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Initial distances from the Sun for planetesimals that collided with forming terrestrial planets and the Moon

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Abstract

Inner layers of each terrestrial planet could be accumulated mainly from material from the neighbourhood of this planet. The outer layers of the Earth and Venus could accumulate similar material from different regions of the feeding zone of the terrestrial planets.

1. The model and initial data used for calculations

In some papers (e.g. [1]) the studies of the probabilities of collisions of planetesimals from different parts of the feeding zone of the terrestrial planets with the planets were based on computer simulations of the evolution of disks of gravitating bodies, combined at collisions. Below for studies of such probabilities I used other calculations. These calculations allow a larger statistics for probabilities of collisions of planetesimals with planet embryos at a few stages of growth of the embryos. The migration of bodies, originally located in a relatively narrow ring, was studied [2] under the gravitational influence of planets or their embryos. In the series *MeN* of runs, all planets (from Mercury to Neptune) were considered. In the series $Me_{01}S$ of calculations, I considered the embryos of the terrestrial planets with masses equal to 0.1 of the present planets' masses moving in present orbits of the planets, and also Jupiter and Saturn with their present masses and their present orbits. For $Me_{03}N$ runs, masses of the embryos of the terrestrial planets equalled to 0.3 of the present planets' masses, and all giant planets were considered. The symplectic integrator from the Swift integration package [3] was used. In this integration, the collisions of bodies with planets were not simulated, but the bodies were excluded from integration when they collided with the Sun or their distances from the Sun exceeded 2000 AU. The orbital elements of the migrated bodies were recorded in the computer memory with a step of 500 years. Based on these arrays, similar to the calculations presented in [4-5], for several considered time intervals (from 0.5 to 50 Myr), I calculated the probabilities of collisions of bodies with planets, the Moon, and with their embryos.

Seven regions in the terrestrial feeding zone were considered. In each run, the initial values a_o of the semi-major axes of the orbits of the bodies varied from a_{omin} to $a_{omin}+d_a$, and the number of bodies with a_o was proportional to $a_o^{1/2}$. The values of a_{omin} in different runs varied with a step of 0.2 AU from 0.3 to 1.5 AU. d_a=0.5 AU for a_{omin}=1.5 AU. For other runs d_a=0.2 AU. In each variant of calculations with a fixed value of a_{omin}, 250 initial bodies were considered. In some variants of the *MeN* calculations, initial eccentricities e_o of orbits equaled to 0.05, and in other runs they were 0.3. For $Me_{01}S$ and $Me_{03}N$ calculations, I considered only e_o=0.05. The initial inclinations i_o were equal to e_o/2 rad. It was obtained in [1] that, due to the mutual gravitational influence of bodies, the mean eccentricity of orbits of bodies in the feeding zone of the terrestrial planets could exceed 0.2.

2. Probabilities of collisions of bodies with embryos of the terrestrial planets and the Moon

Based on the obtained probabilities of collisions of bodies with embryos, I made a few estimates of the growth of the embryos of the terrestrial planets. The considered model does not take into account the mutual gravitational influence of bodies, which increased their eccentricities and mixing of bodies in the zone of the terrestrial planets. The results of $Me_{01}S$ calculations showed that at masses of the embryos of the terrestrial planets of about 0.1 of the masses of the planets, an embryo grew mainly by accumulation of bodies from its neighbourhood, and the embryos of the Earth and Venus grew faster than the embryos of Mercury and Mars. For $Me_{01}S$ runs, at each considered zone, bodies collided mainly only with one embryo, and probabilities of collisions of bodies with other embryos were zero or were much smaller than those for that embryo. Analysis of $Me_{03}N$ runs showed that probabilities of collisions of planetesimals, originally located at distances from 0.7 to 0.9 AU from the Sun, with the embryos of the Earth and Venus with masses equal to 0.3 from the masses of present planets, differed for these embryos by no more than twice.

The amounts of material from different parts of the zone from 0.7 to 1.5 AU from the Sun, which entered into almost formed the Earth and Venus, differed, probably, by no more than 2 times. For initial bodies with a_o<0.7 AU, the fraction of bodies that fell onto Venus was at least several times higher than the fraction of bodies that fell onto the Earth. The Earth and Venus could acquire more than a half of their mass in 5 million years. The ejection of the matter at collisions of planetesimals with planets, that was not taken into account in the considered model, can increase the time of accumulation of the planets. The formation of a Mars's embryo with a mass that was several times smaller than that of Mars, as a result of the compression of a rarefied condensation, can explain the relatively rapid growth of the main mass of Mars. We can also suppose the formation of Mercury's embryo with a mass of 0.02 of the Earth's mass by similar compression. The features of the formation of terrestrial planets can be explained with a relatively smooth decrease of the semi-major axis of Jupiter caused by its ejection of planetesimals into hyperbolic orbits, without considering Jupiter's migration to Mars's orbit and back (the Grand Tack model) and without sharp changes in orbits of the giant planets for the Nice model. In some runs with a_{omin} equaled to 0.3, 1.1, 1.3, and 1.5 AU, more than 10% of bodies could fall onto the Sun.

At the ratio of the masses of the embryos of the Earth and the Moon equaled to 81 (the ratio of the masses of the Earth and the Moon), the ratio of probabilities of planetesimals collided with the embryos of the Earth and the Moon in the considered variants did not exceed 54 and was maximum at the masses of embryos about three times smaller than the present masses of the Earth and the Moon. The ratio of the total mass of the bodies that fell onto the Earth to the mass of the bodies that fell onto the Moon, in the considered *MeN* variants of calculations ranged from 16.9 (for a_{omin}=1.1 AU and e_o=0.3) to 35.6 (for a_{omin}=0.9 AU and e_o=0.05).

Summary and Conclusions

The embryos of the terrestrial planets with masses about 0.1 of masses of the planets accumulated mainly material from their neighbourhoods. The amount of material from different parts of the zone from 0.7 to 1.5 AU from the Sun, which collided with almost formed the Earth and Venus, differed for these planets, probably, by no more than 2 times. Inner layers of each terrestrial planet could be accumulated mainly from planetesimals from the neighbourhood of this planet. The outer layers of the Earth and Venus could accumulate similar planetesimals from the feeding zone of the terrestrial planets.

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