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Migration of icy objects to forming terrestrial planets

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Abstract

Migration is an important process of matter transport in the solar system. We studied migration of bodies and dust to the terrestrial planets from the regions beyond the snowline and estimated delivery of water and volatiles to these planets. It was found that during the growth of Earth's embryo up to a half of its present mass, the mass of water received by the embryo from the feeding zone of Jupiter and Saturn could amount to about 30% of the total mass of water delivered to the Earth from this feeding zone.

1. Introduction

Water and volatiles could be delivered to the terrestrial planets from different distances from the Sun. It is often supposed [1] that the outer asteroid belt was the main source of the delivery of water to the terrestrial planets. Drake and Campins [2] 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 [3] 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.

2. Migration of Jupiter-crossing objects

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 was integrated until all bodies reached 2000 AU from the Sun or collided with the Sun. Based on a set of orbital elements during evolution, we studied [4-6] the probabilities of collisions of migrating bodies and particles (during their dynamical lifetimes) with planets. The mean value of the probability p_E of a collision of considered JFCs with the Earth exceeded 4×10^{-6}. The ratio of mass of water delivered to a planet by such bodies to its bulk mass could be greater for Mars, Venus, and Mercury, than that for Earth. This larger mass fraction would result in relatively large ancient oceans on Mars and Venus.

3. Migration of dust

Based on results of our integration of the orbital evolution of >20,000 dust particles produced by comets and asteroids, we studied [4-7] the probabilities of collisions of migrating particles (during their dynamical lifetimes) with planets. At integration we took into accout the influence of planetary gravity, radiation pressure, Poynting-Robertson drag, and solar wind drag. For dust particles, p_E was found to have a maximum (~0.001-0.02) at diameters of particles ~100 μm. A large amount of material (including water and volatiles) could be delivered by dust particles to the zone of the terrestrial planets from the zone of Jupiter and Saturn just after gas left the latter zone, which could contain a lot of dust. In the present solar system, the amount of matter delivered by dust particles to the Earth can be smaller than that delivered by bodies only by a factor of a few. Dust partcles could be more effective than bodies in delivery of organic matter because they less warm up in the atmosphere.

4. Migration of planetesimals from the feeding zone of Jupiter and Saturn

Recently we made computer simulations of migration of 10^4 planetesimals from the feeding zone of Jupiter and Saturn to forming terrestrial planets under the gravitational influence of 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 the values of p_E for series JS, JN, JS_{01} and JN_{01}.

The results of the calculations showed that the ratio of the fraction of the planetesimals collided with the Earth's embryo was about 2×10^{-6} and 4×10^{-7} for the mass of the embryo equal to the Earth mass m_E and to $0.1m_E$, 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. The total mass of water delivered to the Earth from the feeding zones of the giant planets and from beyond these zones could be comparable with the mass of the Earth's oceans. The total mass of the Earth's ocean water is about $2.25\times10^{-4}m_E$. At $p_E=2\times10^{-6}$, for the total mass of planetesimals in the feeding zone of Jupiter and Saturn equal to $100m_E$, 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 $0.5m_E$). 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 и 0.8, respectively. For the growth of Earth's embryo of mass m by accretion of planetesimals that came from the feeding zone of Jupiter and Saturn, the increase of its mass turned out proportional to $m^{0.74}$.

In our calculations of the migration of the objects which initially moved in cometary-type Jupiter-crossing orbits, the fraction p_E of the objects collided with the Earth exceeded 4×10^{-6} [4-6]. These values of p_E were greater than the above mentioned values of p_E for planetesimals because initial eccentricities of planetesimals were smaller than those of cometary objects, and not all planetesimals reached Jupiter's orbit during their lifetimes. If one takes into account the mutual gravitational influence of planetesimals, then they would get greater eccentricities during evolution and the values of p_E would be greater than those for the model which does not consider the mutual gravitational influence of planetesimals. Orbits of Earth-crossing objects that migrated from outside Jupiter's orbit are typically highly eccentric. For such eccentric orbits, the effective radii of the Earth and the Moon are approximately proportional to their radii, and the amount of the material, including water, delivered to the Moon from outside Jupiter's orbit could be only by an order of magnitude smaller than that delivered to the Earth.

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