MIGRATION OF PLANETESIMALS TO THE EARTH AND THE MOON FROM DIFFERENT DISTANCES FROM THE SUN. S. I. Ipatov, Vernadsky Institute of Geochemistry and Analytical Chemistry, Kosygina st., 19, Moscow 119991, Russia, siipatov@hotmail.com.

Introduction: In our previous papers we studied migration of bodies with initial orbits close to known Jupiter-family comets [1-5] and migration of planetesimals from the zone with initial semi-major axes a from 4.5 to 12 AU [6]. Below I study the migration of planetesimals from different distances from the Sun and the probabilities of collisions of the planetesimals with the Earth and the Moon. Such studies allow one to understand better the delivery of water and volatiles to the Earth and the Moon.

The model and initial data used for calculations: In most calculations, initial semi-major axes a_o of planetesimals varied from a_m to a_m+2.5 AU with a number of initial planetesimals proportional to $a_o^{1/2}$. In other runs, initial semi-major axes of all initial planetesimals equaled to r_f. For different runs, a_m and r_f varied from 2.5 to 40 AU with a step equaled to 2.5 AU. Initial eccentricities e_o of planetesimals equaled to 0.05 or 0.3. Initial inclinations i_o equaled to e_o/2 rad. The mean eccentricities equaled to 0.3 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 [7-8].

The symplectic code from the Swift integration package [9] was used. I made several series of calculations of migration of planetesimals under the gravitational influence of n_{pl}=7 planets (from Venus to Neptune) or of n_{pl}=5 planets (from Venus to Saturn). Integrations were made until planetesimals reached 2000 AU from the Sun or collided with the Sun. However, some runs with large a_m were stopped after a few tens of millions of years (typically after more than at 100 Myr, up to 500 Myr), if the probability p_E of a collision of a planetesimal with the Earth finished increasing during some long time and a small number of planetesimals was left. In principle, p_E could increase (but, probably, a little) after that stopping time. Each run was made for 250 initial planetesimals with different orientations of initial orbits. The probability p_M of a collision of a planetesimal during its dynamical lifetime with the Moon was also calculated. The orbital elements of the migrated planetesimals were recorded in computer memory with steps of 500 years. Based on these arrays, similar to the calculations presented in [1-6], I calculated the probabilities of collisions of planetesimals with the Earth and the Moon.

Results of calculations: For runs with 250 planetesimals, the values of p_E could differ by more than a factor of several tens for the runs with the same initial orbits, but with a different step of integration. For example, at the series of runs with a_m=5 AU and e_o=0.3, 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 8 runs with 2000 planetesimals. At the series of runs with a_m=7.5 AU and e_o=0.3, in one run $p_E=5.2\times10^{-7}$, in another run $p_E=2.64\times10^{-3}$, and $p_E=3.8\times10^{-4}$ for a series of 7 runs with 1750 planetesimals. Some planetesimals did not reach the Earth's orbit during their dynamical lifetimes. A few migrating planetesimals 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 planetesimals with close initial orbits. Such results on the role of a few planetesimals in p_E have been obtained earlier in [1-4] for Jupiter-family comets.

In the below paragraph, exclusive for the last sentence, the data were obtained for e_o=0.3 and n_{pl}=7. The tables with the values of p_E and p_E/p_M obtained for some runs with e_o=0.3 were presented in [10]. At a_m=12.5 AU, the mean value of p_E was 1.7×10^{-6} for 750 planetesimals. The values of p_E were typically greater for smaller a_m, but due to a wide range of possible values of p_E for runs with the same initial data, one needs to consider a greater number of runs for each a_m before making accurate estimates. For most runs with $a_m\geq20$ AU, it was obtained that $p_E<10^{-6}$. However, there were runs with greater values of p_E, that can increase the mean value up to 10^{-6}. For example, in some runs $p_E=7.2\times10^{-6}$ at a_m=22.5 AU and $p_E=1.4\times10^{-6}$ at a_m=37.5 AU. In some above runs, p_E continued to grow after 50 Myr. For runs with a_m=2 AU and r_f=2.5 AU, the values of p_E were of the order of 10^{-3}, i.e. were much greater than for planetesimals located at more than 5 AU from the Sun. For two runs with a_m=2.5 AU, mean value of p_E was 5.4×10^{-5}. The values of p_E for such runs could grow after 100 Myr. The above values of p_E were obtained for n_{pl}=7. For n_{pl}=5 the mean values of p_E at a_m=5 AU and a_m=7.5 AU equaled to 1.7×10^{-6} and were smaller than those for n_{pl}=7.

Probabilities of collisions with the Moon for planetesimals migrated from beyond Jupiter's orbit usually were by about a factor of 16 or 17 smaller than probabilities of collisions with the Earth. At e_o=0.3 probabilities p_{Sun} of collisions of planetesimals with the Sun were 0.17 for a_m=2 AU, 0.04 for a_m=2.5 AU, and 0.76 for r_f=2.5 AU. For all other runs, we have $p_{Sun}<0.01$, and $p_{Sun}=0$ for most runs with 250 planetesimals for a_m or r_f not less than 5 AU.

Probability p_E of a collision with the Earth of one planetesimal which is the mean value for several runs, each with 250 planetesimals, at n_{pl}=7 is presented in the Table for e_o=0.05 and e_o=0.3. Due to a few planetesimals with much higher probabilities p_E than those for other planetesimals, two values of p_E in the Table (p_E=3.8×10^{-4} at a_m=7.5 AU and e_o=0.3, and p_E=3×10^{-5} at a_m=10 AU and e_o=0.05) are much higher than other values. Other values of p_E do not differ much for e_o=0.3 and e_o=0.05. At a_m≤10 AU the values of p_E in the Table were not less than 2×10^{-6}. While considering thousands of planetesimals with 5≤a_m≤10 AU, the mean value of p_E could be larger than 2×10^{-6} by at least a factor of several. It means that if most of the mass of planetesimals in the feeding zone of Jupiter and Saturn was in a large number of relatively small planetesimals, than for estimates of the delivery of material from this zone to the Earth one may use the values of p_E greater than 10^{-5}. On average, for the region 20 - 40 AU the value of p_E could be about 10^{-6}. This region also could play a valuable role in migration of icy bodies to the Earth.

Table. Probability p_E of a collision of one planetesimal with the Earth, which is the mean value for several runs, each with 250 planetesimals, at n_{pl}=7.

a_m, AU	2.5	5.	7.5	10
e_o=0.3	$5\cdot10^{-5}$	$4\cdot10^{-6}$	$3.8\cdot10^{-4}$	$2\cdot10^{-6}$
e_o=0.05	$2\cdot10^{-2}$	$6\cdot10^{-6}$	$2\cdot10^{-6}$	$3\cdot10^{-5}$
a_m, AU	15	20	30	40
e_o=0.3	$1\cdot10^{-6}$	$6\cdot10^{-7}$	$6\cdot10^{-7}$	$1\cdot10^{-6}$
e_o=0.05	$1\cdot10^{-6}$	$2\cdot10^{-6}$	$6\cdot10^{-7}$	$8\cdot10^{-7}$

Based on my calculations, it is possible to conclude that in the case when the masses of the embryos of the terrestrial planets are close to the present masses of these planets, most of the planetesimals falling on the Earth fell on it in time not more than 20 Myr for both the planetesimals from the Earth's feeding zone and from the initial distance of 5-30 AU from the Sun when considering all the giant planets (fell from the feeding zone of Jupiter and Saturn, if Uranus and Neptune have not yet formed). Most of the planetesimals from the zone at 5-30 AU fell onto the Earth at 5<t<20 Myr. This testifies in favor of that the planetesimals from beyond Jupiter's orbit could fall onto the Earth and the Moon in the process of their growth, and the matter, including water and volatiles, delivered from beyond the orbit of Jupiter was incorporated into the internal layers of the Earth and the Moon. The delivery of matter to the Earth and the Moon from the zone of Uranus and Neptune depended on when these giant planets acquired large masses and began to move in orbits close to present orbits. After the planetesimals from this zone began to experience a significant influence of these giant planets, the typical time until the fall of the planetesimals onto the Earth and the Moon often did not exceed 20 Myr, but a small fraction of the planetesimals could fall onto the Earth during hundreds of Myr.

Conclusions: The probabilities of collisions of planetesimals initially located beyond Jupiter's orbit with the Earth and the Moon calculated for 250 planetesimals can differ by more than a factor of several tens for different runs with similar orbits. While considering thousands of planetesimals, the mean probability of a collision of a planetesimal with the Earth for the region between 5 and 10 AU could exceed 2×10^{-6} by at least a factor of several. On average, for the region between 20 and 40 AU the probability could be about 10^{-6}. For planetesimals initially located in the asteroid belt, the probabilities of their collisions with the Earth were about 10^{-4}-10^{-2}, i.e., were much greater than for planetesimals initially located beyond Jupiter's orbit. The ratio of the probabilities of collisions of considered planetesimals with the Earth to those with the Moon was mainly in the range from 16 to 17.

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