

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

Introduction: Gladman et al. [1] and Reyes-Ruiz et al. [2] studied the motion of bodies ejected vertically from the Earth during 30 Kyr. The orbital evolution of bodies ejected from Mars and Moon was studied by Wetherill [3], Gladman et al. [4,5], and Gladman [6]. Gladman and Coffey [7] studied the motion of bodies ejected from Mercury.

I made computer simulations of the evolution of orbits of bodies ejected from the terrestrial planets and the Moon. Each calculation variant was made for 250 bodies at the fixed values of an ejection velocity and an ejection angle for the same ejection point. Ejection velocities varied from the values of the parabolic velocities at the surface of the celestial object to 20 km/s. Ejection velocities varied between 15 and 90 degrees. Six opposite ejection points were considered. For the starting points F and C, the motion of the bodies started at most and least distant points of the planet's surface from the Sun, respectively. For the points W and B, the bodies started from the forward point on the planet's surface in the direction of the planet's motion and from the back point on the opposite side of the planet, respectively (from apex and antapex). For the points U and D, the bodies started from points on the planet's surface with the maximum and minimum values of z (with the z axis perpendicular to the plane of the planet's orbit), respectively. The evolution of orbits of bodies was studied under the gravitational influence of the Sun and all eight planets with the use of the symplectic code from the SWIFT integration package [8]. The calculations were made until all bodies collided with planets or the Sun or reached 2000 AU from the Sun. Some bodies collided with planets after a few hundreds of million years.

My studies of the motion of bodies ejected from the Earth have been published in [9, 10]. Short information about the motion of bodies ejected from Mars was published in [11], and short information about the probabilities of collisions of bodies ejected from Mars, Mercury, and the Moon is in [12]. Probabilities of collisions of ejected bodies with planets were different for different ejection velocities v_{ej} , ejection angles i_{ej} and ejection points. The values of the probabilities for points W and B differed more from the values at other four points. Below I discuss the main intervals of the values of these probabilities. At a velocity of ejection close to the parabolic velocity, most of bodies fell onto the planet from which they had been ejected. Below results are presented not for such small ejection velocities.

Ejection of bodies from the Earth: The fraction p_E of bodies ejected from the Earth that fall back onto the Earth was about 0.15-0.25 at ejection velocities about 12-14 km/s. The probability of collisions of bodies ejected from the Earth with the Moon moving in its present orbit was of the order of 0.01. The total number of bodies ejected from the Earth and delivered to Venus probably did not differ much from that delivered to the Earth. The values p_V of the fraction of bodies collided with Venus 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. Probabilities of collisions of bodies ejected from the Earth with Mercury were about 0.02-0.08 at ejection velocities greater than 11.3 km/s. The probabilities of collisions of bodies ejected from the Earth with Mars did not exceed 0.025.

On average, about a half and less than 10% of initial ejected bodies remained moving in elliptical orbits in the Solar System after 10 and 100 Myr, respectively. A few ejected bodies collided with planets after 250 Myr. A few percent of bodies ejected at the Chicxulub and Popigai events about 36-65 Myr ago can still move in the zone of the terrestrial planets and have small chances to collide with planets, including the Earth. The probability of a collision of a body with Mars during the first 1 Myr was about 0.0002. It is considered that some microbes can survive in space during 1 Myr.

Ejection of bodies from the Moon: For the ejection of bodies from the present orbit of the Moon, the probabilities of collisions of ejected bodies with planets were similar to those ejected from the Earth if we consider smaller ejection velocities from the Moon than from the Earth. At the ejection of bodies from the point F for the present orbit of the Moon and $15^\circ\leq i_{ej}\leq 89^\circ$, 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.

Ejection of bodies from Mars: For ejection of bodies from the points C, D, F, and U, the values of the probability p_{Ma} of a collision of a body ejected from Mars with Mars were mainly about 0.04-0.25, 0.01-0.04, and 0-0.02 at $5.05\leq v_{ej}\leq 5.3$, $5.5\leq v_{ej}\leq 10$, and $15\leq v_{ej}\leq 20$ km/s, respectively. For the point B, the value of p_{Ma} was typically smaller than for the above points. For the point W, p_{Ma} could exceed 0.3 at $v_{ej}=5.05$ km/s, and $p_{Ma}=0$ at $15\leq v_{ej}\leq 20$ km/s.

The probabilities p_E of collisions of bodies ejected from Mars with the Earth for the points C, D, F, and U were mainly about 0.08-0.16 and 0-0.16 at $5.05\leq v_{ej}\leq 10$ and $15\leq v_{ej}\leq 20$ km/s, respectively. For the point B, p_E

could exceed 0.24. For the point W, the values of p_E were in the range between 0 and 0.15.

For the points C, D, F, and U, the probabilities p_V of collisions of bodies ejected from Mars with Venus were mainly about 0.08-0.2 and 0.02-0.2 at $5.05 \leq v_{ej} \leq 10$ and $15 \leq v_{ej} \leq 20$ km/s, respectively. At $v_{ej} \geq 5.2$ km/s, the values of p_V often were slightly greater than p_E . For the point B, the value of p_E could exceed 0.3. For the point W, p_E was in the range between 0 and 0.18. Bodies ejected from Mars could collide with the Earth after 0.1 Myr, and some of the bodies could collide with the Earth after hundreds of million years.

For $v_{ej} \geq 6$ km/s, the fraction of bodies ejected from Mars and then collided with Mercury was usually less than 0.06 and was greater than the fraction of bodies colliding with Mars. For the points C, D, F, U, and B, the values of the fraction of bodies collided with the Sun were typically between 0.2 and 0.9. Usually at $5.1 \leq v_{ej} \leq 8$ km/s more than a half of bodies collided with the Sun. The probability of ejection of a body into a hyperbolic orbit was less than 0.1 at $v_{ej} \leq 6$ km/s, but it could exceed 0.9 at $v_{ej} = 20$ km/s. For the point W and $15 \leq v_{ej} \leq 20$ km/s, almost all bodies were ejected into hyperbolic orbits. For the point B, less than 10% of bodies were ejected into hyperbolic orbits.

Ejection of bodies from Mercury: Usually more than a half of bodies that ejected from Mercury fall back onto Mercury. For points B, C, D, and F, the probabilities p_V of collisions of such ejected bodies with Venus were usually about 0.2-0.4 at $6 \leq v_{ej} \leq 10$ km/s. Probabilities p_E of collisions of bodies with the Earth typically did not exceed 0.05 and 0.1 at v_{ej} less than 8 km/s and 15 km/s, respectively. The values of p_V were greater than p_E typically by an order of magnitude. The difference was greater for smaller ejection velocities. The fraction of bodies ejected into hyperbolic orbits did not exceed 0.02 for most calculation variants. Not more than 20% of bodies usually collided with the Sun.

For ejection from the point W at $v_{ej} \geq 6$ km/s depending on i_{ej} and v_{ej} , about a half of bodies can collide with Venus. More rarely most of such ejected bodies collided with the Sun or left the Solar system.

Ejection of bodies from Venus: First I discuss the values of the probabilities of collisions with planets for bodies ejected from Venus from the points C, D, F, and U at ejection velocities between 10.4 and 16 km/s. In this case, the fraction p_{ej} of bodies ejected into hyperbolic orbits did not exceed 0.06, the fraction p_{Sun} of bodies collided with the Sun was about 0.1-0.4, the fraction p_{Me} of bodies collided with Mercury was about 0.01-0.2, the fraction p_V of bodies collided with Venus was about 0.3-0.8, and the fraction p_E of bodies collided with the Earth was about 0.04-0.2 (was smaller by a factor of several than p_V). The values of p_{Sun} at $v_{ej} = 16$

km/s were greater by about a factor of 2 than at $v_{ej} = 10.4$ km/s. The values of p_{Me} at $v_{ej} = 16$ km/s were greater by about a factor of several (from 2 to 10 depending on the point of ejection and i_{ej}) than at $v_{ej} = 10.4$ km/s. The values of p_V have some tendency (but not at all initial data) to be smaller at greater v_{ej} . The probabilities of collisions of bodies with Mars often did not exceed 0.01 for all considered initial data.

For the points C, D, F, and U at $v_{ej} = 20$ km/s, the values of p_{ej} were about 0.25-0.32 at $i_{ej} = 45^\circ$, and could be about 0.02 at $i_{ej} = 89^\circ$; the values of p_{Sun} were about 0.15-0.3; p_{Me} was about 0.1-0.15; the values of p_V were about 0.23-0.35; the values of p_E were about 0.04-0.1 at $i_{ej} = 45^\circ$, and could be about 0.2 at $i_{ej} = 89^\circ$.

For the point B, the values of p_{ej} were mainly less than 0.04, the values of p_{Sun} were about 0.07-0.3, the values of p_{Me} were about 0.02-0.35 (with maximum at $v_{ej} = 20$ km/s), the values of p_V were about 0.4-0.8, the values of p_E were about 0.04-0.2 (but equaled to 0.01 at $v_{ej} = 20$ km/s and $i_{ej} = 89^\circ$).

For the point W at $v_{ej} \leq 12$ km/s, the values of p_{ej} were mainly less than 0.06, the values of p_{Sun} were about 0.1-0.4, the values of p_{Me} were about 0.01-0.1, the values of p_V were about 0.3-0.8, p_E was about 0.1-0.2. More bodies were ejected from the Solar system at greater v_{ej} . For $v_{ej} = 20$ km/s the fraction of ejected bodies was about 0.8 at $i_{ej} = 45^\circ$ and all bodies were ejected at $i_{ej} = 89^\circ$.

Acknowledgments: The studies were carried out under government-financed research project for the Vernadsky Institute.

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