MIGRATION OF PLANETESIMALS TO FORMING TERRESTRIAL PLANETS FROM THE FEEDING ZONE OF JUPITER AND SATURN.
S. I. Ipatov[1,2] and M. Ya. Marov[1], [1]Vernadsky Institute of Geochemistry and Analytical Chemistry of Russian Academy of Sciences, Kosygina 19, 119991, Moscow, Russia; [2]Space Research Institute of Russian Academy of Sciences, Profsoyuznaya st. 84/32, Moscow, Russia. Contact: siipatov@hotmail.com.

Introduction: There are a few papers devoted to computer simulations of migration of planetesimals and delivery of water to the Earth from the feeding zones of the giant planets and the outer asteroid belt. In such simulations, the present masses of the terrestrial planets were usually considered. Below we study migration of planetesimals not only to the present terrestrial planets, but also to their embryos.

Initial data for computer simulations: Our previous studies [e.g., 1-4] of the delivery of water and volatiles to the terrestrial planets were based on our computer simulations of the orbital evolution of several tens of thousands of small bodies and dust particles which orbits were close to orbits of discovered comets.

In our new runs, as in our previous runs, the gravitational influence of considered planets was taken into account. The symplectic method was used for integration. In series JS, we considered the present orbits and masses of the terrestrial planets, Jupiter and Saturn. It is considered in several cosmogonic models that Jupiter and Saturn have been almost formed when masses of forming terrestrial planets were far from the present masses. Therefore, in series JS_{01}, masses of planets in the terrestrial zone were smaller by a factor of ten than masses of the present terrestrial planets. In series JN and JN_{01}, in addition to the initial data for series JS and JS_{01}, we also considered present Uranus and Neptune.

In these four series, semi-major axes a of initial orbits of planetesimals varied from a_{min}=4.5 to a_{max}=12 AU, and the number of planetesimals with semi-major axis a was proportional to $a^{1/2}$. Initial eccentricities and inclinations of planetesimals were equal to 0.3 and 0.15 rad, respectively. Such eccentricities could be reached due to gravitational influence of planetesimals and planets [5].

Results of computer simulations: Based on obtained arrays of orbital elements of planetesimals during their dynamical lifetimes (until their ejections into hyperbolic orbits or collisions with planets or the Sun), we calculated the probabilities of collisions of migrating planetesimals with planets. For series JS, JS_{01}, JN and JN_{01}, the probabilities of collisions of a planetesimal with the terrestrial planets during its dynamical lifetime are presented in Table 1. Based on the arrays of orbital elements of migrating planetesimals, we calculated the probabilities not only for the mass of the Earth's embryo that was used in a considered simulation of the evolution of a disk of planetesimals, but also for another value of the mass of the embryo. The values p_E and p_{E01} of the probabilities of collisions of a migrating planetesimal with a planet presented in Table 2 were calculated for a planet in Earth's orbit for the mass of the planet equal to m_E or $0.1m_E$, respectively, where m_E is the mass of the Earth.

In series JS and JN, for consideration of several thousands of planetesimals, the probability p_E of a collision of a planetesimal with the Earth is about 2×10^{-6}. It is smaller than the value of $\geq4\times10^{-6}$ obtained in our previous calculations for initial bodies in Jupiter-crossing cometary orbits. In the new series of runs, not all planetesimals got highly eccentrical Jupiter-crossing orbits, and the probabilities of their collisions with the Earth during evolution were greater for planetesimals from the inner part of the considered disk than for the outer part of the disk. In series JS_{01}, the probability p_{E01} of a collision of a planetesimal with the Earth's embryo of mass $0.1m_E$ was obtained to be equal to 4×10^{-7}.

In the series JS, JS_{01}, JN and JN_{01}, the fraction of planetesimals that reached the orbit of the Earth during evolution was about 12–14%. If we consider only such planetesimals (that became Earth-crossing), then the probabilities of collisions of such planetesimals with the Earth are greater than 2×10^{-6} by almost an order of magnitude.

We also made calculations for the series of runs for which the giant planets of present masses initially were located more close to each other than the present giant planets (the maximum values of their initial semi-major axes varied between 15 and 20 AU), and a_{max} did not exceed 23 AU. For such runs, at least one giant planet (not Jupiter) was ejected into a hyperbolic orbit during evolution. The values of p_E and p_{E01} for such runs were usually not smaller than the values for series JS, JS_{01}, JN and JN_{01}.

Delivery of water to the terrestrial planets: Several scientists (see, e.g., [6]) consider the zone of the outer asteroid belt to be the main source of water on the Earth. Drake and Campins [7] noted that the key argument against an asteroidal source of Earth's water is that the O's isotopic composition of Earth's primitive upper mantle matches that of anhydrous ordinary chondrites, not hydrous carbonaceous chondrites.

At p_E=2×10^{-6}, for the total mass of planetesimals in the feeding zone of Jupiter and Saturn to be about a hundred of Earth masses [5], and at the fraction of water in planetesimals equal to 0.5, one can obtain that the total mass of water delivered from these zones to the Earth can be about a half of the mass of water in Earth's oceans. About the same amount of water could be delivered to the Earth from distances greater than 12 AU. The main delivery from such greater distances could be later than from the feeding zone of Jupiter and Saturn, and could take place when the Earth was almost formed.

In series JS, the ratios of the probabilities of collisions of migrating planetesimals with the Earth to the probabilities of their collisions with Venus, Mars, and Mercury were about 1, 4.6, and 13, respectively (see Table 1), and the ratio of the probability of a collision of a planetesimal with a planet to the mass of the planet was greater by about a factor of 2 and 1.4 for Mars and Mercury, respectively, than for the Earth.

Based on the arrays of orbital elements of migrating planetesimals obtained in our runs, we calculated the probabilities p_E and p_{E01} of a collision of a planetesimal with a planet in the Earth's orbit for the mass of the planet equal to m_E и $0.1m_E$, respectively The obtained ratio p_E/p_{E01} of the probabilities was mainly between $5\approx10^{0.7}$ and $5.5\approx10^{0.74}$. Therefore, the ratio of the total mass of the planetesimals collided with a planet to the mass of the planet at the mass of the planet equal to $0.1m_E$ is greater by about a factor of 2 than at m_E. The above estimates are for planetesimals from the zone of the giant planets. Below we denote them as g-planetesimals. For the planetesimals from the terrestrial zone, their typical eccentricities are smaller than those for g-planetesimals, and the index of power could be greater than 0.74. For the increase of the mass a planet embryo of mass m due to accumulation of g-planetesimals proportional to $m^{0.74}$, the ratio of the increase of the mass of the embryo due to accumulation of g-planetesimals during the growth of the mass of the embryo (mainly by accumulation of 'local' planetesimals) from 0 to $k\cdot m_E$ to the increase of the mass of the embryo by accumulation of g-planetesimals during the growth of the mass of the embryo from 0 to m_E is equal to $k^{1.74}$. In particular, $0.5^{1.74}\approx0.3$ and $0.8^{1.74}\approx0.68$. The fraction of g-planetesimals collided with the embryo at the growth of its mass from 0 to $k\cdot m_E$ can be smaller than $k^{1.74}$, if at the late stages of formation of the planet, the ratio of the income of g-planetesimals to the income of "local" planetesimals was greater than at the previous stages of the growth of the planet embryo. Based on the above estimates, we can conclude that at the growth of the mass of the Earth's embryo up to $0.5m_E$, the mass of water delivered to this embryo could be about 30% of all water delivered to the embryo from the feeding zone of Jupiter and Saturn. These estimates show that a considerable fraction of water could be delivered to the embryo of the Earth when its mass was smaller than the present mass of the Earth.

Conclusions: The mass of water delivered from behind the orbit of Jupiter during the formation of the Solar System could be comparable with the mass of water in the Earth's oceans. The mass of water delivered to the Earth's embryo during the growth of its mass to a half of the Earth mass could be about 30% of all water delivered to the embryo from the feeding zone of Jupiter and Saturn during the growth of the mass of the embryo to the Earth mass.

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References: [1] Marov M.Ya., Ipatov S.I. (2001) In: *Collisional processes in the solar system*. M.Ya. Marov, H. Rickman. Eds. Astrophys. & Space Science Library. Vol. 261. Dordrecht: Kluwer Academic Publishers. P. 223-247. [2] Marov M.Ya. and Ipatov S.I., (2005) *Solar System Research*, 39, 374-380. [3] Ipatov S.I. and Mather J.C. (2007) In: *Proc. IAU Symp. No. 236 "Near-Earth Objects, Our Celestial Neighbors: Opportunity and Risk*". A. Milani, G.B. Valsecchi, D. Vokrouhlický. Eds. Cambridge: Cambridge Univ. Press. P. 55-64. [4] Ipatov S.I. (2010) In: *Proc. IAU Symposium S263. Vol. 5. "Icy bodies in the Solar System"*. J.A. Fernandez, D. Lazzaro, D. Prialnik, R. Schulz. Eds. Cambridge: Cambridge Univ. Press. P. 41-44. [5] Ipatov S.I. (1993) *Solar System Research*, 27, 65-79. [6] Petit J.-M., Morbidelli A., Chambers J. (2001) *Icarus*, 153, 338-347. [7]. Drake M., Campins H. (2006) In: *IAU Symp. 229 "Asteroids, Comets, & Meteors"*. P. 381-394.

Table 1. The probability of a collision of a planetesimal from the feeding zone of Jupiter and Saturn with a considered terrestrial planet.

	Mercury	Venus	Earth	Mars
JS	1.58×10^{-7}	2.05×10^{-6}	2.02×10^{-6}	4.35×10^{-7}
JN	0.92×10^{-7}	1.15×10^{-6}	1.92×10^{-6}	7.2×10^{-7}

Table 2. The probabilities p_E and p_{E01} of a collision of a planetesimal from the feeding zone of Jupiter and Saturn with a planet in the Earth's orbit at a mass of the planet equal to m_E and $0.1m_E$, respectively. $lgp=lg(p_{E01}/p_E)$

	JS	JS_{01}	JN	JN_{01}
p_E	2.02×10^{-6}	1.83×10^{-6}	1.92×10^{-6}	1.11×10^{-6}
p_{E01}	3.66×10^{-7}	3.63×10^{-7}	3.68×10^{-7}	1.99×10^{-7}
lgp	0.74	0.70	0.72	0.746