PROBABILITIES OF COLLISIONS OF BODIES EJECTED FROM THE EARTH WITH PLANETS AND THE MOON

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The model and initial data used for calculations: In each calculation variant, migration of 250 bodies ejected from the Earth was studied for the same values of an ejection angle i_{ej} (measured from the surface plane), a velocity v_{esc} of ejection, and a time step t_s of integration. The bodies started their motion at the height of 10 km from the point of Earth's surface located most far from the Sun. In different variants, the values of i_{ej} equaled to 30°, 45°, or 60°, and v_{esc} equaled to 11.22, 12, 12.7 or 16.4 km/s. The symplectic code from the SWIFT integration package [1] was used for integration of the motion equations with t_s equal to 1, 2, 5, or 10 days. The gravitational influence of the Sun and all eight planets was taken into account. Bodies that collided with planets or the Sun or reached 2000 AU from the Sun were excluded from integration. The motion of bodies was studied during dynamical lifetime T_{end} of all bodies which was about 200-350 Myr. The probabilities of collisions of bodies with the Moon were calculated based on the arrays of orbital elements of migrated bodies (stored with a step of 500 years) similar to [2].

Calculations with different values of an integration time step: Most of calculations were made with a step t_s equal to 10 days. The motion of considered bodies is chaotic due to close encounters of bodies with planets. Therefore, the probabilities of collisions of bodies with planets are different for integrations with a different time step and for close initial data. Calculations with smaller values of a time step (equaled to 1, 2, and 5 days), made for v_{esc}=11.22 km/s and i_{ej}=30° or i_{ej}=45°, and at v_{esc}=12.7 km/s and i_{ej}=45°, showed that the probabilities of collisions of considered bodies with the Earth, the Sun, Mercury and Mars and of ejection into hyperbolic orbits obtained at $t_s=10^d$ are similar to those obtained at smaller t_s. However, the ratio of the probability p_V of a collision of a body with Venus at $t_s=10^d$ to that at smaller t_s was in the range from 1.2 to 1.8 at a time interval T=10 Myr and from 1 to 1.2 at T=100 Myr.

Probabilities of collisions of bodies with the Earth: The fraction p_E of bodies collided with the Earth during the first million years was about 0.01-0.02 at v_{esc} equal to 11.22 and 12 km/s, and it equaled to 0.004 at v_{esc}=16.4 km/s. For T=10 Myr, p_E was about 0.056-0.12 at v_{esc} equal to 11.22, 12 and 12.7 km/s, and was in the range 0.02-0.05 at v_{esc}=16.4 km/s. For T=10 Myr, the ratio of the values of p_E at i_{ej}=45° to the values at i_{ej}=30° was mainly greater at greater v_{esc} and varied between 1.2 and 2.4. At i_{ej}=60° the value of p_E was mainly not smaller than that at i_{ej}=45°. For T=100 Myr and at $T=T_{end}$, the values of p_E were typically greater by a factor of 1.5-2 than at T=10 Myr, and were in the range 0.1-0.2. In total for the considered calculations, about 16% of bodies fall back onto the Earth during T_{end}. The values of p_E at $T=T_{end}$ usually exceeded the values of p_E at T=100 Myr by less than a factor of 1.1.

Probabilities of ejection of bodies and of collisions of bodies with other planets and with the Sun: After 100 Myr less than 10% of bodies were left in elliptical orbits. The fraction p_{ej} of bodies ejected into hyperbolic orbits during a whole considered time interval T_{end} did not exceed 0.1, exclusive for v_{esc}=16.4 km/s and i_{ej}=30° (with p_{ej}=0.26). At $12 \le v_{esc} \le 16.4$ km/s p_{ej} was greater for i_{ej}=30° than for i_{ej}=45° and i_{ej}=60°. The values of p_{ej} were mainly greater for greater v_{esc}. The fraction p_{Sun} of bodies collided with the Sun was between 0.34 and 0.49. The probability of a collision of a body with Mercury was between 0.036 and 0.08, and the probability of a collision with Mars did not exceed 0.024. The probability p_V of a collision of a body with Venus was about 0.2-0.25.

Discussion on the growth of the Moon embryo: The ratio of probabilities of collisions of bodies with the Earth and the Moon was mainly about 20-30, and the values of the probability with the Moon were often about 0.006. In my calculations of the ejection of bodies from the Earth, I considered bodies that left the Hill's sphere of the Earth and moved in heliocentric orbits. At some collisions, the mass of the Moon could not increase due to ejection of material. With the present orbit of the Moon, the probability of collisions of the ejected bodies with the Moon was even less for the bodies that did not leave the Hill's sphere of the Earth than for the bodies that moved in heliocentric orbits. Bodies ejected from the Earth could participate in the formation of the outer layers of the Moon. In order to contain the present fraction of iron, the Moon had to accumulated the main fraction of its mass from the mantle of the Earth [3]. Bodies ejected from the Earth and fallen onto the Moon embryo in its present orbit probably were not enough for the growth of the Moon from a small embryo. So formation of a large Moon embryo close to the Earth is preferred.

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References: [1] Levison H.F., Duncan M.J. (1994) *Icarus* 108:18-36. [2] Ipatov S.I. (2019) *Solar System Research* 53:332-361. https://arxiv.org/abs/2003.11301. [3] Ipatov S.I. (2018) *Solar System Research* 52:401-416. https://arxiv.org/abs/2003.09925.