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Migration of planetesimals from beyond Mars' orbit to the Earth

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Migration of planetesimals to the Earth from the zone beyond the orbit of Jupiter was considered by us e.g. in [1-3]. References to papers of several other authors on migration of bodies to the Earth were presented in [1]. In [1] we considered migration of planetesimals from the zone from 4.5 to 12 AU. In [2-3] migration of planetesimals with initial semi-major axes a0 of their orbits between 5 and 40 AU was considered. Below I also consider migration of planetesimals with a0 between 3 and 5 AU to the Earth.

Migration of planetesimals under the gravitational influence of 7 planets (from Venus to Neptune) or 5 planets (from Venus to Saturn) was calculated with the use of the symplectic code from [4]. The. In each variant of the calculations, the initial values of semimajor axes of orbits of planetesimals varied from amin to amax=amin+da, the initial eccentricities were equal to eo, and the initial inclinations equaled to eo/2 rad. Orbital elements of the migrated planetesimals were recorded in computer memory with a step of 500 years. Based on these arrays of orbital elements, I calculated the probabilities of collisions of planetesimals with the Earth, and for some runs I also calculated the probabilities of collisions of the planetesimals with other terrestrial planets, the Moon and their embryos. The calculations were made similar to those in [1-3, 5-7].

In the series of calculations considered in [2-3], da=2.5 AU, and amin took values from 2.5 to 40 AU in increments of 2.5 AU. The initial eccentricities equaled to 0.3 or 0.05. In each calculation variant, 250 planetesimals were considered, but for the same values of amin, da, and eo, several (up to 8) calculation variants were performed. So the total number of considered planetesimals for a set with fixed values of amin, da and e0 could reach 2000. Some calculations were made for da=0. In the recent series of calculations, da=0.1 AU, and amin took values from 3.0 to 4.9 AU in increments of 0.1 AU. For this series of calculations, the initial eccentricities equaled to 0.02 or 0.15. In Figs. 1-6 for several series of calculations, we present the values of 10^6pE, where pE is the probability of a collision of a planetesimal with the Earth. In Figs. 1-2 the values of 10^6pE are presented for time intervals equaled to 1, 10 and 100 Myrs. For other figures usually greater time intervals (up to 2 Gyrs) were considered (until the values of pE finished to grow with time). For variants presented in Figs. 1-4 and 6, the gravitational influence of 7 planets (from Venus to Neptune) was taken into account. For runs for Fig. 5, Uranus and Neptune were excluded.

At amin≤10 AU, the value of pE calculated for a run with 250 bodies could vary hundreds of times for different calculation variants with the same values of amin, da and eo. Such difference was earlier found for calculations of migration of Jupiter-crossing objects [5-6]. One among several hundreds or among thousands of such objects moved in Earth-crossing orbits during millions or even tens of millions of years, and the probability of a collision of such object with the Earth was greater than that for hundreds or even thousands of other objects. The values of pE in Figs. 1-6

vary from a value less than 10^{-7} to values of the order of 10^{-3}, but they are mainly between 10^{-6} and 10^{-5}. On average, pE is smaller for greater amin. There were no runs with $pE>10^{-5}$ at amin≥12.5 AU or for the runs without Uranus and Neptune. $pE\leq1.5\times10^{-6}$ at e0=0.3 and amin≥27.5 AU. In Figs. 1-2, the fraction of runs with $pE>10^{-5}$ at e0=0.15 is greater than at e0=0.02. In some runs there was a considerable growth of pE after 10 Myr. At da=0.1 AU and e0=0 or e0=0.15, there were more runs with $pE>2\times10^{-5}$ for 3.2≤amin≤4.1 AU than for other values of amin.

Calculations showed that the amount of material delivered from beyond Jupiter's orbit to the Earth could exceed the mass of the Earth's oceans if the total mass of planetesimals beyond Jupiter's orbit was about 200 Earth masses. Some (perhaps 1/3) of this material consisted of water and volatile substances. The mass of the substance delivered to the planet to the mass of the planet for Mars was approximately two times greater than for Earth, and such relations for Mercury and Venus were slightly larger than for Earth. The total mass of planetesimals migrating from beyond the orbit of Jupiter and colliding with the Moon was 16 or 17 times less than the total mass such bodies collided with the Earth.

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

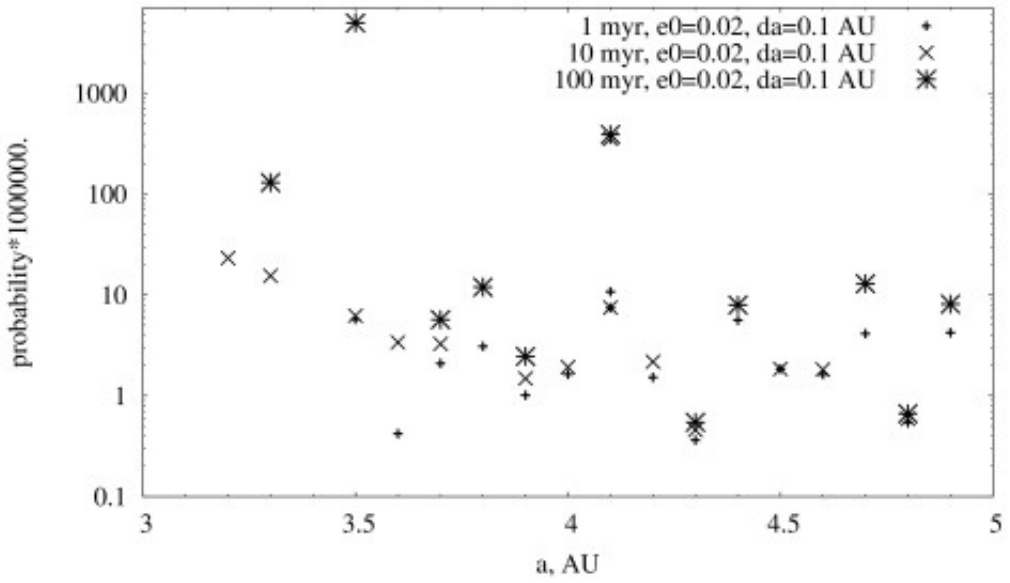

Fig. 2. Probability of a collision of a body with the Earth multiplied by a million

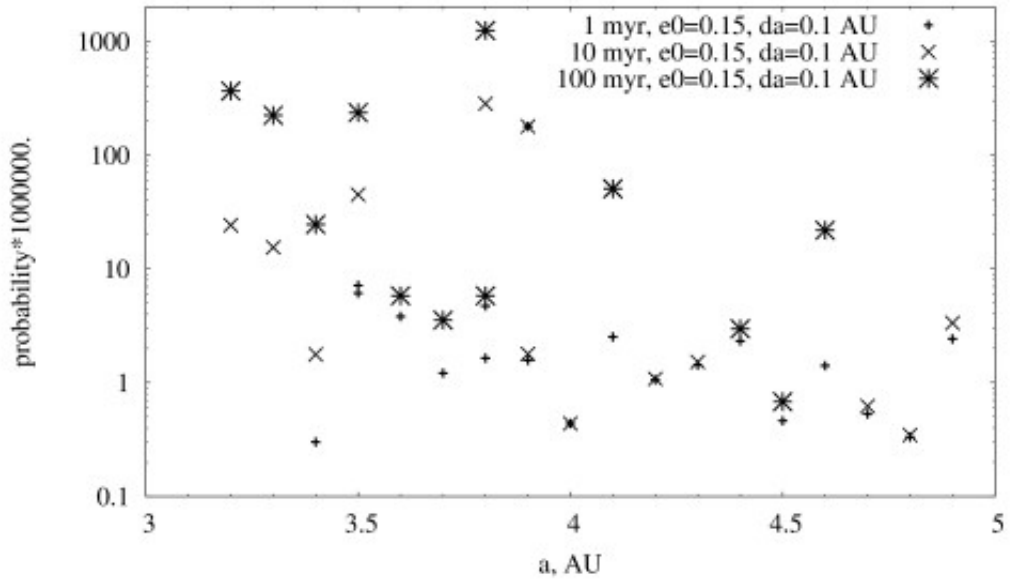

Fig. 3. Probability of a collision of a body with the Earth multiplied by a million

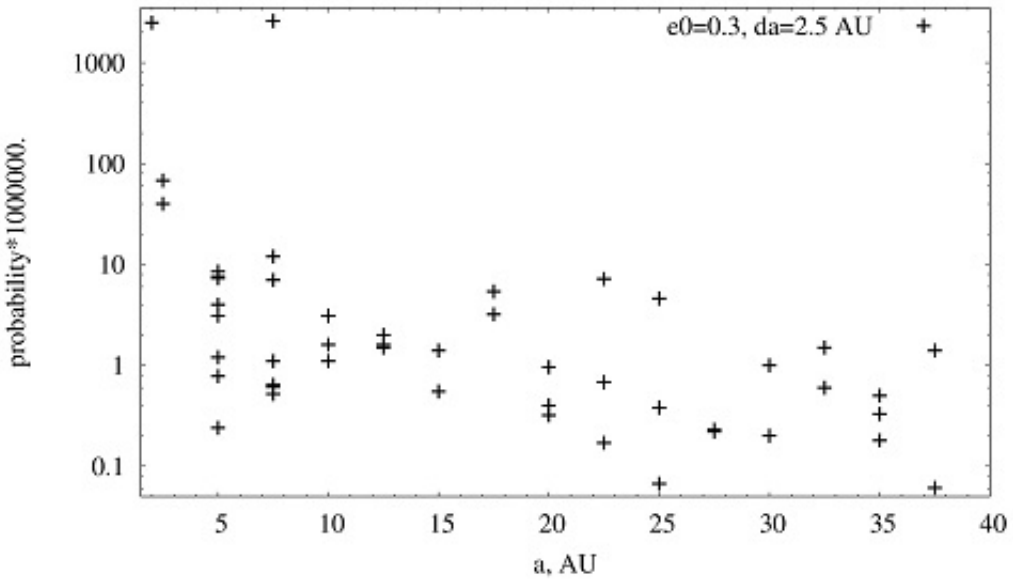

Fig. 4. Probability of a collision of a body with the Earth multiplied by a million

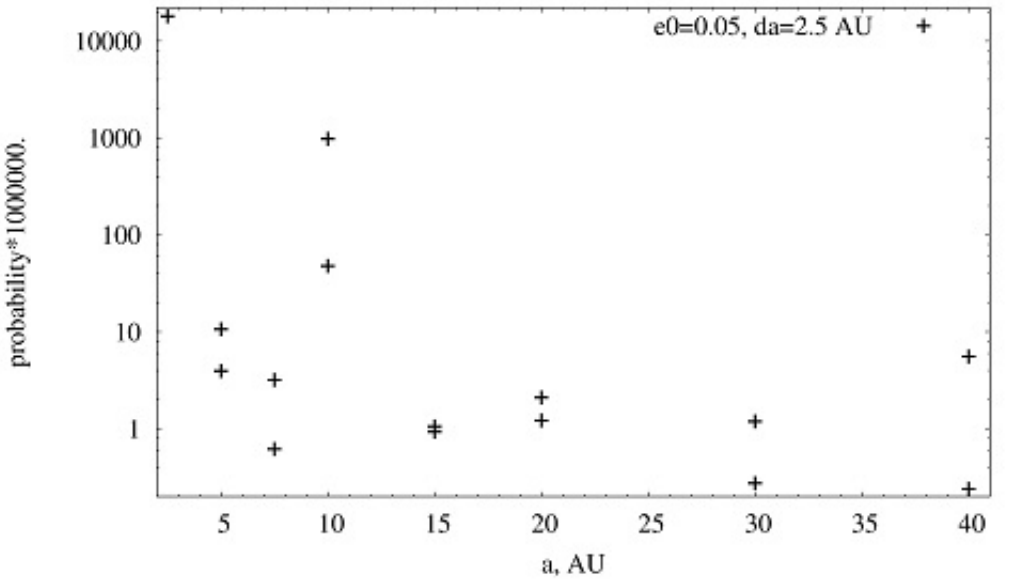

Fig. 5. Probability of a collision of a body with the Earth multiplied by a million

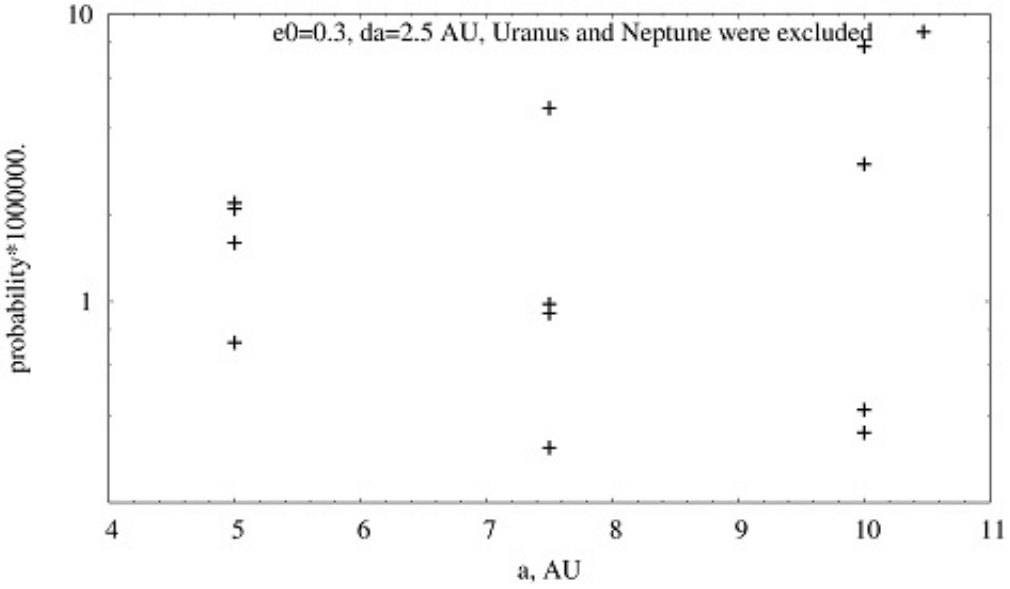

Fig. 6. Probability of a collision of a body with the Earth multiplied by a million