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Formation and migration of trans–Neptunian objects

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We support the Eneev's idea [1] that the largest (with diameter d>100 km) trans-Neptunian objects (TNOs) moving now in not very eccentric orbits could be formed directly by the compression of rarefied dust condensations (with a>30 AU) of the protoplanetary cloud (we do not support Eneev's opinion that planets were formed directly from large condensations) but not by the accretion of smaller (for example, 1-km) planetesimals, because such accretion could take place only at a large total mass of TNOs (several tens of Earth masses) and very small eccentricities (~ 0.001), which probably could not exist during the time needed for such accretion. Probably, some planetesimals with $d \sim$ 100–1000 km in the feeding zone of the giant planets and even large main–belt asteroids also could be formed directly by such compression. Some smaller objects (TNOs, planetesimals, and asteroids) could be debris of larger objects, and other such objects could be formed directly by compression of condensations. A small portion of planetesimals from the feeding zone of the giant planets that entered into the trans–Neptunian region could remain in eccentric orbits beyond Neptune and became so called "scattered objects". These objects could supply most of bodies that collided the Earth at the end of its bombardment 4 Gyr ago. The total amount of water delivered to the Earth during the formation of the giant planets was about the mass of water in the Earth's oceans.

The motion of TNOs to Jupiter's orbit was investigated by several authors. We considered 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 $e < 0.9$. For observed near–Earth objects 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 = V, Earth = E, Mars = M)

		V	V	E	E	E	M	M	–	–
	N	T	P_r	T	P_r	T_c	T	P_r	r	r_2
JCOs	2000	9.3	6.62	14	6.65	2110	24.7	2.03	1.32	1.15
10P	500	24.9	16.3	44	24.5	1800	96.2	5.92	1.49	1.34

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. The obtained values of T and P_r are larger than those in [2], because in our last runs we considered much larger (than in [2]) number of JCOs and obtained several former JCOs that moved in orbits with aphelia inside Jupiter's orbit (mainly with $Q < 4.7$ AU) during more than 1 Myr. The probability of collisions with the Earth for 3 former JCOs from such orbits was 1.5 times greater than that for the other 1997 JCOs. About 1 of 300 JCOs collided with the Sun. The analysis of the results of the orbital evolution of JCOs and TNOs showed that, in principle, as it was suggested earlier by T. M. Eneev, the trans–Neptunian belt can provide up to 100% of Earth–crossing objects, but, of course, some of them came from the main asteroid belt. 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 (by a factor of 3 in our runs) for Mars than that for Earth and Venus.

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References

1. Eneev T. M. About possible structure of outer (trans–Neptunian) regions of the Solar system. Pis'ma v astron. zhurnal, 1980, **6**, 295–300 (in Russian).

2. Ipatov S. I. Comet Hazard to the Earth, Advances in Space Research, 2001, **28**, 1107–1116.