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Formation and Migration of Trans-Neptunian Objects

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Abstract. Some large trans-Neptunian objects could be formed by the compression of rarefied dust condensations, but not by the accumulation of smaller planetesimals. A considerable portion of near-Earth objects could have come from the trans-Neptunian region. Our runs of the evolution of thousands orbits of Jupiter-family comets under the gravitational influence of planets showed that former Jupiter-family comets collide with the terrestrial planets mostly from orbits with aphelia located deep inside Jupiter's orbit. The total mass of water delivered by planetesimals from beyond Jupiter's orbit to the Earth could exceed the mass of Earth's oceans.

1. Formation of Tran-Neptunian Objects

Many scientists considered that large trans-Neptunian objects (TNOs) and asteroids were formed by accumulation of smaller (e.g., 1-km) planetesimals. Such process of accumulation of TNOs needs small ($\sim$0.001) eccentricities and a massive belt which probably could not exist during the time needed for such accumulation. Therefore Ipatov (2001) considered that large TNOs and some main-belt asteroids could be formed directly from dust rarefied condensations. It is assumed by many authors that a lot of dust condensations were formed from a dust disk around the forming Sun. These initial condensations coagulated under collisions and formed larger condensations, which compressed and formed solid planetesimals. To our opinion, during the time needed for compression of condensations into planetesimals, some largest final condensations could reach such masses that they formed initial planetesimals with diameter equal to several hundreds kilometers. As in the case of accumulation of planetesimals, there could be a "run-away" accretion of condensations. Some smaller objects (TNOs, planetesimals, 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 be left in eccentrical orbits beyond Neptune and became so called "scattered disk objects" (SDOs). The end of the bombardment of the terrestrial planets could be caused mainly by those planetesimals that had become SDOs. Our estimates (Ipatov 1995, 2001) showed that collisional lifetimes of 1-km TNOs and asteroids are about 1 Gyr. Typical TNOs can be even more often destroyed by SDOs than by other TNOs.

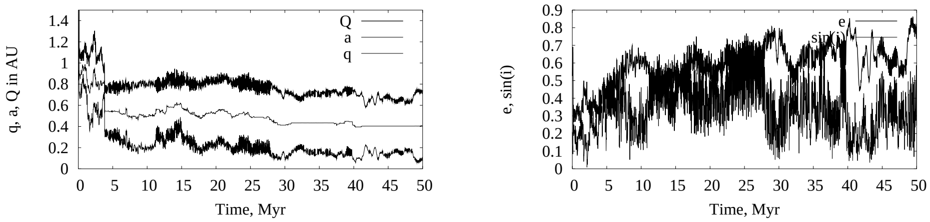

Figure 1. Time variations in a, q, Q, e, $\sin i$ for a former JCO in initial orbit close to that of Comet 10P (a>1.5 AU at t<0.123 Myr)

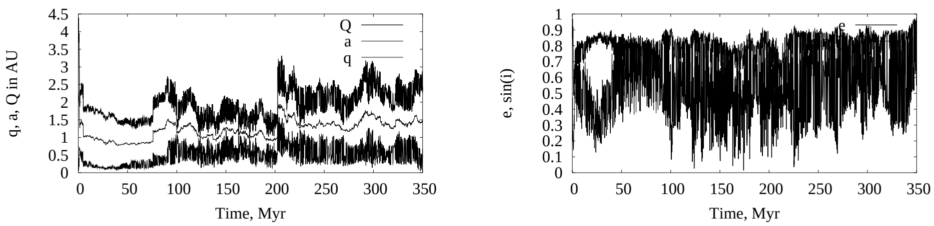

Figure 2. Time variations in a, q, Q, e, $\sin i$ for a former JCO in intial orbit close to that of Comet 2P

Mutual gravitational interactions of TNOs can play a larger role in variations of their orbital elements than collisions.

2. Orbital Evolution of Jupiter-Family Comets

The motion of TNOs to Jupiter's orbit was investigated by several authors (e.g., Levison & Duncan 1997). Proceeding from the total of 5×10^9 1-km TNOs within 30<a<50 AU, assuming the mean time $T_{JCO}\approx 0.12$ Myr for a body to move in a Jupiter-crossing orbit, similar to Ipatov (2001), 2001), we obtain that about 10^4 of former 1-km TNOs now are Jupiter-crossers. In the present paper we pay the main attention to the migration of Jupiter-crossing objects (JCOs). Our present investigations are based on our runs of the orbital evolution of thousands JCOs under gravitational influence of all planets, except for Mercury and Pluto, for intervals $T_S\geq 10$ Myr (for Comet 2P we also considered Mercury). The integration package by Levison & Duncan (1994) was used. Below we present the results obtained by the method by Bulirsh and Stoer at the relative error per integration step less than ε which was 10^{-9}, 10^{-8}, or some intermediate value. For $\varepsilon\leq 10^{-12}$ and for a symplectic method, we considered the evolution of 6000 orbits and got results similar to those presented below (but the portion of objects colliding with the Sun or getting resonant orbits was different).

In the first series of runs (denoted as $n1$) we investigated the orbital evolution of N=1900 JCOs moving in initial orbits close to those of 20 real JCOs with period 5<P_a<9 yr. In each of other series of runs we considered initial orbits close to that of one comet (2P, 9P, 10P, 22P, 28P, or 39P). We also studied the evolution of asteroids initially moving in the resonances 3:1 and 5:2 with Jupiter. Approximate values of initial semi-major axes a, eccentricities e and inclinations

i of considered objects are presented in Table 1. For JCOs we varied only initial mean anomaly, and for asteroids we varied also initial value of the longitude of the ascending node. Examples of time variations in orbital elements are presented in Figs. 1-2. As these two objects have large probabilities of collisions with the terrestrial planets, they are not included in the Table. In Fig. 3 we present the time in Myr during which 7852 former JCOs had semi-major axes in the interval with a width of 0.005 AU (left) or 0.1 AU (right).

Table 1. Values of T (in Kyr), P_r, and r (Venus=V, Earth=E, Venus=V)

					V	V	E	E	M	M	
	N	a	e	i	P_r	T	P_r	T	P_r	T	r
$n1$	1900				2.42	4.23	4.51	7.94	6.15	30.0	0.7
2P	501	2.22	0.85	12	141	345	110	397	10.5	430	18.
9P	800	3.12	0.52	10	1.34	1.76	3.72	4.11	0.71	9.73	1.2
10P	2149	3.10	0.53	12	28.3	41.3	35.6	71.0	10.3	169.	1.6
22P	1000	3.47	0.54	4.7	1.44	2.98	1.76	4.87	0.74	11.0	1.6
28P	750	6.91	0.78	14	1.7	21.8	1.9	34.7	0.44	68.9	1.9
39P	750	7.25	0.25	1.9	1.06	1.72	1.19	3.03	0.31	6.82	1.6
total	7850				17.9	37.7	18.8	51.5	5.29	85.9	2.6
3 : 1	288	2.5	0.15	10	1286	1886	1889	2747	488	4173	2.7
5 : 2	288	2.82	0.15	10	101	173	318	371	209	1455	0.5

combined

We did not simulate collisions of objects with planets, but basing on orbital elements obtained with a step 500 yr, for all N objects and all considered time spans we calculated the total impacting probability P_Σ and the total time interval T_Σ to reach perihelion distance q less than a semi-major axis of a planet, and then impact probabilities per one object $P{=}10^{-6}P_r{=}P_\Sigma/N$ and $T{=}T_\Sigma/N$ were estimated. In Table 1 we also present the ratio r of time spent in Apollo orbits ($a{>}1$ AU, $q{=}a(1-e){<}1.017$ AU) at $e{<}0.999$ to that in Amor orbits ($1.017{<}q{<}1.33$ AU). One object initially moving in orbit close to that of Comet 10P after having Aten-type orbit ($a{<}1$ AU, $Q{=}a(1+e){>}0.983$ AU) during 3 Myr (the probability of its collision with the Earth was 0.34) got orbits with aphelion distance $Q{<}0.983$ AU (Fig. 1). The probability of its collision with Venus during $t{\leq}50$ Myr was $\approx$3, so more probable that it collided Venus at $t{\approx}15$ Myr. For another object (Fig. 2) the probability of its collisions with Venus, Earth and Mars was 0.224, 0.172 and 0.065 (for this object, mean inclinations at $a{<}1.5$ AU were $\sim$40-50°), whereas the total probability of 7850 JCOs was 0.14, 0.15, and 0.04, respectively.

Specific mass of the matter delivered by JCOs to an inner planet (normalized to its mass) turns out to be nearly the same for Earth and Venus though greater for Mars. The total collisional probability with the inner planets was mainly caused by a small ($\sim$0.01-0.001) fraction of bodies residing in orbits deep inside Jupiter's orbit for more than 1 Myr. Fifteen considered objects with initial orbits close to those of 10P and 2P moved in Earth-crossing orbits with $1{<}a{<}2$ AU during more than 0.5 Myr each. At $n1$, objects moved with periods $P_a{<}10$

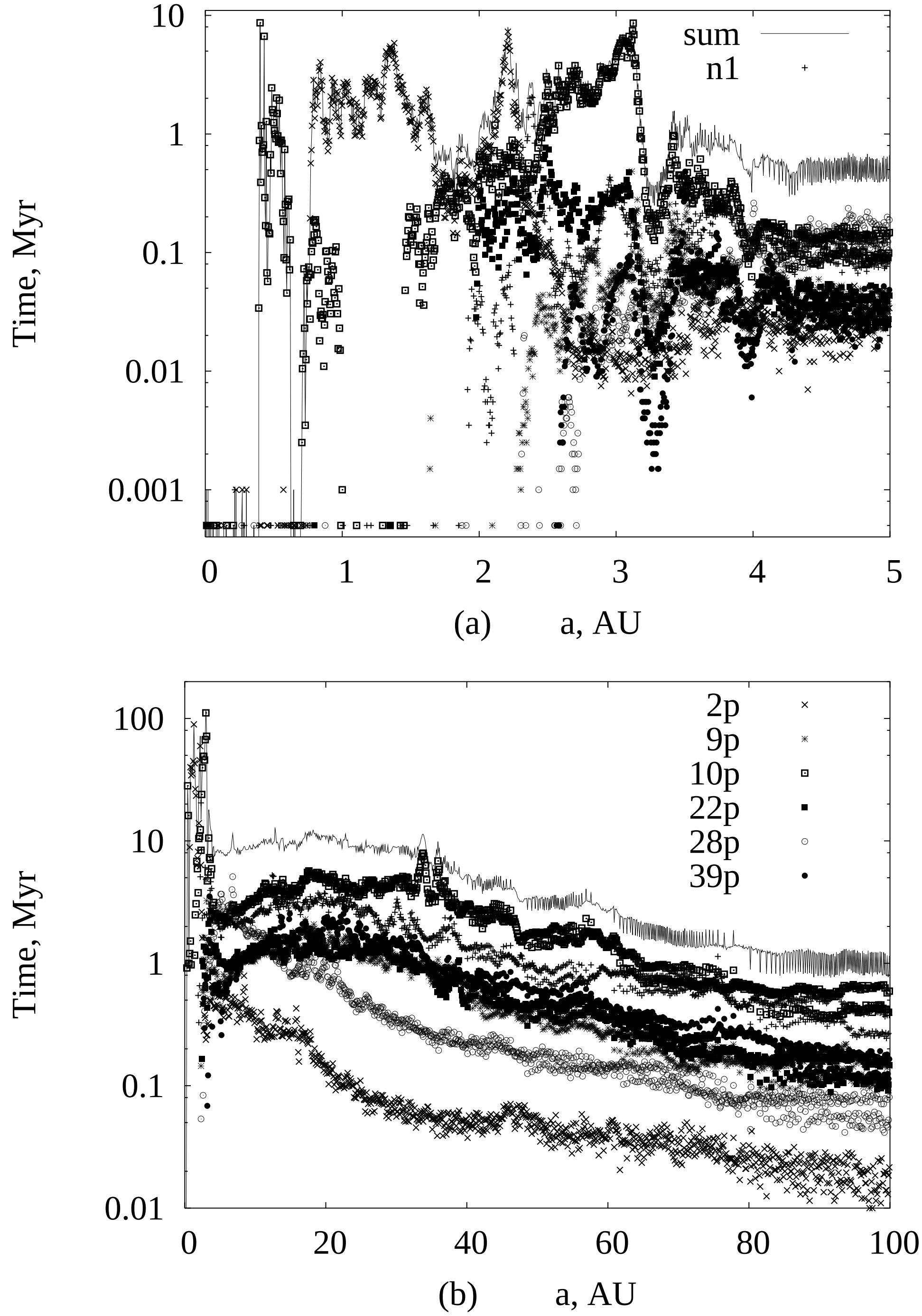

Figure 3. Distribution of migrating objects with their semi-major axes. The curves plotted in (b) at a=40 AU are (top-to-bottom) for sum, 10P, n1, 39P, 22P, 9P, 28P, and 2P.

and $10<P_a<20$ yr during 11% and 21% of T_{JCO}, respectively. More details of the runs can be found in our papers in http://arXiv.org/archive/astro-ph.

3. Migration of Trans-Neptunian Objects to the Near-Earth Space

In total, 7852 considered JCOs moved during 171, 659, 86, 411, and 10 Myr (145, 207, 3.4, 23, and 10 Myr for 7350 JCOs without 2P) in Amor, Apollo, and Aten orbits, orbits with $1<a<2$ AU and $q<1$ AU, and inner-Earth orbits (with $Q<0.983$ AU), respectively (the above times for inner-Earth and Aten orbits are mainly due only to one and two objects, respectively). So, if we consider 10^4 former 1-km TNOs now moving in Jupiter-crosing orbits, then for T_{JCO}=0.12 Myr their number for the above five types of orbits is about 1880 (1750), 7200 (2500), 950 (40), 4500 (250), and 110 (120), respectively (the data in parenthesis are based on the times exclusive 2P). As we simulated mainly orbits with large probabilities of collisions with the Earth, the above numbers can be smaller by a factor of several. Mean eccentricities of such orbits are larger and the probabilities of collisions with the terrestrial planets are smaller than those of the observed near-Earth objects (NEOs). Probably, most of such former TNOs (extinct comets) are not yet observed, as most of the time they move relatively far from the Earth. It is considered that about 750 of 1-km bodies are located in the Earth-crossing orbits (half of them are in orbits with $a<2$ AU), although this number does not include those in high eccentric orbits. Our estimates show that, in principle, the trans-Neptunian belt can provide a considerable portion of Earth-crossing objects, at least many of those with $a>2$ AU, but, of course, some NEOs came from the main asteroid belt. It may be possible to explore former TNOs near the Earth's orbit without sending spacecrafts beyond Neptune.

Based on the estimated collision probability $P=6\times10^{-6}$ (this value is a little larger than that for $n1$, but is smaller by an order of magnitude than $P=8\times10^{-5}$ obtained for 7852 JCOs) and assuming the total mass of planetesimals that ever crossed Jupiter's orbit is $\sim100m_\oplus$ ($m_\oplus$ is mass of the Earth), we found that the total mass of bodies impacted on the Earth is $6\times10^{-4}m_\oplus$. If ices composed only half of this mass, then the total mass of ices that were delivered to the Earth from the feeding zone of the giant planets turns out by the factor of 1.5 greater than the mass of the Earth oceans. The ratio of the total mass of the former JCOs that collided with a planet to the mass of the planet can be greater for Mars and Venus than that for Earth. So ancient oceans on Mars and Venus could be also large. Larger (than those obtained by other scientists) values of P are caused mainly by that we have considered a larger number of initial objects and among them there were objects with large collision probabilities.

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