EPSC Abstracts
Vol. 15, EPSC2021-100, 2021
https://doi.org/10.5194/epsc2021-100
Europlanet Science Congress 2021

Migration of planetesimals to the Earth and the Moon from the region of the outer asteroid belt

Sergei Ipatov
Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, Russian Federation (siipatov@hotmail.com)

The problem of the delivery of water to the terrestrial planets was studied by several scientists (see references e.g. in [1]). Below I present the results of migration of planetesimals under the gravitational influence of 7 planets (from Venus to Neptune). In each variant of the calculations, the initial values of semi-major axes of orbits of 250 planetesimals varied from $a_{\min}$ to $a_{\min}+d_a$ with d_a =0.1 AU, their initial eccentricities equaled to e_o, and the initial inclinations equaled to $e_o/2$ rad. $a_{\min}$ varied from 3 to 4.9 AU with a step of 0.1 AU, e_o=0.02 or e_o=0.15. The calculations of the probability p_E of a collision of a planetesimal with the Earth were made similar to those in [1-3]. In [1-3], it was concluded that the total mass of water delivered to the Earth from outside Jupiter's orbit could be about the mass of Earth's oceans for the total mass of planetesimals beyond that orbit about 200 Earth's masses.

In Figs. 1-2 the values of $10^6 p_E$ are presented for several calculations at $a_{\min}$ from 3 to 4.9 AU, e_o =0.02 or e_o=0.15, and for time interval T equal to 1, 10, 100, 200, 500, and 1000 Myr. Results of calculations with T>1000 Myr (up to 5000 Myr) are presented as "end" runs in the figures. Similar plots were presented in [4] for calculations at $a_{\min}$ from 5 to 40 AU and d_a=2.5 AU.

For some values of $a_{\min}$ and e_o, the values of p_E calculated for 250 planetesimals can differ by a factor up to several hundreds for different calculations with almost the same initial orbits. This difference can be caused by that one of thousands of planetesimals could move in an Earth-crossing orbit for millions of years. Such difference was also noted earlier in [2-3] for initially Jupiter-crossing objects. The mean time of motion of a former Jupiter-crossing object in Earth-crossing orbit was about 30 Kyr.

For some calculations at $a_{\min}$ from 3 to 3.8 AU, there was a considerable growth of p_E after 10 Myr. At T=100 Myr and $3 \le a_{\min} \le 4.9$ AU, the values of p_E vary from values less than 10^{-6} to values of the order of 10^{-3} (and of 0.01 at T=1000 Myr), but they are often between 10^{-6} and 10^{-5}, as for many our previous calculations with $a_{\min} \ge 5$ AU. There were more runs with $p_E > 2\times10^{-5}$ for $3.2 \le a_{\min} \le 3.3$ AU, $a_{\min}$=3.5 AU and $3.7 \le a_{\min} \le 4.1$ AU than for other values of $a_{\min}$, including the values of $a_{\min} \ge 5$ AU. The delivery of water and volatiles from such distances from the Sun was more effective (up to hundreds of times for some initial data) than from other distances. It is not clear how much material was at distances from 3 to 4 AU from the Sun, compared to that in the zone of the giant planets. If we suppose that the density of a protoplanetary disk is proportional to $R^{-0.5}$, then the ratio of the mass of material with a distance R from the Sun between 4 and 15 AU is greater by a factor of 209/7≈30 than that with R between 3 and 4 AU. For such a model, the amount of material delivered to the Earth from the outer asteroid belt can be comparable with the amount of material delivered from the zone of Jupiter and Saturn.

For T=100 Myr, at $3.0 \le a_{min} \le 3.6$ AU or a_{min}=4.2 AU and e_o=0.02, and also at $3.0 \le a_{min} \le 3.1$ AU and e_o=0.15, more than a half of planetesimals were left in elliptical orbits. At a_{min}=4.2 AU planetesimals were close to the Hilda family asteroids. Planetesimals that originally crossed the orbit of Jupiter may have come to the Earth's orbit mostly within the first million years. Most of collisions with the Earth of bodies, originally located at a distance of 4 to 5 AU from the Sun, occurred during the first 10 million years. The times elapsed before the collisions of some bodies from the Uranus and Neptune zones with the Earth could exceed 20 million years. For $3 \le a_{min} \le 3.5$ AU and $e_o \le 0.15$, individual bodies could fall onto the Earth and the Moon in a few billion years. For example, $p_E = 4\times10^{-5}$ for a_{min}=3.3 AU, e_o=0.02 at $0.5 \le t \le 0.8$ Myr (the time of the late-heavy bombardment) and $p_E = 6\times10^{-6}$ at $2 \le t \le 2.5$ Myr. For a_{min}=3.2 AU and e_o=0.15, p_E=0.015 at $0.5 \le t \le 1$ Myr, and $p_E = 6\times10^{-4}$ at $1 \le t \le 2$ Myr. The zone of the outer asteroid belt can be one of the sources of the late heavy bombardment.

The ratio of the number of bodies colliding with the Earth to that with the Moon varied mainly from 20 to 40 for planetesimals from the feeding zone of the terrestrial planets [5]. For bodies arriving from distances from the Sun greater than 3 AU, this ratio was mainly in the interval from 16.4 to 17.4. So more planetesimals per mass of a celestial body collided with the Moon than with the Earth. However, at collisions of planetesimals with the Moon the fraction of ejected material was greater than that for the Earth.

The characteristic velocities of collisions with the Moon and the Earth of bodies in calculations with a_{min} from 3 to 15 AU were mainly from 20 to 23 km/s and from 23 to 26 km/s, respectively. The characteristic velocities of collisions of planetesimals from the feeding zone of the terrestrial planets with the Moon varied from 8 to 16 km/s depending on initial semi-major axes and eccentricities of planetesimals.

Studies of collisions of bodies with the Earth were carried out within the framework of the state assignment of the GEOKHI RAS No. 0137-2021-0004. Studies of collisions of bodies with the Moon were carried out with the support of the Russian Science Foundation grant No. 21-17-00120, https://rscf.ru/project/21-17-00120/.

[1] Marov M.Ya., Ipatov S.I. Solar System Research, 2018, 52, 392-400. https://arxiv.org/ftp/arxiv/papers/2003/2003.09982.pdf

[2] Ipatov S.I., Mather J.C. Annals of the NYAS, 2004, 1017, 46-65. http://arXiv.org/format/astro-ph/0308448

[3] Ipatov S.I., Mather J.C. Advances in Space Research, 2004, 33, 1524-1533. http://arXiv.org/format/astro-ph/0212177

[4] Ipatov S.I. EPSC2020-71, 2020. https://meetingorganizer.copernicus.org/EPSC2020/EPSC2020-71.html.

[5] Ipatov S.I. Solar System Research, 2019, 53, 332-361. http://arxiv.org/abs/2003.11301

Fig. 1. Probability of a collision of a body with the Earth multiplied by a million

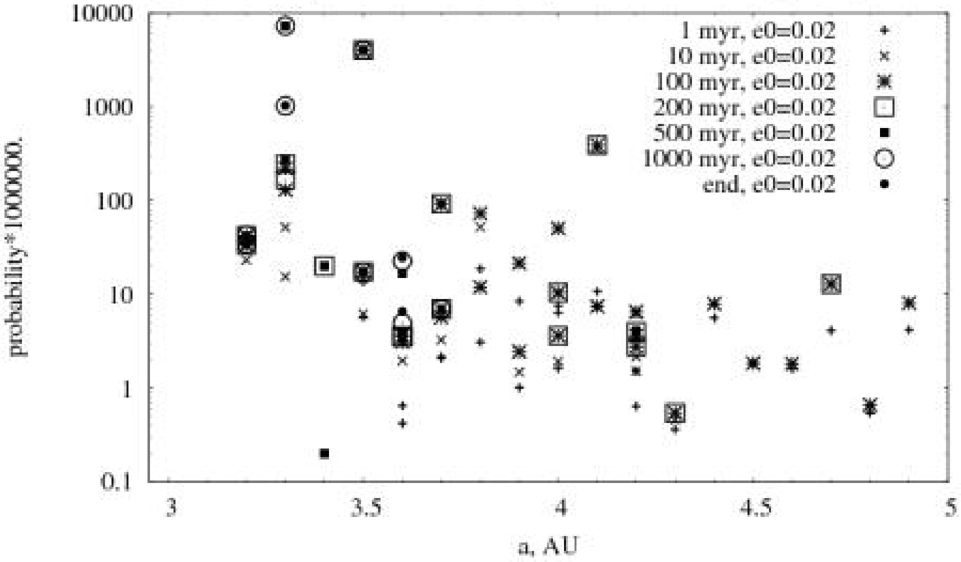

Fig. 2. Probability of a collision of a body with the Earth multiplied by a million