MIGRATION OF DUST PARTICLES AND THEIR COLLISIONS WITH THE TERRESTRIAL PLANETS.

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Introduction. Our review of previously published papers on dust migration can be found in [1], where we also present different distributions of migrating dust particles. We considered a different set of initial orbits for the dust particles than those in the previous papers. Below we pay the main attention to the collisional probabilities of migrating dust particles with the planets based on a set of orbital elements during their evolution. Such probabilities were not calculated earlier.

Migration of Asteroidal Dust Particles. Using the Bulirsh–Stoer method of integration, we investigated the migration of dust particles under the influence of planetary gravity (excluding Pluto), radiation pressure, Poynting–Robertson drag, and solar wind drag for values of the ratio between the radiation pressure force and the gravitational force β equal to 0.002, 0.004, 0.01, 0.05, 0.1, 0.25, and 0.4. For silicates, such values of β correspond to particle diameters d of about 200, 100, 40, 9, 4, 1.6, and 1 microns, respectively (for water ice, the corresponding diameters are greater by a factor of 3 than the above values). We assume the ratio of the solar wind drag to the Poynting–Robertson drag to be 0.35. The relative error per integration step was taken to be less than 10^{-8}. The simulations continued until all of the particles either collided with the Sun or reached 2000 AU from the Sun.

The initial positions and velocities of the asteroidal 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. In our runs, planets were considered as material points, but using orbital elements obtained with a step d_t of $\leq$20 yr (d_t=10 yr for β equal to 0.1 and 0.25, and d_t=20 yr for other values of β), we calculated the mean probability P=P_Σ/N (P_Σ 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_Σ/N as the mean time during which the perihelion distance q of a particle was less than the semi-major axis of the planet. With $\beta\geq$0.01 the values of P_r=10^6P and T are shown in Table 1 for N=250 (for β=0.1 we present two runs with 250 different particles). For $\beta\leq$0.004 the first lines are for dust particles starting from the first 100 numbered asteroids, and the second lines (marked by *) are for those starting from the next 150 asteroids.

Table 1: Values of T and P_r obtained for asteroidal dust particles (Venus=V, Earth=E, Mars=M)

	V	V	E	E	M	M
β	P_r	T	P_r	T	P_r	T
0.002	2002	48.0	1934	104	537	298
0.002*	9679	35.3	10641	80.1	508	274
0.004	12783	40.5	11350	90.	1204	220
0.004*	2704	38.4	2267	81.9	342	208
0.01	1534	19.2	1746	44.2	127	100
0.05	195	4.0	190	8.1	36.7	20
0.1	141	2.4	132	4.8	16.4	12
0.1*	366	2.4	279	4.8	20.9	12
0.25	79.2	1.4	63.8	2.9	5.60	5.9
0.4	12.4	1.5	8.0	2.5	0.72	8.8

The ratio of the number of particles that collided with the Sun to the total number of particles $P_{Sun}\geq$0.99 at $\beta\leq$0.1, P_{Sun}=1.0 at $\beta\leq$0.01, and P_{Sun} was equal to 0.6 and 0.3 at β equal 0.25 and 0.4, respectively (note that for the model without planets with N=250, the values of P_{Sun} for β=0.25 and β=0.4 of 0.91 and 0.55, respectively, are greater than for the model with planets). The values of T and P are greater for smaller β, and T is almost proportional to $1/\beta$ at 0.004$\leq\beta\leq$0.1. For $\beta<$0.004, T does not depend considerably on β. The probability of a collision of a migrating dust particle with the Earth for $\beta\leq$0.01 is greater by more than two orders of magnitude than that for β=0.4. Cratering records in lunar material and on the panels of the Long Duration Exposure Facility showed that the mass distribution of dust particles encountering Earth peaks at d=200 μm. Using the data from Table 1, we obtained that such mass distribution takes place, if the number of particles with diameters greater than D is proportional to $D^{-\alpha}$, where 2<α<3.

The mean time t_a during which an asteroidal dust particle had a semi-major axis a in an interval of fixed width is greater for smaller β at semi-major axes a<3 AU (exclusive of the gap at a=1 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 they are usually a maximum at $a\approx$2.3 AU. For β=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 2.3–2.4 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. The

Table 2: Values of T, P_r, and P_{Sun} obtained for kuiperoidal dust particles (Venus=V, Earth=E, Mars=M)

		V	V	E	E	M	M
β	P_{Sun}	P_r	T	P_r	T	P_r	T
0.05	0.18	156	0.18	134	0.40	12.6	1.2
0.1	0.2	76.2	0.75	35.2	1.42	2.74	2.8
0.2	0.12	182	0.22	150	0.46	13.3	1.2
0.4	0.08	44.4	0.24	13.2	0.45	0.63	0.8

greater the β, 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 β, the smaller the corresponding values of a. A small 1:1 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 $a<4$ AU the maximum eccentricities for $\beta \geq 0.25$ were greater than those for $\beta \leq 0.1$. At $\beta = 0.01$ some particles migrated 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 β.

Migration of Kuiperoidal Dust Particles. In another series of runs, initial positions and velocities of the particles were the same as those of the first $N=50$ discovered trans-Neptunian objects (JDT 2452600.5). We stored orbital elements with a step of 100 yr.

Particles with $e>0.5$ had their perihelia mainly near the semi-major axis of the giant planets. The mean eccentricity e_m of kuiperoidal dust particles increased with a at $a>50$ AU, and it exceeded 0.5 at $a>60$ AU.

For kuiperoidal particles the values of P_{Sun} and T (see Table 2) were smaller by a factor of several (by a factor of 5 for P_{Sun}) than those of asteroidal particles at the same β, but the ratio of the probability of collisions of asteroidal particles with Earth or Venus to that of kuiperoidal particles was usually smaller than 5, and at $\beta \geq 0.2$ P was even greater for kuiperoidal particles, because the mean eccentricities and inclinations of particles near the terrestrial planets were smaller for kuiperoidal particles than those for asteroidal particles. Though the maximum of lifetimes of particles was smaller for greater β, the mean time spent in Jupiter-crossing orbits at $\beta = 0.4$ (6 Myr) was greater by an order of magnitude than that at $\beta = 0.05$ (0.7 Myr).

The trans-Neptunian belt is considered to be the main source of Jupiter-family comets. Some of these comets can reach typical near-Earth object orbits, move in them for millions of years [2], and produce dust while moving in such orbits.

Migration of Cometary Dust Particles. The migration of particles which initial positions and velocities were the same as those of Comet 2P Encke was also investigated. We considered particles starting near perihelion (runs denoted as Δt_o=0), near aphelion (Δt_o=0.5), and when the comet had orbited for $P_a/4$ after perihelion passage, where P_a is the period of the comet (such runs are denoted as Δt_o=0.25). Variations in time τ when perihelion was passed was varied with a step $d\tau$=0.1 day for series 'S' and with a step 1 day for series 'L'. For each β we considered N=101 particles for "S" runs and 150 particles for "L" runs. The results obtained are presented in [1].

In contrast to the asteroidal dust particles, the values of T did not differ much between Venus, Earth, and Mars for the cometary dust particles. For some runs at $\beta \geq 0.2$, all particles starting close to perihelion got hyperbolic orbits just after starting from the comet.

All particles with $\beta \leq 0.01$ for Δt_o=0 or with $\beta \leq 0.2$ for $\Delta t_o \geq 0.25$ collided with the Sun. The values of P and T are greater for larger particles (i.e., for smaller β), and the values of P are greater for Venus than for Earth by a factor of 2 or more. Collision probabilities with Earth were greater by a factor of 10–20 than those with Mars and greater for particles starting at perihelion than aphelion. For the same values of β, the probability of cometary dust particles colliding with a terrestrial planet was several times smaller than for asteroidal dust particles, mainly due to the greater eccentricities and inclinations of the cometary particles. This difference is greater for larger particles.

Conclusions. The collision probabilities of dust particles with the terrestrial planets during lifetimes of particles were considerably greater for larger asteroidal and cometary particles. The peaks in the 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.

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References:

[1] Ipatov, S.I., Mather, J.C., and Taylor, P.A. (2004) In *"Astrodynamics, Space Missions, and Chaos"*, ed. by E. Belbruno and P. Gurfil, *Annals of the New York Academy of Sciences*, in press (http://arXiv.org/format/-astro-ph/0308450).

[2] Ipatov, S. I. and Mather, J. C. (2003) *Advances in Space Research*, in press (http://arXiv.org/format/astro-ph/0212177).