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Temperature-influenced dynamics of small dust particles

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ABSTRACT

The motion of spherical dust particles under the action of gravity, electromagnetic radiation force and Lorentz force (LF) is studied theoretically for materials with temperature-dependent dielectric functions in the visible (VIS) spectral range. Even a weak variation of the optical constants with heliocentric distance may influence predominately a long-term dynamical behaviour of submicron-sized and small micron-sized dust grains. It is shown that the lifetime of carbonaceous or Si particles may change by several tens of per cent because of the temperature dependence of particle refractive indices. The orbital inclination is the most evident difference between the evolution of a dust particle with temperature-dependent optical properties and one without. While carbonaceous 2-μm-sized particles with optical constants independent of temperature may evolve in orbits with inclinations greater than an initial value, grains of the same size with variable refractive indices will be spread along orbits characterized with inclinations lower than the initial one. Here the temperature works as a separation factor for particles having slightly different temperature dependences of the optical constants.

Key words: interplanetary medium – dust, extinction.

1 INTRODUCTION

The motion of cosmic dust particles is influenced by various forces. Dealing with the dynamics of interplanetary dust particles, we have to take into account gravitational attraction of the Sun and, perhaps, planets. Several other non-gravitational forces may influence the orbital evolution of the particles. Our study focuses on micrometeoroids with sizes smaller than about 0.1 mm. The lifetimes of micron-sized spherical particles are determined by the solar electromagnetic radiation and the corresponding evolution of these particles is known as the Poynting–Robertson (P–R) effect.

The P–R effect corresponds to a special form of interaction of a dust particle with incident electromagnetic radiation (Klačka & Kocifaj 2001; Klačka 2004). It is valid under the assumption that the total momentum of the radiation after interaction with the particle is proportional to the momentum of parallel incident beams, in the proper frame of reference of the particle (Klačka 1992). The coefficient of proportionality equals zero for the special case of the perfectly absorbing spherical particle, treated by Robertson (1937). In general, the coefficient of proportionality depends on the physical and optical properties of the particle [its size, internal stratification of the mass (assumed to have a concentric character), refractive index, ...] and can be written as $1 - Q_{\mathrm{pr}} \equiv 1 - (Q_{\mathrm{ext}} - \langle\cos\Theta\rangle\, Q_{\mathrm{sca}})$, where Q_{ext} and Q_{sca} are dimensionless efficiency factors for extinction and scattering, and $\langle\cos\Theta\rangle \equiv \int_{4\pi} \cos\Theta\, p(\Theta, \Phi)\, \mathrm{d}\Omega$. The phase function p fulfills the normalization condition $\int_{4\pi} p(\Theta, \Phi)\, \mathrm{d}\Omega = 1$, where $\mathrm{d}\Omega = \sin\Theta\, \mathrm{d}\Theta\, \mathrm{d}\Phi$ is an elementary solid angle into which the particle scatters the light. As a consequence, the equation of motion for the particle in the reference frame of the source of radiation, e.g. Sun for the case of the Solar system, is proportional to the efficiency factor Q_{pr} and the terms generated by the simultaneous action of the Doppler effect, the change of concentration of photons and the aberration of light.

The dynamical evolution of micrometeoroids is efficiently influenced by their optical characteristics such as the complex refractive index and its internal distribution in the particle. It is known that the optical properties of any material vary with its temperature. The largest temperature dependences of refractive indices occur in the far-infrared(IR) (Hudgins et al. 1993; Draine & Lee 1984; Suh 1999). The changes of the optical constants with temperature in the visible (VIS) spectra are usually neglected because they are small and not many data have been reported for materials of astronomical interest. However, these data are important for dust dynamics in the Solar system because of the solar energy spectrum peaks in the middle of the submicron wavelength range (i.e. at $\lambda \approx 0.5\ \mu$m). Lamy (1974) has already pointed out that interplanetary grains experience large temperature variation in the Solar system implying evident variation of their refractive indices. He concluded that

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simulations of dust motion can show only an approximate behaviour when optical constants of the dust particles are assumed to be independent of temperature, i.e. fixed in time. Nevertheless, he has not succeeded in taking this variation into account due to the lack of data, especially for the two most typical groups of astronomical materials: dielectrics (ices, silicates, etc.) and metals.

At present, there exists a limited number of laboratory experiments, which deal with temperature-dependent refractive indices for certain materials in the VIS spectral range (Lautenschlager et al. 1987; Do et al. 1992; Yavas et al. 1993; Jellison & Modline 1994; Chiang, Leung & Tse 1997). The experimental data showed that optical 'constants' may in reality change up to several tens of per cent, in their dependence on material composition and the temperature of the particles. Although these measurements were mostly realized for non-astronomical materials (due to other physical interests), the obtained results provide sufficient motivation for our theoretical study in the evaluation of the temperature variation during the orbital evolution of dust particles.

2 CHANGE OF THE OPTICAL PROPERTIES OF DUST PARTICLES WITH DISTANCE FROM THE SUN

The studies on some composite materials (Chiang et al. 1997) or Si materials (Yavas et al. 1993) showed that both real and imaginary parts of the refractive index $n + i\,k$ can be successfully approximated as a linear function of T at VIS wavelengths. Nevertheless, most of the existing experimental and theoretical studies were limited to room temperature condition and thus optical properties of such composite materials at elevated temperatures are rarely reported in the literature (Sato, Yanagida & Yamanaka 1989). One of the well documented temperature dependences of optical constants is available for amorphous carbon (Jäger et al. 2003), which is also one of the main constituent elements of interstellar dust (Zubko et al. 1996). The data were obtained by heating cellulose from 400 to 1000°C, which unfortunately leads to an irreversible structural change. It means that only if amorphous carbon is forced to condense at, say, such a low temperature as 400°C will a material form with similar properties as the one the original data are referring to. If, however, amorphous carbon condenses at, say 1000°C, it will hardly transform into the kind of amorphous carbon produced by heating cellulose to only 400°C (Posch, private communication). When heating cellulose, a loss of organic compounds, a carbonization and an increase of the conductivity takes place. In general, not many substances are known that show a similar behaviour. However, the amorphous carbon is the one of example material, which may suffer a significant variation of refractive index in VIS spectra due to changes of grain temperature.

It is also customary to consider micronic and submicronic spheres of silicates, iron, or water ices as cosmic dust analogues in interplanetary space. In this study, the solution of the interaction of a solar radiation field with dust particles is based on conventional Mie theory (Mie 1908) taking into account the wavelength- and temperature-dependence of the refractive indices of the grain constituents. Although attention is paid to spherical particles, it is meaningful to remark that the temperature of the grains is almost independent of their shape. In an extreme case (infinite cylinders, thin needled, flat discs), the discrepancy in the temperature is only 10 per cent compared to spheres (Lamy 1974). The equilibrium grain temperature $T_{\rm g}$ can be obtained when solving an equation of the energy balance of the grain:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(c_{\rm g}T_{\rm g}\right) = \int_0^\infty \mathrm{d}\lambda \int_{\Delta\Omega} C_{\rm abs}(R,\lambda)\, F_\odot(\lambda)\,\mathrm{d}\Omega - 4\pi\int_0^\infty C_{\rm abs}(R,\lambda)\, B(\lambda, T_{\rm g})\,\mathrm{d}\lambda, \qquad (1)$$

where $c_{\rm g}$ is the heat capacity of the grain, $C_{\rm abs}(R, \lambda)$ is the cross-section of absorption for a spherical particle with radius R, $F_\odot(\lambda)$ is the monochromatic flux density of the solar radiation, $B(\lambda, T_{\rm g})$ is the Planck function, and $\Delta\,\Omega$ is a solid angle subtended by the Sun at the point where the grain is located. The first integral on the right-hand side (RHS) of equation (1) characterizes the energy absorbed by a grain of radius R within a unit time interval, while the second term on the RHS represents a loss of energy due to isotropic radiation by a spherical particle. The quantity $c_{\rm g}$ does not depend on the Debye temperature and under the condition of thermal equilibrium the left-hand side (LHS) approaches zero. The thermal equilibrium becomes stable when (Shul'man 1987)

$$\frac{\mathrm{d}^2(c_{\rm g}T_{\rm g})}{\mathrm{d}t^2}\left[\frac{\mathrm{d}(c_{\rm g}T_{\rm g})}{\mathrm{d}t}\right]^{-1} = \int_0^\infty \mathrm{d}\lambda \int_{\Delta\Omega} \frac{\partial C_{\rm abs}(R,\lambda)}{\partial T_{\rm g}} F_\odot(\lambda)\,\mathrm{d}\Omega - 4\pi\int_0^\infty \frac{\partial}{\partial T_{\rm g}}[C_{\rm abs}(R,\lambda)B(\lambda, T_{\rm g})]\,\mathrm{d}\lambda < 0. \qquad (2)$$

The requirement that the grain materials are close to thermal equilibrium restricts the imaginary part of the dielectric function to be positive (Draine & Lee 1984). This fact affects predominately the behaviour of the $Q_{\rm abs} = C_{\rm abs}/\pi R^2$ and thus $Q_{\rm ext} = Q_{\rm abs} + Q_{\rm sca}$. Because the equilibrium grain temperature $T_{\rm g}$ changes with heliocentric distance and grain optical properties with $T_{\rm g}$, the $Q_{\rm pr}$ appears to be unstable for spherical particles orbiting around the Sun. In such a way, the dynamical non-dimensional parameter β (which is often called the ratio of the radiation pressure force to the gravitational force) will change too.

3 THEORETICAL ASPECTS OF DUST DYNAMICS IN THE SOLAR SYSTEM

3.1 Equation of motion

The trajectory of a spherical submicron-sized and small micron-sized dust particle is considerably influenced by solar gravity, solar electromagnetic radiation, solar wind, and the Lorentz force (LF). The relevant equation of motion, to first order in $\boldsymbol{v}/c$, is

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{4\pi^2}{r^2}\boldsymbol{e}_R + \frac{q}{M}(\boldsymbol{v}-\boldsymbol{v}_{\rm sw})\times\boldsymbol{B} + \beta\frac{4\pi^2}{r^2} \times\left[\boldsymbol{e}_R - \left(1+\frac{\eta}{\bar{Q}_{\rm pr}}\right)\left(\frac{\boldsymbol{v}\cdot\boldsymbol{e}_R}{c}\boldsymbol{e}_R + \frac{\boldsymbol{v}}{c}\right)\right],$$

$$\boldsymbol{e}_R \equiv \boldsymbol{r}/|\boldsymbol{r}|,$$

$$\beta = 7.6\times10^{-4}\,\bar{Q}_{\rm pr}\,\frac{A(m^2)}{M(\mathrm{kg})}, \qquad (3)$$

where $\boldsymbol{v}$ (measured in au yr^{-1}) is the dust grain heliocentric velocity, $\boldsymbol{r}$ (measured in au) is the position vector of the particle with respect to the Sun, A is the geometrical cross-section of a spherical particle, M is the mass of the particle, $\bar{Q}_{\rm pr}$ is the spectrally averaged dimensionless efficiency factor for radiation pressure, and $\eta \approx 1/3$ corresponds to the effect of solar wind. As for the Lorentz acceleration, the charge of the grain is $q = 4\pi\varepsilon_0 UR$, where ε_0 is the permitivity of the vacuum, U is the surface potential given by Kimura & Mann (1998), radially expanding solar wind is given by

$$\boldsymbol{v}_{\rm sw} = v_{\rm sw}\boldsymbol{e}_R, \tag{4}$$

the magnetic field is considered in the form (Parker 1958; Grűen et al. 1994)

$$\begin{aligned} \boldsymbol{B} &= B_R\boldsymbol{e}_R + B_T\boldsymbol{e}_T, \\ B_R &= B_0\,(r_0/r)^2\cos(\pi t[\mathrm{yr}]/11 + \varphi_0), \\ B_T &= B_0\,(r_0/r)\cos\vartheta\,\cos(\pi t[\mathrm{yr}]/11 + \varphi_0), \\ B_0 &= 3\times 10^{-9}T, \\ r_0 &= 1\,\mathrm{au}, \qquad \boldsymbol{e}_T = \boldsymbol{\omega}\times\boldsymbol{e}_R, \end{aligned} \tag{5}$$

where $\boldsymbol{\omega}$ defines the magnetic axis of the Sun, ϑ is the altitude from the solar equatorial plane, and different orientations of the magnetic field for the Northern and Southern hemispheres are also considered.

The dynamics of small submicron-sized particles is significantly affected by the LF. Its efficiency changes with dust surface potential U. In equations (3), we assume radial dependence of $U(r)$ according to Kimura & Mann (1998) with the value $U = +3V$ in the central part of the Solar system. We analyse the particle motion for the solar wind speed 400 km s^{-1} (Zirker 1981; Hanslmeier 2002). The phase angle of the magnetic field $\varphi_0 = 0$ is assumed.

The coefficient $\bar{Q}_{\rm pr}$ in equation (3) is a complex function of particle composition and size and depends also on the spectral characteristics of incident radiation, so the total radiation cross-section of the particle employs a form

$$\bar{C}_{\rm pr} = \frac{\int_{\lambda_1}^{\lambda_2} F_\odot(\lambda) C_{\rm pr}\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} F_\odot(\lambda)\,\mathrm{d}\lambda}, \tag{6}$$

where the single cross-section for radiation pressure $C_{\rm pr} = Q_{\rm pr}\pi R^2$ and the interval (λ_1, λ_2) covers the VIS spectrum and the near-IR spectral band in this computational model.

3.2 Change of dust optical properties with T_g

The temperature-induced change of the dielectric function mainly influences $Q_{\rm pr}$ for small particles, with a size comparable to the wavelength of incident radiation. Particles with size parameter $x = 2\pi R/\lambda$ greater than about 100 are in principle not influenced as $Q_{\rm pr}$ changes very slightly when approaching an asymptotic behaviour (Shah 1992). There exist various approximations for calculating the macroscopic optical response of the spherical particles. For instance, Laor & Draine (1993) successfully employed the Rayleigh–Gans theory to approximate the scattering asymmetry factor $\langle\cos\Theta\rangle\ (x)$ with the function $0.3x^2/(1 + 0.3x^2)$ on the whole scale $0 < x < \infty$. Nevertheless, the given approximation is not applicable to any cosmic dust material and also $\langle\cos\Theta\rangle\ (x)$ rarely approaches 1 at large x. In such a case, $Q_{\rm pr}$ is always formed by both the scattering and absorption properties of the dust particles. Systematic numerical calculations showed that the amplitude of the fluctuations of $Q_{\rm pr}$ at $R > 10\ \mu$m is less than $\approx$0.005 for many materials (except carbonaceous solids).

Solving equation (2) under the condition of thermal equilibrium, one can find $T_{\rm g}$ for various materials as a function of heliocentric distance r. Several calculations were performed already in the past for typical cosmic dust samples and cosmic dust analogues (Lamy 1974; Röser & Staude 1978; Swamy et al. 1989; Hanner et al. 1997). It was shown that the temperature of the small dust grains may change in a large interval, from less than 100 K up to more than 1000 K depending on the particle composition.

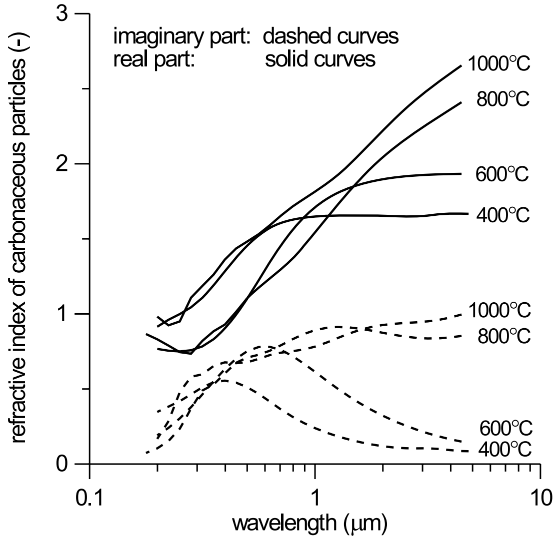

Figure 1. Optical constants of carbonaceous dust and their temperature dependence; data from Jäger et al. (2003).

3.3 Carbonaceous dust particles

The optical properties of carbonaceous interplanetary dust particles and their temperature dependence at elevated temperatures (Fig. 1) were modelled in agreement with data derived by Jäger et al. (2003). The optical constants at low temperatures were adopted according to Rouleau & Martin (1991). The optical data satisfactorily cover the temperature range, which was calculated from equation (1) for carbon particles under conditions of thermal equilibrium.

The dynamics of the dust grain is influenced by values of $\bar{Q}_{\rm pr}$, as follows from equation (3). We calculated averaged efficiency factors for radiation pressure $\bar{Q}_{\rm pr}$ using equation (6) employing relation $\bar{Q}_{\rm pr} = \bar{C}_{\rm pr}/\pi R^2$. As the dielectric function varies considerably at high temperatures, the quantity $\bar{Q}_{\rm pr}$ suffers a step change close to the Sun. However, carbonaceous grains sublimate near 4 R$_\odot$ (Kimura, Ishimoto & Mukai 1997), therefore we avoid numerical runs in the vicinity of the Sun. To clarify the given facts, we illustrate a behaviour of $\bar{Q}_{\rm pr}$ in Fig. 2 for spherical particles with the radii interval $\langle 0.1, 2\ \mu\mathrm{m}\rangle$ moving in the interplanetary space above Earth's orbit. Particles of these sizes show the motional behaviour mostly dependent on temperature changes. It was shown that optical properties of the particles smaller than 1 μm in size respond to the variation of temperature efficiently also at large heliocentric distances r.

In spite of the evident asymptotic behaviour of $\bar{Q}_{\rm pr}$ already at r larger than a few au, the differences in optical responses of the carbonaceous dust particles are still obvious at heliocentric distances of several au (Fig. 3). Taking into account that $\bar{Q}_{\rm pr}$ varies mainly between 1 and 2 (see Fig. 2), the radiation pressure on submicron-sized particles undergoes an entirely identifiable change at distances above the Earth's orbit. For instance, the $\bar{Q}_{\rm pr}$ for a 0.8-μm-sized particle ($R = 0.4$ μm) decreases by about 5 per cent when the particle moves from large distances to $r \approx 1$ au. As the particle approaches the Sun, the radiation pressure fluctuates with an amplitude ≈ 0.1, i.e. between 5–10 per cent of its initial value. A similar behaviour was found at larger heliocentric distances, but with smaller amplitudes of $\delta\bar{Q}_{\rm pr}$, i.e. 0.05 at $r = 2$ au and 0.02 at $r = 5$ au. The computational results indicate that the greatest evolutionary advancements of submicron-sized carbonaceous spherical particles occur in the inner parts of Earth's orbit. Near the Sun, both the absolute values and the fluctuations of $\bar{Q}_{\rm pr}$ are of the same order. This fact

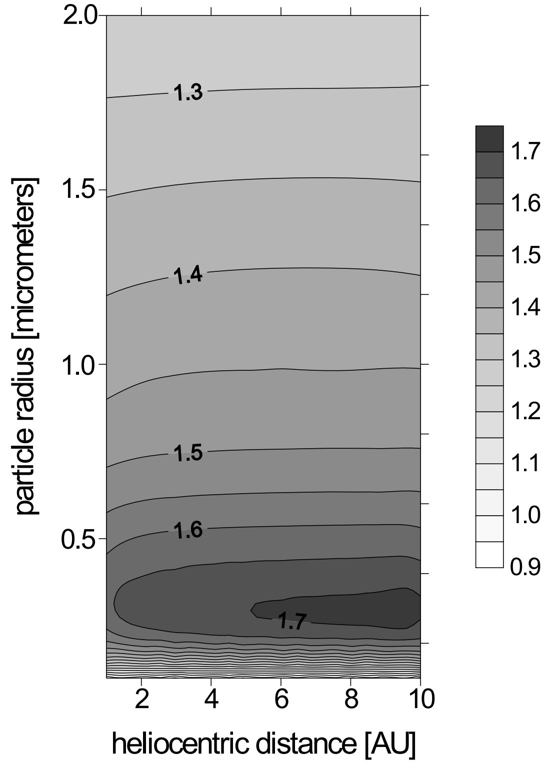

Figure 2. The values of $\bar{Q}_{pr}$ for carbonaceous particles of different radii.

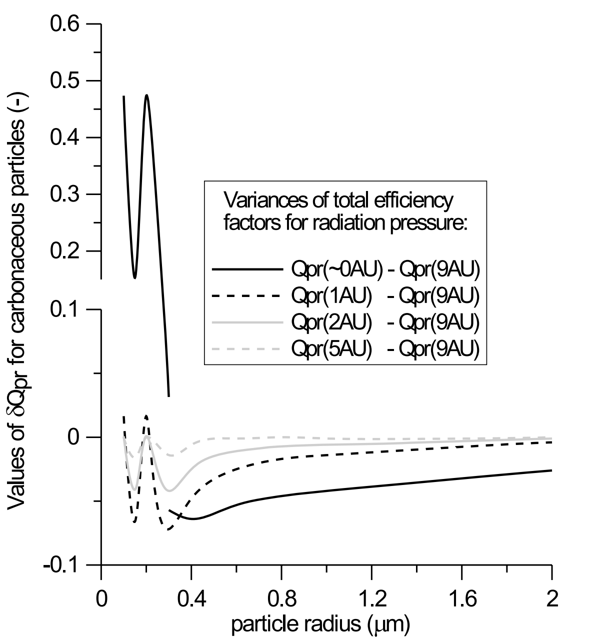

Figure 3. Relative change of $\bar{Q}_{pr}$ for carbonaceous particles of different size when the particles move from heliocentric distances of 9 au to a given distance from the Sun (0, 1, 2, or 5 au).

definitely influences the lifetime of the particle, whereas the oscillating character of $\delta\bar{Q}_{pr}$ may strongly decelerate the spiralling of the grain towards the Sun. Moreover, the grain may be exceptionally blown off by increasing radiation pressure, or temporarily stabilized in a certain region due to alternating $\bar{Q}_{pr}$.

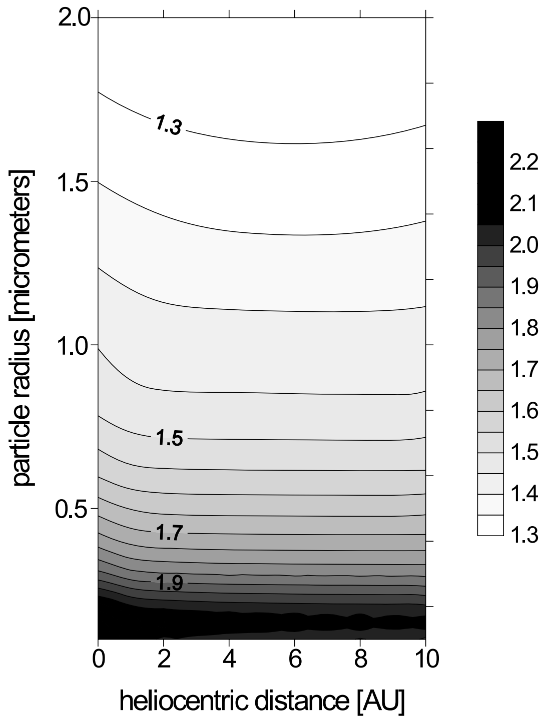

Figure 4. The values of $\bar{Q}_{pr}$ for Si particles of different radii.

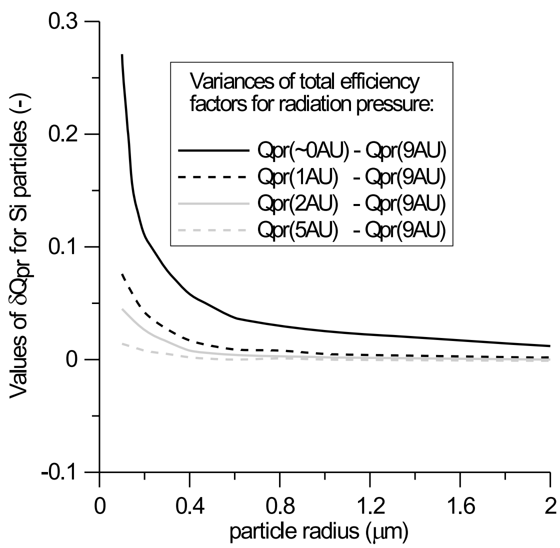

Figure 5. Relative change of $\bar{Q}_{pr}$ for Si particles moving from heliocentric distances of 9 au to a present position at 0, 1, 2, or 5 au from the Sun.

3.4 Si dust particles

We modelled the amorphous phase of Si material using a temperature-dependent dielectric function taken from Yavas et al. (1993), while pure silicon shows another temperature behaviour (Lautenschlager et al. 1987; Jellison & Modline 1994). For the temperature change of the imaginary and real parts of the silicon refractive indices, we used piecewise linear interpolation to model the dielectric function at various temperatures. Due to the high values of the refractive indices, $\bar{Q}_{pr}$ may be fairly large especially at small particle radii. In contrast to carbonaceous particles, $\bar{Q}_{pr}$ decreases with heliocentric distance for amorphous silicon (Fig. 4). It is documented also by the results presented in Fig. 5, where the behaviour of

$\delta \bar{Q}_{pr}$ is shown for particles of different radii. Because of the weak temperature dependence of the real part of the refractive index and the small values of the imaginary part of the refractive index of amorphous silicon at $T_g < 300$ K, a variance of the radiation pressure is less important in the outer region above the Earth's orbit. Unlike amorphous silicate, m and $\delta \bar{Q}_{pr}$ change significantly with temperature for pure silicon. This fact will surely result in a completely different orbital evolution of particles composed of this material.

4 NUMERICAL RESULTS

We want to show the temperature effect on the orbital evolution of spherical interplanetary dust particles. As the effect depends on the distances from the Sun, we have to consider high eccentric orbits of the particles.

The orbital evolution of the particle was calculated using the equation of motion equation (3). The numerical solution was based on the well-known Runge–Kutta method. As a result of the Runge–Kutta method, the position vector $\boldsymbol{r}$ and velocity vector $\boldsymbol{v}$ were obtained for a given time. The orbital evolution in terms of orbital elements can be gained on the basis of these two vectors $\boldsymbol{r}$ and $\boldsymbol{v}$.

Although the orbital evolution of a given particle strongly depends on its size, it is not the aim to simulate the large ensembles of particles. The main attention is paid to: (i) recognize some features of particle motion influenced by temperature; (ii) show a spectrum of the orbital evolutions of the particles caused by changing optical properties of the particles at different heliocentric distances; and (iii) compare these results with those assuming the dielectric function to be independent of temperature (the reference refractive index was taken for 1 au). Numerical simulations made for particles of size ranging from 0.2 to 60 μm showed that the temperature effect on dust dynamics is negligible for particles with radii R larger than ≈ 2 μm. This is due to the asymptotic behaviour of $\bar{Q}_{pr}$ at large size parameters x. The impact of T_g on the orbital evolution of dust particles is therefore presented only for small grains with $R < 2$ μm and a mean bulk density $2\,\mathrm{g\,cm^{-3}}$, which are well representative values for dust in the Solar system (Corrigan et al. 1997).

Although the particles with $R < 2$ μm form only a small fraction of the total mass of the interplanetary dust population, they certainly contribute to the zodiacal light in VIS spectra. It is evident from the following two facts: (i) the intensity of the scattered light is a product of the number size distribution $f(R)$ and cross-section of dust particles [i.e. it is a function of the surface distribution $R^2 f(R)$]; and (ii) $f(R)$ for the small micronic particles (less than ≈ 20 μm) is proportional to $\sim R^{-2.3}$ (Fixsen & Dwek 2002). Thus, if mass distribution $\sim R^3 f(R)$ peaks at $R \approx 30$ μm, the particles of these radii are less important contributors to the VIS component of the zodiacal light.

The important result is that the temperature-dependent P–R effect alone is negligible. However, its simultaneous action with the LF may be significant.

Results depicted later in Figs 6–11 hold for the case when particles start they motion with orbital elements $a = 2.2$ au (semimajor axis), $e = 0.85$ (eccentricity), $i = 12°$ (inclination) at the aphelion and at this moment all considered non-gravitational forces (equation 3) start to act. This choice was motivated by a sufficiently large dispersion in distances from the Sun. Concurrently, the zone is covered by the data for temperature dependence and close encounters with giant planets do not occur. Higher eccentricities can cause ejection of the dust grain from the Solar system, due to the radiation pressure.

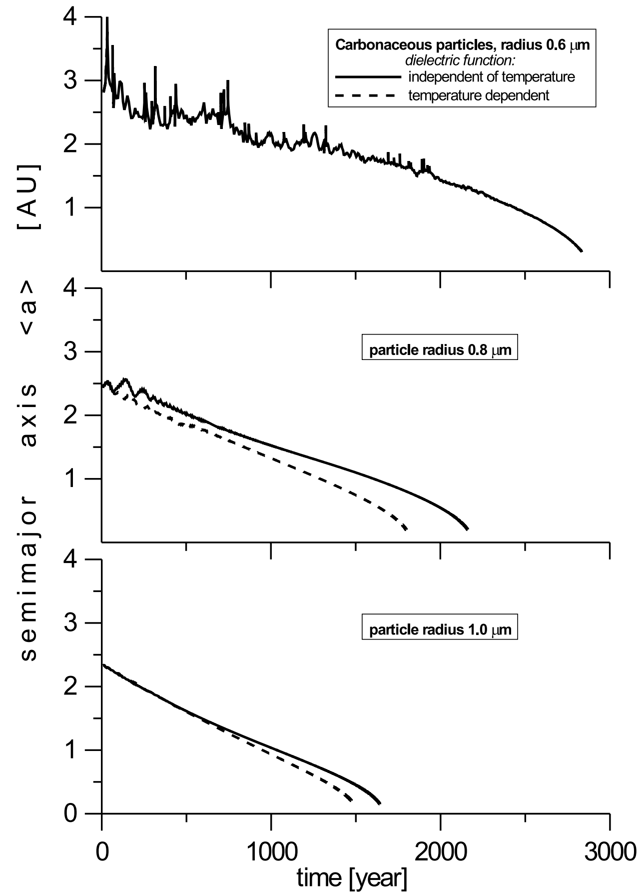

Figure 6. Secular time evolution of the semimajor axis for carbonaceous particles of different radii orbiting the Sun. Solid curves are the dielectric function of carbonaceous particles independent of temperature; dashed curves are the real conditions. The particle of the radius 0.6 μm with a temperature-dependent refractive index (dashed curve) escaped from the Solar system 55 yr after starting the calculation.

4.1 Carbonaceous dust particles

For the purpose of astronomical application of equation (3), it is interesting to calculate the orbital evolution of cosmic dust particles in terms of orbital elements. To describe the long-term orbital evolution, one can deal with mean values of orbital elements. These values may be defined as time averaged values of orbital elements when the true anomaly changes over 2π rad.

There are two situations, which are excluded from further evaluations in this paper: (i) when particles move in the evaporation zone around the Sun [i.e. their distance from the Sun is less than $\approx 3\,R_\odot$ (Ragot 2001)]; and (ii) when the particles are characterized by eccentricities larger than 1 (escape from the Solar system). The runs showed that spherical particles with $R > 0.6$ μm will fall on the Sun. The particles smaller than 1 μm in size may exhibit a quite complex dynamical evolution. Before they hit the Sun, both an increase and decrease of orbitally averaged semimajor axis $\langle a \rangle$ can occur (Fig. 6). Such behaviour is due to the LF as the vibrational ripple structure of the resulting curves is not produced by gravity and electromagnetic radiation force.

Assuming a temperature dependence of the dielectric function, it was found that the lifetime of small carbonaceous particles ($R < 1$ μm) is reduced by more than about 15 per cent in comparison with particles with fixed optical constants. The difference between these

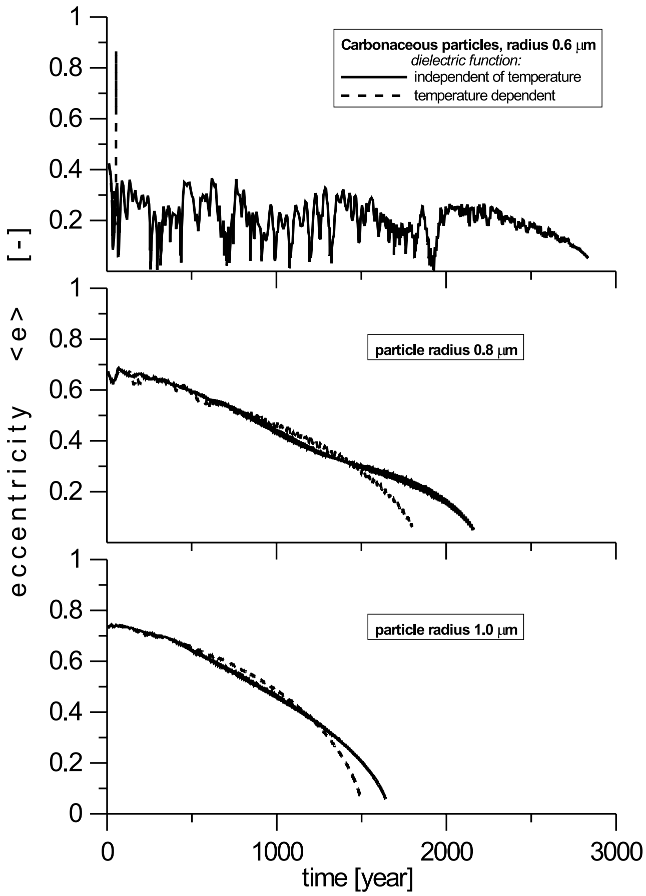

Figure 7. Secular time evolution of eccentricity for carbonaceous particles of different radii orbiting the Sun. Solid curves are assuming the dielectric function of the carbonaceous particles does not change with temperature; dashed curves are the real conditions.

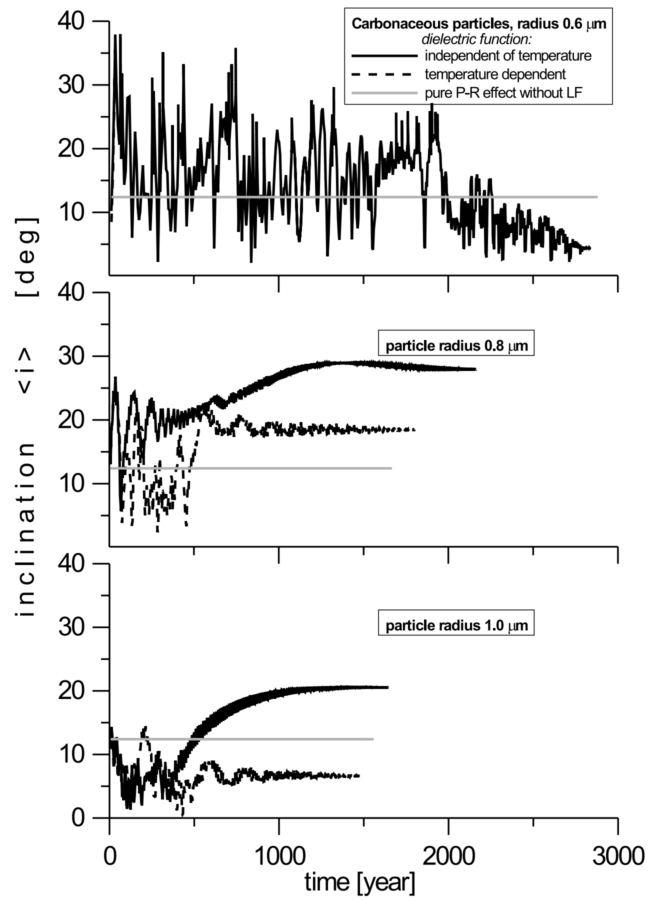

Figure 8. Secular time evolution of inclination for carbonaceous particles of different radii orbiting the Sun. Solid curves are obtained with a temperature-independent dielectric function for carbonaceous particles, unlike the real conditions documented by dashed curves.

lifetimes rapidly grows with a decrease of particle radius (e.g. it is already 25 per cent for $R = 0.8\ \mu$m). A ripple structure which is obvious for the time evolution of $\langle a \rangle$ for particles with radii $R < 0.5\ \mu$m strongly diminishes at $R > 1\ \mu$m because of the reduced efficiency of the LF. However, an impact of the LF on the lifetime of the particles is more complex. The detailed numerical runs on carbonaceous particles give the following results.

(1) For the temperature-dependent dielectric function, the LF:

(i) may reduce the lifetime of both the small submicron-sized and even the 2-μm-sized particles by ≈5 per cent; but it

(ii) increases the lifetime of intermediate-sized particles with $R = 0.8\ \mu$m by 10 per cent.

(2) For refractive indices independent of temperature, the LF:

(i) increases the lifetime by 6 per cent for particles of radii $R = 1\ \mu$m, and by 25 per cent for slightly smaller particles with $R = 0.8\ \mu$m; but in contrast, the LF

(ii) decreases the lifetime of submicron-sized particles, e.g. by 3 per cent when $R = 0.6\ \mu$m.

Such a complex behaviour is a combination of the LF and the electromagnetic radiation force, which changes with the optical properties of dust particles. It is therefore apparent that results collected above will differ from those gained for Si particles.

Eccentricity shows some interesting behaviour (Fig. 7), which for $R < 1\ \mu$m significantly differs from the smooth secular decrease typical for the pure P–R effect. In comparison to the time evolution of particle with a temperature-independent dielectric function, the variable refractive index 'keeps' the carbonaceous grain for a longer time on more elongated orbits, but causes a more rapid decrease of the eccentricity if the semimajor axis is already less than 1 au. It is also accompanied by a decrease in the inclination of the orbit, which for particles characterized by a temperature-dependent dielectric function is about 10°–15° less than for particles having constant optical properties (Fig. 8). The grey line in Fig. 8 reflects the time evolution and the lifetime of the particle in the case of a pure P–R effect (the inclination of such a dust particle is a constant function of time and equals the initial inclination).

Small-scale features of the ripple structure observed with orbital elements characterize a further instability in the time evolution of particles with a temperature-dependent dielectric function. These features are caused by fluctuations of the parameter β, which varies with time for such particles. As a consequence, the third term in equation (3) is time dependent too, so the Keplerian term is given only by gravity. The LF concurrently with the radiation force are therefore responsible for the dispersion of the carbonaceous dust in various directions, although the dominant amount of matter will be spread along the initial Keplerian orbital plane. A considerable amount of these grains is characterized with inclinations differing less than 10° from the initial inclination.

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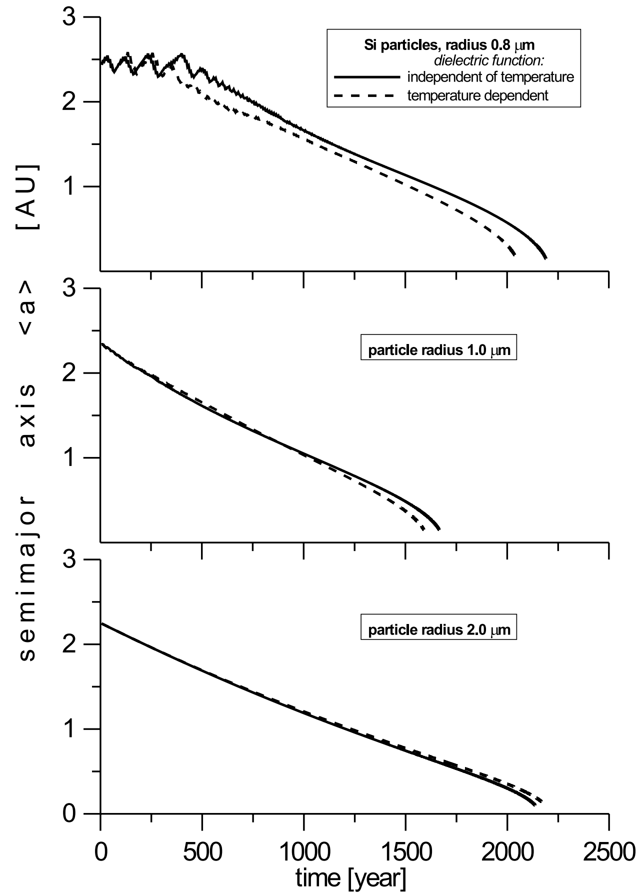

Figure 9. Secular time evolution of the semimajor axis for amorphous Si particles of different radii orbiting the Sun. Solid curves are with a temperature-independent dielectric function for Si particles, unlike the real conditions documented by dashed curves.

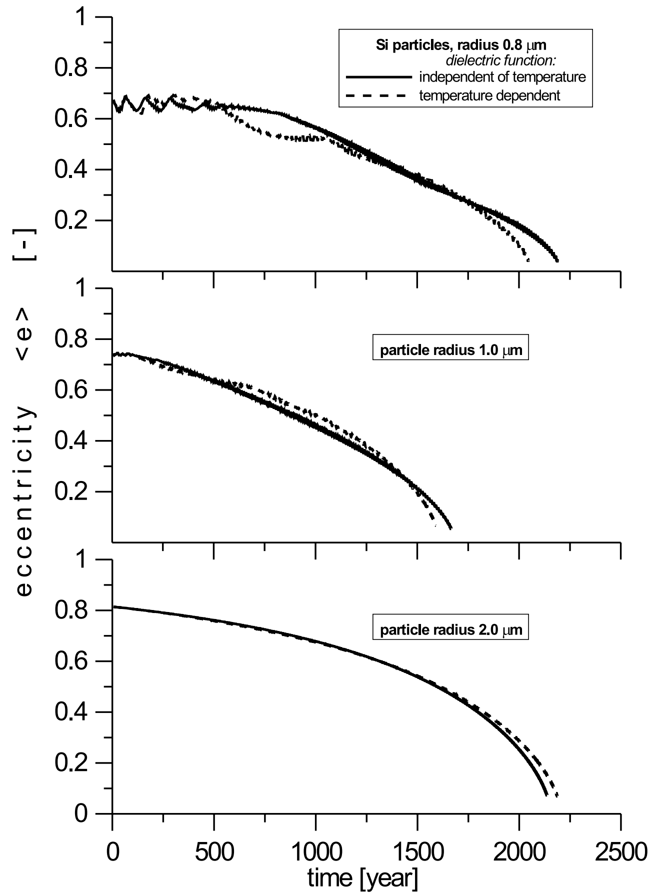

Figure 10. Secular time evolution of the eccentricity for amorphous Si particles of different radii orbiting the Sun. Solid curves are obtained under the assumption that the dielectric function of Si particles does not change with temperature, unlike the real conditions documented by dashed curves.

4.2 Si dust particles

The time evolution of the orbital parameters of amorphous Si particles is less peculiar as found for carbonaceous material because of a weak dependence of the refractive index on grain temperatures. A ripple structure of the time evolution of $\langle a \rangle$ is present only for particles with radii less than $R = 0.8$ μm and definitely does not exist for particles with $R \geqslant 1$ μm (Fig. 9). As indicated in the previous subsection, the final dynamical behaviour of small dust particles is definitely impacted by the LF and the electromagnetic radiation force, which is a complex function of the particle optical properties. Even with the bulk density of dust grains assumed to be constant, one can expect non-equal time evolutions of particles composed of different materials.

For instance, the lifetime of 2-μm-sized Si particles with temperature-dependent optical constants is approximately 5 per cent smaller than the lifetime of particles for which the temperature effects are not taken into account. This difference is about 15 per cent for particles with radii 0.8 μm. However, the behaviour is the opposite for large particles: already 4-μm-sized particles with a temperature-dependent dielectric function will survive in the Solar system for a longer time than the same particles with refractive indices fixed in time. An impact of the LF on the lifetime of Si particles differs from that found for carbonaceous grains. The detailed numerical runs showed that the LF will, in general, cause an increase in the lifetime of particles with radii smaller than 1 μm of:

(i) at least about 4 per cent (but it is already about 17 per cent for slightly smaller particles with $R = 0.8$ μm) if a temperature-dependent dielectric function is assumed; and

(ii) at least about 8 per cent (but about 25 per cent when $R = 0.8$ μm) if a dielectric function is assumed to be fixed in time.

The time evolutions of eccentricities and inclinations are similar to those for carbonaceous particles, although with small differences. For example, a floating eccentricity in the first 500 yr after ejection of a 1.6-μm-sized particle (Fig. 10) conduces a temporal decrease of eccentricity during a further 500 yr. This period of particle evolution is characterized by the growth of the inclination (dashed curve in Fig. 11), which finally exceeded the value $\langle i \rangle$ computed for a dielectric function independent of temperature (solid curve). While for optical constants independent of T_g a final inclination of 2-μm-sized carbonaceous dust particles is larger than initial inclination i_0, the inclination obtained for the particles of the same size is smaller than i_0 when the temperature dependence of the dielectric function is taken into account. In contrast, the final inclinations of Si particles of the same size are always larger than the starting value of i_0. Even larger particles show a smaller spread of inclinations: Si material with a temperature-dependent dielectric material is distributed along inclinations above the Keplerian orbital plane, while particles with optical constants independent of T_g will have trajectories with $\langle i \rangle < i_0$.

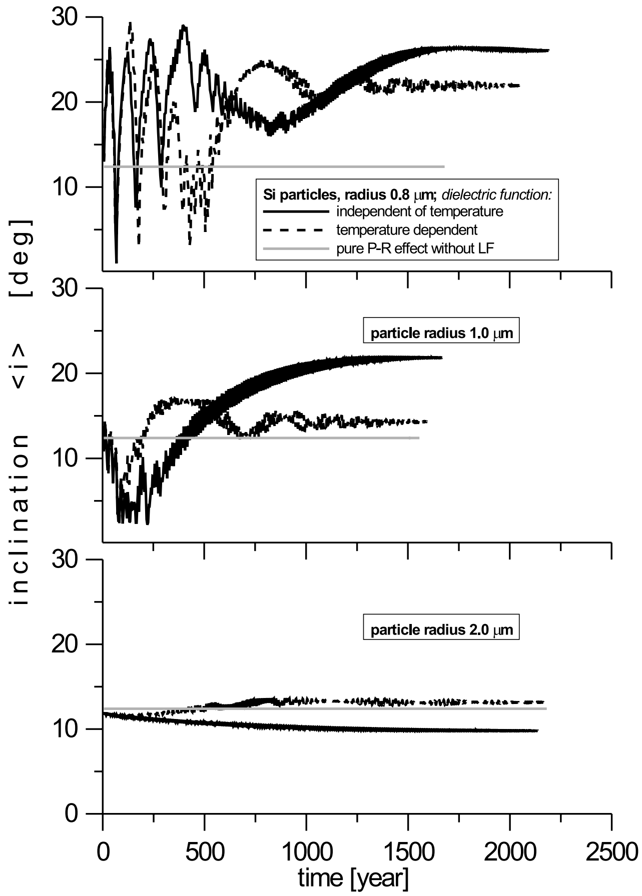

Figure 11. Secular time evolution of the inclination for amorphous Si particles of different radii orbiting the Sun. Solid curves are obtained under assumption that the dielectric function of Si particles does not change with temperature, unlike the real conditions documented by dashed curves.

5 CONCLUSIONS

It is widely accepted that temperature effects on optical constants are not expected to be very strong. In general, the dielectric function of some materials (e.g. of semiconductors) changes with temperature at IR and far-IR wavelengths, but such a change is scarcely recognized in VIS spectra for a number of materials. A temperature evolution of the optical properties in VIS spectra is unimportant in many situations, so this is a probable reason why such studies are rare in the literature. However, already weak temperature dependence of the dielectric function can play a substantial role in the Universe when dealing with the long-term time evolution of small dust particles.

The paper shows that the lifetime of small submicron- and micron-sized particles can be certainly affected when the dielectric function is assumed to be temperature dependent in VIS spectra. The simulations were done for particles with optical constants for carbonaceous and Si materials. The change of real and imaginary parts of the refractive index of the dust particle with its distance from the Sun is followed by a complex particle orbital evolution. The semimajor axis of small micron-sized particles decreases with time more rapidly in the case when optical properties of the material depend on temperature. Consequently, the lifetime of such particles is reduced (e.g. by about 25 per cent for carbonaceous grains with radii $R = 0.8$ μm, and approximately by 15 per cent for Si spheres of the same size). The temperature-dependent dielectric function may be also responsible for the complex distribution of dust material along Keplerian orbital planes. For instance, two systems of carbonaceous particles, the first one characterized by temperature-dependent optical properties and the second one with temperature-independent optical properties, are evidently spatially separated in the interplanetary environment. Especially the inclinations of the orbits differ. In such a way, 2-μm-sized carbonaceous particles are orbiting at trajectories with inclinations larger than the original one if the refractive index is assumed to be fixed in time. In contrast, the final inclinations of particles of the same size will lie below initial value of inclination if variability of optical properties with distance to the Sun (i.e. with temperature) is taken into account.

Nevertheless, the influence of temperature-dependent optical properties on the dynamical behaviour of a spherical particle is important only under simultaneous action of electromagnetic radiation and the LFs. This suggests also that some other non-regular non-gravitational forces may significantly increase the temperature effect. Namely, one should take into account that real particles are non-spherical (aggregates with a complex morphology rather than rotationally symmetric bodies, as usually assumed for numerical simulations). However, the numerical simulations of the orbital evolutions are enormously time-consuming for irregular targets: the dielectric function is temperature dependent and also orientations of the arbitrarily shaped dust grain have to be considered.

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