COLLISIONS OF BODIES EJECTED FROM SEVERAL PLACES ON THE EARTH AND THE MOON WITH THE TERRESTRIAL PLANETS AND THE MOON. 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: The evolution of the orbits of bodies ejected from the Earth or the Moon was studied. The probabilities of collisions of the bodies with the Earth, the Moon, and other planets were calculated. The ejection of bodies from six opposite points on the Earth's surface (not from one point, as in [1]), as well as from the Moon, was considered. The range of considered velocities and ejection angles of bodies was greater than in [1]. The motion of bodies ejected from the Earth or the Moon was studied during the dynamical lifetime T_{end} of all bodies, which in the calculation variants was about 200–500 Myr. Such ejection of bodies was often at the stages of the Earth's accumulation and late heavy bombardment. In [2-3] 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 [2-3] were perpendicular to the surface of the Earth.

In each variant of the calculations, the motion of 250 bodies ejected from the Earth was studied at fixed values of the ejection angle i_{ej} (measured from the surface plane or from another parallel 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 symplectic algorithm from [4] was used to integrate the equations of motion. The considered time 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 probabilities of collisions of bodies with the Moon were calculated on the basis of the arrays of orbital elements of migrating bodies (stored with a step of 500 years).

In the *vf* and *vc* series, the motion of the bodies started at the height h 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 *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 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 most calculations h=0, i.e. the bodies were launched directly from the Earth. Calculations were also made for series *vf* at h=38500 km=60r_E, where r_E is the radius of the Earth, and 60r_E is the semi-major axis of the Moon's orbit. Such calculations corresponded to the motion of bodies ejected from the Moon, but did not take into account the gravitational influence of the Moon and its motion around the Earth. However, the real velocities of ejection of bodies from the Moon could differ only a little from those used in the calculations. The calculations for h=37r_E correspond to the case when the Moon has not yet reached its current orbit. In different variants, the values of i_{ej} were 15°, 30°, 45°, 60°, 89°, and 90°. The ejection velocity v_{esc} was mainly equal to 11.22, 11.5, 12, 12.7, 14, or 16.4 km/s, but other values in the range from 11.22 to 11.5 km/s were also considered. At h=60r_E, the calculations were also carried out for the velocity v_{esc} equal to 2.5 and 5 km/s. For the Moon, the parabolic velocity is 2.38 km/s.

Probabilities of collisions of bodies ejected from the Earth with the Earth: The probabilities p_E of collisions of bodies with the Earth were approximately the same for calculations with different considered values of the integration step t_s. At h=0 and 11.5≤v_{esc}≤14 km/s, p_E did not strongly depend on the point of ejection from the Earth's surface. The values of p_E were generally smaller at higher v_{esc} rates. At ejection velocities v_{esc}≤11.3 km/s, i.e. slightly greater than the parabolic velocity, most of the ejected bodies fell back onto the Earth. Over the entire considered time interval, with h=0 and v_{esc} equal to 11.5, 12, and 14 km/s, the values of p_E were approximately 0.3, 0.2, and 0.15–0.2, respectively. The only significant difference was in the *vw* variant (when a body was ejected from the forward point of the Earth's motion) at v_{esc}=16.4 km/s and 45°≤i_{ej}≤90°. In these cases, at least 80% of the bodies were ejected into hyperbolic orbits, and most of other bodies collided with the Sun. The average value of p_E depends on the distribution of bodies over v_{esc} and i_{ej}. At i_{ej}=90° in some variants p_E was less than at i_{ej}≤60°, and in other variants it was more.

Probabilities of collisions of bodies ejected from the Moon with the Earth: For h=60r_E (at ejection of bodies from the Moon), a considered time interval T=10 Myr and 30°≤i_{ej}≤60°, p_E was about 0.2–0.25 at v_{esc}=2.5 km/s, 0.13–0.14 at v_{esc}=5 km/s, and 0.06–0.07 at

$12 \leq v_{esc} \leq 16.4$ km/s. At $T=T_{end}$, p_E was about 0.3–0.32 at $v_{esc}=2.5$ km/s, 0.2–0.22 at $v_{esc}=5$ km/s, and 0.1–0.14 at $12 \leq v_{esc} \leq 16.4$ km/s. That is, at velocities v_{esc} slightly greater than the parabolic velocity, the values of p_E are approximately the same for the Earth and the Moon, but for different ejection velocities. At $h=60r_E$, these values of p_E show the fraction of bodies that could collide with the Earth after their ejection from the Moon, moving along 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.

Probabilities of collisions of bodies with other planets and with the Sun and probabilities of ejection of bodies into hyperbolic orbits: The probabilities of collisions of bodies with other planets and the Sun and the probabilities of ejection of bodies into hyperbolic orbits were also calculated. In the *vf* series for $h=0$, $30^o \leq i_{ej} \leq 60^o$, and $T=10$ Myr, the ratio p_V/p_E of the probability p_V of a collision of a body with Venus to the probability p_E of its collision with the Earth was about 0.6, 1-1.2 and 0.7-1.6 at velocities 11.5, 12, and 16.4 km/s, respectively, that is, it was less at lower ejection velocities. The total number of bodies delivered to the Earth and Venus probably did not differ much. For the entire considered time interval, the probabilities of a collision of a body with Mercury and Mars were usually in the ranges of 0.02-0.06 and 0-0.02, respectively. In most calculations, the probability of a collision of a body with the Sun was about 0.05–0.2 at $T=10$ Myr, and it could reach 0.5 at $T=T_{end}$. In most series of calculations, the values of the probability p_{ej} of ejection of bodies into hyperbolic orbits were in the range of 0.016-0.064 at $T=T_{end}$, $h=0$, $30^o \leq i_{ej} \leq 60^o$, $11.5 \leq v_{esc} \leq 12$ km/s. For *vw* variant at $v_{esc}=16.4$ km/s, p_{ej} varied from 0.05 to 0.9 for i_{ej} from 15 to 90^o.

Probabilities of collisions of ejected bodies with the Moon: The Moon was not included in the integration of motion of bodies. The probabilities of collisions of bodies with the Moon and the Earth and then the ratio of probabilities of collisions of bodies with the Earth and the Moon were calculated based on the arrays of orbital elements of migrated bodies. This ratio was mostly between 20 and 30 (for planetesimals from the Earth's feeding zone, this ratio could reach 40), and the probability of collisions of bodies with the Moon was often about 0.01. In the considered calculations of the motion of bodies ejected from the Earth, most of the bodies left the Earth's Hill sphere and moved along heliocentric orbits. At the present orbit of the Moon, the probability of collisions of bodies ejected from the Earth with the Moon for bodies that did not leave the Hill sphere of the Earth could be even less than for the bodies that got heliocentric orbits.

Bodies ejected from the Earth could participate in the formation of the outer layers of the Moon. In order to contain the current fraction of iron, the Moon must have accumulated most of its mass from the Earth's mantle [5]. From the obtained estimates of the probabilities of collisions of bodies ejected from the Earth with the Moon moving in its present orbit, we can conclude that in order for the Moon to acquire most of its mass from the matter ejected from the Earth during its repeated bombardment, the mass of matter ejected from the Earth during its accumulation should be comparable to the mass of the Earth. Therefore, the bodies ejected from the Earth and falling on the Moon's embryo were probably not enough for the Moon to grow from a small embryo in its current orbit. This result testifies in favor of the formation of a large lunar embryo near the Earth. During the late heavy bombardment, as in the earlier stages of the accumulation of the Earth and the Moon, there could be an exchange of matter between the Earth and the Moon. In a collision with a body, the Moon, due to its smaller mass, would lose a larger fraction of its mass than the Earth. Calculations have shown that the fractions of bodies that fell onto the Earth and onto the Moon do not depend much on whether these bodies would have been ejected from the Earth or the Moon. The mass of bodies ejected from the Moon and falling onto the Earth could be comparable to the mass of bodies ejected from the Earth and falling onto the Moon.

Conclusions: The fraction of bodies ejected from the Earth and the Moon at impacts of bodies-impactors that fall back onto the Earth was about 0.2. The probability of collisions of such bodies with the Moon moved in its present orbit was about 0.01. The bodies ejected from the Earth and the Moon could move in the zone of the terrestrial planets for up to a few hundred million years. A large Moon embryo should be formed close to the Earth in order to accumulate material less rich in iron.

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