

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

Considered model: The terrestrial planets and the Moon were bombarded by bodies-impactors mainly during formation of planets and at the stage of late-heavy bombardment. After such collisions some material was ejected from planets and the Moon. The references to the papers which studied the motion of bodies ejected from planets can be found in [1-4]. I studied migration of bodies ejected from the Earth [1-2], other terrestrial planets [3-4] and the Moon [5-6]. In each my calculation variant, the motion of 250 bodies ejected from a planet or the Moon was studied for the fixed values of an ejection angle i_{ej} (measured from the surface plane), a velocity v_{ej} of ejection, and an ejection point. In different variants, the values of i_{ej} varied from 15° to 90° , and v_{ej} varied from a parabolic velocity to 20 km/s. Six points on the planet's surface were considered as a starting point of ejection. For point C, the motion of bodies started from the point of planet's surface located most close to the Sun. For points W and B on planet's surface, the bodies started from the forward point in the direction of the planet's motion and from the back point on the opposite side of the planet, respectively. Bodies started from points U and D with the maximum and minimum values of z (with the Oz axis perpendicular to the plane of the planet's orbit), respectively. For point F, the motion of bodies started from the height h from the point of planet's surface located most far from the Sun in the direction from the Sun to the planet.

Bodies started directly from a surface of a planet. In order to simulate ejection of bodies from different possible orbits of growing Moon, some calculations were made from point F at the height h of ejection above the Earth's surface equaled to $h=3r_E$, $h=5r_E$, $h=7r_E$, and $h=36r_E$ (the distance from the center of the Earth is greater than h by r_E), where r_E is the radius of the Earth. There were also calculations for the present orbit of the Moon (its mean distance from the center of the Earth is $385000 \text{ km}=60r_E$, and is a little greater than the semi-major axis of the Moon equaled to 384748 km due to eccentricity $e=0.054$). Such calculations with $h>0$ correspond to the motion of bodies ejected from the Moon, though the gravitational influence of the Moon and its motion about the Earth were not included in integrations. In this case, real velocities of ejection of bodies from the Moon differed a little from those used in calculations. The calculations at $3r_E \leq h \leq 36r_E$ correspond to the case when the Moon had not yet reached its present orbit.

The gravitational influence of all eight planets was taken into account. Calculations were made until all

bodies collided with the Sun or planets or reached 2000 AU from the Sun. The considered time interval usually equaled to a few hundreds of Myr. More details about the model and the code used for calculations are presented in [1-3].

Probabilities and velocities of collisions of bodies ejected from the Earth with the Moon: In [1] I studied the probabilities of collisions of bodies ejected from the Earth with the Moon and velocities of collisions of ejected bodies with the Earth and the Moon. The Moon was not included in the integration of motion of bodies. Based on the arrays of orbital elements of migrated bodies and on analytical formulas, I calculated the probabilities of collisions of bodies with the Moon and the Earth and the ratio of probabilities of collisions of bodies with the Earth and the Moon. The probability of a collision of a body ejected from the Earth with the Moon in its present orbit was by a factor $k_{EM}=15\text{-}35$ smaller than the probability of a collision of a body with the Earth at $v_{ej} \geq 11.5 \text{ km/s}$. The factor k_{EM} was about 35-45 at $v_{ej}=11.3 \text{ km/s}$ and 15-30 at $v_{ej}=16.4 \text{ km/s}$. The probability of a 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 $v_{ej}=12 \text{ km/s}$. It was greater at lower ejection velocities and was in the range of 0.01-0.02 at $v_{ej}=11.3 \text{ km/s}$. It was concluded in [1] that in order to contain the present fraction of iron, the Moon should form not far from the Earth.

Velocities of collisions of bodies with the Moon and the Earth depended on ejection angles i_{ej} , ejection velocities v_{ej} and on ejection points. The values of velocities of collisions of ejected bodies with the Earth were about 13, 14-15, 14-16, 14-20, and 14-25 km/s for ejection velocities equal to 11.3, 11.5, 12, 14, and 16.4 km/s, respectively. The average collision velocities are greater at a greater ejection velocity. The velocities of collisions of bodies with the Moon were also higher at higher 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 Mars, Mercury and Venus with the Moon: The probability p_{moon} of a collision of a body ejected from a terrestrial planet with the Moon in its present orbit can be estimated to be mainly about by a factor of 15-30 smaller than the probability p_e of a collision with the Earth. The ratio $k_{em}=p_e/p_{moon}$ can be different for different ejected bodies and typically is less for greater v_{ej} . For example, for $i_{ej}=45^\circ$ and point F, the ratio equaled to 30, 29, and 18 for ejection from Venus at v_{ej}

equal to 10.5, 12, and 20 km/s, k_{em} equaled to 23, 23, and 14 for ejection from Mars at v_{ej} equaled to 5.3, 6, and 20 km/s, and k_{em} equaled to 19, 16, and 21 for ejection from Mercury at v_{ej} equaled to 5.3, 6, and 20 km/s, respectively.

For points C, D, F, U, and W, probabilities p_e of collisions of bodies **ejected from Mars** with the Earth 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 point B, p_e could exceed 0.24. At $p_e=0.1$ and $k_{em}=20$, the probability of a collision of a body with the Moon can be estimated as $p_{moon}=0.005$.

Probabilities p_e of collisions of bodies **ejected from Mercury** with the Earth were less than 0.03-0.05 (depending on a point of ejection) at $4.23 \leq v_{ej} \leq 6$ km/s. For large velocities in some variants, p_e reached 0.2. At $p_e=0.04$ and $k_{em}=20$, the probability of a collision of a body with the Moon can be estimated as $p_{moon}=0.002$.

At $10.4 \leq v_{ej} \leq 16$ for middle" points C, D, F, and U km/s, the fraction p_E of bodies **ejected from Venus** and collided with the Earth was about 0.04-0.1 at $i_{ej}=45^\circ$, and could be about 0.2 at $i_{ej}=89^\circ$. At $p_e=0.09$ and $k_{em}=30$, the probability of a collision of a body with the Moon can be estimated as $p_{moon}=0.003$.

Probabilities of collisions of bodies ejected from the Moon with the Earth: For ejection of bodies from the present orbit of the Moon, $T=10$ Myr and $30^\circ \leq i_{ej} \leq 60^\circ$, p_e was about 0.2-0.25 at $v_{ej}=2.5$ km/s, 0.13-0.14 at $v_{ej}=5$ km/s, and 0.06-0.07 at $12 \leq v_{ej} \leq 16.4$ km/s. At $T=T_{end}$ (at the end of evolution) 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. That is, at velocities slightly greater than the parabolic velocity, the values of p_e are approximately the same for the ejection of bodies from the Earth and the Moon, but for different ejection velocities. These p_e values show the fraction of bodies that could collide with the Earth after being ejected from the Moon moving in its present orbit. This fraction is approximately the same as for bodies ejected from the Earth, if we take into account the lower minimum velocities of bodies ejected from the Moon.

At $h=36r_E$, the probabilities p_e of collisions of bodies ejected from the Moon with the Earth were in the range 0.07-0.2 for $30^\circ \leq i_{ej} \leq 60^\circ$ and $11.2 \leq v_{ej} \leq 16.4$ km/s, and were greater for smaller velocities. At $v_{ej}=5$ km/s, $T=T_{end}$, and $h=5r_E$, the value of p_e was about 0.3 (0.26-0.37) for $15^\circ \leq i_{ej} \leq 89^\circ$.

Bodies ejected from the **lunar embryo, which was moving close to the Earth**, fell back to the Earth and the Moon if their initial velocity was less than the corresponding parabolic velocity. At $v_{ej}=2.5$ km/s and $h=3r_E$, the dynamic lifetime of the ejected bodies was less than 5 days. At $h=5r_E$, $i_{ej} \geq 30^\circ$, and $v_{ej}=2.5$ km/s, most of the ejected bodies quickly fell onto the Earth.

For $h=7r_E$, $v_{ej}=2.5$ km/s, $30^\circ \leq i_{ej} \leq 60^\circ$, and $(h=5r_E, v_{ej}=2.5$ km/s, $i_{ej}=15^\circ)$, and $(h=3r_E, v_{ej}=5$ km/s, $15^\circ \leq i_{ej} \leq 45^\circ)$, more than a half of bodies still moved around the Earth after more than 100 Myr. The collisions with the Moon were not included in integrations. So actually such bodies should collide with the Moon.

At $v_{ej}=5$ km/s, the values of p_e were in the range (for different i_{ej}) 0.26-0.37, 0.25-0.29, and 0.20-0.22 for $h=5r_E$, $h=7r_E$, and the present orbit, respectively. At $v_{ej}=12$ km/s, the values of p_e were in the range 0.13-0.14, 0.11-0.14, and 0.11-0.16 for $3r_E \leq h \leq 5r_E$, $h=7r_E$, and the present orbit of the Moon, respectively. The ratios of probabilities of collisions of bodies with other planets to that of the Earth for ejections from the Moon were mainly similar to the ratios for ejection from the Earth. The probabilities of collisions of bodies ejected from the Earth with planets were considered in [2]. For ejection from the Moon, I will present such probabilities in a publication with a larger number of pages than it is allowed in this abstract.

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In Russian. The English text is only for abstract, contents, and a list of publications.

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