MIGRATION OF BODIES FROM THE ZONE OF THE OUTER ASTEROID BELT TO THE EARTH.

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Introduction: Migration of bodies to the Earth from different distances from the Sun was considered in several papers. Such papers were discussed in [1]. Earlier we studied migration of planetesimals to planets mainly from the zones beyond the orbit of Jupiter [1-4]. Migration of bodies-planetesimals with initial semi-major axes between 3 and 5 AU is considered below.

Initial data: Gravitational influence of 7 planets (from Venus to Neptune) was taken into account with the use of the symplectic code from [5]. In some calculations a step of integration equaled to 10 days, in other calculations it was equal to 15 days. In each variant of the calculations, the initial values of semi-major axes of orbits of 250 bodies-planetesimals varied from $a_{\rm min}$ to $a_{\rm min}$+0.1 AU, their initial eccentricities equaled to $e_{\rm o}$, and the initial inclinations equaled to $e_{\rm o}/2$ rad. The number of planetesimals with a semi-major axis a was proportional to $a^{1/2}$. The values of $a_{\rm min}$ varied from 3 to 4.9 AU. In Table 1 I present the results of calculations at $e_{\rm o}$=0.02 and in Table 2 at $e_{\rm o}$=0.15. Orbital elements of migrated planetesimals were recorded in computer memory with a step of 500 years. Based on these arrays of orbital elements, I calculated the probabilities $p_{\rm E}$ of collisions of bodies-planetesimals with the Earth during time interval T (up to 5 Gyr in some variants). The calculations of $p_{\rm E}$ were made similar to the calculations presented in [1-4, 6-8]. The value of $p_{\rm E}$ is the ratio of the sum of the probabilities of collisions of 250 bodies with the Earth to 250. For some bodies such probabilities can be equal to 0. In the tables the values of $p_{\rm E}$ were presented for 10, 100 Myr, and for the values of T presented in the tables. The tables also include the number $N_{\rm ell}$ of bodies-planetesimals left in elliptical orbits.

Results of calculations: The value of $p_{\rm E}$ could vary by more than a hundred of times for different calculation variants with 250 bodies and the same values of $a_{\rm min}$ and $e_{\rm o}$ (see lines for $a_{\rm min}$ equaled to 3.5 AU in Table 1 and to 3.8 and 3.9 AU in Table 2). Such difference was earlier found for calculations of migration of Jupiter-crossing objects [6-7]. One among hundreds or 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 the total probability for hundreds or even thousands of other objects. In Tables 1-2 at time interval T=100 Myr, nonzero values of $p_{\rm E}$ vary from values less than 10^{-6} to values of the order of 10^{-3}, but they are often between 10^{-6} and 10^{-5}, as for many our previous calculations with $a_{\rm min}\geq$5 AU considered in [1-4].

At T=100 Myr the mean values of $p_{\rm E}$ for 500 bodies exceeded 2×10^{-5} for $a_{\rm min}$=3.2, 3.3, 3.5, 3.7, 3.8, and 4.1 AU both at $e_{\rm o}$=0.02 and $e_{\rm o}$=0.15 (at $e_{\rm o}$=0.15 also for $a_{\rm min}$=4.2 AU). There were runs with $p_{\rm E}>10^{-3}$ at T=100 Myr, $a_{\rm min}$=3.5 AU, $e_{\rm o}$=0.02, and also at $a_{\rm min}$ equal to 3.2 and 3.8 for T=100 Myr and $e_{\rm o}$=0.15. In some runs there was a considerable growth of $p_{\rm E}$ after 10 and 100 Myr. The growth of $p_{\rm E}$ by more than 10^{-3} at T>100 Myr were at $a_{\rm min}$=3.0 and 3.2 AU for $e_{\rm o}$=0.15. These results show that the zone of the outer asteroid belt, especially from 3 to 4 AU, could made a valuable contribution to the delivery of water to the Earth.

After 100 Myr only not more than about 2% of initial bodies left in elliptical orbits at $a_{\rm min}\geq$3.8 AU (exclusive for $a_{\rm min}$=4.2 AU) and $e_{\rm o}$=0.02, and also at $a_{\rm min}\geq$3.5 AU and $e_{\rm o}$=0.15. For smaller values of $a_{\rm min}$ some bodies can still move in elliptical orbits even after 5 Gyr.

The fraction $p_{\rm Sun}$ of bodies collided with the Sun during 100 Myr for $e_{\rm o}$=0.02 was less than 4%, and it was less than 2% at $a_{\rm min}\leq$3.1 AU and $a_{\rm min}\geq$3.4 AU. For $e_{\rm o}$=0.15 it was less than 9%, and it was less than 1% at $a_{\rm min}\leq$3.1 AU and $a_{\rm min}\geq$3.4 AU (exclusive for $a_{\rm min}$=4.5 AU with $p_{\rm Sun}$ equal to 1.6%). At T>100 Myr for the considered variants of calculations such inequalities were also true, exclusive for $a_{\rm min}$=3.4 AU, $e_{\rm o}$=0.15, and T=4 Gyr, when the fraction of bodies collided with the Sun reached 17%.

Conclusions: The probabilities of collisions with the Earth of bodies-planetesimals with initial semi-major axes from 3.2 to 3.4 and from 3.5 to 3.6 AU were usually greater than those for the planetesimals initially located beyond the orbit of Jupiter. The zone of the outer asteroid belt, especially from 3 to 4 AU, could made a valuable contribution to the delivery of water to the Earth.

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Table 1. Probability p_E of a collision of a planetesimal with the Earth during time interval *T*. N_{ell} is the number of planetesimals left in elliptical orbits. Initial semi-major axes of planetesimals were between a_{min} and a_{min}+0.1 AU, and their initial eccentricities equaled to 0.02.

T, Myr	10	100	100			
a_{min}, AU	10^6p_E	N_{ell}	10^6p_E	*T*, Myr	N_{ell}	10^6p_E
3.0	0	250	0	1000	247	5.2
3.1	0	250	0	600	250	0
3.2	23.19	168	33.54	700	162	34.1
3.2	39.87	171	41.60	1000	161	42.73
3.3	15.44	156	129.8	1500	126	7379.8
3.3	51.80	156	219.6	2000	121	1020
3.4	0	247	0	500	233	0.20
3.4	0	250	0	500	230	20.06
3.5	6.20	146	4009.	1800	131	4009.3
3.5	14.64	152	17.33	1000	132	17.36
3.6	3.38	194	3.59	1500	74	6.24
3.6	1.96	172	3.15	5000	5	27.189
3.7	3.26	76	5.68	500	16	6.98
3.7	6.97	42	91.84	500	15	92.03
3.8	11.9	5	11.93			
3.8	52.12	1	72.91			
3.9	1.48	6	2.45			
3.9	21.24	4	21.46			
4.0	50.31	2	50.31			
4.0	1.92	4	3.62	200	2	3.62
4.0	10.20	2	10.47	200	2	10.47
4.1	352.8	8	388.7			
4.1	7.47	1	7.47			
4.2	2.17	120	3.40	200	85	3.40
4.3	0.46	3	0.54	884	0	0.54
4.4	7.90	3	7.92			
4.5	1.84	1	1.84			
4.6	1.82	3	1.83			
4.7	12.90	2	12.90			
4.8	0.588	2	0.66			
4.9	8.08	2	8.08			

Table 2. Probability p_E of a collision of a planetesimal with the Earth during time interval *T*. N_{ell} is the number of planetesimals left in elliptical orbits. Initial semi-major axes of planetesimals were between a_{min} and a_{min}+0.1 AU, and their initial eccentricities equaled to 0.15.

T, Myr	10	100	100			
a_{min}, AU	10^6p_E	N_{ell}	10^6p_E	*T*, Myr	N_{ell}	10^6p_E
3.0	0	234	3.70	1000	178	6504.2
3.1	0	250	0	600	248	1.07
3.2	24.19	118	365.5	4000	3	20791.1
3.2	39.87	104	4429.	5000	2	7714.4
3.3	46.54	84	223.5	2000	26	344.3
3.3	33.79	82	65.38	1000	48	392.9
3.4	1.77	70	24.55	2000	2	27.7
3.4	1.02	56	4.17	1000	3	27.8
3.5	44.91	2	235.9	473	0	235.9
3.5	10.62	4	10.62			
3.6	5.80	4	5.80			
3.6	4.04	3	4.07	200	2	4.07
3.7	3.54	2	3.54			
3.7	5.00	1	5.11			
3.8	283	5	1243.	200	2	1243.2
3.8	5.80	1	5.80			
3.9	178.6	3	178.6			
3.9	1.79	2	1.80			
4.0	0.44	6	2.45			
4.0	2.56	5	2.56			
4.1	49.93	1	50.60			
4.1	2.61	0	2.62			
4.2	1.08	2	1.08			
4.2	24.12	1	48.87			
4.3	1.52	1	1.52			
4.4	2.97	1	2.97			
4.5	6.80	2	6.80			
4.6	21.80	1	21.80			
4.7	0.62	0	0.62			
4.8	0.35	0	0.35			
4.9	3.34	2	3.34			