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Migration of matter from the Edgeworth–Kuiper and main asteroid belts to the Earth

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A considerable portion of near-Earth objects could have come from the trans-Neptunian belt. Some of them have aphelia deep inside Jupiter's orbit during more than 1 Myr.

1. INTRODUCTION

The main asteroid belt (MAB), the Edgeworth–Kuiper belt (EKB), and comets belong to the main sources of dust in the Solar System. Most of Jupiter-family comets came from the EKB. Comets can be destructed due to close encounters with planets and the Sun, collisions with small bodies, and internal forces. We support [7,9] the Eneev's idea [3] that the largest objects in the EKB and MAB could be formed directly by the compression of rarefied dust condensations of the protoplanetary cloud but not by the accretion of small (for example, 1-km) planetesimals. The total mass of planetesimals that entered the EKB from the feeding zone of the giant planets during their accumulation could exceed tens of Earth's masses $m_\oplus$ [4,5]. These planetesimals increased eccentricities of 'local' trans-Neptunian objects (TNOs) and swept most of these TNOs. A small portion of such planetesimals could left beyond Neptune's orbit in highly eccentric orbits. The results of previous investigations of migration and collisional evolution of minor bodies were summarized in [8,9]. Below we present mainly our recent results.

2. MIGRATION OF MATTER TO A NEAR-EARTH SPACE

Asteroids leave the MAB via some regions corresponding to resonances with Jupiter, Saturn, and Mars. They get into these regions mainly due to collisions. Gravitational influence of the largest asteroids plays a smaller role. The number of resonances delivering bodies to the Earth is not small (more than 15) [11]. So even due to small variations in semimajor axes a, some asteroids can get into the resonances, and the role of mutual gravitational influence of asteroids in their motion to the Earth may not be very small. Small bodies can get into the resonant regions also due to the Yarkovsky orbital drift. For dust particles we also need to take into account the Pointing–Robertson effect, radiation pressure, and solar wind drag.

Objects leave the EKB mainly due to the gravitational influence of planets [2]. During last 4 Gyr several percents of TNOs could change a by more than 1 AU due to the gravitational interactions with other TNOs [9]. For most of other TNOs such variations in a were less than 0.1 AU. The role of mutual gravitational influence of TNOs in evolution of their orbits may be greater than that of their collisions. Even small variations in orbital elements of TNOs due to their mutual gravitational influence and collisions can cause large variations in orbital elements due to the gravitational influence of planets. TNOs can leave the EKB (and comets leave the Oort cloud) without collisions. Therefore, some cometary objects migrating inside the Solar System can be large. The largest objects (with $d \geq 10$ km) that collided the Earth during last 4 Gyr could be mainly of cometary origin.

We investigated the evolution for intervals $T_S \geq 5$ Myr of 2500 Jupiter-crossing objects (JCOs) under the gravitational influence of all planets, except for Mercury and Pluto (without dissipative factors). In the first series we considered N=2000 orbits near the orbits of 30 real Jupiter-family comets with period <10 yr, and in the second series we took 500 orbits close to the orbit of Comet 10P Tempel 2 ($a \approx 3.1$ AU, $e \approx 0.53$, $i \approx 12°$). We calculated the probabilities of collisions of objects with the terrestrial planets, using orbital elements obtained with a step equal to 500 yr and then summarized the results for all time intervals and all bodies, obtaining the total probability P_Σ of collisions with a planet and the total time interval T_Σ during which perihelion distance q of bodies was less than a semimajor axis of the planet. The values of $P_r = 10^6 P = 10^6 P_\Sigma / N$ and $T = T_\Sigma / N$ are presented in the Table together with the ratio r of the total time interval when orbits were of Apollo type (at $a > 1$ AU, $q = a(1-e) < 1.017$ AU, $e < 0.999$) to that of Amor type ($1.017 < q < 1.33$ AU); r_2 is the same as r but for Apollo objects with eccentricity $e < 0.9$. For observed near-Earth objects (NEOs) r is close to 1.

Table: Values of T (in kyr), $T_c = T/P$ (in Myr), P_r, r, r_2 for the terrestrial planets

		Venus	Venus	Earth	Earth	Earth	Mars	Mars	–	–
	N	T	P_r	T	P_r	T_c	T	P_r	r	r_2
JCOs	2000	9.3	6.62	14.0	6.65	2110	24.7	2.03	1.32	1.15
comet 10P	500	24.9	16.3	44.0	24.5	1800	96.2	5.92	1.49	1.34
3 : 1 reson.	144	739	529	1227	626	510	2139	116	2.05	1.78
5 : 2 reson.	144	109	54.5	223	92.0	416	516	19.4	1.28	1.15

For integrations we used the Bulirsh-Stoer method (BULSTO) and a symplectic method. The probabilities of collisions of former JCOs with planets were close for these methods, but bodies got resonant orbits more often in the case of BULSTO. Besides JCOs, we considered asteroids with initial values of e and i equal to 0.15 and 10°, respectively. For the asteroids initially located at the 3:1 resonance with Jupiter, we found that the ratio r_{hc} of the number of asteroids ejected into hyperbolic orbits to that collided with the Sun was 5.6 for BULSTO and 0.38 and 0.87 for a symplectic method for a step of integration equal to 10 and 30 days, respectively. So in some cases a symplectic method can give a large error. For the 5:2 resonance with Jupiter, r_{hc} equaled 20 and 10 for BULSTO and symplectic methods, respectively. In the Table for asteroids we present only results obtained by the BULSTO code at T_S=50 Myr (at T_S=10 Myr the values of P and T are smaller by a factor less than 1.2 and 1.01 for the 3:1 and 5:2 resonances, respectively) and for TNOs we present results obtained by both codes.

The total time during which former 2000 JCOs were in Apollo-type and Amor-type orbits was 28.7 and 21.75 Myr, respectively, but 12.7 and 11.4 Myr of the above times were due to three objects. We found several former TNOs that moved for more than 1

Myr in orbits with aphelion distance Q<4.7 AU. The time interval during which a body had Q less than 3.2 and 3.7 AU exceeded 0.1 and 2.6 Myr, respectively.

Most of the collisions of former JCOs with the Earth were from orbits with aphelia inside Jupiter's orbit. The probability of collisions with the Earth for 3 former JCOs, each of which moved for more than 1 Myr in Earth-crossing orbits (mainly with Q<4.7 AU) was 1.5 times greater than that for the other 1997 JCOs. About 1 of 300 JCOs collided with the Sun. In [10] we considered a much smaller number of objects, which didn't get aphelia inside Jupiter's orbit and the values of P_r and T were smaller than those in the Table. For 2000 JCOs we consider, the mean probability of collisions with Venus is about the same as with Earth, and that with Mars is smaller by a factor of 3. These values are mainly due to a few bodies that moved during more than 1 Myr in orbits with aphelia deep inside Jupiter's orbit (for such bodies usually more than 80% of collisions with planets were from orbits with Q<4.2 AU). If we consider 1000 JCOs, for which most of the collisions with planets were from orbits with Q>4.2 AU, then the mean probability for Venus and Mars is less by a factor of 1.6 and 3, respectively, than that for Earth. Therefore, the ratio of the total mass of icy planetesimals that migrated from the feeding zone of the giant planets and collided with the planet to the mass of this planet was greater for Mars than that for Earth and Venus.

The mean time during which an object crossed Jupiter's orbit was 0.13 Myr for 2500 JCOs. An object had period P_a<10 yr usually only during about 12% of this time, so we think that our consideration of initial objects with only P_a<10 yr does not influence much on the obtained results. At N=2000 for 10<P_a<20, 20<P_a<50, 50<P_a<200 yr, we got 23%, 22% and 16%, respectively. One former JCO spent some time in orbits with aphelia deep inside Jupiter's orbit, and then it moved for tens of Myr in the trans-Neptunian region, partly in low eccentricity and partly in high eccentricity orbits. This result shows that some bodies can get from the MAB into the trans-Neptunian region, and that typical TNOs can become scattered objects (with high eccentricities) and vice versa.

3. COLLISIONS WITH THE EARTH

The number of TNOs migrating to the inner regions of the Solar System can be evaluated on the basis of simple formulas and the results of numerical integration. Let $N_J=p_{JN}P_N N_{TNO}$ be the number of former TNOs with $d>D$ reaching Jupiter's orbit for the given time span T_{SS}, where N_{TNO} is the number of TNOs with $d>D$; P_N is the fraction of TNOs leaving the EKB and migrating to Neptune's orbit during T_{SS}; and p_{JN} is the fraction of Neptune-crossing objects which reach Jupiter's orbit for their lifetimes. Then the current number of Jupiter-crossers that originated in the zone with $30<a<50$ AU equals $N_{Jn}=N_J\Delta t_J/T_{SS}$, where Δt_J is the average time during which the object crosses Jupiter's orbit. According to [2], the fraction P_N of TNOs that left this zone during T_{SS}=4 Gyr under the influence of the giant planets is 0.1-0.2 and p_{JN}=0.34. As mutual gravitational influence of TNOs also takes place [9], we take P_N=0.2. Hence, at Δt_J=0.13 Myr and $N_{TNO}=10^{10}$ (d>1 km), we have $N_{Jn}=2\cdot 10^4$. The number of former TNOs now moving in Earth-crossing orbits equals $N_E=N_{Jn}T/\Delta t_J$. The characteristic time T_{cN} between collisions of former TNOs with the Earth is $T/(N_{Jn}P)$. For T=0.014 Myr and Δt_J=0.13 Myr, we have N_E=2150 and $T_{cN}\sim$0.1 Myr. N_E is larger than the estimated number N_{Ee} of Earth-crossers with d>1 km (750), and T_c=T/P is larger than the characteristic time T_{co}≈100 Myr elapsed till a collision with the Earth obtained for fixed orbits of the observed NEOs. Such difference can be caused by the fact that it is difficult to observe NEOs with high e and i and N_{Ee} doesn't include such NEOs. It may be also probable that the number of 1-km TNOs is smaller than 10^{10}. As comets can get NEO and asteroidal orbits, a considerable portion of dust produced by NEOs and even some dust produced in the MAB can be of comet origin.

The total mass of water delivered to the Earth during the formation of the giant planets is M_w=$M_J P_{JE} k_i$, where M_J is the total mass of planetesimals from the feeding zones of these planets that became Jupiter-crossers during evolution, P_{JE} is a probability P of a collision of a former JCO with the Earth during its lifetime, and k_i is the portion of water ices in the planetesimals. For M_J=100$m_\oplus$, k_i=0.5, and P_{JE}=$6.65 \cdot 10^{-6}$, we have M_w=$3.3 \cdot 10^{-4} m_\oplus$. This value is greater by a factor of 1.5 than the mass of the Earth oceans. The mass of water delivered to Venus can be of the same order of magnitude and that delivered to Mars can be less by a factor of 3. Some TNOs with a>50 AU can also migrate to the orbits of Jupiter and Earth. Collisions of comets with small bodies and nongravitational forces can decrease Q. Asher *et al.* [1] showed that the rate at which objects may be decoupled from Jupiter and attain orbits like NEOs is increased by a factor of four or five, if nongravitational forces are included as impulsive effects. So the values of P_r and T can be larger than those in the Table. Rickman *et al.* [12] also concluded that comets play an important role among all km-sized impactors. As it is easier to destroy icy bodies than stone or metal bodies, the portion of TNOs among NEOs for bodies with d<100 m may be greater than that for 1-km bodies. In future, when people will make settlements on the Moon and terrestrial planets, small icy comets can be move by rockets to the orbits around these celestial bodies in order to be sources of water.

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