



Migration of bodies ejected from the Earth and the Moon

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- **Introduction:** Earlier in (Gladman et al., 2005; Reyes-Ruiz M. et al., 2012) the motion of bodies ejected from the Earth at collisions of bodies-impactors with the Earth was studied during time interval equal to 30 Kyr. Considered initial velocities were perpendicular to the surface of the Earth. According to (Shuvalov, 2011), the values of an ejection angle i_{ej} are mainly between 20° and 55° , especially between 40° and 50° .
- **The model and initial data used for calculations:** In each my calculation variant, the motion of 250 bodies ejected from the Earth was studied for the fixed values of an ejection angle i_{ej} , a velocity v_{ej} of ejection, and a time step t_s of integration. In different variants, the values of i_{ej} equaled to 15° , 30° , 45° , 60° , 89° or 90° , and v_{ej} equaled mainly to 11.22, 11.5, 12, 12.7, 14, 16.4, or 20 km/s. In most calculations, bodies started directly from the Earth. In each variant, bodies started from one of six considered opposite points (Ipatov, 2024). Such ejection was often at the stage of accumulation of the Earth, e.g. at the Late Heavy Bombardment.
- The motion of bodies was studied during the dynamical lifetime T_{end} of all bodies, which equaled to a few hundreds of Myr. During this time interval, all bodies collided with planets or the Sun or were ejected into hyperbolic orbits. 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 symplectic code from the SWIFT integration package (Levison, Duncan, 1994) was used for integration of the motion equations. The considered time integration step t_s equaled to 1, 2, 5, or 10 days, and the results of calculations with different t_s were compared. Most of calculations were done with an integration time step equal to 5 days. Similar calculations were made for migration of bodies ejected from the Moon, but for smaller minimum values of v_{ej} close to the parabolic velocity.
- **Probabilities of collisions of bodies ejected from the Earth with the Earth:** On average, about a half and less than 10% of initial ejected bodies still moved in elliptical orbits after 10 and 100 Myr, respectively. A few ejected bodies collided with planets after 250 Myr. The probabilities p_E of collisions of bodies ejected from the Earth with the Earth were approximately the same for calculations with different considered integration steps t_s . The fraction p_E is greater for a smaller ejection velocity. At $v_{ej} \leq 11.25$ km/s, i.e., at v_{ej} slightly greater than the parabolic velocity, most of the ejected bodies fell back onto the Earth. At $v_{ej} = 11.5$ km/s, the values of p_E were about 0.2-0.3 and did not differ much for different starting points on the Earth's surface. At $v_{ej} = 12$ km/s, p_E was about 0.16-0.27, and mean velocities of collisions with the Earth and the Moon were about 14-20 and 10-16 km/s, respectively. The significant difference in the results for different ejection points was in the vw variant (when bodies were ejected from the forward point of the Earth's motion) at $v_{ej} \geq 16.4$ km/s and $i_{ej} = 45^\circ$ or $i_{ej} = 60^\circ$. In this case, $\geq 80\%$ of the bodies were thrown into hyperbolic orbits, most of other bodies collided with the Sun, and p_E could be 0.
- The ratio of the probability of collisions of bodies with the Earth to the probabilities of collisions of bodies with other planets and the Sun usually decreased with time.
- **Probabilities of collisions of bodies ejected from the Earth with the Moon:** The probability of collisions of such bodies with the Moon in its present orbit was of the order of 0.01 (Ipatov, 2024). A large Moon embryo should be formed close to the Earth in order to accumulate material not rich in iron. For more efficient growth of the Moon embryo, it is desirable that after some collisions of impactor bodies with the Earth, the ejected bodies did not simply fly out of the crater, but some of the matter went into orbits around the Earth, as in the multi-impact model.

- In considered calculations, the **probabilities p_v of collisions of the bodies with Venus** at the end of evolution were often about 0.2-0.35 at $11.5 \leq v_{ej} \leq 16.4$ km/s. The values of p_v were about p_e at $v_{ej} = 11.5$ km/s, were greater than p_e at $v_{ej} \geq 12$ km/s and were less than p_e at $v_{ej} \leq 11.4$ km/s. The total number of ejected bodies delivered to the Earth and Venus probably did not differ much.
- **Probabilities of collisions of bodies with Mercury** at the end of evolution (at $T = T_{end}$) were about 0.02-0.08 and 0.03-0.05 at $11.3 \leq v_{ej} \leq 11.5$ and $12 \leq v_{ej} \leq 20$ km/s, respectively. The **probabilities of collisions of bodies with Mars** were smaller than those with Mercury and did not exceed 0.012 and 0.025 at $T = 10$ Myr and $T = T_{end}$, respectively. More material ejected from the Earth was delivered to Mercury than to Mars. The probabilities of collisions of bodies **with Jupiter** were of the order of 0.001. The fraction of bodies collided **with the Sun** often was between 0.2 and 0.5 at different $v_{ej} \geq 11.3$ km/s.
- **The fraction of bodies ejected into hyperbolic orbits** was mainly greater for a greater ejection velocity. During a whole considered time interval it did not exceed 0.1 at an ejection velocity not more than 12 km/s. At an ejection velocity greater than 16 km/s and an ejection angle not less than 60° degrees, all bodies were ejected from the Solar System if they started from the front (in the direction of the motion) point of the Earth. At an ejection angle equal to 45° and an ejection velocity equal to 16.4 km/s the fraction of bodies ejected from the Solar System was about 0.25-0.27 if points of ejection were not in the front or back of the Earth's motion.
- The fractions of collisions of bodies ejected from the Earth with planets could be similar to the fractions of collisions of planetesimals with planets for planetesimals that were left in the feeding zone of the Earth at the late stages of its formation. The obtained results testify in favour of that the upper layers of Earth and Venus can contain similar material.
- **Probabilities of collisions of bodies ejected from the Moon with the Earth:** For the ejection of bodies from the present orbit of the Moon (at a distance from the Earth equal to $r_{ME} = 60r_E$, where r_E is the radius of the Earth), $T = T_{end}$ and $15^\circ \leq i_{ej} \leq 89^\circ$, the value of p_E was about 0.27–0.35 at $v_{ej} = 2.5$ km/s, 0.2-0.25 at $v_{ej} = 5$ km/s, and 0.1-0.14 at $12 \leq v_{ej} \leq 16.4$ km/s. At $v_{ej} = 2.5$ km/s and $r_{ME} = 3r_E$ the dynamical lifetime of the ejected bodies was less than 5 days. At $r_{ME} = 5r_E$ and $v_{ej} = 2.5$ km/s, most of the ejected bodies quickly fell onto the Earth, but at $i_{ej} \leq 30^\circ$ some of the bodies left the Hill sphere of the Earth. At $v_{ej} = 5$ km/s (approximately the parabolic velocity of the Earth at $r_{ME} = 5r_E$), $T = T_{end}$ and $r_{ME} = 5r_E$, the value of p_E was about 0.3 (0.26-0.37) for the considered ejection angles i_{ej} from 15° to 89° .
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