MIGRATION OF ASTEROIDAL DUST

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ABSTRACT

We numerically investigate the migration of dust particles with initial orbits close to those of the numbered asteroids. The fraction of silicate particles that collided with the Earth during their lifetimes varied from 0.2\% for 40 micron particles to 0.008\% for 1 micron particles. Almost all particles with diameter $d \geq 4$ microns collided with the Sun. The peaks in the migrating asteroidal dust particles’ semi-major axis distribution at the $n/(n+1)$ resonances with Earth and Venus and the gaps associated with the 1:1 resonances with these planets are more pronounced for larger particles.

INTRODUCTION

The orbital evolution of interplanetary dust particles has been simulated by several authors. Liou et al. (1996), Liou and Zook (1999), Gorkavyi et al. (2000), Ozernoy (2000), Moro-Martin and Malhotra (2002) 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. The main contribution to the zodiacal light is from particles that range from 20 to 200 $\mu$m in diameter. It has been estimated that 20,000 to 40,000 tons of small dust particles (micrometer-to-millimeter-sized) fall to the Earth every year with the mass distribution of dust particles peaking at about 200 $\mu$m in diameter. 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 (they considered production of dust from Encke-type parent bodies in the case when initial mean longitudes were random).

Analysis of the Pioneer 10 and 11 meteoroid detector data showed (Humes, 1980; Grün, 1994) 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. This result was confirmed in the runs by Liou and Zook (1999) for 23 $\mu$m trans-Neptunian dust particles. In the runs by Moro-Martin and Malhotra (2002) [Fig. 13], the surface (not spatial) density was approximately constant in this region. Spatial density of 1.4-10 $\mu$m particles obtained basing on the Voyager 1 data was constant at 30 to 51 AU.

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 only important for kuiperoidal grains larger than about 6 $\mu$m (9 $\mu$m in Liou et al., 1996) and particles larger than 50 $\mu$m may also survive collisions because interstellar grains are too small to destroy these in a single impact. These authors noted that for silicate particles of 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 µm, respectively.

In the present paper we consider different initial orbits of dust particles, and for the first time, investigate the collisional probabilities of migrating particles with the planets based on a set of orbital elements during evolution. We also present plots of the orbital elements of the migrating particles.

MODELS

Using the Bulirsh–Stoer method of integration, we investigated the migration of dust particles under the gravitational influence of all of the planets (excluding Pluto), radiation pressure, Poynting–Robertson drag and solar wind drag, for the values of the ratio between the radiation pressure force and the gravitational force $\beta$ equal to 0.01, 0.05, 0.1, 0.25, and 0.4. For silicate particles such values of $\beta$ correspond to diameters of about 40, 9, 4, 1.6, and 1 microns, respectively. $\beta$ values of 0.01 and 0.05 correspond to particle masses of $10^{-7}$ g and $10^{-9}$ g, respectively. Burns et al. (1979) obtained $\beta=0.573 Q_{pr}/(\rho s)$, 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 µm). For water ice particles with $\rho=1$ g cm$^{-3}$ particle diameters are 120, 23, 11, 6, and 3 µm for $\beta=0.01$, 0.05, 0.1, 0.2, and 0.4, respectively (Burns et al., 1979). 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 $10^{-8}$.

Initial positions and velocities of the particles were the same as those of the first numbered main-belt asteroids (JDT 2452500.5), i.e., dust particles are assumed to leave the asteroids with zero relative velocity. For each $\beta \geq 0.05$ we considered $N=500$ particles ($N=250$ for $\beta=0.01$). In each run we took $N=250$, because for $N \geq 500$ the computer time per calculation for one particle was several times greater than for $N=250$. These runs were made until all of the particles collided with the Sun or reached 2000 AU from the Sun. The lifetimes of all considered asteroidal dust particles were less than 0.8 Myr, except for one particle with a lifetime of 19 Myr. We also made similar runs for the model without planets in order to investigate the role of planets in migration of dust particles.

COLLISIONS WITH PLANETS AND THE SUN

In our runs planets were considered as material points, but, based on orbital elements obtained with a step $d_t$ of $\leq 20$ yr ($d_t=10$ yr for $\beta$ equal to 0.1 and 0.25, and $d_t=20$ yr for other values of $\beta$), as in Ipatov and Mather (2003), we calculated the mean probability $P=P_2/N$ ($P_2$ 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 $T=T_2/N$ as the mean time during which the perihelion distance $q$ of a particle was less than the semi-major axis of the planet. Below, $P_{Sun}$ is the ratio of the number of particles that collided with the Sun to the total number of considered particles, and $P_{Sun}^{250}$ is the same ratio for the first 250 particles. $T_{Sun}^{\text{min}}$ and $T_{Sun}^{\text{max}}$ are the minimum and maximum values of the time until the collision of a particle with the Sun, and $T_{2000}^{\text{min}}$ and $T_{2000}^{\text{max}}$ are the minimum and maximum values of the time when the distance between a particle and the Sun reached 2000 AU. The values of $P_{Sun}^{250}$, $P_r=10^6 P$, $T$, $T_1$, $T_{Sun}^{\text{min}}$, $T_{Sun}^{\text{max}}$, $T_{2000}^{\text{min}}$, $T_{2000}^{\text{max}}$, and $P_{Sun}$ are shown in Table 1 for $N=250$ (for $\beta=0.1$ we present two runs with 250 different particles), and $P_{Sun}$ was obtained for all considered particles at a fixed $\beta$.

The minimum time $T_{Sun}^{\text{min}}$ needed to reach the Sun is smaller for smaller particles, but the ratio $T_{Sun}^{\text{max}}/T_{Sun}^{\text{min}}$ is much greater and the ratio $T_{2000}^{\text{max}}/T_{Sun}^{\text{max}}$ is smaller for $\beta \geq 0.25$ than for $\beta \leq 0.1$. For $\beta=0.05$, 498 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 19.055 Myr, respectively. The latter object had perihelion near Saturn’s orbit for a long time.

For smaller particles (i.e., those with larger $\beta$), $P_{Sun}$ is smaller and the probability of collisions of particles with the terrestrial planets is smaller. The probability of a collision of a migrating dust particle with the Earth for $\beta=0.01$ is greater by a factor of 220 than for $\beta=0.4$. 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 Earth peaks at $d=200$ µm.
Table 1. Values of $T$, $T_J$, $T_S^{min}$, $T_S^{max}$, $T_{2000}^{min}$, and $T_{2000}^{max}$ (in Kyr), $P_r$, $P_{Sun}^{250}$, and $P_{Sun}$ obtained for asteroidal dust particles for several values of $\beta$ (Venus=V, Earth=E, Mars=M)

| $\beta$ | $P_{Sun}$ | $P_{Sun}^{250}$ | $P_r$ | $T$ | $T_r$ | $T_e$ | $T_f$ | $T_J$ | $T_S^{min}$ | $T_S^{max}$ | $T_{2000}^{min}$ | $T_{2000}^{max}$ |
|---------|-----------|-----------------|-------|-----|-------|-------|-------|------|------------|------------|----------------|-----------------|
| 0.01    | 1.000     | 1.000           | 1534  | 19  | 1746  | 44.2  | 127   | 99.9 | 0    | 142        | 422        | 3.0            | 3.0             |
| 0.05    | 0.996     | 1.000           | 195   | 4.0 | 190   | 8.1   | 36.7  | 20.5 | 0    | 30         | 89         | 3.0            | 3.0             |
| 0.1     | 0.990     | 0.988           | 141   | 2.4 | 132   | 4.8   | 16.4  | 12.0 | 2.21 | 16         | 44         | 2.8            | 793             |
| 0.1*    | 0.990     | 0.992           | 366   | 2.4 | 279   | 4.8   | 20.9  | 12.0 | 0.92 | 7.2        | 43         | 6.0            | 534             |
| 0.25    | 0.618     | 0.660           | 79.2  | 1.4 | 63.8  | 2.9   | 5.60  | 5.9  | 31.7 | 5.9        | 385        | 65             | 1.6             |
| 0.4     | 0.316     | 0.324           | 12.4  | 1.5 | 8.0   | 2.5   | 0.72  | 8.8  | 32.3 | 4.3        | 172        | 40             | 1.7             |

ORBITAL EVOLUTION

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 are presented in Figs. 1-8. For Fig. 1-2 the number of bins in the semi-major axis $a$ is 1000. For other figures the number of bins in $a$ or $R$ is 100, and the number of bins in $e$ or $h$ is usually slightly less than 100. The width of a bin in $i$ is $1^\circ$.

In Figs. 1-2, 4-8 for calculations of orbital elements we added the coefficient $(1-\beta)$ to the mass of the Sun, which is due to the radiation pressure. If not stated otherwise, we consider such orbital elements. Fig. 3 is similar to Fig. 4, but in Fig. 3 (and also in the figures presented by Ipatov et al., 2003) for calculations of osculating orbital elements we did not add this coefficient to the mass of the Sun, (i.e., to transfer from rectangular coordinates to orbital elements we used the same formulas as those for massive bodies). For transformations between semi-major axes and eccentricities for the above two systems of orbital elements we used the formulas obtained by Kortenkamp and Dermott (1998). In total, Figs. 3 and 4 are similar, but they differ in some details. For example, for $\beta=0.4$ in Fig. 4 there are some pairs of $a$ and $e$ corresponding to the perihelion near Saturn’s orbit. There are no such pairs in Fig. 3 for $\beta=0.4$.

We obtained that the mean time $t_a$ (the total time divided by the number $N$ of particles) during which an asteroidal dust particle had a semi-major axis $a$ in an interval of fixed width is greater for smaller $\beta$ at semi-major axes $a<3$ AU (exclusive of the gap at $a=1$ AU and $\beta=0.01$). In Fig. 1b curves plotted at 40 AU are (top-to-bottom) for $\beta$ equal to 0.25, 0.4, 0.05, 0.1, and 0.01. 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 they are usually a maximum at $a\approx 2.3$ AU. For $\beta=0.01$ 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 2.4 AU. There are several other local maxima (Fig. 1c) corresponding to the $n/(n+1)$ resonances with Earth and Venus (e.g., the 7:8 and 4:5 resonances with Venus). Dermott et al. (1994a-b) considered $\beta=0.037$ and showed that these resonances with the Earth cause the Earth’s asteroidal ring. 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; the greater the $\beta$, the smaller the corresponding values of $a$. A small gap for Mars is seen only at $\beta=0.01$. There are also gaps corresponding to the 3:1, 5:2, and 2:1 resonances with Jupiter.

For all considered $\beta$, $t_a$ decreases considerably with a decrease of $a$ at $a<1$ AU and usually decreases with an increase of $a$ at $a>5$ AU (Fig. 1). Relatively large values of $t_a$ at $a>40$ AU for $\beta=0.05$ are due to only one particle. For $a>5$ AU the values of $t_a$ are usually a little greater at $\beta=0.25$ than those at $\beta=0.04$. The number of particles, which got $a>5$ AU, at $\beta=0.25$ is smaller than at $\beta=0.4$, but they move more slowly to 2000 AU than at $\beta=0.4$. Analyzing Fig. 1a, we can conclude that the portion of greater particles among all particles is on average greater at the zone of the terrestrial planets than in the asteroid belt.

In Fig. 2 we present the results obtained for the model without planets. In this case, migration outside 5 AU is smaller than in the model with planets and, of course, there are no peaks and gaps caused by planets (compare Figs. 1 and 2). For 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. The values of $P_{Sun}^{250}$ were 0.908 and
Fig. 1. Mean time $t_a$ (the total time $tasum$ divided by the number $N$ of particles) during which an asteroidal dust particle had a semi-major axis in an interval with a width of (a) 0.005 AU, (b) 0.1 AU, or (c) 0.001 AU. The values of $t_a$ at 2 AU are greater for smaller $\beta$. Curves plotted at 40 AU are (top-to-bottom) for $\beta$ equal to 0.25, 0.4, 0.05, 0.1, and 0.01. For calculations of orbital elements we added the coefficient $(1-\beta)$ to the mass of the Sun, which is due to the radiation pressure (the same orbital elements are used in Figs. 1-2, 4-8). Initial velocities and coordinates of dust particles were the same as those of the first $N=500$ numbered asteroids ($N=250$ for $\beta=0.01$) at JDT 2452500.5.
Fig. 2. Same as for Fig. 1 but without gravitational influence of planets and for a smaller number of initial dust particles ($N=250$ at $\beta \geq 0.05$, and $N=100$ at $\beta \leq 0.01$). The values of $a>6.2$ AU were reached only at $\beta=0.4$.

0.548 for $\beta=0.25$ and $\beta=0.4$, respectively (greater than for the model with planets). For $\beta \leq 0.1$ all particles collided with the Sun.

We now return to the model with planets. At $a<4$ AU the maximum eccentricities for $\beta \geq 0.25$ were greater than those for $\beta \leq 0.1$ (Figs. 4-5). At $\beta=0.01$ some particles got into the 1:1 resonance with Jupiter. For $a>10$ AU perihelia were usually near Jupiter’s orbit (for $\beta=0.05$ and $\beta=0.25$ also near Saturn’s orbit). In almost all cases, the inclinations $i<50^\circ$; at $a>10$ AU the maximum $i$ was smaller for smaller $\beta$ (Fig. 6).

In Fig. 5 we present the distributions of dust particles in $a$ and $e$, and in $a$ and $i$ for $\beta=0.1$. The plots on the left were obtained for initial positions and eccentricities close to those of the asteroids with numbers 1-250, and the plots on the right, to those of the asteroids with numbers 251-500 (Figs. 1-4, 6-8 were obtained using all particles). In total, the left and the right plots are similar, but for the left plots particles spent more time outside 5 AU. At $\beta=0.05$ none of the first 250 particles reached Jupiter’s orbit, but two particles with numbers 361 and 499 migrated to 2000 AU having their perihelia near the orbits of Jupiter and Saturn (Fig. 4).

Usually there are no particles with $h/R>0.7$ at $R<10$ AU, with $h/R>0.25$ at $R>20$ AU for $\beta \leq 0.1$, and with $h/R>0.5$ at $R>50$ AU for $\beta \geq 0.25$. For $\beta \geq 0.25$ at $R<1000$ AU the entire region with $h/R<0.3$ was not empty (Fig. 7).

The total time spent by 250 particles in inner-Earth, Aten, Apollo and Amor orbits was 5.6, 1.4, 4.5, and 7.5 Myr at $\beta=0.01$, and 0.09, 0.08, 0.48, and 0.76 Myr at $\beta=0.4$, respectively. The spatial density of a dust cloud and its luminosity (as seen from outside) were greater for smaller $R$. For example, depending on $\beta$ they were by a factor of 2.5-8 and 7-25 (4 and 12-13 at $\beta \leq 0.05$) greater at 1 AU than at 3 AU for the spatial density and luminosity, respectively. This is in accordance with the observations for the inner solar system (inversion of zodiacal light observations by the Helios spaceprobe in the inner solar system revealed a particle density $n(R) \propto R^{-1.3}$, Pioneer 10 observations between the Earth’s orbit and the asteroid belt yielded $n(R) \propto R^{-1.5}$ and IRAS observations have yielded $n(R) \propto R^{-1.1}$, Reach, 1992; the intensity $I$ of zodiacal light falls off with heliocentric distance $R$ as $I \sim R^{-\gamma}$, with $\gamma=2$ to 2.5; beyond about 3 AU zodiacal light was no longer observable above the background light, Grün, 1994). As in Liou and Zook (1999), we approximately defined the brightness of each particle as $R^{-2}$. Beyond Jupiter’s orbit even the number of asteroidal particles at some distance $R$ from the Sun is smaller for greater $R$, so asteroidal dust particles cannot explain the constant space density of dust particles at $R=3-18$ AU. Besides dust particles that came
from the trans-Neptunian belt, many dust particles at such distances could have come from the comets that pass through this region.

MIGRATION OF TRANS-NEPTUNIAN AND COMETARY DUST PARTICLES

We also began a series of runs in which initial positions and velocities of the particles were the same as those of the first trans-Neptunian objects (JDT 2452600.5), and our initial data were different from those in previous papers. The number of particles was \(N=250\) at \(\beta=0.4\), \(N=100\) at \(\beta=0.2\) and \(\beta=0.1\), and \(N=50\) at \(\beta=0.05\). We store orbital elements with a step of 100 yr. However, these runs have not been finished at the present time.

The distributions of dust particles with semi-major axis \(a\) and eccentricity \(e\) or inclination \(i\), and with distance \(R\) from the Sun and height \(h\) above the initial plane of the Earth’s orbit are presented in Fig. 8. The left plots were obtained for \(\beta=0.05\), \(N=50\), for a time interval of 2 Myr, and the right plots were made for \(\beta=0.1\), \(N=100\), and \(t\leq3.5\) Myr. For both values of \(\beta\), bodies with \(e>0.4\) had their perihelia mainly near the semi-major axis of Neptune. There were also bodies with perihelion distance \(q\) near the semi-major axis of Uranus. Inclinations were less than 35°. For \(\beta=0.1\), there was an increase in \(i\) at \(a\approx10-12\) AU.

The values of \(h\) were maximum (26 AU) at \(R=47-50\) AU for \(\beta=0.05\), and were maximum (30 AU) at \(R=57\) AU for \(\beta=0.1\). For \(\beta=0.05\) at \(t\leq2\) Myr and for \(\beta=0.1\) at \(t\leq3\) Myr, the values of the number \(n_R\) of particles at distance \(R\), and also the values of \(n_R/R\) (surface density), \(n_R/R^2\) (spatial density), and even \(n_R/R^3\) (similar to luminosity) were maximum at \(\sim40-45\) AU, but at that time only a few objects had reached \(R<20\) AU (Fig. 6).

At \(\beta=0.4\) most particles were outside 50 AU after only 0.02 Myr. If we consider positions of particles for \(t\leq0.05\) Myr, then 84% of them had \(R>100\) AU. At that time \(n_R/R\), \(n_R/R^2\), and \(n_R/R^3\) were maximum at \(\sim40-55\) AU. For \(\beta=0.2\) at \(t\leq1\) Myr, the luminosity was maximum at 30-65 AU (differed by a factor of less than 3 in this region), but \(R>100\) AU for only 1% of orbital positions.

For each \(\beta\), the mean eccentricity \(e_m\) of former trans-Neptunian dust particles increased with \(a\) for \(a>48\) AU, and it exceeded 0.5 at \(a>60\) AU. Bodies that migrated inside Neptune’s orbit had \(e_m<0.2\). We usually obtained \(h/R<0.5\), and in the zone of the Edgeworth–Kuiper belt the ratio of the number of particles at \(h=kR\) dropped usually to 10% of the number at \(h=0\) at \(k=0.1\), but sometimes at \(k=1/4\).

The trans-Neptunian belt is considered to be the main source of Jupiter-family comets. As Jupiter-family comets produce much dust, they can produce trans-Neptunian dust just inside Jupiter’s orbit. Some of these comets can reach typical near-Earth objects’ orbits (Ipatov and Mather, 2003). 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.

CONCLUSIONS

We investigated collision probabilities of migrating asteroidal dust particles with the terrestrial planets during the lifetimes of these particles. These probabilities were considerably larger for larger particles, which is in accordance with the analysis of micrometeorites. Almost all particles with diameter \(d\geq4\ \mu m\) collided with the Sun. In almost all cases, inclinations \(i<50^\circ\), and at \(a>10\) AU maximum \(i\) was smaller for larger asteroidal particles. The spatial density of asteroidal particles decreases considerably at \(a>3\) AU, so the portion of asteroidal particles among other particles beyond Jupiter’s orbit is small. The peaks in distribution of migrating asteroidal dust particles with semi-major axis corresponding to the \(n/(n+1)\) resonances with Earth and Venus and the gaps associated with the 1:1 resonances with these planets are more pronounced for larger particles.

NOTES

This version of the paper differs from the first version submitted to the Proceedings of the international conference ”New trends in astrodynamics and applications” (20-22 January 2003, University of Maryland, College Park). We do not know which version will appear in the proceedings.

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Fig. 3. Distribution of asteroidal dust particles with semi-major axis and eccentricity (designations of the number of particles in one bin are the same in Figs. 3-7). For the transfer from rectangular coordinates to orbital elements we used the same formulas as those for massive bodies. For Figs. 1-2, 4-8 for calculations of orbital elements we added the coefficient \((1-\beta)\) to the mass of the Sun, which is due to the radiation pressure.
Fig. 4. Distribution of asteroidal dust particles with semi-major axis and eccentricity (designations of the number of particles in one bin are the same in Figs. 3-7).
Fig. 5. Distribution of asteroidal dust particles with semi-major axis and eccentricity, and with semi-major axis and inclination for $\beta=0.1$. The left figures correspond to the runs with initial positions and velocities close to those of the first 250 numbered main-belt asteroids, and the right figures correspond to the runs with initial positions and velocities close to those of the asteroids with numbers 251-500 (JDT 2452500.5).

Fig. 6. Distribution of asteroidal dust particles with semi-major axis and inclination.
Fig. 7. Distribution of asteroidal dust particles with distance $R$ from the Sun and height $h$ above the initial plane of the Earth’s orbit (designations of the number of particles in one bin are the same in Figs. 3-7).
Fig. 8. Distribution of trans-Neptunian (kuiperoidal) dust particles with semi-major axis $a$ and eccentricity $e$ or inclination $i$, and with distance $R$ from the Sun and height $h$ above the initial plane of the Earth’s orbit. The considered time interval is 2 Myr and 3.5 Myr for $\beta=0.05$ ($N=50$) and $\beta=0.1$ ($N=100$), respectively.