MIGRATION OF DUST PARTICLES TO THE TERRESTRIAL PLANETS

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ABSTRACT

The orbital evolution of asteroidal, trans-Neptunian, and cometary dust particles under the gravitational influence of planets, the Poynting-Robertson drag, radiation pressure, and solar wind drag was integrated. Results of our runs were compared with the spacecraft observations of the number density of dust particles and with the WHAM observations of velocities of zodiacal particles. This comparison shows that the fraction of cometary dust particles of the overall dust population inside Saturn's orbit is significant and can be dominant. The probability of a collision of an asteroidal or cometary dust particle with the Earth during its dynamical lifetime is at a maximum at a particle diameter d~100 μm.

1. INTRODUCTION

There are a lot of papers on the migration of dust (e.g., [1-12], see more references and comparison of our runs with previous results in [13-14]). In this paper, we summarize our previous studies [13-14] based on a larger number of integrations than previously. Particular attention is paid to the probabilities of collisions of dust particles with the terrestrial planets. In contrast to papers by other scientists, we studied the orbital evolution of dust particles and the probabilities of their collisions with the Earth for a wider range of diameters of asteroidal and cometary particles.

2. MODEL

We integrated [13-14] the orbital evolution of about 15,000 asteroidal, cometary, and trans-Neptunian dust particles under the gravitational influence of planets, the Poynting-Robertson drag, radiation pressure, and solar wind drag, varying the values of the ratio β between the radiation pressure force and the gravitational force from ≤0.0004 to 0.4 (for silicates, such values of β correspond to particle diameters d between ≥1000 and 1 microns; d is proportional to 1/β). The cometary particles were launched from comets 2P/Encke (a≈2.2 AU, e≈0.85, i≈12°), 10P/Tempel 2 (a≈3.1 AU, e≈0.526, i≈12°), 39P/Oterma (a≈7.25 AU, e≈0.246, i≈2°), from test long-period comets (LPCs) with e=0.995 and q=a(1-e)=0.9 AU or q=0.1 AU, and from test Halley-type comets (HTCs) with e=0.975 and q=0.5 AU (for test comets, i was uniformly distributed between 0 and 180° and particles started at perihelion). Comets 10P and 39P are examples of typical Jupiter-family comets located inside and outside of Jupiter's orbit, respectively. The integration continued until all of the particles either collided with the Sun or reached 2000 AU from the Sun. For small β, the considered times exceeded 50-80 Myr (240 Myr for trans-Neptunian particles). In our runs, the orbital elements were stored with a step of d_t of ≤20 yr for asteroidal and cometary particles, and 100 yr for trans-Neptunian particles. The planets were assumed to be material points; however, using orbital elements obtained with a step d_t, we calculated the mean collisional probability of a particle with a planet during a dynamical lifetime of the particle (destruction of particles at their mutual collisions was not considered) P=P_Σ/N, where P_Σ is the probability for all N considered particles in one run.

3. PROBABILITIES OF COLLISIONS OF DUST WITH THE TERRESTRIAL PLANETS

The probability P of collisions of dust particles with the Earth versus β are presented in Fig. 1.

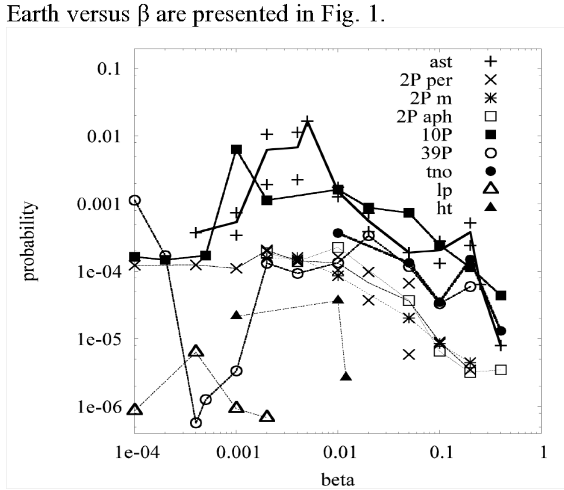

Figure 1. The probability P of collisions of dust particles with the Earth versus β for particles launched from asteroids (ast), trans-Neptunian objects (tno), Comet 2P at perihelion (2P per), Comet 2P at aphelion (2P aph), Comet 2P in the middle between perihelion and aphelion (2P m), Comet 10P (10P), Comet 39P (39P), long-period comets (lp) at e=0.995 and q=0.9 AU, and Halley-type comets (ht) at e=0.975 and q=0.5 AU.

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For some values of β, we considered two runs with slightly different initial data [14]. The obtained values of P can differ by a factor of several, for two such runs, because the number N of particles in each run was small (100-250), and a few objects can have orbits (e.g., with small inclinations) with a relatively high probability of a collision with the Earth. Results presented in Fig. 1 were obtained for the model when particles were removed at direct collisions with the Sun. If we remove particles when their perihelion distances reach the Sun, then for particles started from LPCs and HTCs (and sometimes from Comet 2P at β~0.1), the dynamical lifetimes of particles and values of P can be smaller by a factor of 1.5-2 than those in Fig. 1 (for other runs, the values of P are practically the same).

The probability P of a collision of an asteroidal dust particle with the Earth was found to have a maximum (~0.001-0.02) at $0.002 \leq \beta \leq 0.01$, i.e., at particle diameter d~100 μm. This is in accordance with the cratering records in the lunar soil and also with the particles record 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 [5, 15]. The probability P of collisions of asteroidal particles with Venus did not differ much from that for the Earth, whereas for Mars, it was by an order of magnitude smaller at $\beta \geq 0.01$ compared to Earth, and was nearly similar to those for the Earth at β~0.0004-0.001 [14]. We suppose that smaller values of P at smaller $\beta<0.005$ in Fig. 1 are caused by the fact that particles with d~100 μm have more often less inclined and less eccentric Earth-crossing orbits, which cause a higher probability of collisions, than the more massive particles.

The probability P of a collision of a particle launched from Comet 10P with a terrestrial planet sometimes differed by a factor of several from that for an asteroidal particle of the same size. In turn, for Comet 2P dust debris, the P values were found to be usually smaller than for asteroidal and Comet 10P particles: for Earth at $0.002 \leq \beta \leq 0.01$, P was by an order of magnitude (and sometimes even more) smaller for Comet 2P particles than for asteroidal particles. So the fraction of particles started from high-eccentricity comets such as Comet 2P (among particles from different sources) is much smaller for particles that collided with the Earth, than for particles moving in near-Earth space. For Comet 2P particles at some β, P is by a factor of 2 or 4 greater for Venus than for Earth.

For trans-Neptunian and Comet 39P particles, the maximum values of the probability of their collisions with the Sun (0.2-0.3) were reached at $0.05 \leq \beta \leq 0.1$. For $\beta \geq 0.05$, the fraction of trans-Neptunian particles that collided with the Sun was less than that of asteroidal particles by a factor of 4-6. At $0.01 \leq \beta \leq 0.2$, the probabilities of collisions of trans-Neptunian particles with the Earth and Venus were ~$(0.3\text{-}4) \cdot 10^{-4}$ and were usually less than those for asteroidal particles by a factor of less than 4. The ratio of values of time T during which a particle has a perihelion distance q<1AU for asteroidal particles to the values of T for trans-Neptunian particles was about 3-7 at $\beta \geq 0.1$, and about 20 at β=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. Nevertheless, the ratio P/T was greater for trans-Neptunian particles. It may be caused by the fact that the perihelia or aphelia of migrating trans-Neptunian particles more often were close to the orbit of the Earth, or the fraction of Earth-crossing trans-Neptunian particles with small e and i was greater (though e_m and i_m were greater) than for asteroidal particles.

At β=0.0001, one Comet 39P particle moved in an Earth-crossing orbit located inside Jupiter's orbit for 6 Myr, and due to this particle, the values of P and T for this run were much greater than those for other Comet 39P runs. For Comet 39P particles at $\beta \leq 0.001$, one needs to consider many thousands of particles in order to acuire reliable statistics because, for such runs, the probability of a collision of one particle with a terrestrial planet can be greater than the total probability of collisions of thousands of other particles. Comet 39P is located outside of Jupiter's orbit, and studies of the orbital evolution of dust particles produced by this comet help to better understand migration of trans-Neptunian particles to the terrestrial planets at small β. At $0.01 \leq \beta \leq 0.2$, the values of P for trans-Neptunian particles were similar to those for Comet 39P particles (~10^{-4}), but the times in Earth-crossing orbits for trans-Neptunian particles were smaller by a factor of several than those for Comet 39P particles. Due to a small fraction of large (d>1000 μm) particles that can move in Earth-crossing orbits for a long time, it may be possible that the probability of a collision of such trans-Neptunian particles with the Earth can be of the same order of magnitude as that for d<50 μm.

At $\beta \geq 0.004$, all particles launched from LPCs reached 2000 AU at $t \leq 5$ Kyr. At $\beta \leq 0.002$ for q=0.9 AU and at $\beta \leq 0.0004$ for q=0.1 AU, dynamical lifetimes of some particles launched from LPCs (and from HTCs at $\beta \leq 0.01$) exceeded several Myr. So only relatively large (d>100 μm) particles started from near-parabolic comets collided with the Earth ($P \approx 2 \cdot 10^{-5}$ for LPC-runs and q=0.1 AU at β=0.0004).

Interstellar particles can be effective in the destruction of trans-Neptunian dust particles through collisions, especially for $9 \leq d \leq 50$ μm, as it is argued in [7]. Larger particles may survive because interstellar grains are too small to be destroyed in a single impact. Since the total mass of the trans-Neptunian belt exceeds that of the asteroid belt by two orders of magnitude (or even more), and the mean residence times ratio in orbits with q<1 AU for asteroid and trans-Neptunian particles derived in our model is less than 20 at $\beta \geq 0.05$, than for d~1-10 μm, the fraction of non-icy trans-Neptunian dust of the overall dust population can be significant even at R<3 AU.

4. DISTRIBUTION OF MIGRATING DUST OVER DISTANCE FROM THE SUN

Based on the above runs, we studied [14] the distribution of number density n_s (i.e., the number of particles per unit of volume) near the ecliptic with a distance R from the Sun. The plot of n_s versus R at β=0.05 is presented in Fig. 2. For asteroidal particles, n_s quickly decreases with an increase of R. For β=0.2, n_s was smaller at R=5 AU than at R=3 AU by a factor of 8, 5, and 8 for asteroidal, Comet 2P, and Comet 10P particles, respectively. For β<0.05 such particles almost never reach 5 AU, and the above factor is much greater. So dust particles originating from small bodies located inside of Jupiter's orbit can not explain the constant number density of dust particles at R~3-18 AU, which was observed during the flights of Pioneer 10 and 11. At R>5 AU, many of the dust particles could have come from bodies moving beyond Jupiter's orbit.

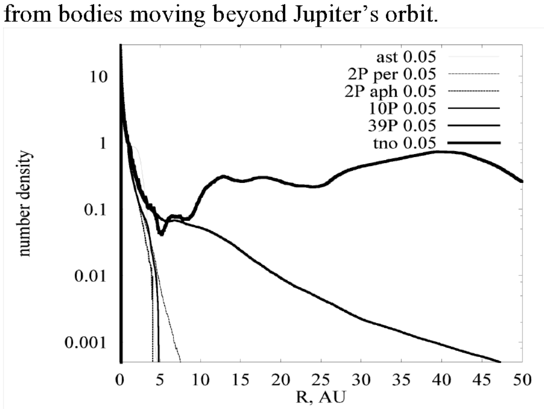

Figure 2. The number density of migrating dust particles over their distance R from the Sun at β=0.05 for particles started from asteroids (ast), trans-Neptunian objects (tno), Comet 2P at perihelion (2P per), Comet 2P at aphelion (2P aph), Comet 10 P, and Comet 39P. Number density at 1 AU is considered to be equal to 1.

In our runs at $\beta \geq 0.05$, the number density n_s of trans-Neptunian particles near the 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 β=0.05 for 11<R<50 AU) for trans-Neptunian particles, n_s varied with R by less than a factor of 4, but at R=5 AU it was smaller by at least a factor of 2 than at 15 AU. The number density of trans-Neptunian dust particles is smaller by a factor of several at 5<R<10 AU than at R=18 AU, so the fraction of cometary dust particles at R~5-10 AU is considerable. Similar conclusions were made in the previous studies of number density vs. R (e.g., [12, 16]) for other values of β and for other sources of cometary particles.

5. VELOCITIES OF DUST PARTICLES

Taking into account the Doppler shift, we studied [14, 17-18] how the solar spectrum was changed after solar light was scattered by the dust particles. The positions of particles were taken from the runs of the migration of the dust particles. For each such stored position, we calculated many (~10^2-10^4 depending on a run) different positions of a particle and the Earth during the period P_{rev} of the revolution of the particle around the Sun, considering that orbital elements do not vary during $P_{rev.}$ Three different scattering functions were considered [14, 17]. For each considered position, we calculated the velocity of a dust particle relative to the Sun and the Earth, and used that velocity and the scattering function for a construction of the solar spectrum received at the Earth after light have been scattered by the particles located at some beam from the Earth. The direction of the beam is characterized by an elongation ε and an inclination i. Particles in the cone of 2.5° around this direction were considered. All positions of particles during their dynamical lifetimes obtained in a single run (with a fixed β and the same source of particles) were used for the construction of one plot.

The plots of velocities of the Mg I line (at i=0) versus elongation ε (measured eastward from the Sun), were compared [14, 17-19] with the WHAM observational plots presented in [20]. Such a comparison with the WHAM observations was not made by other scientists. The plots obtained for different scattering functions were similar at 30°<ε<330°, the difference was greater for ε closer to 0 or 360°. For future observations of velocities of the zodiacal light, it is important to pay particular attention to ε between 90° and 120°. For these values of ε, the difference between different plots for different sources of dust was at a maximum. In our opinion, the main conclusion of the comparison of the 'velocity-elongation' plots obtained at observations, with those for our models, is that asteroidal dust doesn't dominate the zodiacal light, and that a lot of zodiacal dust particles were produced by comets, including dust produced by high eccentricity comets. This result is in agreement with our studies of the dynamics of Jupiter-family comets [21-23], which showed that there could be a lot of extinct comets moving in orbits with high eccentricities inside of Jupiter's orbit. A significant contribution of cometary dust to the zodiacal cloud was considered by several other authors (e.g., in [24] it was supposed to be ~75%).

The values of the 'full width at half maximum' (FWHM), i.e., the x-width at y=($y$min+$y$max)/2, for a plot of the intensity of light vs. its wavelength near the Mg I line (see e.g. Fig. 5 in [18]) are mainly greater than the FWHM obtained in our runs for asteroidal dust, but are mainly smaller than the FWHM for particles started from Comet 2P and long-period comets. Such a FWHM characterizes the scatter in velocities. For particles launched from asteroids, comets 2P, 10P and 39P, and LPCs and HTCs, the mean values of the FWHM are about 74, 81-88, 76-77, 76-77, 73-86, 81-90 km/s, respectively (the observational value is equal to 77).

6. CONCLUSIONS

The probabilities of collisions of migrating asteroidal and cometary dust particles with the terrestrial planets during the dynamical lifetimes of these particles were at a maximum at particle diameter d~100 µm, which is in accordance with the analysis of microcraters [15].

Cometary dust particles (produced both inside and outside Jupiter's orbit) are needed to explain the constant number density of particles at 3-18 AU. Comparison of the velocities of particles obtained in our runs with the velocities of zodiacal particles obtained at the WHAM observations shows that only asteroidal dust particles cannot explain these observations, and particles produced by comets, including high-eccentricity comets, are needed for such an explanation.

7. REFERENCES

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