Migration of Small Bodies and Dust to Near-Earth Space

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Abstract

The orbital evolution of Jupiter-family comets (JFCs), resonant asteroids, and asteroidal, trans-Neptunian, and cometary dust particles under the gravitational influence of planets was integrated. For dust particles we also considered radiation pressure, Poynting-Robertson drag, and solar wind drag. The probability of a collision of one former JFC with a terrestrial planet can be greater than analogous total probability for thousands other JFCs. If those former JFCs that got near-Earth object (NEO) orbits for millions of years didn’t disintegrate during this time, there could be many extinct comets among NEOs. The maximum probability of a collision of an asteroidal or cometary dust particle with the Earth during its lifetime was for diameter $d \sim 100$ microns. At $d < 10$ micron, the collision probability of a trans-Neptunian particle with the Earth during a lifetime of the particle was less than that for an asteroidal particle by only a factor of several.

Key words: migration, small bodies, interplanetary dust, collisions with the Earth

1 INTRODUCTION

Duncan et al. (1995) and Kuchner et al. (2002) investigated the migration of TNOs to Neptune’s orbit, and Levison and Duncan (1997) studied the migra-

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tion from Neptune’s orbit to Jupiter’s orbit. Ipatov (2002), Ipatov and Mather (2003, 2004a-b) integrated the orbital evolution of Jupiter-family comets (JFCs) under the gravitational influence of planets, paying the main attention to their migration to the near-Earth space and collisional probabilities with the terrestrial planets. In section 2 of the present paper we summarize our investigations of this problem.

Liou et al. (1996), Liou and Zook (1999), Gorkavyi et al. (2000), Ozernoy (2001), Moro-Martin and Malhotra (2002, 2003) considered the migration of dust particles from the trans-Neptunian belt, Liou et al. (1999) from Halley-type comets, Liou et al. (1995) from Comet Encke, and Reach et al. (1997), Kortenkamp and Dermott (1998), and Grogan et al. (2001) from asteroid families and short-period comets. Further references are presented in the above papers and by Dermott et al. (2002).

Ozernoy (2001) considered 1 \( \mu \text{m} \) and 5 \( \mu \text{m} \) particles while constructing the brightness of a disk of asteroidal, cometary, and trans-Neptunian (kuiperoidal) dust particles which fit the COBE/DIRBE data and concluded that the trans-Neptunian dust contributes as much as 1/3 of the total number density near the Earth. Liou et al. (1995) showed that the observed shape of the zodiacal cloud can be accounted for by a combination of about 1/4 to 1/3 asteroidal dust and about 3/4 to 2/3 cometary dust. The mass distribution of dust particles falling to the Earth peaks at about 200 \( \mu \text{m} \) in diameter (Grün et al., 1985).

In the present paper we consider a wider range of masses (including particles up to 1000 \( \mu \text{m} \)) of asteroidal and cometary dust particles than the aforementioned authors and Ipatov et al. (2004a). We pay more attention to the migration of trans-Neptunian dust particles to the near-Earth space than Liou and Zook (1999) and Moro-Martin and Malhotra (2002, 2003).

2 ORBITAL EVOLUTION OF JUPITER-FAMILY COMETS

Ipatov (2002), and Ipatov and Mather (2003, 2004a-b) investigated migration of JFCs to the near-Earth space. Note that the paper by Ipatov and Mather (2004a) was based on more recent runs than other above papers. References on papers by other scientists can be found in our previous papers. We integrated the orbital evolution of \( \sim 30,000 \) JFCs and 1300 resonant main-belt asteroids under the gravitational influence of planets during dynamical lifetimes of the small objects. We omitted the influence of Mercury (except for Comet 2P/Encke) and Pluto and used the Bulirsch-Stoer and symplectic methods (BULSTO and RMVS3 codes) from the integration package of Levison and Duncan (1994). In two series of runs, initial orbits were close to those of sev-
eral (10 and 20) real JFCs, and in each of other series they were close to the orbit of a single real JFC (2P, 9P, 10P, 22P, 28P, 39P, or 44P). In our runs, planets were considered as material points, so literal collisions did not occur. However, using the orbital elements sampled with a 500 yr step, we calculated the mean probability $P$ of collisions (see our previous papers for details).

In our runs, some former JFCs moved in typical near-Earth object (NEO) orbits, and a few of them got orbits with aphelion distance $Q<3$ AU for millions of years. The main portion of the probability of collisions of former JFCs with the terrestrial planets was due to a small ($\sim 0.1\%$) portion of objects that moved during several Myrs in orbits with $Q<4.2$ AU. The mean collision probabilities of JFCs with the terrestrial planets can differ for different comets by more than two orders of magnitude. The ratio of the mean probability of a JFC with semi-major axis $a>1$ AU with a planet to the mass of the planet was greater for Mars by a factor of several than that for Earth and Venus. Four considered former JFCs even got inner-Earth orbits (with $Q<0.983$ AU) or Aten orbits ($a<1$ AU, $Q>0.983$ AU) for Myrs. One former JFC got Aten orbits during $>3$ Myr and inner-Earth orbits for $\sim 10$ Myr, but probabilities of its collisions with Earth and Venus were greater than those for $10^4$ other former JFCs. The number of JFCs considered was greater than that considered by Bottke et al. (2002) by an order of magnitude, so that is why these scientists didn’t obtain orbits with $a<2$ AU. Note that Ipatov (1995) obtained migration of JFCs into inner-Earth and Aten orbits using the method of spheres.

Former JFCs can get typical asteroidal orbits, but even less often than NEO orbits. After 40 Myr one considered object (with initial orbit close to that of Comet 88P) got $Q<3.5$ AU, and it moved in orbits with $a=2.60-2.61$ AU, perihelion distance $1.7<q<2.2$ AU, $3.1<Q<3.5$ AU, eccentricity $e=0.2-0.3$, and inclination $i=5-10^\circ$ for 650 Myr. Another object (with initial orbit close to that of Comet 94P) moved in orbits with $a=1.95-2.1$ AU, $q>1.4$ AU, $Q<2.6$ AU, $e=0.2-0.3$, and $i=9-33^\circ$ for 8 Myr (and it had $Q<3$ AU for 100 Myr). In our opinion, it can be possible that Comet 133P (Elst-Pizarro) moving in a typical asteroidal orbit was earlier a JFC and it circulated its orbit also due to non-gravitational forces.

The results obtained by the Bulirsh-Stoer method (BULSTO code) with the integration step error less than $\varepsilon$, where $10^{-9} \leq \varepsilon \leq 10^{-8}$ and $\varepsilon \leq 10^{-12}$, and by a symplectic method (RMVS3 code) at integration step $d_s \leq 10$ days were usually similar. The difference at these three series was about the difference at small variation of $\varepsilon$ or $d_s$. In the case of close encounters with the Sun (i.e., for Comet 2P, Comet 96P, and the 3:1 resonance with Jupiter), the values of collision probability $P_S$ with the Sun obtained by BULSTO and RMVS3 and at different $\varepsilon$ or $d_s$ were different, but all other results were usually similar, as most bodies didn’t move long after close encounters.
In comparison with Ipatov and Mather (2003, 2004a-b), we made additionally a series of runs for Comet 2P at $d_s \leq 3$ days. Earlier runs were made for $d_s=10$ and $d_s=30$ days. The obtained values of $P_S$ were similar for different $d_s$; they were 0.98, 0.99, 0.99, 0.96, and 0.99 for $d_s$ equal to 0.1, 0.3, 1, 3, and 10 days, respectively. Note that for BULSTO $P_S=0.88$ at $\varepsilon=10^{-13}$ and $\varepsilon=10^{-12}$ ($P_S$ was even smaller for larger $\varepsilon$), i.e., $P_S$ was smaller than for RMVS3. In all runs the minimum values of times elapsed up to a collision of an object with the Sun were about 40-60 Kyr, but the maximum values of times varied considerably in different runs (from 1 Myr to 400 Myr). At $d_s=3$ days, a lifetime of one object was 400 Myr, and it moved on Inner-Earth, Aten, Apollo, and Amor orbits during 2.5, 2.2, 44.9, and 80.8 Myr, respectively. At $t=6.5$ Myr this object got an orbit with $e=0.03$ and $a=1.3$ AU, and then until 370 Myr the eccentricity was less than 0.4 and often was even less than 0.2. The probability of a collision of this object with the Earth was about 1, and it was greater than that for all other 99 objects in that run by two orders of magnitude.

Ipatov and Mather (2004a) showed that during the accumulation of the giant planets the total mass of icy bodies delivered to the Earth could be about the mass of water in Earth’s oceans. Many Earth-crossing objects can move in highly eccentric ($e>0.6$) orbits and, probably, most of 1-km objects in such orbits have not yet been discovered. If one observes former JFCs in NEO orbits, then most of them could have already moved in such orbits for millions (or at least hundreds of thousands) 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 typically dark surface material, thus brightening their low albedo and assuming the aspect typical of an asteroid (for most observed NEOs, the albedo is greater than that for comets). On the contrary, Napier et al. (2004) suggested that the surfaces of inner comets became extremely dark and most of such comets became invisible. If many of extinct comets disintegrated, then there can be many mini-comets in the near-Earth space, and the Tunguska comet could be one of them. At least one of the below conclusions follow from our runs: 1) the portion of 1-km former trans-Neptunian objects (TNOs) among NEOs can exceed several tens of percent, 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.

3 Models for migration of dust particles

Using the Bulirsh–Stoer method of integration, we investigated the migration of dust particles under the influence of planetary gravity (excluding Pluto for

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asteroidal and cometary particles), radiation pressure, Poynting–Robertson
drag, and solar wind drag. The initial positions and velocities of the asteroidal
particles were the same as those of the first $N$ numbered main-belt asteroids
(JDT 2452500.5), i.e., dust particles are assumed to leave the asteroids with
zero relative velocity. For the runs marked with * in Table 1, we considered
next $N$ asteroids. The initial positions and velocities of the trans-Neptunian
particles were the same as those of the first TNOs (JDT 2452600.5), and our
initial data were different from those in previous papers. In each run we took
$N \leq 250$ particles, because for $N \geq 500$ the computer time per calculation for
one particle was several times greater than for $N=250$. In the main series of
runs, the initial positions and velocities of the cometary particles were the
same as those of Comet 2P Encke ($a \approx 2.2$ AU, $e \approx 0.85$, $i \approx 12^\circ$). We consid-
ered Encke particles starting near perihelion (runs denoted as $\Delta t_o=0$), near
aphelion ($\Delta t_o=0.5$), and when the comet had orbited for $P_a/4$ after perihe-
lion passage, where $P_a$ is the period of the comet (such runs are denoted as
$\Delta t_o=0.25$). Variations in time $\tau$ when perihelion was passed varied with
a step 0.1 day for series with $N=101$ and with a step 1 day for series with
$N=150$, so for $N=101$ initial positions of Encke particles were more compact.
We also studied migration of dust particles started from Comet 10P/Tempel
2 ($a \approx 3.1$ AU, $e \approx 0.526$, $i \approx 12^\circ$). The initial value of time $\tau$ when perihelion
was passed was varied for different particles with a step $d\tau=1$ day (from 645
to 894 days) near the actual value of $\tau$ for Comet 10P at JDT 2452200.5.

For asteroidal and Encke particles, values of the ratio between the radiation
pressure force and the gravitational force $\beta$ varied between 0.0001-0.0004 and
0.4. Burns et al. (1979) obtained $\beta=0.573Q_{pr}/(\rho s)$, where $\rho$ is the particle’s
density in grams per cubic centimeter, $s$ is its radius in micrometers, and $Q_{pr}$
is the radiation pressure coefficient ($Q_{pr}$ is close to unity for particles larger
than 1 $\mu$m). For silicates, the $\beta$ values 0.004, 0.01, 0.05, 0.1, and 0.4 correspond
to particle diameters of about 120, 47, 9.4, 4.7, and 1 microns, respectively.
Silicate particles with $\beta$ values of 0.01 and 0.05 have masses of $10^{-7}$ g and $10^{-9}$ g. For water ice, our $\beta$ values correspond to particle diameters of 290, 120, 23,
11.7, and 2.9 $\mu$m. As did Liou et al. (1999) and Moro-Martin and Malhotra
(2002), we assume the ratio of solar wind drag to Poynting–Robertson drag
to be 0.35. The relative error per integration step was taken to be less than
$10^{-8}$ for asteroidal and trans-Neptunian particles and to be less than $10^{-9}$ or
$10^{-8}$ for cometary particles. The simulations continued until all of the particles
either collided with the Sun or reached 2000 AU from the Sun.
4 Probabilities of collisions of dust particles with the terrestrial planets

Orbital elements were stored with a step of \( d_t \) of \( \leq 20 \) yr for asteroidal and cometary particles (\( d_t = 10 \) yr for asteroidal particles at \( \beta \) equal to 0.1 and 0.25, and \( d_t = 20 \) yr for other runs) and of 100 yr for trans-Neptunian particles. In our runs, planets were considered as material points, but using orbital elements obtained with a step \( d_t \), similar to (Ipatov and Mather, 2004a) we calculated the mean probability \( P = P_s/N \) (\( P_s \) is the probability for all \( N \) considered particles) of a collision of a particle with a planet during the lifetime of the particle. We define \( T = T_s/N \) as the mean time during which the perihelion distance \( q \) of a particle was less than the semi-major axis of the planet and \( T_J \) as the mean time spent in Jupiter-crossing orbits. Below, \( P_{\text{Sun}} \) is the ratio of the number of particles that collided with the Sun to the total number of particles. \( T_s^{\text{min}} \) and \( T_s^{\text{max}} \) are the minimum and maximum values of the time until collision of a particle with the Sun, and \( T_{2000}^{\text{min}} \) and \( T_{2000}^{\text{max}} \) are the minimum and maximum values of time when the distance between a particle and the Sun reached 2,000 AU. The values of \( P_{\text{Sun}}, P_t = 10^6 P, T_s, T_J, T_s^{\text{min}}, T_s^{\text{max}}, T_{2000}^{\text{min}}, \) and \( T_{2000}^{\text{max}} \) (times are in Kyr) are shown in Tables 1-4 for several runs with asteroidal, Encke, Tempel 2, and trans-Neptunian particles at different \( \beta \).

All asteroidal particles collided with the Sun at \( 0.004 \leq \beta \leq 0.01 \), and \( P_S \geq 0.96 \) at \( 0.0004 \leq \beta \leq 0.1 \). \( P_S \) is smaller for greater \( \beta \) at \( \beta \geq 0.1 \). The minimum time \( T_s^{\text{min}} \) needed to reach the Sun is smaller for smaller particles (i.e., for larger \( \beta \)). The ratio \( T_s^{\text{max}}/T_s^{\text{min}} \) is much greater for \( \beta \geq 0.2 \) than for \( \beta \leq 0.1 \). For \( \beta = 0.05 \), 498 of 500 asteroidal particles collided with the Sun in less than 0.089 Myr, but two particles (with initial orbits close to those of the asteroids 361 and 499), which reached 2000 AU, lived for 0.21 Myr and 19.06 Myr, respectively. The latter object’s perihelion was near Saturn’s orbit for a long time. At \( \beta = 0.05 \) the first 250 asteroidal particles did not migrate outside Jupiter’s orbit, so \( T_J = 0 \) in Table 1. In most runs all Encke particles collided with the Sun, but in a few runs (e.g., at \( N = 101 \) and \( \Delta t = 0 \) for \( \beta \) equal to 0.4, 0.2, and 0.1) all particles were ejected into hyperbolic orbits.

The probability of collisions of asteroidal dust particles with the Earth was maximum (\( \sim 0.001-0.02 \)) at \( 0.002 \leq \beta \leq 0.01 \), i.e., at diameters of particles \( d \sim 100 \) \( \mu \)m. These probabilities of collisions are in accordance with cratering records in lunar material and on the panels of the Long Duration Exposure Facility, which showed that the mass distribution of dust particles encountering the Earth peaks at \( d = 200 \) \( \mu \)m (Kortenkamp and Dermott, 1998). For asteroidal particles with \( \beta > 0.01 \), collision probabilities with the terrestrial planets were smaller for larger \( \beta \). Values of \( P \) for Venus didn’t differ much from those for Earth. At \( \beta \geq 0.01 \) the values for Mars were smaller by an order of magnitude.
### Table 1
Values of $T$, $T_j$, $T_S^{\min}$, $T_S^{\max}$, $T_{\min}^{\text{Sun}}$, $P_r$, and $P_{\text{Sun}}$ obtained for asteroidal dust particles at several values of $\beta$ (Venus=V, Earth=E, Mars=M)

| $\beta$ | V | V | E | E | M | M |
|---------|---|---|---|---|---|---|
| 0.0004  | 100 | 0.960 | 338 | 13.2 | 375 | 61.4 | 338 | 225 | 3.68 | 1485 | 7950 | 336 | 2747 |
| 0.001   | 100 | 0.980 | 105 | 9.1  | 737 | 27.8 | 939 | 211 | 1.20 | 407  | 3111 | 626 | 1230 |
| 0.001*  | 150 | 0.993 | 228 | 5.2  | 342 | 20.9 | 287 | 215 | 0.8  | 509  | 4472 | 884 | 884  |
| 0.002   | 100 | 1.000 | 2002 | 48.0 | 1934 | 104 | 537 | 298 | 0    | 592  | 1756 | –   | –    |
| 0.002*  | 150 | 0.987 | 9679 | 35.3 | 10641| 80.1 | 508 | 274 | 2    | 666  | 2064 | 449 | 928  |
| 0.004   | 100 | 1.000 | 12783| 40.5 | 11350| 90. | 1204| 220 | 0    | 348  | 932  | –   | –    |
| 0.004*  | 150 | 1.000 | 2704 | 38.4 | 2267 | 81.9| 342 | 208 | 0    | 338  | 1215 | –   | –    |
| 0.005   | 100 | 1.000 | 12207| 33.2 | 16700| 76.6| 1020| 184 | 0    | 248  | 1013 | –   | –    |
| 0.01    | 250 | 1.000 | 1534 | 19.2 | 1746 | 44.2| 127 | 100 | 0    | 142  | 422  | –   | –    |
| 0.01*   | 250 | 0.996 | 1168 | 15.2 | 1269 | 33.9| 134 | 84.8| 0.02 | 50   | 422  | 211 | 211  |
| 0.02    | 250 | 0.996 | 403  | 9.7  | 387  | 20.5| 52.6| 48.2| 0.2  | 65.4 | 178  | 650 | 650  |
| 0.02*   | 250 | 0.992 | 490  | 9.2  | 728  | 19.3| 73.9| 45.7| 0.8  | 71.8 | 400  | 112 | 303  |
| 0.05    | 250 | 1.000 | 195  | 4.0  | 190  | 8.1 | 36.7| 20  | 0    | 30   | 89   | –   | –    |
| 0.1     | 250 | 0.988 | 141  | 2.4  | 132  | 4.8 | 16.4| 12  | 2.21 | 16   | 44   | 138 | 793  |
| 0.1*    | 250 | 0.992 | 366  | 2.4  | 279  | 4.8 | 20.9| 12  | 0.92 | 7.2  | 43   | 9   | 534  |
| 0.2     | 250 | 0.852 | 285  | 1.6  | 242  | 3.4 | 21.7| 3.7 | 15.6 | 8.0  | 734  | 9.0 | 815  |
| 0.2*    | 250 | 0.796 | 642  | 1.5  | 522  | 3.1 | 30.8| 7.3 | 24.7 | 7.2  | 416  | 2.0 | 1375 |
| 0.25    | 250 | 0.618 | 79.2 | 1.4  | 63.8 | 2.9 | 5.60| 5.9 | 31.7 | 5.9  | 385  | 1.6 | 567  |
| 0.4     | 250 | 0.316 | 12.4 | 1.5  | 8.0  | 2.5 | 0.72| 8.8 | 32.3 | 4.3  | 172  | 1.7 | 288  |

than those for Earth, but at $\beta \sim 0.0004-0.001$ they were about the same.

For Encke particles colliding with Venus, Earth, and Mars, the values of $P$ at $0.0004 \leq \beta \leq 0.02$ were about $0.0002-0.0006$, $0.0001-0.0002$, and $(4-14) \cdot 10^{-6}$, respectively. They were much smaller at $\beta \geq 0.05$. For these planets at all $\beta$, the values of $P$ for Encke particles were smaller than those for asteroidal particles. Collision probabilities of Encke particles with Earth were greater by a factor of 10-20 than those with Mars and greater for particles starting at perihelion than aphelion (exclusive for $\beta = 0.4$). For the same value of $\beta$, the probability of Encke dust particle colliding with a terrestrial planet was less than for an asteroidal dust particle by a factor of several, mainly due to the greater eccentricities and inclinations of Encke particles (see Table 5).
| \( \beta \) | \( \Delta t_o \) | \( N \) | \( P_{Sun} \) | \( P_r \) | \( T \) | \( P_r \) | \( T \) | \( P_r \) | \( T \) | \( P_r \) | \( T \) | \( T_S^{\text{min}} \) | \( T_S^{\text{max}} \) | \( T_{P_{2000}}^{\text{min}} \) | \( T_{P_{2000}}^{\text{max}} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0001 | 0 | 101 | 100 | 251 | 149 | 123 | 156 | 7.0 | 156 | 0 | 85.1 | 5854 | – | – |
| 0.0004 | 0 | 101 | 100 | 319 | 110 | 125 | 110 | 9.9 | 110 | 0 | 83.4 | 679 | – | – |
| 0.001 | 0 | 101 | 100 | 257 | 94.0 | 111 | 94.6 | 9.6 | 94.6 | 0 | 78.8 | 648 | – | – |
| 0.002 | 0 | 101 | 100 | 470 | 91.1 | 200 | 94.6 | 12.0 | 95.5 | 0 | 72.3 | 551 | – | – |
| 0.002 | 0 | 150 | 100 | 632 | 92.9 | 208 | 93.6 | 13.9 | 93.5 | 0 | 75.2 | 370 | – | – |
| 0.002 | 0.25 | 101 | 100 | 408 | 84.3 | 156 | 84.3 | 12.9 | 84.3 | 0 | 80.0 | 208 | – | – |
| 0.002 | 0.5 | 101 | 100 | 432 | 86.3 | 189 | 86.3 | 13.2 | 86.3 | 0 | 80.9 | 240 | – | – |
| 0.004 | 0 | 101 | 100 | 370 | 62.3 | 148 | 62.9 | 8.9 | 63.0 | 0 | 43.7 | 231 | – | – |
| 0.004 | 0 | 150 | 100 | 303 | 65.8 | 139 | 66.0 | 9.0 | 66.0 | 0 | 43.7 | 164 | – | – |
| 0.004 | 0.25 | 101 | 100 | 430 | 55.0 | 160 | 55.0 | 9.3 | 55.0 | 0 | 47.3 | 109 | – | – |
| 0.004 | 0.5 | 101 | 100 | 235 | 56.4 | 140 | 56.3 | 8.1 | 56.4 | 0 | 45.9 | 108 | – | – |
| 0.01 | 0 | 101 | 100 | 191 | 24.9 | 105 | 25.1 | 5.4 | 25.1 | 0 | 17.1 | 67.4 | – | – |
| 0.01 | 0 | 150 | 100 | 386 | 28.1 | 163 | 28.5 | 6.4 | 28.5 | 0 | 18.1 | 79.7 | – | – |
| 0.01 | 0.25 | 101 | 100 | 238 | 24.2 | 86 | 24.2 | 4.2 | 24.2 | 0 | 20.0 | 59.2 | – | – |
| 0.01 | 0.5 | 251 | 100 | 495 | 9.1 | 226 | 9.1 | 15.2 | 9.1 | 0 | 19.1 | 48.9 | – | – |
| 0.02 | 0 | 101 | 0.93 | 413 | 20.8 | 98.3 | 24.1 | 3.7 | 27.1 | 22.4 | 4.5 | 1019 | 2.9 | 473 |
| 0.02 | 0 | 150 | 100 | 89.6 | 13.5 | 37.5 | 13.6 | 1.9 | 13.6 | 0.5 | 8.0 | 426 | – | – |
| 0.05 | 0 | 101 | 0.96 | 12.0 | 7.7 | 5.9 | 9.3 | 0.6 | 11.6 | 23.0 | 2.1 | 527 | 9.4 | 1070 |
| 0.05 | 0 | 150 | 0.99 | 142 | 7.1 | 67 | 7.8 | 2.9 | 8.2 | 0.8 | 1.8 | 85.6 | 3.0 | 3.0 |
| 0.05 | 0.25 | 101 | 100 | 37.1 | 4.6 | 20.5 | 4.6 | 1.6 | 4.6 | 0 | 4.4 | 4.7 | – | – |
| 0.05 | 0.5 | 101 | 100 | 96.2 | 6.3 | 37.2 | 6.4 | 2.3 | 6.4 | 0 | 5.0 | 20.6 | – | – |
| 0.1 | 0 | 150 | 0.91 | 23.1 | 5.2 | 9.1 | 6.1 | 0.66 | 7.3 | 3.6 | 1.1 | 112 | 1.1 | 229 |
| 0.1 | 0.25 | 101 | 100 | 22.4 | 2.8 | 8.6 | 2.8 | 0.6 | 2.8 | 0 | 2.4 | 3.3 | – | – |
| 0.1 | 0.5 | 101 | 100 | 13.0 | 2.7 | 6.6 | 2.7 | 0.47 | 2.7 | 0 | 2.5 | 2.7 | – | – |
| 0.2 | 0 | 150 | 0.60 | 7.4 | 3.3 | 3.5 | 3.6 | 0.27 | 3.8 | 3.0 | 1.3 | 119 | 0.4 | 3.6 |
| 0.2 | 0.25 | 101 | 100 | 20.3 | 1.9 | 4.5 | 1.9 | 0.39 | 1.9 | 0 | 1.8 | 2.2 | – | – |
| 0.2 | 0.5 | 101 | 100 | 12.4 | 1.6 | 3.2 | 1.6 | 0.22 | 1.6 | 0 | 1.6 | 1.65 | – | – |
| 0.4 | 0.25 | 101 | 0.58 | 23.6 | 1.3 | 4.3 | 1.3 | 0.32 | 1.3 | 0 | 1.1 | 1.7 | 1.2 | 1.7 |
| 0.4 | 0.5 | 101 | 0.57 | 13 | 1.3 | 3.5 | 1.3 | 0.22 | 1.3 | 0 | 1.3 | 1.6 | 1.3 | 1.5 |
Table 3
Values of $T$, $T_J$, $T_S^{\min}$, $T_S^{\max}$, $T_{2000}^{\min}$, $T_{2000}^{\max}$ (in Kyr), $P_{Sun}$, and $P_r$ for particles started from Comet 10P Tempel 2 (Venus=V, Earth=E, Mars=M)

| $\beta$ | $N$ | $P_{Sun}$ | $P_r$ | $T$ | $P_r$ | $T$ | $P_r$ | $T$ | $T_J$ | $T_S^{\min}$ | $T_S^{\max}$ | $T_{2000}^{\min}$ | $T_{2000}^{\max}$ |
|--------|-----|-----------|-------|-----|-------|-----|-------|-----|-------|--------------|--------------|----------------|-----------------|
| 0.05   | 250 | 1.00      | 778   | 5.4 | 734   | 14.6| 28.7  | 29.7| 0     | 20.3         | 93.8         | -              | -               |
| 0.1    | 250 | 1.00      | 277   | 2.9 | 246   | 7.2 | 18.7  | 17.5| 0     | 11.3         | 30.5         | -              | -               |
| 0.2    | 250 | 0.76      | 153   | 1.6 | 114   | 3.7 | 7.9   | 7.4 | 21.7  | 7.4          | 358          | 6.3            | 691             |
| 0.4    | 250 | 0.50      | 60.3  | 2.2 | 44.1  | 4.0 | 3.7   | 6.5 | 5.8   | 4.8          | 64.0         | 4.9            | 171             |

Table 4
Values of $T$, $T_J$, $T_S^{\min}$, $T_S^{\max}$, $T_{2000}^{\min}$, $T_{2000}^{\max}$ (in Kyr), $P_{Sun}$, and $P_r$ for kuiperoidal dust particles at $N=50$ (Venus=V, Earth=E, Mars=M). The run at $\beta=0.01$ have not yet finished.

| $\beta$ | $P_{Sun}$ | $P_r$ | $T$ | $P_r$ | $T$ | $P_r$ | $T$ | $T_J$ | $T_S^{\min}$ | $T_S^{\max}$ | $T_{2000}^{\min}$ | $T_{2000}^{\max}$ |
|--------|-----------|-------|-----|-------|-----|-------|-----|-------|--------------|--------------|----------------|-----------------|
| 0.01   | 0.06      | >3    | >0.4| >3    | >0.5| >0.6  | >0.8| >60   | 42,303       | 102,530      | 2,379          | >177,370       |
| 0.05   | 0.18      | 156   | 0.18| 134   | 0.40| 12.6  | 1.2 | 16.0  | 5,568        | 18,221       | 2,895          | 50,198         |
| 0.1    | 0.2       | 76.2  | 0.75| 35.2  | 1.42| 2.74  | 2.8 | 47.4  | 3,659        | 17,439       | 3,730          | 53,949         |
| 0.2    | 0.12      | 182   | 0.22| 150   | 0.46| 13.3  | 1.2 | 59.6  | 5,237        | 10,789       | 2,490          | 26,382         |
| 0.4    | 0.08      | 44.4  | 0.24| 13.2  | 0.45| 0.63  | 0.8 | 121.6 | 4,503        | 13,246       | 5              | 14,383         |

The values of $T$ for asteroidal dust particles and the Earth were maximum ($\sim$80-100 Kyr) at $\beta\sim$0.002-0.004, and they were smaller for greater $\beta$ at $\beta\geq0.004$. The ratio $P_r/T$ differed for different $\beta$ by a factor of 50. It may be caused by that in some runs perihelia or aphelia of some particles could be close to the orbit of the Earth or some particles moved almost in the same plane as the Earth. At $\beta\geq0.002$ for asteroidal dust particles, the values of $T$ for Venus were about twice less than those for Earth, and the values for Mars were greater than those for Earth by a factor of 2-3.5. For Encke particles the values of $T$ were almost the same for Venus, Earth, and Mars, but they differed on $\Delta t_o$ and were greater for smaller $\beta$.

For $\beta\geq0.05$, the fraction $P_{Sun}$ of trans-Neptunian particles collided with the Sun was less than that of asteroidal particles by a factor of 4-6. At these values of $\beta$, collision probabilities $P$ with Earth and Venus differed for asteroidal and trans-Neptunian particles usually by less than a factor of 2, but the difference in $T$ was greater (by a factor of 3-7 at $\beta\geq0.1$ and by a factor of 20 at $\beta=0.05$). The mean values $e_m$ and $i_m$ of eccentricities and inclinations at distance $R=1$ AU from the Sun were mainly greater for trans-Neptunian particles than those for asteroidal particles (Table 5). Nevertheless, the ratio $P/T$ was greater for
Table 5
Mean values $e_m$ and $i_m$ (in degrees) of eccentricities and inclinations at $R=1$ AU

|          | $\beta$ | 0.001 0.05 0.1 0.2 0.4 |
|----------|---------|------------------------|
| dust     |         |                        |
| trans-Neptunian $e_m$ | 0.7 0.15 0.2 0.22 0.40 |
| trans-Neptunian $i_m$ | 16 16 13 16 21          |
| asteroidal $e_m$     | 0.13 0.09 0.12 0.22 0.40|
| asteroidal $i_m$     | 9.2 9.4 8.5 9.6 19      |
| Encke     | $e_m$   | 0.57 0.51 0.45 0.48 0.85|
| Encke     | $i_m$   | 7.5 12.8 20.9 23.4 11.7 |

trans-Neptunian particles. It may be caused by that perihelia or aphelia of migrating trans-Neptunian particles more often were close to the orbit of the Earth.

*Lifetimes* of particles usually were greater for smaller $\beta$. At the same $\beta$, for Encke particles they were smaller by a factor of several than those for asteroidal particles. Lifetimes of trans-Neptunian particles were $\sim$1-100 Myr (Table 4), i.e., were much greater than those of asteroidal particles. The run at $\beta=0.002$ have not yet finished, and at 3.4 Myr all trans-Neptunian particles were still moving in elliptical orbits.

Liou et al. (1996) noted that interstellar dust particles with an average size of 1.2 $\mu$m can destroy dust particles formed in the solar system and that the collisional lifetimes for 1, 2, 4, 9, 23 $\mu$m particles are 104, 49, 19, 4.8, 0.86 Myr, respectively. In these size ranges mutual collisions are not as important as collisions with interstellar grains. Moro-Martin and Malhotra (2002) concluded that *collisional destruction* is most important for kuiperoidal grains between 6 $\mu$m (9 $\mu$m in Liou et al., 1996) and 50 $\mu$m. Particles larger than 50 $\mu$m may survive because interstellar grains are too small to destroy them in a single impact. Taking into account lifetimes of trans-Neptunian particles presented in Table 4, we can conclude that most of 1-8 $\mu$m silicate particles can reach the Sun without destruction, but the fraction of larger particles destroyed during the motion to the Sun can be considerable. As the mass of the trans-Neptunian belt is greater than the mass of the asteroid belt by more than two orders of magnitude, and the values of $T$ in Table 1 are greater by less than a factor of 20 than those in Table 4 at the same $\beta$ for $\beta\geq0.05$, then for $d\sim$1-10 $\mu$m the fraction of trans-Neptunian particles among particles from different sources can be considerable even at $R<3$ AU, but they are not icy, as icy trans-Neptunian particles evaporate before they reach the near-Earth space. Liou et al. (1996) and Moro-Martin and Malhotra (2002) noted that for silicate particles 1-40 $\mu$m in diameter, the sublimation temperature ($\sim$1500 K) is
reached at $R<0.5$ AU, but for water ice particles the sublimation temperature ($\sim 100$ K) is reached at 27, 19, 14, 10, and 4.3 AU for the sizes of 3, 6, 11, 23, and 120 $\mu$m, respectively.

For particles started from Comet 10P, the obtained results were closer to those for particles started from asteroids than from Comet 2P Encke. In considered runs the values of $T$ for Comet 10P were even greater than those for asteroids.

For asteroidal particles and the model without planets, the values of $T_{S}^{min}$ were about the same as those presented in Table 1, but the values of $T_{S}^{max}$ sometimes were smaller (Ipatov et al., 2004a). With $N=250$ the values of $P_{Sun}$ for $\beta=0.25$ and $\beta=0.4$ of 0.908 and 0.548, respectively, are greater than for the model with planets. For $\beta\leq 0.1$ all of the particles collided with the Sun.

5 Migration of dust particles

At $\beta \leq 0.1$ most of asteroidal and cometary particles didn’t migrate outside Jupiter’s orbit. Several plots of the distribution of migrating asteroidal particles in their orbital elements and the distribution of particles with their distance $R$ from the Sun and their height $h$ above the initial plane of the Earth’s orbit were presented by Ipatov et al. (2004a). For all considered $\beta$, the mean time $t_{a}$ (the total time divided by the number $N$ of particles) during which an asteroidal dust particle (below in this paragraph we consider asteroidal particles) had a semi-major axis $a$ in an interval of fixed width decreases considerably with a decrease of $a$ at $a<1$ AU, and it is usually greater for smaller $\beta$ at $a<3$ AU. For $\beta \leq 0.1$ the values of $t_{a}$ are much smaller at $a>3.5$ AU than at $1<a<3$ AU, and the local maxima of $t_{a}$ corresponding to the 6:7, 5:6, 3:4, and 2:3 resonances with the Earth are greater than the maximum at $a\approx 2.3$ AU.

There are several other local maxima corresponding to the $n:(n+1)$ resonances with Earth and Venus (e.g., the 7:8 and 4:5 resonances with Venus). The trapping of dust particles in the $n:(n+1)$ resonances cause Earth’s asteroidal ring (Dermott et al., 1994a-b). Ipatov et al. (2004a) showed that the greater the $\beta$, the smaller the local maxima corresponding to these resonances. At $\beta \leq 0.1$ there are gaps with $a$ a little smaller than the semi-major axes of Venus and Earth that correspond to the 1:1 resonance for each; the greater the $\beta$, the smaller the corresponding values of $a$. A small gap for Mars is seen only at $\beta \leq 0.01$. There are also gaps corresponding to the 3:1, 5:2, and 2:1 resonances with Jupiter. At $\beta=0.01$ some asteroidal particles migrated into the 1:1 resonance with Jupiter. For $a>10$ AU perihelia were usually near Jupiter’s orbit, but sometimes also near Saturn’s orbit.

The mean time spent by an asteroidal dust particle in inner-Earth ($Q = a(1 + e)<0.983$ AU), Aten ($a<1$ AU, $Q>0.983$ AU), Apollo ($a>1$ AU, $q =$
$a(1 - e)<1.017$ AU, and Amor ($a>1$ AU, $1.017<q<1.300$ AU) orbits was 22, 5.6, 18, and 30 Kyr at $\beta=0.01$ and 0.4, 0.3, 1.8, and 3.0 Kyr at $\beta=0.4$, respectively. The ratio of mean times spent by Encke particles in inner-Earth, Aten, and Apollo orbits was about $1.5:1:2$, but varied from run to run. The total mass of comets inside Jupiter’s orbit is much smaller than the total mass of asteroids, but a comet produces more dust per unit minor body mass than an asteroid.

Analysis of the Pioneer 10 and 11 meteoroid detector data (Humes, 1980; Grün, 1994) showed that a population of $10^{-9}$ and $10^{-8}$ g ($\sim 10 \mu$m) particles has a constant spatial density between $3$ and $18$ AU. The spatial density of 1.4-10 $\mu$m particles obtained with Voyager 1 data was constant from $30$ to $51$ AU. Liou et al. (1999) and Liou and Zook (1999) concluded that dust grains released by Halley-type comets cannot account for this observed distribution, but trans-Neptunian dust particles can.

In our runs, beyond Jupiter’s orbit even the number $n_R$ of asteroidal particles at some distance $R$ from the Sun is smaller for greater $R$, and a spatial density $n_s$ is proportional to $n_R/R^2$. For asteroidal and cometary particles, $n_s$ quickly decrease with an increase of $R$, e.g., for $\beta=0.2$, $n_s$ was smaller at $R=5$ AU than at $R=1$ AU by a factor of 70 and 50 for asteroidal and Encke particles, respectively. So asteroidal dust particles cannot explain the constant spatial density of dust particles at $R\sim 3$-18 AU. At such distances, many of the dust particles could have come from the trans-Neptunian belt or from passing comets. In our runs at $\beta\geq 0.05$ a spatial density $n_s$ of considered trans-Neptunian particles near ecliptic at $R=1$ AU was greater than at $R>1$ AU. At $0.1 \leq \beta \leq 0.4$ and $2<R<45$ AU (at $\beta=0.05$ for $11<R<50$ AU) for trans-Neptunian particles, $n_s$ varied with $R$ by less than a factor of 4. This result is in agreement with the observations and with the simulations made by Liou and Zook (1999) with the use of RADAU integrator.

The spatial density of dust particles was greater for smaller $R$ at $R<4$ AU (exclusive for Encke particles at $\beta=0.4$). For asteroidal and trans-Neptunian dust, depending on $\beta$, it was more at $1$ AU than at $3$ AU by a factor of 2.5-8 (by a factor of 10-16 for Encke particles at $0.01 \leq \beta \leq 0.2$). This is in accordance with the observations for the inner solar system: inversion of zodiacal light observations by the Helios spaceprobe revealed a particle density $n_s \propto R^{-1.3}$, Pioneer 10 observations between the Earth’s orbit and the asteroid belt yielded $n_s \propto R^{-1.5}$, and IRAS observations have yielded $n_s \propto R^{-1.1}$ (Reach, 1992).
Ipatov et al. (2004b) investigated how the solar spectrum is changed by scattering by dust particles (a detailed paper will be prepared). Positions of particles were taken from the runs discussed above. For each such stored position, we calculated $>10^3$ different positions of a particle and the Earth during the period $P_{rev}$ of revolution of the particle around the Sun, considering that orbital elements do not vary during $P_{rev}$. Three different scattering functions were considered. In the first model, the scattering function depended on a scattering angle $\theta$ in such a way: $1/\theta$ for $\theta<c$, $1+(\theta-c)^2$ for $\theta>c$, where $\theta$ is in radians and $c=2\pi/3$ radian. In the second model, we added the same dependence on elongation $\epsilon$ (considered westward from the Sun). In the third model, the scattering function didn’t depend on these angles at all. For all these three models, the scattering function was proportional to $\lambda^2 \cdot (R-r)^{-2}$, where $r$ is the distance between a particle and the Earth and $\lambda$ is a wavelength of light. For each considered position, we calculated velocities of a dust particle relative to the Sun and the Earth and used these velocities and the scattering function for construction of the solar spectrum received at the Earth after been scattering by different particles located at some beam (view of sight) from the Earth. The direction of the beam is characterized by $\epsilon$ and inclination $i$. Particles in the cone of $2^\circ$ around this direction were considered. In each run, particles of the same size (at the same $\beta$) and the same source (i.e., asteroidal) were studied.

The plots of the obtained spectrum (e.g., Fig. 1) are in general agreement with the observations made by Reynolds et al. (2004) who measured the profile of the scattered solar Mg I$\lambda$5184 absorption line in the zodiacal light. Unlike results by Clarke et al. (1996), our modeled spectra don’t exhibit strong asymmetry. As these authors, we obtained that minima in the plots of dependencies of the intensity of light on its wavelength near 5184 Angstrom are not so deep as those for the initial solar spectrum. The details of plots depend on diameters, inclinations, and a source of particles. Different particles populations produce clearly distinct model spectra of the zodiacal light. For example, for $i=0$ and kuiperoidal particles, the shift of the plot to the blue was greater than those for asteroidal and Encke particles at $\epsilon=90^\circ$, and the shift to the red was greater at $\epsilon=270^\circ$. The results of modeling are relatively insensitive to the scattering function considered, the difference was greater for more close direction to the Sun. Our preliminary models and comparison with observational data indicate that for more precise observations it will be possible to distinguish well the sources of the dust and impose constrains on the particle size.

For asteroidal and Encke particles at $i=0$, about 65-89% and 70-85% of brightness was due to the particles at distance from the Earth $r<1$ AU (83-96% for
Fig. 1. Dependence of the intensity of light vs its wavelength $\lambda$ (in Angstrom) at $\beta=0.2$, $\epsilon=270^\circ$, and $i=0$. Zero of $\Delta \lambda=\lambda-\lambda_0$ corresponds to $\lambda=\lambda_0=5184$ Angstrom. The most thin line denotes the initial solar spectrum. Solar spectra for asteroidal (‘ast’) and Encke (‘com’) particles are practically the same for three scattering functions. For trans-Neptunian (‘tn’) particles for the first and the second models (e.g., denoted as ‘tn 1’ and ‘tn 2’, respectively) the plots are practically the same, but the plot for the third model (denoted simply as ‘tn’) is different. For observations (made by Reynolds et al., 2004) only the value of elongation is presented in the legend. Designation ”observ/sol spectr” corresponds to the case for which the plot based on the observations was stretched in such a way that the minimum became the same as that for the initial solar spectrum. The maximum value was considered to be the same (equal to 1) for all plots.

$r<1.5$ AU; 80-98% for $R<2$ AU). For trans-Neptunian particles, 14-78%, 22-85%, 26-78%, and 40-90% of brightness was due to $r<1$ AU, $r<1.5$ AU, $R<2$ AU, and $R<5$ AU, respectively. The above ranges were caused by different values of $\beta$ and $\epsilon$ and different scattering functions considered. Only a few trans-Neptunian particles in one run reached the near-Earth space, so statistics was not good and could increase the above intervals. According to Grün (1994), the intensity $I$ of zodiacal light falls off with heliocentric distance $R$.
as $I \sim R^{-\gamma}$, with $\gamma = 2$ to 2.5 and beyond about 3 AU zodiacal light was no longer observable above the background light. At $\beta \geq 0.05$ the brightness of all trans-Neptunian dust particles located at $R > 3$ AU was less by only a factor of several than that at $R < 3$ AU, so the contribution of trans-Neptunian dust particles at $d < 10 \, \mu m$ to the zodiacal light may not be large (else zodiacal light will be observed beyond 3 AU), but this problem needs more accurate estimates. Based on our runs, we suppose that the fraction of trans-Neptunian dust particles among particles of different origin for larger particles can be much smaller than those for $d < 10 \, \mu m$. Note that it is considered that the main contribution to the zodiacal light is from particles with diameters of about 20 to 200 $\mu m$.

Velocities of dust particles relative to the Earth that mainly contributed to brightness were different for different $\epsilon$. At $i = 0$ they were between -25 and 25 km/s.

7 Conclusions

Some Jupiter-family comets (JFCs) can reach typical near-Earth object (NEO) orbits and remain there for millions of years. While the probability of such events is small ($\sim 0.1 \%$), nevertheless the majority of collisions of former JFCs with the terrestrial planets are due to such objects. Most former TNOs that have typical NEO orbits moved in such orbits for millions of years, so during most of this time there were extinct comets. If those former JFCs that got NEO orbits for millions of years didn’t disintegrate during this time, there could be many (up to tens of percent) extinct comets among NEOs.

Collision probabilities of migrating asteroidal and cometary dust particles with the terrestrial planets during the lifetimes of these particles were maximum at diameter $d \sim 100 \, \mu m$, which is in accordance with the analysis of microcraters. The probability of collisions of cometary particles with the Earth is smaller than for asteroidal particles, and this difference is greater at $d \sim 100 \, \mu m$. At $d < 10$ micron, the mean time spent by a former trans-Neptunian particle in NEO orbits is less than that for an asteroidal dust particle by an order of magnitude, and the difference in collision probabilities with the Earth during a lifetime of a particle is less than the difference in the mean time.

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