DELIVERY OF BODIES TO THE EARTH AND THE MOON FROM THE ZONE OF THE OUTER ASTEROID BELT

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• **Introduction:** Delivery of material to the Earth from different distances from the Sun was studied by different scientists. In [1] I presented the probabilities of collisions with the Earth for bodies migrated from distances from the Sun from 5 to 40 AU. Migration of bodies-planetesimals with initial semi-major axes between 3 and 5 AU is considered below.

• **Initial data**: The motion of bodies under the gravitational influence of 7 planets (from Venus to Neptune) was studied with the use of the symplectic code from [2]. In each variant of the calculations, the initial values of semi-major axes of orbits of 250 bodies-planetesimals varied from a_{min} to a_{min}+0.1 AU, their initial eccentricities equaled to e_o=0.02 or to e_o=0.15, and the initial inclinations equaled to e_o/2 rad. The number of planetesimals with a semi-major axis a was proportional to $a^{1/2}$. The values of a_{min} varied from 3 to 4.9 AU with a step of 0.1 AU. Based on the obtained arrays of orbital elements of migrated bodies, I calculated the probability p_E of a collision of a body-planetesimal with the Earth during time interval T (up to 5 Gyr in some variants). The calculations of p_E were made similar to the calculations presented in [3-5]. In each calculation variant the value of p_E is the ratio of the sum of the probabilities of collisions of 250 bodies with the Earth to 250. The values of $p_E\times10^6$ are presented in Figs. 1-3 for a_{min} from 3 to 4.9 AU. In Figs. 1-2 each value on the plot was averaged over 250 planetesimals. In Fig. 3 each value of p_E was averaged over several hundreds (up to 2000) planetesimals during considered time intervals (which can be different for different a_{min}).

• **Results of calculations:** The value of p_E could vary by a factor more than a hundred for different calculation variants with 250 bodies and the same values of a_{min} and e_o. Such difference was earlier found for calculations of migration of Jupiter-crossing objects [3-4]. One among hundreds or thousands of such objects moved in an Earth-crossing orbit during millions or even tens of millions of years, though the mean time of motion of a former Jupiter-crossing object in an Earth-crossing orbit was about 30 Kyr.

• At $3.0\le a_{min}\le3.6$ AU or a_{min}=4.2 AU and e_o=0.02, and also at $3.0\le a_{min}\le3.1$ AU and e_o=0.15, more than a half of bodies still moved in an elliptical orbit after T=100 Myr. At a_{min}=4.2 AU bodies were close to the Hilda family asteroids. At $a_{min}\ge4.2$ AU and e_o=0.02, the values of p_E mainly were in the range from 10^{-6} and 10^{-5}, as for many calculations with $a_{min}\ge5$ AU considered in [1]. At some other values of a_{min} and e_o, the values of p_E could be much greater – up to the values of the order of 10^{-3} at T=100 Myr and of 0.01 at T=1000 Myr. Though p_E=0 at a_{min}=3 AU and e_o=0.02. 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 ≈20 than that with R between 3 and 4 AU. For such a model, the amount of material delivered to the Earth from the zone of the outer asteroid belt could be comparable with the amount of material delivered from the zone of Jupiter and Saturn.

• Initially Jupiter-crossing bodies that have come to the Earth's orbit did it mostly within the first million years. Most of collisions with the Earth of bodies, originally located at a distance from 4 to 5 AU from the Sun, occurred during the first 10 million years. At $3\le a_{min}\le3.5$ AU and $e_o\le0.15$, some bodies could fall onto the Earth in a few billion years. For example, for a_{min}=3.3 AU and e_o=0.02, $p_E=4\times10^{-5}$ at $0.5\le t\le0.8$ Myr and $p_E=6\times10^{-6}$ at $2\le t\le2.5$ Myr. For a_{min}=3.2 AU and e_o=0.15, p_E=0.015 at $0.5\le t\le1$ Myr, and $p_E=6\times10^{-4}$ at $1\le t\le2$ Myr. The zone of the outer asteroid belt can be one of the sources of the late heavy bombardment.

• At a_{min}>3 AU, the ratio of the number of bodies colliding with the Earth to that with the Moon was mainly in the interval from 16.4 to 17.4. This ratio varied mainly from 20 to 40 for planetesimals from the feeding zone of the terrestrial planets [5]. 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 with 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.

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References: [1] Ipatov S.I. (2020) *EPSC2020-71*, https://doi.org/10.5194/epsc2020-71 . [2] Levison H.F., Duncan M.J. (1994) *Icarus* 108:18-36. [3] Ipatov S.I., Mather J.C. (2004) *Annals of the NYAS* 1017:46-65. http://arXiv.org/format/astro-ph/0308448 . [4] Ipatov S.I., Mather J.C. (2004) *Advances in Space Research* 33: 1524-1533. http://arXiv.org/format/astro-ph/0212177 . [5] Ipatov S.I. (2019) *Solar System Research* 53: 332-361. http://arxiv.org/abs/2003.11301.

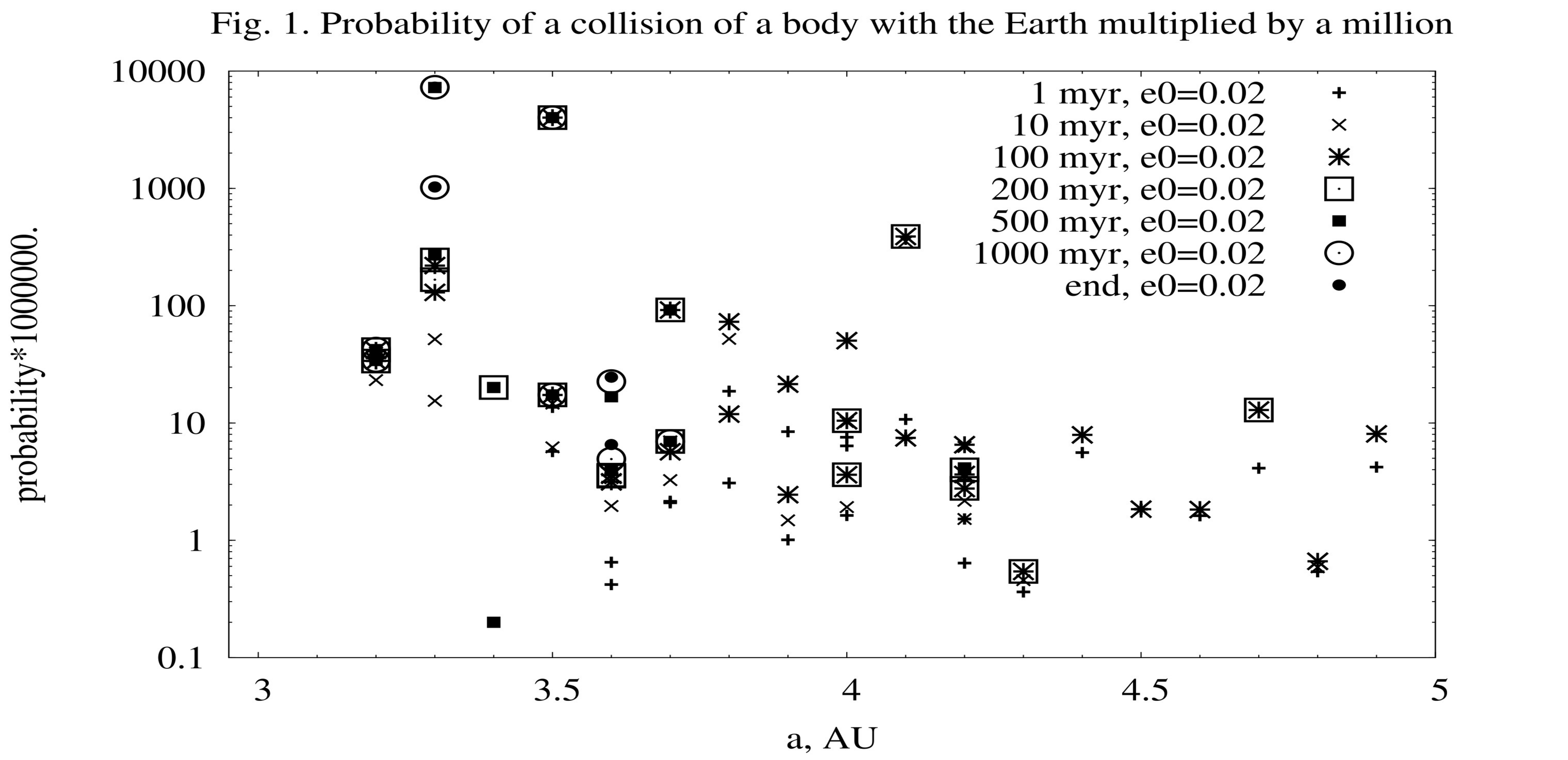

Figure 1. Probability p of a collision of a planetesimal with the Earth vs. the initial value of a semi-major axis (in AU) at initial eccentricity equal to 0.02. Each value was averaged over 250 initial planetesimals.

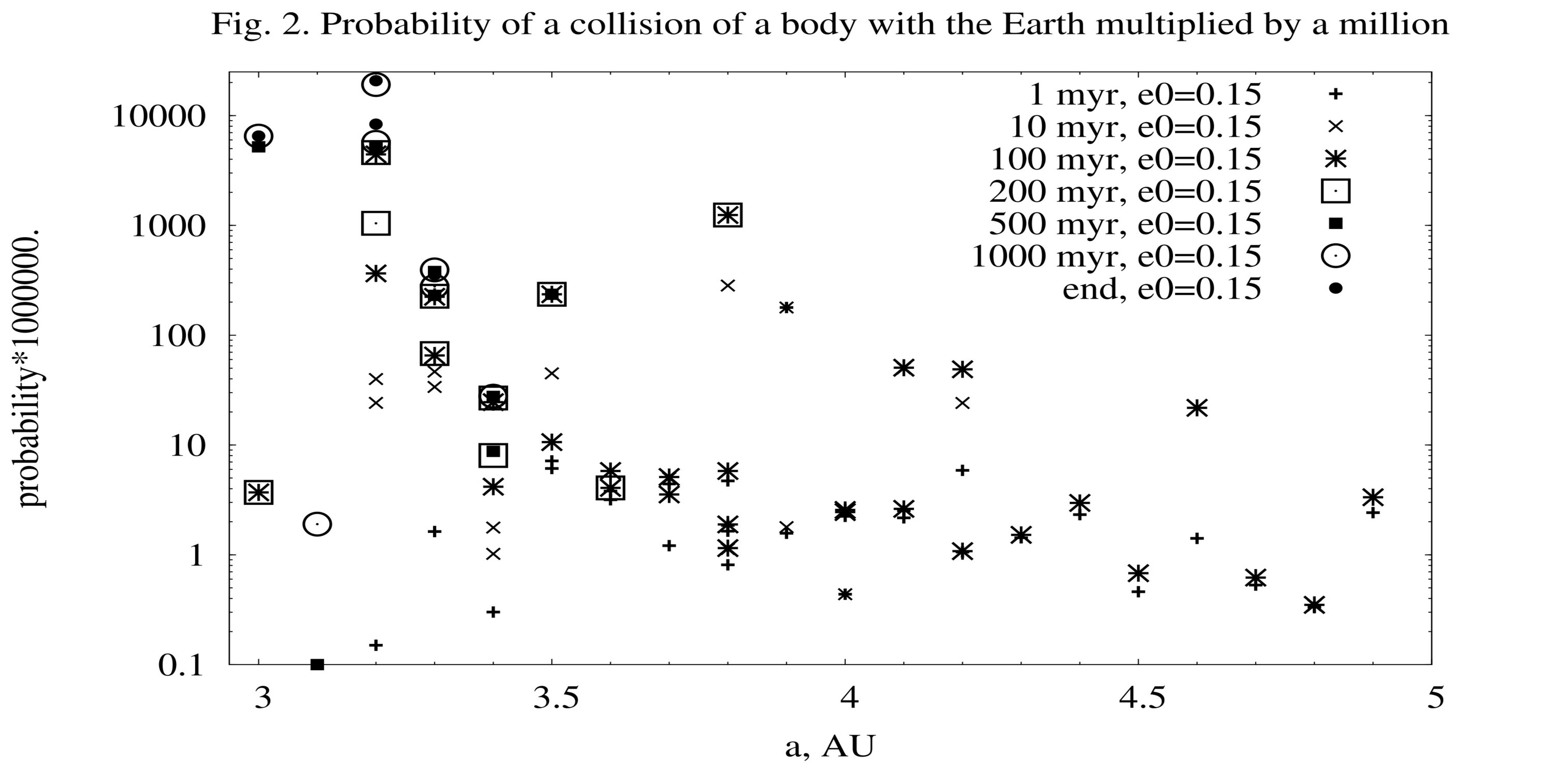

Figure 2. Probability p of a collision of a planetesimal with the Earth vs. the initial value a_{min} of a semi-major axis (in AU) at initial eccentricity equal to 0.15. Each value was averaged over 250 initial planetesimals.

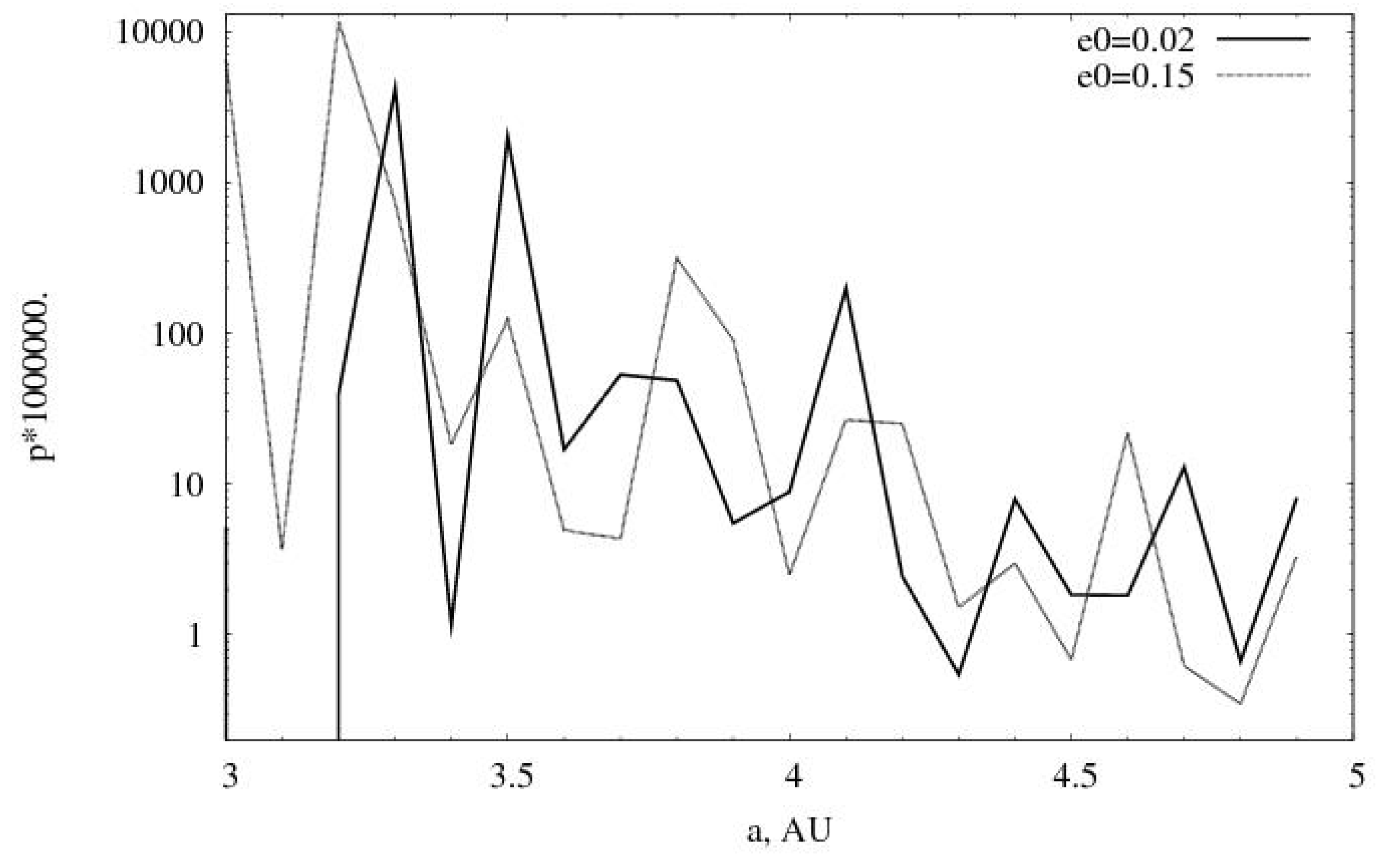

Figure 3. Probability p of a collision of a planetesimal with the Earth vs. the initial value a_{min} of a semi-major axis (in AU). Each value was averaged over several hundreds (up to 2000) initial planetesimals. Different lines correspond to eccentricities equal to 0.02 and 0.15.