

Comet and asteroid hazard to the terrestrial planets

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Abstract

We estimated the rate of comet and asteroid collisions with the terrestrial planets by calculating the orbits of 13,000 Jupiter-crossing objects (JCOs) and 1300 resonant asteroids and computing the probabilities of collisions based on random-phase approximations and the orbital elements sampled with a 500 years step. The Bulirsh–Stoer and a symplectic orbit integrator gave similar results for orbital evolution, but may give different collision probabilities with the Sun. A small fraction of former JCOs reached orbits with aphelia inside Jupiter's orbit and some reached Apollo orbits with semi-major axes less than 2 AU, Aten orbits and inner-Earth orbits (with aphelia less than 0.983 AU) and remained there for millions of years. Though less than 0.1% of the total, these objects were responsible for most of the collision probability of former JCOs with Earth and Venus. We conclude that a significant fraction of near-Earth objects could be extinct comets that came from the trans-Neptunian region or most of such comets disintegrated during their motion in near-Earth object orbits.

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1. Introduction

The main asteroid belt, the trans-Neptunian belt and the Oort cloud are considered to be the main sources of the objects that could collide with the Earth. Reviews of the asteroid and comet hazard were given by Ipatov (2000, 2001) and Bottke et al. (2002). Many scientists, e.g., Bottke et al. (2002), Binzel et al. (2002) and Weissman et al. (2002), believe that asteroids are the main source of near-Earth objects (NEOs, i.e., objects with perihelion distance $q < 1.3$ AU). Bottke et al. (2002) considered that there are 200 ± 140 km-sized Jupiter-family comets at $q < 1.3$ AU, with $\sim 80\%$ of them being extinct comets. Duncan et al. (1995) and Kuchner et al. (2002) investigated the migration of trans-Neptunian objects (TNOs) to Neptune's orbit and Levison and Duncan (1997) studied the migration from Neptune's orbit to Jupiter's

orbit. Ipatov and Hahn (1999) considered the migration of Jupiter-crossing objects (JCOs) with initial orbits close to the orbit of Comet P/1996 R2 and found that on average such objects spend about 5000 years in orbits which cross both the orbits of Jupiter and Earth. Using these results and additional orbit integrations and assuming that there are 5×10^9 1-km TNOs with $30 < a < 50$ AU (Jewitt and Fernandez, 2001), Ipatov (1999, 2000, 2001) found that about 10^4 1-km former TNOs are Jupiter-crossers now and 10–20% or more 1-km Earth-crossers could have come from the Edgeworth-Kuiper belt into Jupiter-crossing orbits. In the present paper we use the estimates by Ipatov (2001), but now include a much larger number of JCOs. Preliminary results were presented by Ipatov (2002a,b), who also discussed the formation of TNOs and asteroids.

2. Probabilities of collisions of near-Earth objects with planets in the model of fixed orbital elements

As the actual collisions of migrating objects with terrestrial planets are rare, we use an approximation of

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Table 1

Characteristic collision times T_f (in Myr) of minor bodies with planets, coefficient k and number N_f of simulated objects for the set of NEOs known in 2001

Planet	Atens			Apollos			Amors			NEOs			JFCs	
	T_f	k	N_f	T_f	k	N_f	T_f	k	N_f	T_f	k	N_f	T_f	k
Venus	106	1.2	94	186	1.7	248				154	1.5	343	2900	2.5
Earth	15	0.9	110	164	1.4	643	211	2.0	1	67	1.1	756	2200	2.3
Mars	475	0.4	6	4250	0.9	574	5810	1.1	616	4710	1.0	1197	17,000	1.8

random phases and orientations to estimate probabilities of collision for families of objects with similar orbital elements. We suppose that their semi-major axes a , eccentricities e and inclinations i are fixed, but the orientations of the orbits can vary. When the orbit of a minor body crosses the orbit of a planet at a distance R from the Sun, the characteristic time to collide, T_f , is a factor of $k = v/v_c = \sqrt{2a/R - 1}$ times that computed with an approximation of constant velocity, where v is the velocity at the point where the orbit of the body crosses the orbit of the planet and v_c is the velocity for the same semi-major axis and a circular orbit. This coefficient k modifies the formulas obtained by Ipatov (1988a, 2000) for characteristic collision and close encounter times of two objects moving around the Sun in crossing orbits. These formulas depend also on the synodic period and improve on Öpik's formulas when the semi-major axes of the objects are close to each other. As an example, at $e = 0.7$ and $a = 3.06$ AU, we have $k = 2.26$.

Based on these formulas, we calculated probabilities ($1/T_f$) for ~ 1300 NEOs, including 343 Venus-crossers, 756 Earth-crossers and 1197 Mars-crossers. The values of T_f (in Myr), k and the number N_f of objects considered are presented in Table 1. We considered separately the Atens, Apollos, Amors and several Jupiter-family comets (JFCs). The relatively small values of T_f for Atens and for all NEOs colliding with the Earth are due to several Atens with small inclinations discovered during the last three years. If we increase the inclination of the Aten object 2000 SG344 from $i = 0.1^\circ$ to $i = 1^\circ$, then for collisions with the Earth we find $T_f = 28$ Myr and $k = 0.84$ for Atens and $T_f = 97$ Myr and $k = 1.09$ for NEOs. These times are much longer and illustrate the importance of rare objects. Due to observational biases actual values of T_f can be greater than those in Table 1.

3. Orbital evolution of Jupiter-family comets and resonant asteroids

As the next step in estimating probabilities, we calculated the orbital evolution for thousands of test particles with initial orbits similar to known comets and asteroids, but having slightly different initial conditions. The results confirm that most of the collision probability

comes from a handful of very rare cases in which the test particle is Earth-crossing for an extended period of time.

For initial investigations of the migration of bodies under the gravitational influence of the planets, we used the integration package of Levison and Duncan (1994). In most cases we omitted the influence of Mercury and Pluto. Here and in Tables 2 and 3 and Figs. 1, 2 and 4 we present the results obtained by the Bulirsh–Stoer method (BULSTO code) with the integration step error less than $\varepsilon \in [10^{-9} - 10^{-8}]$ and in the next section we compare them with those of BULSTO at $\varepsilon \leq 10^{-12}$ and a symplectic method.

In the first series of runs (denoted as $n1$) we calculated the evolution of 1900 JCOs moving in initial orbits close to those of 20 real JCOs with period $5 < P_a < 9$ years. In other series of runs, initial orbits were close to those of a single comet (2P, 9P, 10P, 22P, 28P, or 39P). For the 2P runs, we included Mercury in the integrations. We also investigated the orbital evolution of asteroids initially moving in the 3:1 and 5:2 resonances with Jupiter. For the JCOs we varied only the initial mean anomaly v . The number of objects in one run usually was ≤ 250 . In most JCO cases the time τ when perihelion was passed was varied with a step $d\tau < 1$ day (i.e., v was varied with a step $< 0.2^\circ$). Near the τ estimated from observations, we used smaller steps. In most JCO cases the range of initial values of τ was less than several tens of days. For asteroids, we varied initial values of v and the longitude of the ascending node from 0° to 360° . The approximate values of initial orbital elements are presented in Table 2. We initially integrated the orbits for $T_S \geq 10$ Myr. After 10 Myr we tested whether some of remaining objects could reach inside Jupiter's orbit; if so, the calculations were usually continued. Therefore the results for orbits crossing or inside Jupiter's orbit were the same as if the integrations had been carried to lifetimes of objects. For Comet 2P and resonant asteroids, we integrated until all objects were ejected into hyperbolic orbits or collided with the Sun. In some previous publications we have used smaller T_S , so these new data are more accurate.

In our runs, planets were considered as material points so literal collisions did not occur. However, using the formulas of the previous section and the orbital elements sampled with a 500 years step, we calculated the mean probability P of collisions. We define P as P_S/N , where P_S is the probability for all N objects of a collision

Table 2

Mean probability $P = 10^{-6}P_r$ of a collision of an object with a planet (Venus = V, Earth = E, Mars = M) during its lifetime, mean time T (in Kyr) during which $q < a_{pl}$, $T_c = T/P$ (in Gyr), mean time T_j (in Kyr) spent in Jupiter-crossing orbits, mean time T_d (in Kyr) spent in orbits with $Q < 4.2$ AU and ratio r of times spent in Apollo and Amor orbits

	N	a	e	i (°)	V			E			M			r	T_j	T_d
					P_r	T	T_c	P_r	T	T_c	P_r	T	T_c			
$n1$	1900				2.42	4.23	1.75	4.51	7.94	1.76	6.15	30.0	4.88	0.7	119	20
2P	501	2.22	0.85	12	141	345	2.45	110	397	3.61	10.5	430	41.0	18.	173	249
9P	800	3.12	0.52	10	1.34	1.76	1.31	3.72	4.11	1.10	0.71	9.73	13.7	1.2	96	2.6
10P	2149	3.10	0.53	12	28.3	41.3	1.46	35.6	71.0	1.99	10.3	169.	16.4	1.6	122	107
22P	1000	3.47	0.54	4.7	1.44	2.98	2.07	1.76	4.87	2.77	0.74	11.0	14.9	1.6	116	1.5
28P	750	6.91	0.78	14	1.7	21.8	12.8	1.9	34.7	18.3	0.44	68.9	157	1.9	443	0.1
39P	750	7.25	0.25	1.9	1.06	1.72	1.62	1.19	3.03	2.55	0.31	6.82	22	1.6	94	2.7
\sum	7349				9.52	16.2	1.70	12.6	27.9	2.21	4.89	62.4	12.8	1.4	112	41
\sum	7850				17.9	37.7	2.11	18.8	51.5	2.74	5.29	85.9	16.2	2.6	116	54
\sum	7852				130	72.6	0.56	84.5	95.7	1.13	13.5	132	9.81	3.8	116	101
R2	24	3.79	0.31	2.6	0.53	0.6	1.13	2.84	1.6	0.56	6.97	14	2.0			
3:1	288	2.5	0.15	10	1286	1886	1.47	1889	2747	1.45	488	4173	8.55	2.7	229	5167
5:2	288	2.82	0.15	10	101	173	1.71	318	371	1.16	209	1455	6.96	0.5	233	1634

Results from BULSTO code at $\varepsilon \sim 10^{-9} - 10^{-8}$. \sum denotes the sum for several series presented in the above lines. For $N = 7349$, 2P runs were excluded.

Table 3

Times (in Myr) spent by N JCOs and asteroids during their lifetimes, with number of such objects in []

	N	IEOs	Aten	Al2	Apollo	Amor	$a > 5$ AU
JCOs	7852	10 [1]	86 [2]	411 [43]	659	171	7100
JCOs without 2P	7350	10 [1]	3.45 [1]	23 [10]	207	145	7000
3:1 resonance	288	13 [2]	4.5 [4]	433 [27]	790	290	83
5:2 resonance	288	0	0	17 [5]	113	211	253

Results from BULSTO code at $\varepsilon \sim 10^{-9} - 10^{-8}$.

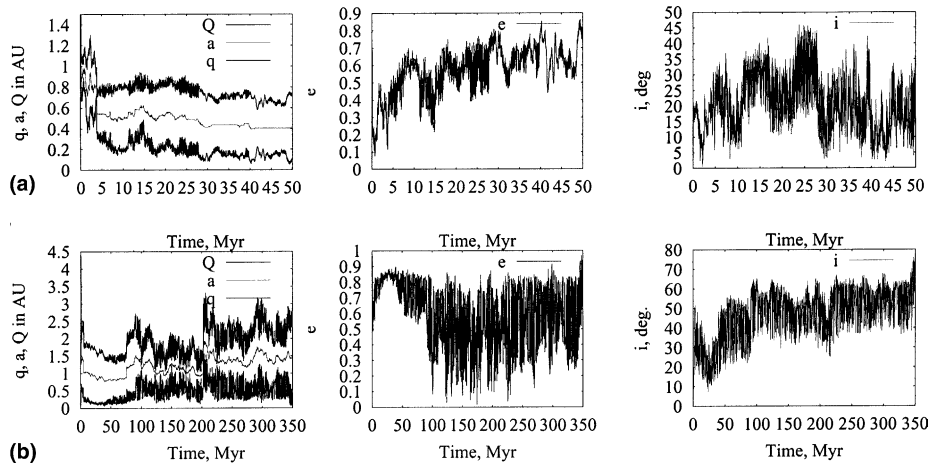


Fig. 1. Time variations in a, e, q, Q and i for a former JCO in initial orbit close to that of Comet 10P (a), 2P (b). For (a) at $t < 0.123$ Myr $Q > a > 1.5$ AU. Results from BULSTO code at $\varepsilon \sim 10^{-9} - 10^{-8}$.

of an object with a planet during its lifetime, the mean time $T = T_\Sigma/N$ during which perihelion distance q of an object was less than the semi-major axis a_{pl} of the planet and the mean time T_j during which an object moved in Jupiter-crossing orbits. The values of $P_r = 10^6P$, T_j and T are shown in Table 2. Here r is the ratio of the total time interval when orbits are of Apollo type ($a > 1$ AU, $q = a(1 - e) < 1.017$ AU) at $e < 0.999$ to that of Amor type ($1.017 < q < 1.3$ AU) and $T_c = T/P$ (in Gyr). In almost all runs T was equal to the mean time in orbits

which cross the orbit of the planet and $1/T_c$ was a probability of a collision per Gyr (similar to $1/T_r$). The results showed that most of the probability of collisions of considered former JCOs with the terrestrial planets is due to a few objects each of which orbited for several Myr with aphelion $Q < 4.2$ AU. Some had typical asteroidal and NEO orbits and reached $Q < 3$ AU for several Myr. Large values of P for Mars in the $n1$ runs were caused by a single object with a lifetime of 26 Myr. Total times spent by N JCOs and asteroids during their

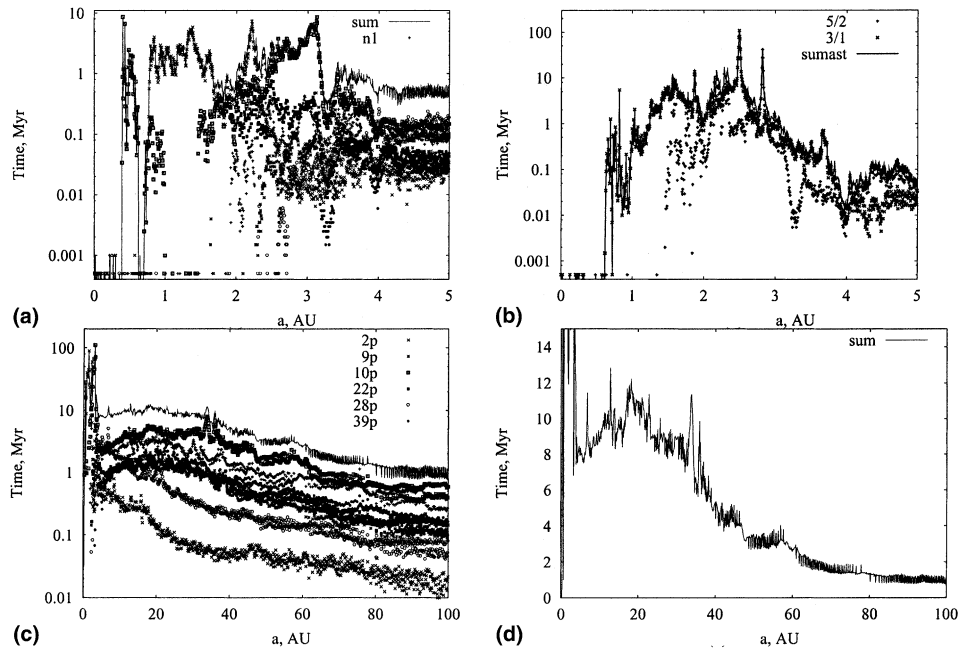


Fig. 2. Distribution of migrating objects with their semi-major axes. The curves plotted in (c) at $a = 40$ AU are (top-to-bottom) for sum, 10P, n1, 39P, 22P, 9P, 28P and 2P. For (a) and (c), designations are the same. Results from BULSTO code at $\varepsilon \sim 10^{-9}$ – 10^{-8} .

lifetimes in orbits typical for inner-Earth objects (IEOs, $Q < 0.983$ AU, Michel et al., 2000), Aten ($a < 1$ AU and $Q > 0.983$ AU), Al2 ($q < 1.017$ AU and $1 < a < 2$ AU), Apollo and Amor objects are presented in Table 3. These times for Earth-crossing objects were mainly due to a few tens of objects with high collision probabilities. Of the JCOs with initial orbits close to those of 10P and 2P, six and nine, respectively, moved into Apollo orbits with $a < 2$ AU (Al2 orbits) for at least 0.5 Myr each and five of them remained in such orbits for more than 5 Myr each. The contribution of all the other objects to Al2 orbits was smaller. Only one and two JCOs reached IEO and Aten orbits, respectively.

One former JCO (Fig. 1(a)), which had an initial orbit close to that of 10P, moved in Aten orbits for 3.45 Myr and the probability of its collision with the Earth from such orbits was 0.344 (so $T_c = 10$ Myr was even smaller than the values of T_f presented in Table 1; i.e., this object had smaller e and i than typical observed Atens), greater than that for the 7850 other simulated former JCOs during their lifetimes (0.15). It also moved for about 10 Myr in IEO orbits before its collision with Venus and during this time the probability $P_V = 0.655$ of its collision with Venus was greater ($P_V \approx 3$ for the time interval presented in Fig. 1(a)) than that for the 7850 JCOs during their lifetimes (0.14). At $t = 0.12$ Myr orbital elements of this object jumped considerably and the Tisserand parameter increased from $J < 3$ to $J > 6$ and $J > 10$ during most of its lifetime. Another object (Fig. 1(b)) moved in highly eccentric Aten orbits for 83 Myr and its lifetime before collision with the Sun was 352 Myr. Its probability of collisions with Earth, Venus

and Mars during its lifetime was 0.172, 0.224 and 0.065, respectively. These two objects were not included in Table 2 except for the entry for $N = 7852$. The data for Comet P/1996 R2 (line R2) were not included in the sums. Ipatov (1995) obtained the migration of JCOs into IEO and Aten orbits using the approximate method of spheres of action for taking into account the gravitational interactions of bodies with planets. The mean time T_E during which a JCO was moving in Earth-crossing orbits is 9.6×10^4 years for the 7852 simulated JCOs, and $\approx 8 \times 10^3$ years for the n1 case. The ratio P_S of the number of objects colliding with the Sun to the total number of escaped (collided or ejected) objects was less than 0.015 for the considered runs (except for 2P).

Some former JCOs spent a long time in the 3:1 resonance with Jupiter and with $2 < a < 2.6$ AU. Other objects reached Mars-crossing orbits for long times. We conclude that JCOs can supply bodies to the regions which are considered by many scientists (Bottke et al., 2002) to belong to the main sources of NEOs.

In Fig. 2 we present the time in Myr during which objects had semi-major axes in the interval with a width of 0.005 AU (Fig. 2(a) and (b)) or 0.1 AU (Fig. 2(c) and (d)). At 3.3 AU (the 2:1 resonance with Jupiter) there is a gap for asteroids that migrated from the 5:2 resonance and for former JCOs (except 2P).

For the n1 data set, $T_j = 0.12$ Myr and, while moving in Jupiter-crossing orbits, objects had orbital periods $P_a < 10$, $10 < P_a < 20$, $20 < P_a < 50$, $50 < P_a < 200$ years for 11%, 21%, 21% and 17% of T_j , respectively. Therefore, there are three times as many JCOs as Jupiter-family comets (for which $P_a < 20$ years). We also found that

some JCOs, after residing in orbits with aphelia deep inside Jupiter's orbit, transfer for tens of Myr to the trans-Neptunian region, either in low or high eccentricity orbits. We conclude that some of the main belt asteroids may reach typical TNO orbits and then become scattered-disk objects having high eccentricities and vice versa. The fraction of objects from the 5:2 resonance that collided with the Earth was only 1/6 of that for the 3:1 resonance. Only a small fraction of the asteroids from the 5:2 resonance reached $a < 2$ AU.

The distributions of migrating former JCOs and resonant asteroids in a and e and in a and i are presented in Fig. 4. For each picture we considered 250 migrating objects (288 for Fig. 4(g) and (h)), 100 intervals for a and about 50–90 intervals for e and i . Different designations correspond to different number n of orbital elements (calculated with a step of 500 years) which get in one bin (in Fig. 4 ' \leq ' means \leq). All considered former JCOs very rarely reached low eccentricity orbits with $2 < a < 3.5$ AU and $11 < a < 28$ AU. There were many positions of objects when their perihelia were close to a semi-major axis of a giant planet, mainly of Jupiter. The pictures are different for different runs.

4. Comparison of orbit integrators

To determine the effect of the choice of orbit integrators and convergence criteria, we made additional runs with BULSTO at $\varepsilon = 10^{-13}$ and 10^{-12} and with a symplectic integrator. The orbital evolution of 5400 JCOs was computed with the RMVS3 code. For the symplectic method we used an integration step d_s of 3, 10 and 30 days. We find that for the purposes of this paper, the differences between integrator choices (at $d_s \leq 10$ days) are comparable to the differences between runs with slightly different initial conditions. Our interpretation is that (1) very small numbers of particles contribute most of the collision probabilities with the terrestrial planets, (2) runs with larger numbers of particles are more reliable and (3) small differences in initial conditions or in the errors of the orbit integrators modify the trajectories substantially.

To illustrate these points, Tables 4 and 5 present the results obtained by BULSTO at $\varepsilon \leq 10^{-12}$ and the symplectic method at $d_s \leq 10$ days. Most of the results obtained with these values of ε and d_s are statistically similar to those obtained for $10^{-9} < \varepsilon < 10^{-8}$. For example, a few objects spent millions of years in Earth-crossing orbits inside Jupiter's orbit (Figs. 1 and 3) and their probabilities of collisions with the Earth were thousands of times greater than for more typical objects. For series $n1$ with RMVS3, the probability of a collision with Earth for one object with initial orbit close to that of Comet 44P was 88.3% of the total probability for 1200 objects from this series and the total probability for

1198 objects was only 4%. This object and the object presented in Fig. 3 and in the first line of Table 4 were not included in Table 5 with $N = 1199$ for $n1$ and with $N = 250$ for 2P, respectively. For the resonance 3:1 at $d_s = 10$ days, 142 objects spent 140 and 84.5 Myr in IEO and Aten orbits, respectively, even longer than for $\varepsilon \sim 10^{-9} - 10^{-8}$. Additionally, up to 40 Myr and 20 Myr were spent in such orbits by two other objects which had estimated probabilities of collisions with the terrestrial planets greater than 1 for the calculated sets of orbital elements. For the 2P runs at $\varepsilon \leq 10^{-12}$ and $N = 100$, the calculated objects spent 5.4 Myr in Apollo orbits with $a < 2$ AU.

The values of P_r presented in Table 5 are usually of the same order of magnitude as those in Table 2 and the difference between the data presented in these tables is comparable to the differences between different runs belonging to a series. For Earth and Venus, the values of P_r presented in both tables are about 1–4 for 9P, 22P, 28P and 39P. For 28P and 39P with the symplectic method P_r is about twice that for BULSTO. For 10P, P_r is several times larger than for the above series and for 2P it is several times larger than for 10P. For the $n1$ run, $P_r > 4$ for Earth. The ratio of P_r to the mass of the planet was typically several times larger for Mars than for Earth and Venus. The main difference in P_r was found for the 3:1 resonance. In this case greater values of P_r were obtained for $d_s = 10$ days, even if two objects, which had collision probabilities for calculated sets of orbital elements greater than unity for the terrestrial planets, were not included in Table 5. These two objects can increase the total value of P_r for Earth by a factor of several.

In Tables 2 and 5 we present the mean time T_d (in Kyr) spent in orbits with $Q < 4.2$ AU. It can differ by three orders of magnitude for different series of runs. In Table 5 in [] we present the number N_d of objects each of which got $Q < 4.2$ AU during at least 1000 years, the second number N_d in [] means the same but only for $q < 1.017$ AU. For series 2P and the 3:1 resonance with Jupiter both values of N_d were almost the same, for 10P they differed by a factor of 2.9 (symplectic runs) or 3.7 (BULSTO) and for other series only a small portion of decoupling objects crossed the orbit of the Earth. For most runs (except for 2P and asteroids) the number of objects which got $Q < 4.7$ AU was several times larger than that for $Q < 4.2$ AU.

We also did some symplectic runs with $d_s = 30$ day. For most of the objects we got similar results, but about 0.1% of the objects reached Earth-crossing orbits with $a < 2$ AU for several tens of Myr and even IEO orbits. These few bodies increased the mean value of P by a factor of more than 10. With $d_s = 30$ days, four objects from the runs $n1$, 9P, 10P had a probability of collisions with the terrestrial planets for calculated sets of orbital elements greater than 1 for each and for 2P there were 21 such objects among 251 considered. For resonant

Table 4

Times (Myr) spent by three objects in various orbits and probabilities of collisions with Venus (p_v), Earth (p_e) and Mars (p_m) during their lifetimes T_{it} (in Myr)

	d_s or ε	IEOs	Aten	Al2	Apollo	Amor	T_{it}	P_v	P_e	P_m
2P	10^d	12	33.6	73.4	75.6	4.7	126	0.18	0.68	0.07
44P	10^d	0	0	11.7	14.2	4.2	19.5	0.02	0.04	0.002
Resonance 3:1	10^{-12}	0	0	20	233.5	10.4	247	0.008	0.013	0.0007

Symplectic method.

Table 5

Probabilities of collisions with the terrestrial planets

	ε or d_s	N	V			E			M			r	T_j	$T_d[N_d]$
			P_r	T	T_c	P_r	T	T_c	P_r	T	T_c			
$n1$	$\leq 10^d$	1200	25.4	13.8	0.54	40.1	24.0	0.60	2.48	35.2	14.2	3.0	117	25.7[41/3]
$n1$	$\leq 10^d$	1199	7.88	9.70	1.23	4.76	12.6	2.65	0.76	16.8	22.1	2.8	117	10.3[40/2]
2P	$\leq 10^{-12}$	100	321	541	1.69	146	609	4.2	14.8	634	42.8	27	20	247[100/100]
2P	10^d	251	860	570	0.66	2800	788	0.28	294	825	2.81	22	0.29	614[251/251]
2P	10^d	250	160	297	1.86	94.2	313	3.32	10.0	324	32.3	35	0.29	585[250/250]
9P	10^d	400	1.37	3.46	2.53	3.26	7.84	2.40	1.62	23.8	14.7	1.1	128	8.0[13/3]
10P	$\leq 10^d$	450	14.9	30.4	2.04	22.4	41.3	1.84	6.42	113.0	17.6	1.5	85	44.[70/24]
22P	10^d	250	0.68	2.87	4.23	1.39	4.96	3.57	0.60	11.5	19.2	1.5	121	0.6[3/0]
28P	10^d	250	3.87	35.3	9.12	3.99	59.0	14.8	0.71	109.0	154	2.2	535	3.3[7/0]
39P	10^d	250	2.30	2.68	1.17	2.50	4.22	1.69	0.45	7.34	16.3	2.2	92	0.5[2/0]
3:1	$\leq 10^{-12}$	70	1162	1943	1.67	1511	5901	3.91	587	803	1.37	4.6	326	8400[70/70]
3:1	10^d	142	27700	8617	0.31	2725	9177	3.37	1136	9939	8.75	16	1244	5000[142/140]
5:2	10^{-12}	50	130	113	0.87	168	230	1.37	46.2	507	11.0	1.4	166	512[50/4]
5:2	10^d	144	58.6	86.8	1.48	86.7	174	2.01	17.	355	20.9	1.7	224	828[144/13]

Designations are same as those for Table 2. T_d is the mean time (in Kyr) spent in orbits with $Q < 4.2$ AU; in [] we present the number N_d of objects each of which got $Q < 4.2$ AU during at least 1000 years, the second number in [] means the same but only for $q < 1.017$ AU. Results from the BULSTO code at $\varepsilon \leq 10^{-12}$ and a symplectic method at $d_s \leq 10$ days.

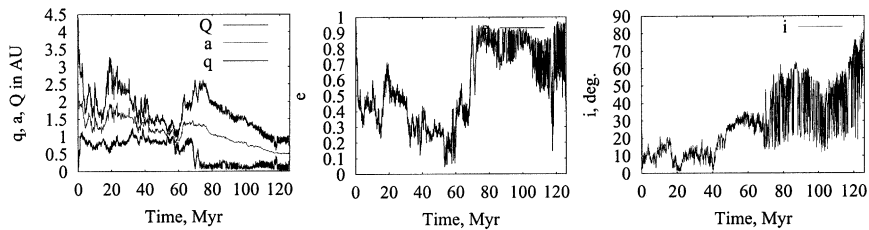


Fig. 3. Time variations in a, e, q, Q and i for a former JCO in initial orbit close to that of Comet 2P. Results from a symplectic method at $d_s = 10$ days.

asteroids, we also obtained much larger values than those with BULSTO for P and T with RMVS3 at $d_s = 30$ days and similarly, for the 3:1 resonance even at $d_s < 10$ days. For this resonance it may be better to use $d_s = 10$ days. Probably, the results of symplectic runs at $d_s = 30$ days can be considered as such migration that includes some nongravitational forces.

In the case of close encounters with the Sun (Comet 2P and resonant asteroids), the probability P_S of collisions with the Sun was larger for RMVS3 than for BULSTO and for $10^{-13} \leq \varepsilon \leq 10^{-12}$ it was greater than for $10^{-9} \leq \varepsilon \leq 10^{-8}$ ($P_S = 0.75$ for the 3:1 resonance at $d_s = 3$ days):

In the direct integrations reported by Valsecchi et al. (1995), 13 of the 21 objects close to Comet 2P fell into the Sun, i.e., $P_S = 0.62$. Note that even for different P_S the data presented in Tables 2 and 5 usually are similar. As we did not calculate collision probabilities of objects with planets by direct integrations, but instead calculated them with the random phase approximation from the orbital elements, we need not make integrations with extremely high accuracy. For Comet 2P the values of T_j were much smaller for RMVS3 than those for BULSTO and they were smaller for smaller ε ; for other runs these values do not depend much on the method. Ipatov

Probability of collisions with the Sun

	$\varepsilon = 10^{-13}$	$\varepsilon = 10^{-12}$	$\varepsilon = 10^{-9}$	$\varepsilon = 10^{-8}$	$d_s = 10$ days	$d_s = 30$ days
Comet 2P	0.88	0.88	0.38	0.32	0.99	0.8
Resonance 3:1	0.46	0.5	0.156	0.112	0.741	0.50
Resonance 5:2		0.06	0.062	0.028	0.099	0.155

(1988b) showed that for BULSTO the integrals of motion were conserved better and the plots of orbital elements for closely separated values of ε were closer to one another at $10^{-9} \leq \varepsilon \leq 10^{-8}$. The smaller the value of ε , the more integrations steps are required, so $\varepsilon \leq 10^{-12}$ for large time intervals are not necessarily better than those for $10^{-9} \leq \varepsilon \leq 10^{-8}$. Small ε is clearly necessary for close encounters. Ipatov and Hahn (1999) and Ipatov (2000) found that former JCOs reached resonances more often for BULSTO than for RMVS3 at $d_s = 30$ days. Therefore we made most of our BULSTO runs with $10^{-9} \leq \varepsilon \leq 10^{-8}$. For a symplectic method it is better to use smaller d_s at a smaller distance R from the Sun, but in some runs R can vary considerably during the evolution.

Bottke pointed out that Levison showed that it is difficult to detect solar collisions in any numerical integrator, so he removed objects with $q < q_{\min}$. The results presented above were obtained considering collisions with the Sun, but we also investigated what happens if we consider q_{\min} equal to k_S radii r_S of the Sun. For $k_S = 2$, some results are presented in Fig. 4(e), (f), (h). The only difference with the runs that considered collisions with the Sun is that for those runs for series 2P and 10P and for the 3:1 resonance, some objects reached $90^\circ < i < 180^\circ$ (mainly with $2 < a < 3.5$ AU) (Fig. 4(b), (d), (g)). For $k_S = 2$ there were no comets with $i > 90^\circ$ and there were only a few orbits of asteroids with $i > 90^\circ$ (Fig. 4(e), (f), (h)). The consideration of q_{\min} at $k_S = 3$ did not influence the collision probabilities with

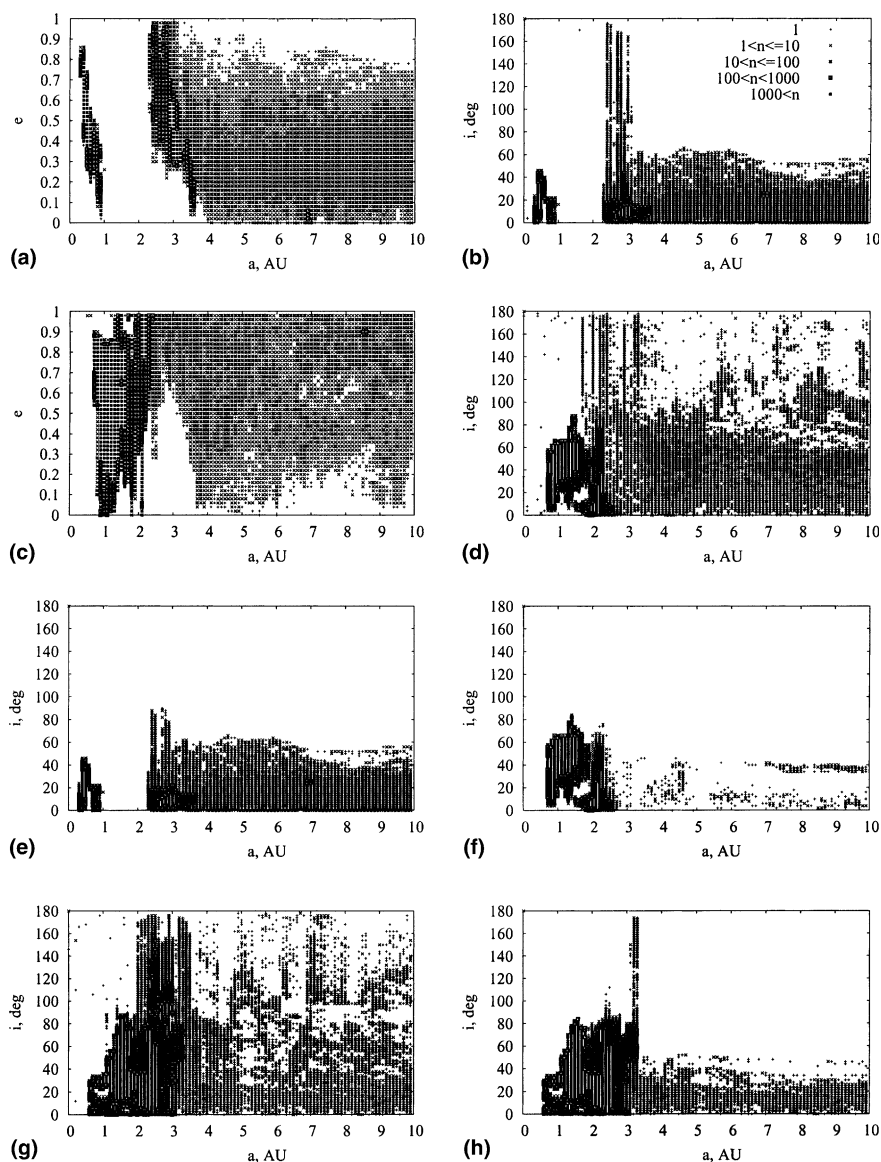


Fig. 4. Distribution of migrating objects in semi-major axes, eccentricities and inclinations for objects in initial orbits close to that of 10P (a, b, e), 2P (c, d, f) and the resonance 3:1 with Jupiter (g, h). BULSTO code at $\varepsilon \sim 10^{-9}$ – 10^{-8} . For (e, f, h) it was considered that an object disappeared when perihelion distance became less than 2 radii of the Sun. In other cases, objects disappeared when they collided with the Sun.

the terrestrial planets or getting orbits with $a < 2$ AU. For example, with BULSTO for the two objects with the largest collision probabilities, the time spent in orbits with $a < 2$ AU decreased by only 0.3% for 2P at $k_S = 3$ and was the same for 10P at $k_S = 10$.

5. Migration from beyond Jupiter to the terrestrial planets

According to Duncan et al. (1995), the fraction P_{TNJ} of TNOs reaching Jupiter's orbit under the influence of the giant planets in 1 Gyr is 0.8–1.7%. As the mutual gravitational influence of TNOs can play a larger role in variations of their orbital elements than collisions (Ipatov, 1995, 2001), we considered the upper value of P_{TNJ} . Using the total of 5×10^9 1-km TNOs with $30 < a < 50$ AU and assuming that the mean time for a body to move in a Jupiter-crossing orbit is 0.12 Myr, we find that about $N_{\text{Jo}} = 10^4$ 1-km former TNOs are now Jupiter-crossers and 3000 are JFCs. Using the total times spent by N simulated JCOs in various orbits, we obtain the following numbers of 1-km former TNOs now moving in several types of orbits:

N	Method	Series	IEOs	Aten	Al2	Apollo	Amor
3100	BULSTO + RMVS3	$n1$	0	0	480	1250	900
1900	BULSTO	$n1$	0	0	25	720	1000
7350	BULSTO	All without 2P	120	40	250	2500	1750
7852	BULSTO	All	110	950	4500	7200	1880

For example, the number of IEOs $N_{\text{IEOs}} = N_{\text{Jo}} t_{\text{IEO}} / (N_{\text{J}} t_{\text{J}})$, where t_{IEO} is the total time during which N_{J} former JCOs moved in IEOs' orbits and $N_{\text{J}} t_{\text{J}}$ is the total time during which N_{J} JCOs moved in Jupiter-crossing orbits. As we considered mainly the runs with relatively high migration to the Earth, the actual number of NEOs is smaller by a factor of several, the actual portion of IEOs and Atens can be smaller and that for Amors can be larger than those in the lines in the Table at $N > 7000$. Even if the number of Apollo objects is smaller than that based on $n1$ runs, it may still be comparable to the real number (750) of 1-km Earth-crossing objects (half of them are in orbits with $a < 2$ AU), although the latter number does not include those in highly eccentric orbits.

The values of the characteristic time (usually T_c) for the collision of a former JCO or a resonant asteroid with a planet (see Tables 2 and 5) are greater than the values of T_f for NEOs in Table 1, $T_c \approx 1.1$ Gyr for 7852 objects, so we expect that the mean inclinations and eccentricities of unobserved NEOs are greater than those for the NEOs that are already known. Jedicke et al. (2003) found similar results. On average, the values of T_c for our $n1$ series and for most of our simulated JCOs were not greater than those for our calculated asteroids and

migrating Earth-crossing objects had similar e and i for both former JCOs and resonant asteroids. Former JCOs, which move in Earth-crossing orbits for more than 1 Myr, while moving in such orbits, usually had larger P and smaller e and i (sometimes similar to those of the observed NEOs, see Figs. 1 and 3) than other JCOs. It is easier to observe orbits with smaller values of e and i and probably, many of the NEOs moving in orbits with large values of e and i have not yet been discovered. About 1% of the observed Apollos cross Jupiter's orbit and an additional 1% of Apollos have aphelia between 4.7–4.8 AU, but these Jupiter-crossers are far from the Earth most of time, so their actual fraction of ECOs is greater than for observed ECOs. The fraction of Earth-crossers among observed Jupiter-family comets is about 10%. This is a little more than T/T_J for our $n1$ runs, but less than for 7850 JCOs. For our former resonant asteroids, T_J is relatively large (≈ 0.2 Myr) and such asteroids can reach cometary orbits.

Comets are estimated to be active for $T_{\text{act}} \sim 10^3$ – 10^4 years. T_{act} is smaller for closer encounters with the Sun (Weissman et al., 2002), so for Comet 2P it is smaller than for other JFCs. Some former comets can move for tens or even hundreds of Myr in NEO orbits, so the number of extinct comets can exceed the number of active comets by several orders of magnitude. The mean time spent by Encke-type objects in Earth-crossing orbits is ≥ 0.4 Myr (even considering q_{min}). This time corresponds to ≥ 40 – 400 extinct comets of this type. Note that the diameter of Comet 2P is about 5–10 km, so the number of smaller extinct comets can be much larger.

The above estimates of the number of NEOs are approximate. For example, it is possible that the number of 1-km TNOs is several times smaller than 5×10^9 , while some scientists estimated that this number can be up to 10^{11} (Jewitt, 1999). Also, the fraction of TNOs that have migrated towards the Earth might be smaller. On the other hand, the above number of TNOs was estimated for $a < 50$ AU and TNOs from more distant regions can also migrate inward. Probably, the Oort cloud could also supply Jupiter-family comets. According to Asher et al. (2001), the rate of a cometary object decoupling from the Jupiter vicinity and transferring to an NEO-like orbit is increased by a factor of 4 or 5 due to nongravitational effects (see also Fernandez and Gallardo, 2002). This would result in larger values of P_f and T than those shown in Tables 2 and 5. Our estimates show that, in principle, the trans-Neptunian belt can provide a significant portion of the Earth-crossing objects, although many NEOs clearly came from the main asteroid belt. It may be possible to explore former TNOs near the Earth's orbit without sending spacecraft to the trans-Neptunian region. According to our results, many former Jupiter-family comets can have orbits typical of asteroids and collide with the Earth from typical NEO orbits.

Based on the collision probability $P = 4 \times 10^{-6}$ we find that 1-km former TNOs now collide with the Earth once in 3 Myr. This value of P is smaller than that for our $n1$ runs, does not include the ‘champions’ in collision probability and is only 1/20 of that for our 7852 JCOs. Using $P = 4 \times 10^{-6}$ and assuming the total mass of planetesimals that ever crossed Jupiter’s orbit is $\sim 100m_{\oplus}$, where m_{\oplus} is the mass of the Earth (Ipatov, 1993, 2000), we conclude that the total mass of bodies that impacted the Earth is $4 \times 10^{-4}m_{\oplus}$. If ices comprised only half of this mass, then the total mass of ices M_{ice} that were delivered to the Earth from the feeding zone of the giant planets is about the mass of the terrestrial oceans ($\sim 2 \times 10^{-4}m_{\oplus}$).

The calculated probabilities of collisions of objects with planets show that the fraction of the mass of the planet delivered by short-period comets can be greater for Mars and Venus than for the Earth (compare the values of P/m_{pl} using P from Tables 2 and 5, where m_{pl} is the mass of the planet). This larger mass fraction would result in relatively large ancient oceans on Mars and Venus. On the other hand, there is the deuterium/hydrogen paradox of Earth’s oceans, as the D/H ratio is different for oceans and comets. Pavlov et al. (1999) suggested that solar wind-implanted hydrogen on interplanetary dust particles could provide the necessary low-D/H component of Earth’s water inventory.

Our estimate of the migration of water to the early Earth is in accordance with Chyba (1989), but is greater than those of Morbidelli et al. (2000) and Levison et al. (2001). The latter obtained smaller values of M_{ice} and we suspect that this is because, they did not take into account the migration of bodies into orbits with $Q < 4.2$ AU and $q < 1$ AU. Perhaps this was because, they modeled a relatively small number of objects and Levison et al. (2001) did not take into account the influence of the terrestrial planets. In our runs the probability of a collision of a single object with a terrestrial planet could be much greater than the total probability of thousands of other objects, so the statistics are dominated by rare occurrences that might not appear in smaller simulations. The mean probabilities of collisions can differ by orders of magnitude for different JCOs. Other scientists considered other initial objects and smaller numbers of JCOs and did not find decoupling from Jupiter, which is a rare event. We believe there is no contradiction between our present results and the smaller migration of former JCOs to the near-Earth space that was obtained in earlier work, including our own papers (e.g., Ipatov and Hahn, 1999), where we used the same integration package.

From measured albedos, Fernandez et al. (2001) concluded that the fraction of extinct comets among NEOs and unusual asteroids is significant (at least 9% are candidates). Rickman et al. (2001) believed that comets played an important and perhaps even dominant

role among all km-size Earth impactors. In their opinion, dark spectral classes that might include the ex-comets are severely underrepresented (see also Jewitt and Fernandez, 2001). Our runs showed that if one observes former comets in NEO orbits, then it is probable that they have already moved in such orbits for millions (or at least hundreds of thousands) years and only a few of them have been in such orbits for short times (a few thousand years). Some former comets that have moved in typical NEO orbits for millions or even hundreds of millions of years and might have had multiple close encounters with the Sun, could have lost their mantles, which causes their low albedo and so change their albedo (for most observed NEOs, the albedo is greater than that for comets; Fernandez et al., 2001) and would look like typical asteroids, or some of them could disintegrate into mini-comets. Typical comets have larger rotation periods than typical NEOs (Binzel et al., 1992), but, while losing considerable portions of their masses, extinct comets can decrease these periods. In future we plan to consider a larger initial number of objects initially located beyond Jupiter.

6. Conclusions

Collision statistics for the terrestrial planets are dominated by very small numbers of bodies that reach orbits with high collision probabilities, so it is essential to consider very large numbers of particles. The initial conditions for the orbit integrations appear to matter more than the choice of orbit integrator. Some Jupiter-family comets can reach typical NEO orbits and remain there for millions of years. While the probability of such events is small (about 0.1% in our runs and perhaps smaller for other initial data), nevertheless the majority of collisions of former JCOs with the terrestrial planets are due to such objects. The amount of water delivered to the Earth during planet formation could be about the mass of the Earth oceans. From the dynamical point of view there could be (not ‘must be’) many extinct comets among the NEOs. For better estimates of the portion of extinct comets among NEOs we will need orbit integrations for many more TNOs and JCOs and wider analysis of observations and craters.

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