Origins: From the Protosun to the First Steps of Life
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Water inventory from beyond the Jupiter's orbit to the terrestrial planets and the Moon

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Abstract. Computer simulations of migration of planetesimals from beyond the Jupiter's orbit to the terrestrial planets have been made. Based on obtained arrays of orbital elements of planetesimals and planets during the dynamical lifetimes of planetesimals, we calculated the probabilities of collisions of planetesimals with planets, the Moon, and their embryos. The results of calculations showed that for the total mass of planetesimals of about 200 Earth masses, the mass of water delivered to the Earth from beyond the orbit of Jupiter could be about the mass of the terrestrial oceans. For the growth of the mass of the Earth 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 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. The ratio of the mass of water delivered from beyond the orbit of Jupiter to a planet to the mass of the planet for Venus, Mars, and Mercury was not smaller than that for the Earth. The mass of water in planetesimals that collided the Moon and migrated from beyond the Jupiter's orbit could be not more than 20 times smaller than that for the Earth.

Keywords. methods: n-body simulations, Earth, Moon, Solar System: formation

1. Introduction

A source of water storage on the Earth and the terrestrial planets is one of the key problems of planetary sciences (Marov 2018). Basically, two main mechanisms are discussed: Endogenous sources (Water adsorption by grains before gas dissipation from the inner Solar System. Direct adsorption of hydrogen from the nebular gas into magma oceans through the reaction of H_2 with FeO. Water coupling in minerals of the early silicate mantle with a potential storage up to a few Earth's oceans) and Exogenous sources (Small bodies coming from the outer asteroid belt and volatile-rich planetesimals and asteroids/comets coming from beyond the Jupiter's orbit). Both endogenous and exogenous models have some constraints. Endogenous model is constrained by the facts that: (1) Temperature in the regions of protoplanetary disk where the inner planets formed exceeded 500-700 K and water/volatiles could not be retained. (2) Efficiency and timescale of the mechanism of water transport from upper mantle to the surface is not clear. Exogenous model is constrained by some geochemical evidence: (1) Os isotopic composition of the Earth's primitive upper mantle matches anhydrous ordinary chondrites rather than hydrous carbonaceous chondrites pertinent to the outer asteroid belt. (2) D/H ratio in water of the majority of known comets is greater than that in the Earth's oceans. We favor exogenous model focusing on the computer simulation of planetesimals and comets coming from beyond the Jupiter's orbit, with the follow up estimates of water delivery.

2. Computer simulations of migration of planetesimals from the feeding zone of Jupiter and Saturn

We made several series of calculations of migration of bodies under the gravitational influence of planets. In most calculations, all planets exclusive of Mercury were considered in their present orbits. In some runs, Uranus and Neptune were excluded. For some integrations, we used the symplectic code. For other runs, we used the Bulirsh-Stoer code. The main results were similar for both methods. Based on arrays of the orbital elements of bodies during their dynamical evolution, we calculated probabilities of collisions of the bodies with planets and the Moon (or with their embryos). Integrations were usually made until all bodies reached 2000 AU from the Sun or collided with the Sun. In a few runs considered time intervals equaled to the age of the Solar System. Earlier (Ipatov & Mather (2004, 2006, 2007) studied the orbital evolution of >30,000 bodies with initial orbits close to those of Jupiter-family comets (JFCs), Halley-type comets, long-period comets, and asteroids in the resonances 3/1 and 5/2 with Jupiter.

Marov & Ipatov (2018) made computer simulations of migration of 10^4 planetesimals from the feeding zone of Jupiter and Saturn to forming terrestrial planets. In series JN, all planets were assumed as having their present orbits and masses. In series JS, Uranus and Neptune were excluded. Initial eccentricities and inclinations of planetesimals were 0.3 and 0.15 rad, respectively. The initial semi-major axes of the planetesimals were between 4.5 and 12 AU. Masses of planets moving in the orbits of the terrestrial planets were equal to present masses of the planets in series JS and JN. In series JS_{01} and JN_{01}, they were smaller by a factor of 10 than the present masses. We also made calculations for which the giant planets of present masses initially were located more close to each other than the present giant planets. For such runs, at least one giant planet (not Jupiter) was ejected into a hyperbolic orbit during evolution. The values of the probability p_E of a collision of a planetesimal with the Earth for such runs were usually not smaller than those for series JS, JN, JS_{01}, and JN_{01}.

In Ipatov (2018), initial semi-major axes a varied from a_{om} to a_{om}+2.5 AU with a number of initial planetesimals proportional to $a^{1/2}$. For different runs, a_{om} varied from 2.5 to 40 AU with a step equaled to 2.5 AU. Initial eccentricities e_o equaled to 0.3 or 0.05, and initial inclinations $i_o = e_o/2$ rad. Eccentricities e_o=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 (Ipatov 1993).

3. Delivery of water and volatiles to the terrestrial planets and the Moon

Water and volatiles could be delivered to the terrestrial planets and the Moon from different distances from the Sun. It is often supposed (Petit *et al.* 1997) that the outer asteroid belt was the main source of the delivery of water to the terrestrial planets. Drake & Campins (2006) argued against an asteroids' source of Earth's water because oxygen isotopic composition in its primitive upper mantle matches that of anhydrous ordinary chondrites, rather than hydrous carbonaceous chondrites. Hallis *et al.* (2015) noted that the deep mantle water has a low D/H ratio and could be acquired due to adsorption of water on fractal grains during Earth's accretion. The ocean water (and its D/H ratio) could be a result of mixing of water from several sources.

The results of the calculations of migration of planetesimals from the feeding zone of Jupiter and Saturn showed that the probabilities of collisions of such planetesimal with the Earth and its embryo of mass equal to $0.1m_E$ (where m_E is the Earth mass) were about $2 \cdot 10^{-6}$ and $4 \cdot 10^{-7}$, respectively. We concluded that during the growth of the mass of the Earth's embryo up to $0.5m_E$, the amount of water delivered to the embryo from the feeding zone of Jupiter and Saturn could be about 30% of the total mass of water delivered to the Earth from this feeding zone.

In our calculations of the migration of the objects which initially moved in cometary-type Jupiter-crossing orbits, the probability p_E of a collision of an object during its dynamical lifetime with the Earth exceeded $4 \cdot 10^{-6}$ (Ipatov & Mather 2004, 2006). For planetesimals from the zones with a width of 2.5 AU, the values of p_E for e_o=0.3 and for e_o=0.05 did not differ much. Ipatov & Mather (2004) mentioned that the value of p_E for one body can be greater than the sum of values for thousands other bodies with similar initial orbits if the orbit of the body became Earth-crossing for a long time. The same result was obtained in our recent calculations. For one run with 250 bodies, the value of p_E (which is calculated as the mean value per one body) was $2.6 \cdot 10^{-3}$ for a_{om}=7.5 and e_o=0.3, and it was $9.8 \cdot 10^{-4}$ for a_{om}=10 AU and e_o=0.05. If we exclude the series of calculations with such larger values of p_E, then p_E typically was about $5 \cdot 10^{-6}$ for a_{om}=5 AU, about $3 \cdot 10^{-6}$ for a_{om}=7.5 AU, and about $2 \cdot 10^{-6}$ for a_{om}=10 AU. The 'a_{om}' series of runs show that the values of p_E could exceed $2 \cdot 10^{-6}$ for the feeding zone of Jupiter and Saturn. In principle, p_E could be greater by a factor of several than $2 \cdot 10^{-6}$, if many thousands of planetesimals migrated to the Earth, and among them there were planetesimals that spent long times in Earth-crossing orbits. For a_{om} from 12.5 to 25 AU, the values of p_E were mainly between 10^{-6} and $3 \cdot 10^{-6}$, i.e., differed not much from the value $2 \cdot 10^{-6}$ mentioned above. For a_{om} from 27.5 to 40 AU, the values of p_E on average exceeded $5 \cdot 10^{-7}$. The main growth of p_E in our calculations was during 20 Myr. However, for bodies initially located beyond Saturn's orbit, p_E could slowly grew even after 200 Myr. For times of migration of planetesimals from beyond the orbit of Saturn, we also need to add time during which massive embryos of Uranus and Neptune reached their present orbits. Results of our calculations of migration of the embryos of Uranus and Neptune from 8 and 10 AU under the gravitational influence of planets and planetesimals to the present orbits of Uranus and Neptune were presented e.g. in Ipatov (1991, 1993).

The total mass of water delivered to the Earth from beyond Jupiter's orbit could be comparable with the mass of the Earth's oceans, which is $2.25 \cdot 10^{-4} m_E$. At $p_E = 2 \cdot 10^{-6}$, for the total mass of planetesimals in the feeding zone of Jupiter and Saturn equal to $100 m_E$, and planetesimals consisted half in water, the planetesimals from this feeding zone could deliver about a half of Earth's ocean water. Another half of the water could come from more distant regions. Most of the water that was delivered from such distant regions to the Earth's embryo came when its mass was not small (e.g., was mainly greater than $0.5 m_E$).

In series JS, the ratio of the mass of water delivered to a planet to the mass of the planet for the Earth was smaller by a factor of 2, 1.25, and 1.3 than that for Mars, Venus and Mercury, respectively. For series JN, the above factor equaled to 3.4, 0.7, and 0.8, respectively. This mass fraction would result in relatively large ancient oceans on Mars and Venus. The estimates are indicative of the presence of ancient oceans on Mars and Venus, which could partially survive deep under the surface, as on Mars, (Usui 2017), or were lost in the course of evolution, as on Venus (Marov & Grinspoon 1998, chapter 9).

In the calculation series JS and JN, the probability p_M of a collision of a planetesimal during its dynamical lifetime with the Moon varied from $7 \cdot 10^{-8}$ to $2.7 \cdot 10^{-7}$; and, in three calculation series with 250 planetesimals, it was approximately $1.2 \cdot 10^{-7}$. In the considered calculation series, the ratio p_E/p_M of the probability of a collision of a planetesimal with the Earth to that with the Moon was mainly in the range from 16 to 17. In the JS and JN calculation runs with 250 planetesimals, the ratio p_E/p_M varied from 16.53 to 16.9 and from 16.08 to 16.74, respectively. For comparison, the squared ratio of the radii of the Earth and the Moon is 13.48. The mass of planetesimals migrated from beyond Jupiter's orbit and collided with the Moon could be smaller than that with the Earth by the factor not more than 20. However, the fraction of water and volatiles that left the Moon at collisions was greater than that for the Earth. For migrating objects, which initial orbits were close to those of Jupiter-family comets, the ratio p_E/p_M varied mainly from 15.2 to 17.6. For asteroids from 3/1 resonance with Jupiter and for comets with initial eccentricity equal to 0.975, p_E/p_M reached 18.6 and 15.2, respectively.

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References

Drake, M. & Campins, H. 2006, in: D. Lazzaro, S. Ferraz-Mello, & J. A. Fernandez (eds.), *Asteroids, Comets, & Meteors*, Proc. IAU Symp. 229 (Cambridge: Cambridge Univ. Press), p. 381

Hallis, L. J., Huss, G. R., Nagashima, K., Taylor, G. J., Halldrsson, S. A., Hilton, D. R., Mottl, M. J., & Meech, K. J. 2015, *Science*, 350, 795

Ipatov, S. I. 1991, *Soviet Astron. Letters*, 17, 113

Ipatov, S. I. 1993, *Solar System Research*, 27, 65

Ipatov, S. I. 2018, *The Ninth Moscow Solar System Symposium 9M-S3* (Space Research Institute, Moscow, Russia, October 8-12, 2018), 9MS3-SB-11, p. 104, https://ms2018.cosmos.ru/

Ipatov, S. I. & Mather, J. C. 2004, *Annals of the New York Academy of Sciences*, 1017, 46, http://arXiv.org/format/astro-ph/0308448

Ipatov, S. I. & Mather, J. C. 2006, *Adv. Sp. Res.*, 37, 126, http://arXiv.org/format/astro-ph/0411004

Ipatov, S. I. & Mather, J. C. 2007, in: G. B. Valsecchi, D. Vokrouhlicky, & A. Milani (eds.), *Near-Earth Objects, Our Celestial Neighbors: Opportunity and Risk*, Proc. IAU Symp. No. 236 (Cambridge: Cambridge Univ. Press), p. 55, http://arXiv.org/format/astro-ph/0609721

Marov M. 2018, in: P. Read, *et al.* (eds), *The Formation and Evolution of the Solar System*, Oxford Research Encyclopedia of Planetary Science (Oxford University Press), id.2

Marov, M. Ya. & Grinspoon, D. H. 1998, *The Planet Venus* (New Haven: Yale University Press), 442 p

Marov, M. Ya. & Ipatov, S. I. 2018, *Solar System Research*, 52, 392

Petit, J.-M., Morbidelli, A., & Chambers, J. 2001, *Icarus*, 153, 338

Usui, T. 2017, *Nature*, 552, 339

Discussion

KHAIBRAKHMANOV: How long does it take for Earth to gain its ocean with contemporary mass?

MAROV: Frankly, it is difficult to answer. There is evidence that the Earth took its oceans as early as 3.8-4.0 Gya, that is in a good coincidence with the LHB (late heavy bombardment) period. My point is that it is the time when volatile-rich bodies migrating from the outskirts of the Solar System fell down on the formed crust and were responsible for the late veneer formation on the Earth's surface, filling up the ancient oceans.