater than that for the Earth, and such ratios for Mercury and Venus were a little greater than that for the Earth. Some material from beyond the Jupiter's orbit was delivered to the forming Earth.

1. The model and initial data used for calculations

We studied the migration of planetesimals from different distances from the Sun to the terrestrial planets and the Moon. Such studies allow one to understand better the delivery of water and volatiles to the Earth and the Moon. Initial semi-major axes a_o of planetesimals varied from a_{min} to a_{max} with a number of initial planetesimals proportional to $a_o^{1/2}$. In our calculations presented in [1] a_{min}=4.5 AU and a_{max}=12 AU. For other series of calculations [2] $a_{max}=a_{min}$+2.5 AU and a_{min} varied with a step of 2.5 AU from 2.5 to 40 AU. Initial eccentricities e_o of planetesimals equaled to 0.05 or 0.3. Initial inclinations i_o equaled to e_o/2 rad. The mean eccentricities equaled to 0.3 could be reached due to mutual gravitational influence of planetesimals during evolution of a disk of planetesimals in the feeding zone of the giant planets [3]. The gravitational influence of 7 planets (from Venus to Neptune) or of 5 planets (from Venus to Saturn) was taken into account. The symplectic code from the Swift integration package [4] was used. The orbital elements of the migrated planetesimals were recorded in computer memory with a step of 500 years. Based on these arrays of the orbital elements, similar to the calculations presented in [1], we calculated the probabilities of collisions of planetesimals with the terrestrial planets, the Moon, and their embryos.

2. Delivery of water to the terrestrial planets from beyond the Jupiter's orbit

The probabilities of collisions of planetesimals initially located beyond the Jupiter's orbit with the Earth and the Moon calculated for 250 planetesimals can differ by more than a factor of several tens for different runs with similar orbits. In our calculations with a_{min}=4.5 AU and a_{max}=12 AU the probability p_E of a collision of a planetesimal with the Earth was about 2×10^{-6}. While considering thousands of planetesimals with $5\leq a_{min}\leq10$ AU and $a_{max}=a_{min}$+2.5 AU, the mean value of p_E could be larger than 2×10^{-6} by at least a factor of several. It means that if most of the mass of planetesimals in the feeding zone of Jupiter and Saturn was in a large number of relatively small planetesimals, then for estimates of the delivery of material from this zone to the Earth one may use the values of p_E about 10^{-5}. On average, for initial planetesimals in the region at 20 - 40 AU from the Sun, the value of p_E was about 10^{-6}. This region also could play a valuable role in migration of icy bodies to the Earth.

At $p_E=2\times10^{-6}$ and the total mass of planetesimals in the feeding zone of Jupiter and Saturn equalled to 100 Earth's masses, for planetesimals contained 30% of water, the total mass of water in the planetesimals collided with the Earth could be about 1/3 of the mass of the terrestrial oceans. The total mass of water

delivered to the Earth from the feeding zone of Uranus and Neptune could be about twice smaller than that from the feeding zone of Jupiter and Saturn for the same total masses of planetesimals in these two feeding zones. The ratio of probabilities of collisions with the Earth and the Moon of planetesimals migrated from beyond the Jupiter's orbit was estimated to be about 16-17. Due to a smaller mass of the Moon, the fraction of the material evaporated and ejected from a celestial object was greater for collisions of planetesimals with the Moon than with the Earth. For the growth of the mass of the Earth's embryo up to a half of the present mass of the Earth, the mass of water delivered to the embryo could be up to 30% of all water delivered to the Earth from the feeding zone of Jupiter and Saturn. The water of the terrestrial oceans and its D/H ratio could be the result of mixing of water from several exogenic and endogenic sources with large and low D/H ratios.

For Mars, the ratio of the mass of water in the planetesimals delivered from beyond the orbit of Jupiter to a planet to the mass of the planet was approximately two to three times greater than that for the Earth. In absolute values, the mass of water in the planetesimals collided with Mars was 3 to 5 times smaller than the mass of water in the planetesimals collided with the Earth. The mass of water in planetesimals delivered to Mercury or Venus, calculated per unit mass of the planet, was a little greater than that for the Earth. These mass fractions would result in relatively large ancient oceans on Mars and Venus [5]. The mass of water in the planetesimals delivered to the Moon from beyond the orbit of Jupiter could be not more than 20 times smaller than that for the Earth.

Most of the planetesimals from the Jupiter's feeding zone were ejected into hyperbolic orbits in a few Myr. Most of collisions with the Earth of bodies initially located in the zone at 5-30 AU from the Sun took place in less than 20 Myr. This testifies in favor of that the planetesimals from beyond the Jupiter's orbit could fall onto the Earth and the Moon in the process of their growth, and the matter, including water and volatiles, delivered from beyond the orbit of Jupiter was incorporated into the internal layers of the Earth and the Moon. The delivery of matter to the Earth and the Moon from the zone of Uranus and Neptune depended on when these giant planets acquired large masses and began to move in orbits close to their present orbits. After the formation of the giant planets, the typical time until the collisions of the planetesimals with the Earth and the Moon often did not exceed 20 Myr, but a small fraction of the planetesimals could fall onto the Earth during hundreds of Myr.

Summary and Conclusions

The total mass of water delivered to the Earth from beyond the Jupiter's orbit could exceed a half of the mass of Earth's oceans. The ratio of probabilities of collisions with the Earth and the Moon of planetesimals migrated from beyond the Jupiter's orbit was estimated to be about 16-17. The total mass of water in the planetesimals collided with a planet to the mass of the planet for Mars was about two times greater than that for the Earth, and such ratios for Mercury and Venus were a little greater than that for the Earth. For the growth of the mass of the Earth's embryo up to a half of the present mass of the Earth, the mass of water delivered to the embryo could be up to 30% of all water delivered to the Earth from beyond the Jupiter's orbit.

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