

Migration of Trans-Neptunian Objects to the Terrestrial Planets

Sergei I. Ipatov

*George Mason University; NASA/GSFC; Institute of Applied Mathematics,
Moscow*

John C. Mather

NASA/GSFC

Abstract.

The orbital evolution of more than 22000 Jupiter-crossing objects under the gravitational influence of planets was investigated. We found that the mean collision probabilities of Jupiter-crossing objects (from initial orbits close to the orbit of a comet) with the terrestrial planets can differ by more than two orders of magnitude for different comets. For initial orbital elements close to those of some comets (e.g. 2P and 10P), about 0.1% of objects got Earth-crossing orbits with semi-major axes $a < 2$ AU and aphelion distances $Q < 4.2$ AU and moved in such orbits for more than a Myr (up to tens or even hundreds of Myrs). Results of our runs testify in favor of at least one of these conclusions: 1) the portion of 1-km former trans-Neptunian objects (TNOs) among near-Earth objects (NEOs) can exceed several tens of percents, 2) the number of TNOs migrating inside solar system could be smaller by a factor of several than it was earlier considered, 3) most of 1-km former TNOs that had got NEO orbits disintegrated into mini-comets and dust during a smaller part of their dynamical lifetimes if these lifetimes are not small.

Keywords: trans-Neptunian objects, Jupiter-family comets, terrestrial planets

1. Introduction

Trans-Neptunian objects (TNOs) are considered to be one of the main sources of near-Earth objects (NEOs). Bottke et al. (2002), Binzel et al. (2002), and Weissman et al. (2002) believe that asteroids are the main source of NEOs. Duncan et al. (1995) and Kuchner et al. (2002) investigated the migration of TNOs to Neptune's orbit, and Levison and Duncan (1997) studied their migration from Neptune's orbit to Jupiter's orbit. Based on the results of migration of Jupiter-crossing objects (JCOs) with initial orbits close to the orbit of Comet P/1996 R2 obtained by Ipatov and Hahn (1999), Ipatov (1999, 2001) found that 10-20% or more of the 1-km Earth-crossers could have come from the Edgeworth-Kuiper belt into Jupiter-crossing orbits. In the present paper we consider a larger number of JCOs than before. Some preliminary results were presented by Ipatov (2002a-b), who also discussed the formation of TNOs and asteroids. The results of the runs of JCOs,



© 2003 Kluwer Academic Publishers. Printed in the Netherlands.

including several figures, can be also found in (Ipatov and Mather, 2003a-b). A wider review on the migration of asteroids and comets to NEO orbits was made by Ipatov (2001).

2. Migration of Jupiter-Family Comets to the Terrestrial Planets

As the migration of TNOs to Jupiter's orbit was investigated by several authors, we have made a series of simulations of the orbital evolution of JCOs under the gravitational influence of planets. We omitted the influence of Mercury (except for Comet 2P/Encke) and Pluto. The orbital evolution of more than 9000 and 13000 JCOs with initial periods $P_a < 20$ yr was integrated with the use of the Bulirsch-Stoer and symplectic methods (BULSTO and RMVS3 codes), respectively. We used the integration package of Levison and Duncan (1994).

In the first series of runs (denoted as $n1$) we calculated the evolution of 3100 JCOs moving in initial orbits close to those of 20 real comets with period $5 < P_a < 9$ yr, and in the second series of runs (denoted as $n2$) we considered 10000 JCOs moving in initial orbits close to those of 10 real comets (with numbers 77, 81, 82, 88, 90, 94, 96, 97, 110, 113) with period $5 < P_a < 15$ yr. In other series of runs, initial orbits were close to those of a single comet (2P/Encke, 9P/Tempel 1, 10P/Tempel 2, 22P/Kopff, 28P/Neujmin 1, 39P/Oterma, or 44P/Reinmuth 2). In order to compare the orbital evolution of comets and asteroids, we also investigated the orbital evolution of asteroids initially moving in the 3:1 and 5:2 resonances with Jupiter. For JCOs we varied only the initial mean anomaly ν in an interval less than several tens of degrees. Usually in one run, there were 250 JCOs or 144 asteroids. For asteroids, we varied initial values of ν and the longitude of the ascending node from 0 to 360° . The approximate values of initial semi-major axes, eccentricities and inclinations of considered comets (a_o , e_o , and i_o) are presented in Table I. We investigated the orbital evolution during the dynamical lifetimes of objects (at least until all the objects reached perihelion distance $q > 6$ AU).

In our runs, planets were considered as material points, so literal collisions did not occur. However, based on the orbital elements sampled with a 500 yr step, we calculated the mean probability P of collisions. We define P as P_Σ/N , where P_Σ is the total probability of collisions of N objects with a planet during their lifetimes, 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, the mean time T_d spent in orbits with aphelion distance $Q < 4.2$ AU, and the mean time T_J during which an

Table I. Semi-major axes (in AU), eccentricities and inclinations of several considered comets

	a_o	e_o	i_o		a_o	e_o	i_o
2P/Encke	2.22	0.85	11.7°	9P/Tempel 1	3.12	0.52	10.5°
10P/Tempel 2	3.10	0.53	12.0°	22P/Kopff	3.47	0.54	4.7°
28P/Neujmin 1	6.91	0.78	14.2°	39P/Oterma	7.25	0.25	1.9°
44P/Reinmuth 2	3.53	0.46	7.0°	88P/Howell	3.13	0.56	4.4°
96P/Machholz 1	3.04	0.96	60.2°	113P/Spitaler	3.69	0.42	5.8°

object moved in Jupiter-crossing orbits. The values of $P_r=10^6 P$, T_J , T_d , and T are shown in Table II. Here r is the ratio of the total time interval when orbits are of Apollo type ($a>1$ AU, $q<1.017$ 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 year.

In Table II we present the results obtained by the Bulirsch-Stoer method with the integration step error less than $\varepsilon\in[10^{-9}-10^{-8}]$ and also with $\varepsilon\leq 10^{-12}$ and by a symplectic method with an integration step $d_s\leq 10$ days. For these three series of runs, the results obtained were similar (except for probabilities of close encounters with the Sun when they were high). For $d_s=30$ days for most of the objects we found similar results, but we found a larger portion of the objects that reached Earth-crossing orbits with $a<2$ AU for several tens of Myr and even inner-Earth orbits (IEOs, i.e. with $Q<0.983$ AU). These few bodies increased the mean values of P by a factor of more than 10, and the mean probabilities were greater than for $d_s\leq 10$ days.

The results can differ considerably depending on the initial orbits of comets. The values of P for Earth were about $(1-4)\times 10^{-6}$ for Comets 9P, 22P, 28P, and 39P. For Comet 10P they were greater by an order of magnitude than for 9P, though initial orbits of 9P and 10P were close. This is a real difference in dynamics of two comets and is not "luck of the draw" in the integrations. P exceeded 10^{-4} for Comet 2P.

The probability of a collision with Earth (or with Venus and Mars) for one object that orbited for several Myr with $Q<4.2$ AU could be much greater than the total probability for hundreds other objects. Some had typical asteroidal and NEO orbits and reached $Q<3$ AU for several Myr. One object with initial orbit close to that of Comet 88P/Howell after 40 Myr got $Q<3.5$ AU and moved in orbits with $a\approx 2.60-2.61$ AU, $1.7<q<2.2$ AU, $3.1<Q<3.5$ AU, $e\approx 0.2-0.3$, and $i\approx 5-10^\circ$ for more than 500 Myr (this run is not yet finished). If we consider this object, then for series n_2 at $d_s\leq 10^d$ the value of T_d will be greater

Table II. 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. Results from BULSTO code at $10^{-9} \leq \varepsilon \leq 10^{-8}$ (marked as 10^{-9}) and at $\varepsilon \leq 10^{-12}$ (marked as 10^{-12}) and with RMVS3 code (Levison and Duncan, 1994) at integration step d_s . In the case of asteroids, for the last four lines $e_o=0.05$ and $i_o=5^\circ$, and for other runs $e_o=0.15$ and $i_o=10^\circ$.

ε or d_s	N	V	V	E	E	E	M	M	r	T_J	T_d	
		P_r	T	P_r	T	T_c	P_r	T				
n1	10^{-9}	1900	2.42	4.23	4.51	7.94	1.76	6.15	30.0	0.7	119	20
n1	$\leq 10^d$	1200	25.4	13.8	40.1	24.0	0.60	2.48	35.2	3.0	117	25.7
n1	$\leq 10^d$	1199	7.88	9.70	4.76	12.6	2.65	0.76	16.8	2.8	117	10.3
n2	10^{-9}	1000	10.2	27.5	14.7	43.4	2.95	2.58	62.6	3.1	187	8.3
n2	$\leq 10^d$	9000	15.3	25.4	15.0	37.0	2.47	2.75	57.3	3.1	148	19.9
2P	10^{-9}	501	141	345	110	397	3.61	10.5	430	18.	173	249
2P	10^{-12}	100	321	541	146	609	4.2	14.8	634	27.	20	247
2P	10^d	251	860	570	2800	788	0.28	294	825	22.	0.29	614
2P	10^d	250	160	297	94.2	313	3.32	10.0	324	35.	0.29	585
9P	10^{-9}	800	1.34	1.76	3.72	4.11	1.10	0.71	9.73	1.2	96	2.6
9P	10^d	400	1.37	3.46	3.26	7.84	2.40	1.62	23.8	1.1	128	8.0
10P	10^{-9}	2149	28.3	41.3	35.6	71.0	1.99	10.3	169.	1.6	122	107
10P	$\leq 10^d$	450	14.9	30.4	22.4	41.3	1.84	6.42	113.	1.5	85	44.
22P	10^{-9}	1000	1.44	2.98	1.76	4.87	2.77	0.74	11.0	1.6	116	1.5
22P	10^d	250	0.68	2.87	1.39	4.96	3.57	0.60	11.5	1.5	121	0.6
28P	10^{-9}	750	1.7	21.8	1.9	34.7	18.3	0.44	68.9	1.9	443	0.1
28P	10^d	250	3.87	35.3	3.99	59.0	14.8	0.71	109.	2.2	535	3.3
39P	10^{-9}	750	1.06	1.72	1.19	3.03	2.55	0.31	6.82	1.6	94	2.7
39P	10^d	250	2.30	2.68	2.50	4.22	1.69	0.45	7.34	2.2	92	0.5
44P	10^{-9}	500	2.58	15.8	4.01	24.9	6.21	0.75	46.3	2.0	149	8.6
44P	10^d	1000	3.91	5.88	5.84	9.69	1.66	0.77	16.8	2.3	121	2.9
3 : 1	10^{-9}	288	1286	1886	1889	2747	1.45	488	4173	2.7	229	5167
3 : 1	10^{-12}	70	1162	1943	1511	5901	3.91	587	803	4.6	326	8400
3 : 1	10^d	142	27700	8617	2725	9177	3.37	1136	9939	16.	1244	5000
5 : 2	10^{-9}	288	101	173	318	371	1.16	209	1455	0.5	233	1634
5 : 2	10^{-12}	50	130	113	168	230	1.37	46.2	507	1.4	166	512
5 : 2	10^d	144	58.6	86.8	86.7	174	2.01	17.	355	1.7	224	828
3 : 1	10^{-9}	144	200	420	417	759	1.82	195	1423	2.1	157	2620
3 : 1	10^d	144	10051	2382	6164	4198	0.68	435	5954	2.5	235	18047
5 : 2	10^{-9}	144	105	114	146	214	1.47	42	501	1.5	193	996
5 : 2	10^d	144	148	494	173	712	4.12	51	1195	2.3	446	984

by a factor of 4 (i.e., ≈ 80 Kyr) than that in the corresponding line of Table II. The times spent by five specific objects that have large probabilities of collisions with the terrestrial planets while in IEO, Aten, Al2 ($1 < a < 2$ AU, $q < 1.017$ AU), Apollo, and Amor orbits are presented in Table III.

With RMVS3 at $d_s \leq 10$ days for 2P run, the value of P for Earth for one object presented in line 1 of Table III was greater by a factor of 30 than for 250 other objects (see Table II). For series $n1$ with RMVS3, the probability of a collision with Earth for one object with initial orbit close to that of Comet 44P/Reinmuth 2 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 (line 2 in Table III) was not included in Table II with $N=1199$ for $n1$.

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

Comet	d_s or ε	IEOs	Aten	Al2	Apollo	Amor	T_{lt}	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
2P	10^{-8}	0.1	83	249	251	15	352	0.224	0.172	0.065
10P	10^{-8}	10	3.45	0.06	0.06	0.05	13.6	0.655	0.344	0.001
113P	6^d	0	0	56.8	59.8	4.8	67	0.037	0.016	0.0001

For BULSTO at $\varepsilon \in [10^{-9} - 10^{-8}]$ two objects (lines 3-4 in Table III) with the largest probabilities were not included in Table II for 2P at $N=501$, and for 10P at $N=2149$. The probabilities of collisions of these two objects with Earth and Venus (see Table III) were greater than for 9350 other objects combined (0.17 for Earth and 0.15 for Venus). Large values of P for Mars in the $n1$ runs with BULSTO were caused by a single object with a lifetime of 26 Myr. 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 times spent by 22000 JCOs in Earth-crossing orbits with $a < 2$ AU were due to a few tens of objects with high collision probabilities. With BULSTO at $10^{-9} \leq \varepsilon \leq 10^{-8}$ six and nine objects, respectively from 10P and 2P series, 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 9337 other objects to Al2 orbits was smaller. Among the 9352 JCOs considered with BULSTO, only one and two JCOs reached IEO and Aten orbits,

respectively. Only one object in series $n2$ (line 5 in Table III) got A12 orbits during more than 1 Myr.

For the $n1$ series of runs, while moving in JCO orbits, objects had orbital periods $P_a < 20$ yr (Jupiter-family comets) and $20 < P_a < 200$ yr (Halley-type comets) for 32% and 38% of $T_J = 0.12$ Myr, respectively.

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. So 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. The probabilities of collisions of bodies with the Earth per unit of time, i.e. the values of $1/T_c$, were of the same order for JCOs and resonant asteroids. Therefore, mean eccentricities and inclinations of Earth-crossers were similar for former TNOs and resonant asteroids. With BULSTO the mean probability of collisions with the Earth for the 5:2 resonance was 1/3 of that for the 3:1 resonance at $e_o = 0.05$ and this difference was greater by a factor of several at $e_o = 0.15$ (see Table II).

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 simulations, except for Comet 2P/Encke, Comet 96P/Machholz 1 from $n2$ series, and resonant asteroids. In the case of close encounters with the Sun, the values of P_S obtained by BULSTO and RMVS3 and at different ε and d_s were different, but all other results were similar, as probabilities of collisions of objects with the terrestrial planets were usually small after their close encounters with the Sun.

The results presented in the paper were obtained for direct modelling of collisions with the Sun, but usually they are practically the same if we consider that objects disappear when perihelion distance q becomes less than the radius r_S of the Sun or even several such radii (i.e., we checked $q < k_S r_S$, where k_S equals 0, 1, or another value). The only noticeable difference was for Comet 96P from $n2$ series and a smaller one for Comet 2P. For $n2$ series, several runs, in which there was an appreciable difference in time spent in orbits with $Q < 4.7$ AU for $k_S = 0$ and for $k_S = 1$ (the times can differ by a factor of several), were not included in Tables 2 and 4. This difference was due to Comet 96P. Eccentricity and inclination of this comet are large, and they become even larger after close encounters with the Sun, so usually even for these runs the collision probabilities of objects with the terrestrial planets were not differed much (by more than 15%) at $k_S = 0$ and $k_S = 1$. There were three runs, for each of which at $k_S = 0$ a body in orbit close to that of Comet 96P was responsible for 70-75% of collision probabilities with the Earth, and for $k_S = 1$ a lifetime of such body was much less than for $k_S = 0$. Nevertheless, for all ($\sim 10^4$) objects from $n2$ series, at $k_S = 0$ the

probabilities of collisions with the terrestrial planets were close to those at $k_S=1$, even if we consider the above runs. The difference for times spent in Earth-crossing orbits is greater than that for the probabilities and is about 20%. For all runs at 2P series, the difference in time spent in orbits with $Q < 4.7$ AU for $k_S=0$ and for $k_S=1$ was less than 4%. In 2P series of runs (and also for the 3:1 resonance with Jupiter), at $k_S=0$ we sometimes got orbits with $i > 90^\circ$, but practically there were no such orbits at $k_S \geq 1$ (Ipatov and Mather, 2003a-b). For Comet 96P we found one object which also got $i > 90^\circ$ for 3 Myr. Inclinations of other orbits initially close to the orbit of this comet did not exceed 90° .

3. Trans-Neptunian Objects in Near-Earth Object Orbits

Using the results of migration of TNOs obtained by Duncan et al. (1995), considering the total of 5×10^9 1-km TNOs with $30 < a < 50$ AU (Jewit and Fernandez, 2001), and assuming that the mean time for a body to move in a Jupiter-crossing orbit is about 0.12 Myr, Ipatov (2001) found that about $N_{Jo}=10^4$ 1-km former TNOs are now Jupiter-crossers, and 3000 are Jupiter-family comets. Using the total times spent by N simulated JCOs in various orbits, we obtained the following numbers of 1-km former TNOs now moving in several types of orbits:

Table IV. Estimates of the number 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
8000	RMVS3	n2	0	0	500	2800	800
8800	BULSTO	without 2P	95	30	230	2600	1560
9352	BULSTO	all	90	770	3700	6500	1700

For example, the number of IEOs $N_{IEOs} = N_{Jo} t_{IEO} / (N_J t_J)$, where t_{IEO} is the total time during which N_J former JCOs moved in IEO orbits, and $N_J t_J$ is the total time during which N_J JCOs moved in Jupiter-crossing orbits. The number of former TNOs in Apollo and Amor orbits can be estimated on the basis of $n1$ and $n2$ runs. The number of NEOs with diameter $d \geq 1$ km is estimated to be about 1500 (Rabinowitz et al., 1994) or 1000 (Morbidelli et al., 2002). Half of NEOs are Earth-crossers. Even if the number of Apollo objects is smaller by a factor of several than that based on $n1$ and $n2$ runs, it is comparable to the real number (500-750) 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 portions of objects in Aten and Al2 orbits are much greater in our 2P runs than in other runs. Our estimates of these portions are very approximate. The above estimates of the portion of former TNOs in NEO orbits are relatively large (up to tens of percents), but it is also possible that the number of TNOs migrating inside solar system could be smaller by a factor of several than it was earlier considered.

Comets are estimated to be active for $T_{act} \sim 10^3 - 10^4$ yr. T_{act} is smaller for closer encounters with the Sun (Weissman et al., 2002), so for Comet 2P it is smaller than for other Jupiter-family comets. Some former comets can move for tens or even hundreds of Myr in NEO and asteroidal 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. This time corresponds to $\geq 40-400$ extinct comets of this type. Note that the diameter of Comet 2P is about 5-8 km (Fernandez et al., 2000; Lowry et al., 2003), so the number of 1-km Earth-crossing extinct comets can exceed 1000. The rate of a cometary object decoupling from the Jupiter vicinity and transferring to an NEO-like orbit can be increased by a factor of several due to nongravitational effects (Asher et al., 2001; Fernandez and Gallardo, 2002).

Based on the collision probability $P = 4 \times 10^{-6}$ we find that 1-km former TNOs collide with the Earth once in 3 Myr. This value of P is smaller than that for our $n1$ and $n2$ runs and does not include the ‘champions’ in collision probability. Using $P = 4 \times 10^{-6}$ and assuming that 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), we concluded that the total mass of water delivered from the feeding zone of the giant planets to the Earth could be about the mass of Earth oceans.

Our runs showed that if one observes former comets in NEO orbits, then most of them could have already moved in such orbits for millions of 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 caused 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 and dust.

Chen and Jewitt (1994) noted that while cometary splitting is sometimes associated with the close passage of a comet by the Sun, it is also known to occur at heliocentric distances of up to 9 AU. At 10m, the near-Earth flux is more than two orders of magnitude greater than

power law extrapolated from larger sizes. Levison et al. (2002) obtained that majority of comets evolved inward from the Oort cloud must physically disrupt, but Jupiter-family comets do not appear to disrupt at the same rate. Bailey (2002) consider that some long-period comets become inert and hence evolve into low-albedo objects resembling asteroids, and another alternative is that Oort cloud comets may easily break up into unobserved smaller bodies or dust.

From measured albedos, Fernandez et al. (2001) concluded that the fraction of extinct comets among NEOs and unusual asteroids is significant ($\geq 9\%$). Rickman et al. (2001) and Jewitt and Fernandez (2001) considered that dark spectral classes that might include the ex-comets are severely under-represented and comets played an important and perhaps even dominant role among all km-size Earth impactors.

We conclude that the trans-Neptunian belt can provide a significant portion of the Earth-crossing objects, or the number of TNOs migrating inside solar system could be smaller than it was earlier considered, or most of 1-km former TNOs that had got NEO orbits disintegrated into mini-comets and dust during a smaller part of their dynamical lifetimes if these lifetimes are not small.

This work was supported by NRC (0158730), NASA (NAG5-10776), INTAS (00-240), and RFBR (01-02-17540). We thank the anonymous referee for helpful remarks.

References

- Asher, D. J., M. E. Bailey, and D. I. Steel, The Role of Non-Gravitational Forces in Decoupling Orbits from Jupiter, in *Collisional Processes in the Solar System*, edited by M. Ya. Marov and H. Rickman, ASSL, 261: 121-130, 2001.
- Bailey, M. E., Where Have All the Comets Gone? *Science*, 296: 2151-2153, 2002.
- Binzel, R. P., D. F. Lupishko, M. Di Martino, et al., Physical properties of near-Earth objects, in *Asteroids III*, edited by W. F. Bottke Jr. et al., Univ. of Arizona, Tucson, 255-271, 2002.
- Bottke, W. F., A. Morbidelli, R. Jedicke, et al., Debaised Orbital and Absolute Magnitude Distribution of the Near-Earth Objects, *Icarus*, 156: 399-433, 2002.
- Chen, J. and D. Jewitt, On the Rate at Which Comets Split, *Icarus*, 108: 265-271, 1994.
- Duncan, M. J., and H. F. Levison, A Disk of Scattered Icy Objects and the Origin of Jupiter-Family Comets, *Science*, 276: 1670-1672, 1997.
- Duncan, M. J., H. F. Levison, and S. M. Budd, The Dynamical Structure of the Kuiper Belt, *Astron. J.*, 110: 3073-3081, 1995.
- Fernandez, J. A. and T. Gallardo, Are There Many Inactive Jupiter-Family Comets Among the Near-Earth Asteroid Population? *Icarus*, 159: 358-368, 2002.
- Fernandez, Y. R., C. M. Lisse, K. H. Ulrich, et. al, Physical Properties of the Nucleus of Comet 2P/Encke, *Icarus*, 147: 145-160, 2000.
- Fernandez, Y. R., D. C. Jewitt, and S. S. Sheppard, Low Albedos Among Extinct Comet Candidates, *Astroph. J.*, 553: L197-L200, 2001.

- Ipatov, S. I., Migration of Bodies in the Accretion of Planets, *Solar System Research*, 27: 65-79, 1993.
- Ipatov, S. I., Migration of Small Bodies to the Earth, *Solar System Research*, 29: 261-286, 1995.
- Ipatov, S. I., Migration of Trans-Neptunian Objects to the Earth, *Celest. Mech. Dyn. Astron.*, 73: 107-116, 1999.
- Ipatov, S. I., Comet Hazard to the Earth, *Advances in Space Research*, Elsevier, 28: 1107-1116, 2001.
- Ipatov, S. I., Migration of Matter from the Edgeworth–Kuiper and Main Asteroid Belts to the Earth, in *Dust in the Solar System and Other Planetary Systems*, edited by S. F. Green, et al., COSPAR Colloquia Series, Pergamon, 15: 233-236 (<http://arXiv.org/format/astro-ph/0205250>), 2002a.
- Ipatov, S. I., Formation and Migration of Trans-Neptunian Objects and Asteroids, in *Asteroids, Comets, Meteors, 2002*, 371-374 (<http://arXiv.org/format/astro-ph/0211618>), 2002b.
- Ipatov, S. I. and G. J. Hahn, Orbital Evolution of the P/1996 R2 and P/1996 N2 objects, *Solar System Research*, 33: 487-500, 1999.
- Ipatov, S. I. and J. C. Mather, Comet and Asteroid Hazard to the Terrestrial Planets, *Advances in Space Research*, in press, 2003a.
- Ipatov, S. I. and J. C. Mather, Migration of Jupiter-Family Comets and Resonant Asteroids to Near-Earth Space, In *Proc. of Intern. Conference "New Trends in Astrodynamics and Applications"*, CD-ROM (<http://arXiv.org/format/astro-ph/0303219>), 2003b.
- Jewitt, D., and Y. Fernandez, Physical Properties of Planet-Crossing Objects, in *Collisional Processes in the Solar System*, edited by M. Ya. Marov and H. Rickman, ASSL, 261: 143-161, 2001.
- Kuchner, M. J., M. E. Brown, and M. Holman, Long-Term Dynamics and the Orbital Inclinations of the Classical Kuiper Belt Objects, *Astron. J.*, 124: 1221-1230, 2002.
- Levison H. F. and M. J. Duncan, The Long-Term Dynamical Behavior of Short-Period Comets, *Icarus*, 108: 18-36, 1994.
- Levison, H. F. and M. J. Duncan, From the Kuiper Belt to Jupiter-Family Comets: The Spatial Distribution of Ecliptic Comets, *Icarus*, 127: 13-23, 1997.
- Levison, H. F., A. Morbidelli, L. Dones, et al., The Mass Disruption of Oort Cloud Comets, *Science*, 296: 2212-2215, 2002.
- Lowry, S. C., P. R. Weissman, M. V. Sykes, and W. T. Reach, Observations of Periodic Comet 2P/Encke: Physical Properties of the Nucleus and First Visual-Wavelength Detection of Its Dust Trail, *34th Annual Lunar and Planetary Science Conference*, abstract no.2056, 2003.
- Morbidelli A., W. F. Bottke Jr., Ch. Froeschlé, and P. Michel, Origin and Evolution of Near-Earth Objects, in *Asteroids III*, edited by W. F. Bottke Jr. et al., Univ. of Arizona, Tucson, 409-422, 2002.
- Rabinowitz, D., E. Bowell, E. Shoemaker, and K. Muinonen, The Population of Earth–Crossing Asteroids, in *Hazards Due to Comets and Asteroids*, ed. by T. Gehrels, The University of Arizona Press, Tucson & London, 285-312, 1994.
- Rickman, H., J. A. Fernandez, G. Tancredi, and J. Licandro, The Cometary Contribution to Planetary Impact Craters, in *Collisional Processes in the Solar System*, edited by M. Ya. Marov and H. Rickman, ASSL, 261: 131-142, 2001.
- Weissman, P.R., W. F. Bottke Jr., and H. F. Levison, Evolution of Comets into Asteroids, in *Asteroids III*, edited by W. F. Bottke Jr. et al., Univ. of Arizona, Tucson, 669-686, 2002.