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Migration of bodies to the Earth from different distances from the Sun

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Abstract

Probabilities of collisions with the Earth for bodies with initial eccentricities equaled to 0.3 were calculated for different initial semi-major axes from 2 to 40 AU. The probabilities calculated for 250 bodies can differ by up to a factor of several tens for different runs with similar orbits. For 1500 bodies in each series of calculations, the probability of a collision of one body with the Earth was about 4.1×10^{-6} for the disk between 5 and 7.5 AU, and it was 2.5×10^{-6} for the disk between 7.5 and 10 AU. On average, for the region between 20 and 35 AU the probability could exceed 10^{-6}. For bodies initially located in the asteroid belt, the probabilities of their collisions with the Earth were about 10^{-4}-10^{-3}, i.e., were much greater than for bodies initially located beyond Jupiter's orbit.

1. Introduction

In order to study the delivery of water and volatiles to the Earth one need to know the probabilities of collisions with the Earth for bodies migrated to the Earth from different distances from the Sun, located beyond the snow line. In our previous papers, we studied the probability p_E of a collision of a body with the Earth for bodies with orbits close to known Jupiter-family comets [3-7] and for planetesimals from the feeding zone of Jupiter and Saturn (with initial semi-major axes a from 4.5 to 12 AU, a number of initial planetesimals proportional to $a^{1/2}$, and initial eccentricities and inclinations equaled to 0.3 and 0.15 rad, respectively) [9]. The mean values of p_E were obtained to be about 2×10^{-6} for the planetesimals, and they usually exceeded 4×10^{-6} for the considered Jupiter-family comets. If migrating objects consisted half of water, then the total amount of water delivered to the Earth is about the mass of Earth's oceans at $p_E=2\times10^{-6}$ and at the total mass of planetesimals equaled to 200 Earth masses. The ratio of probabilities of collisions of bodies with a planet to the mass of the planet for Venus was about the same as that for the Earth, and that for Mars was greater by a factor of 2 or 3 than that for the Earth. Below I study the probabilities of collisions of bodies migrated to the Earth from different distances from the Sun.

2. Initial data used for calculations

Several series of calculations of migration of bodies under the gravitational influence of planets (from Venus to Neptune) have been made. The symplectic code from the Swift integration package [8] was used. In some runs, initial semi-major axes were the same and equaled r_f. In other runs, initial semi-major axes varied from a_{min} to a_{max}, where a_{max}-a_{min}=2.5 AU. For different runs, a_{min} varied from 2 to 40 AU with a step equaled to 2.5 AU. Initial eccentricities and inclinations equaled to 0.3 and 0.15 rad, respectively. Such eccentricities could be reached due to mutual gravitational influence of planetesimals during evolution of a disk of planetesimals in the feeding zone of the giant planets [1-2]. Integrations were made until bodies reached 2000 AU or collided with the Sun. However, some runs were stopped after a few tens of millions of years (typically after more than at 10^8 years), if p_E finished increasing during some time. In principle, p_E could increase after that stopping time, and so the lower limits of p_E are presented below. For each run, 250 bodies with different orientations of initial orbits were considered. For several runs, initial data could be the same, but the difference was only in a step of integration.

3. Results of calculations

Studies of migration of bodies with initial orbits close to those of Jupiter-family comets showed [3-6] that the value of p_E for one body could be greater than the sum of p_E for thousands of bodies with almost the same initial orbits. A few migrating bodies could move in Earth-crossing orbits during many millions of years, and they could provide the major contribution to the mean value of p_E calculated for thousands of bodies with close initial orbits. Some bodies did not reach the Earth's orbit during their dynamical lifetimes.

Similar results on the role of a few bodies in p_E have been obtained in new series of runs. The values of p_E could differ by a factor of several tens for the runs with the same initial orbits, but with a different step of integration. At the series of runs with a_{min}=5 AU, p_E varied from 2.4×10^{-7} to 8.5×10^{-6} for different runs, and $p_E=4.1\times10^{-6}$ for a series of 6 runs with 1500 bodies. At the series with a_{min}=7.5 AU, in one run p_E=0, in another run $p_E=1.15\times10^{-5}$, and $p_E=2.5\times10^{-6}$ for a series of 6 runs with 1500 bodies. At a_{min}=12.5 AU, p_E was about 2×10^{-6} for a series of 2 runs with 500 bodies.

On average, values of p_E were greater for smaller a_{min}, but due to a wide range of possible values of p_E for runs with the same initial data, one need to consider a greater number of runs for each a_{min} before making accurate estimates. For most runs with $a_{min}\geq20$ AU, it was obtained that $p_E<10^{-6}$. However, there were runs with greater values of p_E. For example, $p_E=7.2\times10^{-6}$ at a_{min}=22.5 AU and $p_E=1.5\times10^{-6}$ at a_{min}=32.5 AU. On average, for the region 20 - 35 AU the value of p_E could exceed 10^{-6}. The region could play a valuable role in migration of icy bodies to the Earth. In some above runs, p_E continued to grow after 50 Myrs.

For runs with a_{min}=2 AU and r_f=2.5 AU, the values of p_E were about 10^{-3}, i.e. were much greater than for bodies located at more than 5 AU from the Sun. In runs with a_{min}=2.5 AU, p_E was up to 7×10^{-5}. The values of p_E for such runs could grow after 100 Myrs.

Probabilities of collisions with the Moon for bodies migrated from beyond Jupiter's orbit usually were by about a factor of 16 or 17 smaller than probabilities of collisions with the Earth.

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