

MIGRATION OF BODIES EJECTED FROM THE EARTH AND PROBABILITIES OF THEIR COLLISIONS WITH THE EARTH AND THE MOON. S. I. Ipatov, V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS, Moscow, Russia (siipatov@hotmail.com)

Introduction: Bodies ejected from the Earth at collisions of bodies-impactors with the Earth can move around the Sun and later collide with planets and the Moon. The motion of such bodies was considered in [1-2] during time interval equal to 30 Kyr. Ejection of bodies was considered from a whole surface of the Earth with velocities perpendicular to its surface. Several values of velocities were considered. Actually ejection angles i_{ej} mainly do not exceed 55° and most of ejected bodies still moved in orbits after 30 Kyr. The probability of a collision of an impactor with the Earth is different for different points of the Earth's surface (e.g. it is greater from a space outside the Earth's orbit than from inside the Earth's orbit).

Mass m_{ej} of ejected material is smaller for greater velocity v_{ej} of ejection (m_{ej} is proportional to $v_{esc}^{-1.65}$ [3]). Therefore, most of material leaves the Earth with velocities a little greater than the parabolic velocity. According to [4], the values of ejection angle i_{ej} are between 20° and 55° , and mainly between 40° and 50° . Similar values of i_{ej} were obtained in [5] for collisions of bodies with asteroids. At experiments with micron particles and velocities up to 2.5 km/s, i_{ej} was from 40° to 70° (from 40° to 80° at velocities of about 1 km/s) [6].

The model and initial data used for calculations:

I studied the migration of bodies ejected from the Earth during their dynamical lifetimes for time interval T_{end} up to a few hundreds of millions of years (see Table 1). The bodies started their motion at the height of 10 km from the Earth at the point of Earth's surface which is located at a maximum distance from the Sun. The values i_{ej} of ejection angle (measured from the surface plane) equaled to 30° , 45° , or 60° . Velocity v_{ej} of ejection equaled to 11.22, 12, 12.7, or 16.4 km/s. The symplectic code from the SWIFT integration package [7] was used for integration of the motion equations. The gravitational influence of the Sun and all eight planets was taken into account. There were 250 initial bodies in each calculation variant. Bodies that collided with planets and the Sun were excluded from integration. Below the results of integration with a time step d_s equal to 10 days are presented. Calculations with smaller values of d_s (equaled to 1, 2, or 5 days) showed that the probabilities of collisions of considered bodies with the Earth are similar to those obtained at smaller time steps. However, the probabilities of collisions of bodies with Venus and Mercury can be greater at $d_s=10^d$ than at smaller d_s . The number of collisions of

bodies with the Earth during time T (in Myr) after ejection of bodies from the Earth with velocity v_{ej} (in km/s) at ejection angle i_{ej} (in degrees) is presented in Table 2. Based on the arrays of orbital elements of migrated bodies, similar to [8], I calculated probabilities of collisions of bodies with the Earth and the Moon and the ratio p_E/p_M of these probabilities (see Table 3).

Results of calculations: During the first 30 Kyr in a calculation variant with 250 bodies typically not more than one body collided with the Earth, i.e. the probability p_E of a collision of a body with the Earth did not exceed 0.004. The fraction p_E of bodies collided with the Earth during the first million years was about 0.01-0.02 at v_{ej} equal to 11.22 and 12 km/s, and equaled to 0.004 at $v_{ej}=16.4$ km/s. At $T=10$ Myr, p_E was about 0.056-0.12 at v_{ej} equal to 11.22, 12 and 12.7 km/s, and were 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 $i_{ej}=45^\circ$ to the values of p_E at $i_{ej}=30^\circ$ was mainly greater at greater v_{ej} and varied between 1.2 and 2.4; at $i_{ej}=60^\circ$ p_E was mainly not smaller than at $i_{ej}=45^\circ$. 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 in the considered calculations about 16% of bodies fall back onto the Earth during a few hundreds of millions years.

The ratio p_E/p_M of probabilities of collisions of bodies with the Earth and the Moon was mainly about 20-30. After 100 Myr less than 10% of bodies were left in elliptical orbits, and evolution of disks of ejected bodies finished mainly in about 200-350 Myr.

In my calculations of the ejection of bodies from the Earth, I considered bodies that left the Hill sphere of the Earth and moved in heliocentric orbits. The fraction p_M of bodies that fell onto the Moon during their dynamical lifetimes was relatively small (~ 0.007 at small v_{ej}). For the present orbit of the Moon, the probability of collisions of the ejected bodies with the Moon is even less for bodies that did not leave the Hill sphere of the Earth. 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 [9]. 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. At small angles of bodies with a mass of

$\sim 0.01\text{--}0.1m_E$ (where m_E is the mass of the Earth) falling onto the Earth, the material of the Earth's mantle predominated in the material of the disk formed of ejected material [10]. It is possible that such a predominance of the Earth's matter also exists in the case of smaller projectile masses. However, with small (compared to $0.01\text{--}0.1m_E$) masses of impactors, the ejected matter did not form a new disk around the Earth, although it could be captured by the previous disk, if it existed.

Acknowledgements: The studies of falls of bodies onto the Earth were carried out under government-financed research project for the Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS. The studies of falls of bodies onto the Moon were supported by the Russian Science Foundation, project 21-17-00120, <https://rscf.ru/project/21-17-00120/>.

References: [1] Gladman B. et al. Impact seeding and reseeded in the inner Solar System // *Astrobiology*. 2005. V. 5, p. 483–496.

[2] Reyes-Ruiz M. et al. Dynamics of escaping Earth ejecta and their collision probabilities with different Solar System bodies // *Icarus*. 2012. V. 220, p. 777–786.

[3] Svetsov V. Cratering erosion of planetary embryos // *Icarus*. 2011. V. 214, p. 316–326.

[4] Shuvalov V.V., Trubetskaya I.A. Numerical simulation of high-velocity ejecta following comet and asteroid impacts: preliminary results // *Solar System Research*. 2011. V. 45, p. 392–401.

[5] Raduncan S.D., Davison T.M., Collins G.S. Ejecta distribution and momentum transfer from oblique impacts on asteroid surfaces // 2021. arXiv:2105.01474.

[6] Barnouin O.S. et al. Impacts into coarse-grained spheres at moderate impact velocities: Implications for cratering on asteroids and planets // *Icarus*. 2019. V. 325, p. 67–83.

[7] Levison H.F., Duncan M.J. The long-term dynamical behavior of short-period comets // *Icarus*. 1994. V. 108, p. 18–36.

[8] Ipatov S.I. Probabilities of collisions of planetesimals from different regions of the feeding zone of the terrestrial planets with forming planets and the Moon // *Solar System Research*. 2019. V. 53, p. 332–361. <http://arxiv.org/abs/2003.11301>

[9] Ipatov S.I. Formation of embryos of the Earth and the Moon from the common rarefied condensation and the subsequent growth // *Solar System Research*. 2018. V. 52, N 5, p. 401–416. <http://arxiv.org/abs/2003.09925>

[10] Rufu R., Aharonson O. A multiple-impact origin for the Moon // *Nature Geoscience*. 2017. V. 10, p. 89–94.

Table 1. Time T_{end} (in Myr) of the evolution of a disk of bodies ejected from the Earth with velocity v_{ej} (in km/s) at ejection angle i_{ej} (in degrees).

i_{ej} , deg	11.22 km/s	12 km/s	12.7 km/s	16.4 km/s
30	301.9	337.8	273.2	302.2
45	206.1	290.6	311.0	359.2
60	270.8	349.6	189.2	225.7

Table 2. The number of collisions of bodies with the Earth during time T (in Myr) after ejection of bodies from the Earth with velocity v_{ej} (in km/s) at ejection angle i_{ej} (in degrees).

i_{ej} , deg	T , Myr	11.22 km/s	12 km/s	12.7 km/s	16.4 km/s
30	1	3	4	0	1
30	2	6		3	3
30	5	8		7	4
30	10	15	14	14	5
30	25	26		24	9
30	100	36	27	29	9
30	T_{end}	38	28	34	16
45	1	4	3	6	1
45	2	8	7	8	3
45	5	10	12	17	5
45	10	18	18	21	12
45	25	28	31	27	15
45	100	39	36	32	15
45	T_{end}	39	38	34	22
60	1	4	5	2	1
60	2	11	6	4	1
60	5	20	12	14	8
60	10	29	23	20	12
60	25	42	30	27	17
60	100	47	42	30	29
60	T_{end}	48	42	32	31

Table 3. The ratio p_E/p_M of the probabilities of collisions of bodies with the Earth to those with the Moon at the evolution of a disk of bodies ejected from the Earth with velocity v_{ej} (in km/sec) at ejection angle i_{ej} (in degrees).

i_{ej} , deg	T , Myr	11.22 km/s	12 km/s	12.7 km/s	16.4 km/s
30	1	22.0	29.3	23.5	19.9
30	10	22.4	28.5	22.6	19.4
30	100	20.6	28.5	20.8	18.1
45	1	24.5	23.2	21.7	21.5
45	10	23.4	21.4	23.7	22.5
45	100	23.4	19.8	21.9	24.0
60	10	29.4	26.5	31.2	22.3
60	100	27.3	24.4	28.4	20.4