

PROBABILITIES OF COLLISIONS OF BODIES EJECTED FROM THE EARTH WITH THE TERRESTRIAL PLANETS. S. I. Ipatov, V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS, Moscow, Russia (siipatov@hotmail.com, <https://siipatov.webnode.ru/>)

Introduction and considered model: During accumulation of the terrestrial planets and at late heavy bombardment, migrating bodies could collide with the Earth. Some bodies were ejected at such collisions. In [1-2] 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 in [1-2] were perpendicular to the surface of the Earth.

The probabilities of collisions of the bodies ejected from the Earth with the terrestrial planets were calculated and are discussed below. In each variant of the calculations, the motion of 250 bodies ejected from one of six points on the Earth's surface was studied for fixed values of the ejection angle i_{ej} (measured from the surface plane), the ejection velocity v_{esc} , and the time integration step t_s . 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 the integration. The motion of bodies ejected from the Earth was studied during the dynamical lifetime T_{end} of all bodies. In the calculation variants, this lifetime was about 200–500 Myr.

The symplectic algorithm from [3] was used to integrate the equations of motion. The considered time integration step t_s was equal to 1, 2, 5, or 10 days. Comparison of the calculation results for different t_s did not show significant differences in the results for the considered values of t_s , although the obtained results were slightly different due to the chaotic evolution of the considered orbits. The only difference in calculations with different t_s was that the probabilities of collisions of bodies with Mercury at $t_s=10$ days could be twice greater than the probabilities at $t_s \leq 5$ days.

Bodies were considered to start from one of six points on the Earth's surface. In the vf and vc series, the motion of the bodies started from the most and least distant points of the Earth's surface from the Sun (located on the line from the Sun to the Earth), respectively. In the vu and vd series, the bodies started from points on the Earth's surface with the maximum and minimum values of z (with the z axis perpendicular to the plane of the Moon's orbit), respectively. In the vw and vb series, the bodies started from the forward point on the Earth's surface in the direction of the Earth's motion and from the back point on the opposite side of the Earth, respectively. In different variants, the values of ejection angle i_{ej} equaled to 15°, 30°, 45°, 60°, 89°, or 90°.

The ejection velocity v_{esc} was mainly equal to 11.22, 11.5, 12, 12.7, 14, 16.4, or 20 km/s, but other values in the range from 11.22 to 11.5 km/s were also considered.

Probabilities and velocities of collisions of bodies ejected from the Earth with the Moon. In [4] I studied the probabilities of collisions of ejected bodies with the Moon and velocities of collisions of ejected bodies with the Earth and the Moon. The probabilities of collisions of bodies with the Moon and collision velocities with the Earth and the Moon were calculated based on the arrays of orbital elements of migrated bodies and some formulas. The probability of a collision of a body ejected from the Earth with the Moon in its present orbit was by a factor 15-35 smaller than the probability of a collision of a body with the Earth at $v_{ej} \geq 11.5$ km/s. The probability of collision of such bodies with the Moon was mainly about 0.004-0.008 at ejection velocities of at least 14 km/s and about 0.006-0.01 at $v_{ej}=12$ km/s. It was greater at lower ejection velocities and was in the range of 0.01-0.02 at $v_{ej}=11.3$ km/s. The Moon may contain material ejected from the Earth during the accumulation of the Earth and during the late heavy bombardment. At the same time, as obtained in our calculations, the bodies ejected from the Earth and falling on the Moon embryo would not be enough for the Moon to grow to its present mass from a small embryo moving in the present orbit of the Moon. This result argues in favor of the formation of a lunar embryo and its further growth to most of the present mass of the Moon near the Earth. It seems more likely to us that the initial embryo of the Moon with a mass of no more than 0.1 of the mass of the Moon was formed simultaneously with the embryo of the Earth from a common rarefied condensation [5]. For more efficient growth of the Moon embryo, it is desirable that during some collisions of impactor bodies with the Earth, the ejected bodies do not simply fly out of the crater, but some of the matter goes into an orbit around the Earth, as in the multi-impact model [6]. The average velocities of collisions of ejected bodies with the Earth are greater at greater ejection velocity. The values of these collision velocities were about 13, 14-15, 14-16, 14-20, 14-25 km/s with ejection velocities equal to 11.3, 11.5, 12, 14 and 16.4 km/s, respectively. The velocities of collisions of bodies with the Moon were also higher at high ejection velocities and were mainly in the range of 7–8, 10–12, 10–16 and 11–20 km/s at v_{ej} equal to 11.3, 12, 14 and 16.4 km/s, respectively.

Probabilities of collisions of bodies ejected from the Earth with the terrestrial planets: Below we discuss the probabilities of collisions of the bodies with Earth (p_e), Venus (p_v), Mercury (p_{me}), Mars (p_{ma}), Sun (p_{sun}), and the probability p_{ej} of ejection of a body into hyperbolic orbit. In Tables 1 and 2 the ranges of such probabilities are presented at time intervals $T=10$ Myr and $T=T_{end}$. The ranges are presented for series vc , vd , vf and vu . For a few variants of these series, the probabilities can be out of these ranges. For series vb and vw , the probabilities can be out of the ranges presented in the tables.

Probabilities p_e of collisions of the bodies **with Earth** were greater for smaller ejection velocity v_{esc} . At $T=T_{end}$ mean values of p_e varied from about 1 at $v_{esc} \leq 11.25$ km/s to about 0.1 at $v_{esc} = 20$ km/s, with p_e about 0.3, 0.2-0.25, 0.15-0.2 at v_{esc} equal to 11.5, 12 and 14 km/s. The ratio of values of p_e at $T=T_{end}$ and $T=10$ Myr presented in the tables was usually not more than 2. Such ratio for $T=10$ Myr and $T=1$ Myr was often about 2. It could be more than 2 for $T=1$ Myr and $T=0.1$ Myr. For vb series, values of p_e , p_v and p_{me} were usually greater than the values presented in the tables at $v_{esc} \geq 14$ km/s. For vw series, values of p_e , p_v and p_{me} were about 0 at $i_{ej} \geq 45^\circ$ and $v_{esc} \geq 16.4$ km/s.

In Table 2 probabilities p_v of collisions of the bodies **with Venus** at $T=T_{end}$ were often about 0.2-0.3 and less depended on v_{esc} than p_e . For $T=T_{end}$ on average p_v was about p_e at $v_{esc} = 11.5$ km/s, was greater than p_e at $v_{esc} \geq 11.5$ km/s and was less than p_e at $v_{esc} \leq 11.5$ km/s. The ratio of p_v/p_e was typically smaller at smaller T . The total number of bodies delivered to the Earth and Venus probably did not differ much.

In Tables 1-2, probabilities of collisions **with Mercury and Mars** usually did not exceed 0.1 and 0.02, respectively. At $T=10$ Myr they were usually at least 2 times less than at $T=T_{end}$. They were 0 at $T=1$ Myr. In different variants, the probability p_{sun} of collisions of bodies **with the Sun** varied from 0 to 0.7. Often it was between 0.2 and 0.5 and was greater at greater v_{esc} .

The **fraction p_{ej} of ejected bodies** was less than 0.1 at $v_{esc} \leq 12$ km/s. For vw variants, it reached 1 at $v_{esc} = 16.4$ km/s and $i_{ej} \geq 60^\circ$ and at $v_{esc} = 20$ km/s and $i_{ej} \geq 45^\circ$. For other points of ejection and $v_{esc} \geq 16.4$ km/s, it was smaller for greater i_{ej} . For many calculation variants there was no ejection at $T \leq 1$ Myr. However, for vf variant and $v_{esc} = 16.4$ km/s, about 20% of initial bodies were ejected during the first million years, and they were 70% of all ejected bodies.

The average values of p_e , p_v , p_{me} , p_{ma} , p_{sun} , and p_{ej} depend on the distribution of bodies over v_{esc} , i_{ej} and points of ejection. These distributions depend on

velocities and masses of impactors with the Earth. It is considered that maximum ejection is at i_{ej} about 45° .

Conclusions: The probabilities of collisions of the bodies ejected from the Earth with the terrestrial planets were calculated. The total number of bodies delivered to the Earth and Venus probably did not differ much.

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Table 1. Values of p_e , p_v , p_{me} , p_{ma} , p_{sun} , and p_{ej} at $T=10$ Myr for series vc , vd , vf and vu .

	p_e	p_v	p_{me}	p_{ma}	p_{sun}	p_{ej}
11.3	0.37-0.52	0.08-0.16	0-0.03	0-0.008	0.01-0.06	0-0.03
11.4	0.25-0.35	0.13-0.2	0-0.03	0-0.004	0-0.03	0-0.03
11.5	0.12-0.2	0.14-0.22	0-0.05	0-0.008	0-0.1	0-0.03
12	0.16-0.27	0.13-0.2	0-0.03	0-0.008	0.05-0.1	0-0.03
14	0.0-0.1	0.05-0.15	0-0.04	0-0.008	0.05-0.25	0-0.15
16.4	0.03-0.1	0.04-0.14	0.03-0.15	0-0.012	0.02-0.25	0-0.33
20	0.03-0.1	0.03-0.12	0.02-0.06	0-0.004	0.02-0.12	0-0.4

Table 2. Values of p_e , p_v , p_{me} , p_{ma} , p_{sun} , and p_{ej} at $T=T_{end}$ for series vc , vd , vf and vu .

	p_e	p_v	p_{me}	p_{ma}	p_{sun}	p_{ej}
11.3	0.45-0.55	0.18-0.25	0.02-0.06	0-0.016	0.1-0.25	0.01-0.04
11.4	0.3-0.45	0.23-0.33	0.02-0.08	0-0.02	0.2-0.32	0.01-0.05
11.5	0.25-0.35	0.22-0.33	0.02-0.08	0-0.016	0.22-0.33	0.02-0.06
12	0.16-0.27	0.25-0.37	0.04-0.08	0-0.02	0.3-0.43	0.02-0.08
14	0.1-0.2	0.2-0.3	0.04-0.1	0-0.02	0.3-0.5	0.03-0.15
16.4	0.1-0.15	0.18-0.25	0.03-0.1	0-0.025	0.2-0.5	0.05-0.33
20	0.08-0.15	0.15-0.25	0.05-0.1	0-0.012	0.2-0.6	0-0.4