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Dynamical Effects on Circumsolar Dust Grains

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Abstract. The motion of the interplanetary dust particles in the vicinity of the Sun is not only governed by the gravitational attraction of the Sun but much more effected by the interaction with the solar radiation field. For the interpretation of the data of the micrometeoroid experiment on board Helios 1 we want to establish theoretically a dynamical model of the interplanetary dust cloud.

This requires a thorough investigation of the various interactions of the interplanetary dust grains with the solar radiation field. In this paper we present our results for the radiation pressure force and the temperature distribution of cosmic dust grains in the grain size interval 0.01 to 100 μm.

Key words: Dynamics of interplanetary dust – Grain temperatures.

1. Introduction

Small dust particles in interplanetary space are caused by the Poynting-Robertson effect (Robertson, 1937; Wyatt and Whipple, 1950) to spiral in towards the Sun. With decreasing heliocentric distance evaporation from the surface of such particles increases due to increasing temperature and their size is being reduced accordingly. With decreasing particle size the solar radiation pressure gradually becomes more effective reducing the solar gravitational attraction. By this effect the particle evaporation tends to increase the orbit dimensions, thus acting against the Poynting-Robertson effect. Therefore the inward spiraling, far exceeding the dynamical effect from evaporation at large heliocentric distances, slows down as the particle approaches the sun and ceases when the critical distance is reached, where the two forces approximately balance each other. Then the perihelion distance stabilizes, while the eccentricity starts increasing very rapidly until the particle leaves the solar system. A schematic view of the dynamical effects acting on solid particles in the solar system is given in Figure 1. Not included in the picture are the electric charging of the particles, the interactions with the interplanetary plasma and magnetic field and the rotational bursting (c.f. Schmidt and Elsässer, 1967).

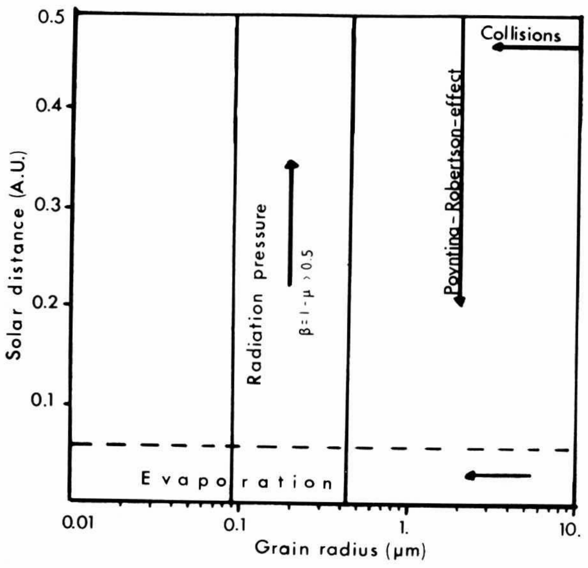


Fig. 1. Dynamical effects acting on solid particles in the solar system. The arrow indicates the direction where the effect changes mass or orbit (ref. Grün, 1974)

All dynamical effects influence the orbit and mass distribution of micrometeoroids: the distribution of cosmic dust reflects the distribution of sources and sinks altered by a variety of dynamical effects acting on the particles. To establish a dynamical model of the interplanetary dust cloud all these effects must be thoroughly investigated. In the following we want to discuss our results for the radiation pressure force acting on the grains and for the temperature distribution $T(R, r)$ of grains of given material as a function of the heliocentric distance R and grain radius r.

2. Radiation Pressure

The force acting on an interplanetary dust particle due to solar radiation pressure at a distance R from the Sun is given by

$$F_{\text{rad}} = \frac{\pi r^2}{c} \frac{R_0^2}{R^2} \int_0^\infty Q_{\text{pr}}[m(\lambda), x(\lambda)]\, s_\lambda \, d\lambda$$

with $R_0 = 1$ a.u., r the radius of the particle, $m(\lambda)$ its complex refractive index, c the velocity of light, λ the wavelength, s_λ the solar flux outside the earth's atmosphere per unit area and wavelength range. The function Q_{pr} is the efficiency factor for the radiation pressure as given by Mie-theory for spherical particles, which depends on the refractive index m and the size parameter x of the particle defined as the ratio of the circumference of the particle to the wavelength (Debye, 1909).

The radiation pressure acts against the gravitational attraction

$$F_{\text{grav}} = \frac{f \cdot M_\odot \cdot m}{R^2}$$

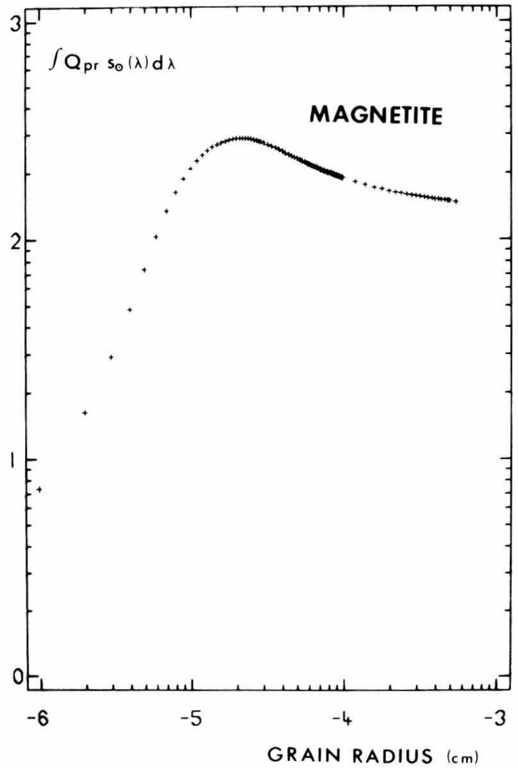


Fig. 2. Integral for radiation presure for magnetite as a function of grain radius logarithmic scale)

by the Sun ($M_\odot$) on the dust grain (m). As both forces fall off with the square of the distance R from the Sun we can subtract the radiation pressure force from the gravitational force

$$F = -F_{\mathrm{grad}} + F_{\mathrm{rad}} = -F_{\mathrm{grav}}(1-\beta)$$

and can look at a particle as it moves in a gravitational potential, which is modified by a factor $(1-\beta)$. The parameter β fully describing the particle properties with respect to this effective potential is given by

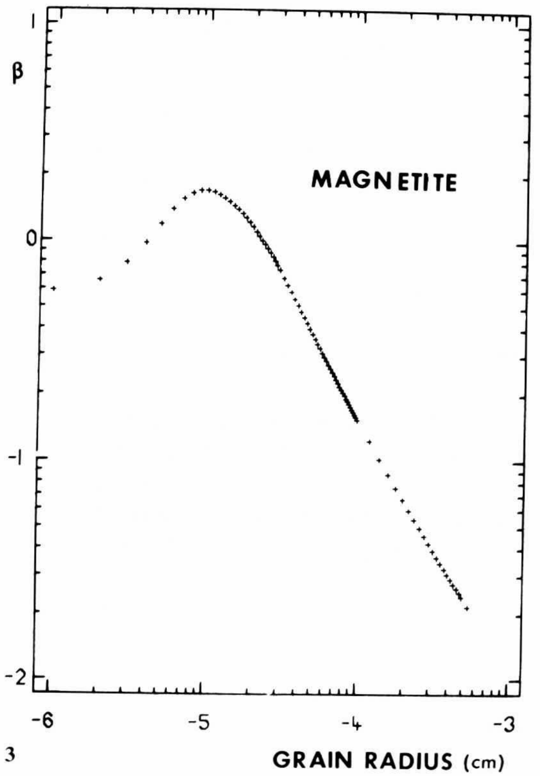
$$\beta = \frac{F_{\mathrm{rad}}}{F_{\mathrm{grav}}} = \frac{3 \cdot R_0^2}{4cfM_\odot} \cdot \frac{1}{\rho \cdot r} \int_0^\infty Q_{\mathrm{pr}} \cdot s_\lambda \, d\lambda$$

which is the ratio of the force due to gravitational attraction to the solar radiation pressure. It is independent of the distance of the particle from the sun and is essentially determined by the radius r and the density ρ of the particle.

The computer program which has been used to calculate the efficiency factors is described in detail in Giese et al. (1974). For the solar radiation flux, values given by Labs and Neckel (1970) have been used. In Figure 2 a typical curve for the efficiency factor for radiation pressure integrated over the solar radiation field is plotted for magnetite as a function of particle radius. β has been

Table 1

Material	References
Ice	Irvine and Pollack (1968)
Obsidian	Pollack et al. (1973)
Andesite	Pollack et al. (1973)
Quarz	Isobe (1975)
Olivine	Huffman (1976)
Magnetite	Steyer and Huffman (1976)



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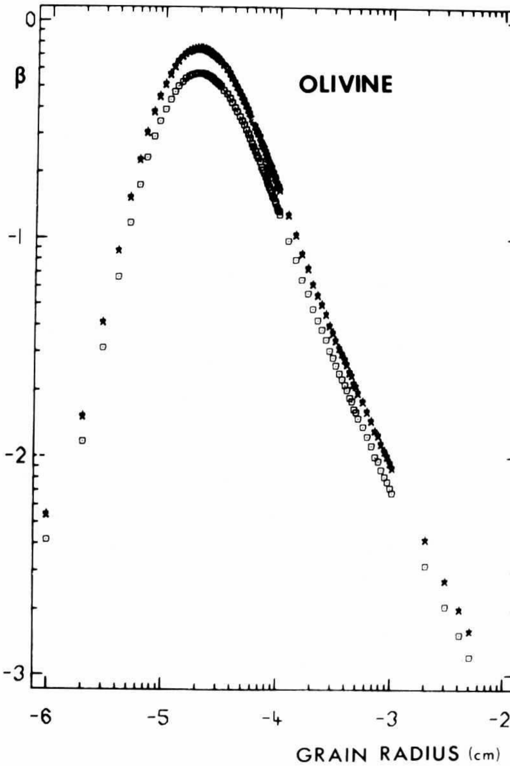

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Fig. 3. The ratio β – in logarithmic scale – of the solar radiation pressure force to the solar gravitational force for magnetite spheres as a function of their radii ($\rho_{magnetite} = 5.2$ g/cm^3)

Fig. 4. β values – in logarithmic scale – for olivine as a function of particle radius for different densities of the material (□ = 4.39 g/cm^3, x = 3.4 g/cm^3, — = 3.28 g/cm^3)

evaluated for different materials regarding the wavelength dependence of their complex indices of refraction. The integration was carried out for every value of the radius over the whole range of wavelengths from 0.1 to 100 µm.
The materials we used in our calculations and the references for their measured refractive indices are given in Table 1.

Figures 3 and 4 show two examples of the β-values for magnetite (Fig. 3) and olivine spheres (Fig. 4). The shape of both curves is very similar, with the maximum of β being at a grain radius of 0.2 microns. While in the case of olivine and the other materials the radiation pressure is not effective for very small particles ($<0.08\,\mu$), for submicron magnetite particles β is always greater 0.5, the critical limit for the particles to escape from the solar system (Dohnanyi, 1972). For larger particles ($>0.8\,\mu$) β drops off very sharply in all cases considered, so that the radiation pressure force is effective only for particles in a very narrow size interval and one should expect a cutoff size for small particles leaving the solar system on hyperbolic orbits (cf. Fig. 7 of the paper by Grün et al., this volume).

One should note, however, that these calculations have been based on the idealistic assumption of spherical particles and of refractive indices of pure materials using the density of the material as found on earth. In space we have to assume a rather "fluffy-type" material with much lower densities (ref. Giese, this volume), therefore the radiation pressure force on the particle can be much higher than the calculated β, as it is inversely proportional to the density of the particle. Further we have to consider radiation damage effects in the grains (Drapatz and Michel, 1977), which yield higher absorption and lead to higher efficiency cross sections for radiation pressure.

3. Temperature Distribution

To determine the temperature distribution we look for the energy balance of a spherical particle in local thermodynamic equilibrium (LTE). This implies that the solar energy absorbed is balanced by the energy reemitted by the particle. To get a simple equation we assume that the particle will have the equilibrium temperature, which is acceptable since the sizes of the grains are so small that the heating is isotropic and heat flow by conduction inside the grain can be neglected. The energy absorbed by a spherical grain of radius r during one second is

$$r^2 \left(\frac{R_0}{R}\right)^2 \int_0^\infty Q_{abs}[m(\lambda), x(\lambda)]\, s_\lambda \, d\lambda$$

where Q_{abs} is the efficiency factor for the absorption of radiation, s_λ again the solar radiation flux.

The energy reemitted by the grain is equal to

$$4\pi r^2 \int_0^\infty Q_{abs}[m(\lambda), x(\lambda)]\, \pi B(\lambda, T_g)\, d\lambda$$

where $B(\lambda, T_g)$ is the Kirchhoff-Planck-function for a grain with temperature T_g.

We thus get for the equation to calculate T_g

$$\left(\frac{R_0}{R}\right)^2 \int_0^\infty Q_{abs}\, s_\lambda \, d\lambda = 4 \int_0^\infty Q_{abs}\, \pi B(\lambda, T_g)\, d\lambda .$$

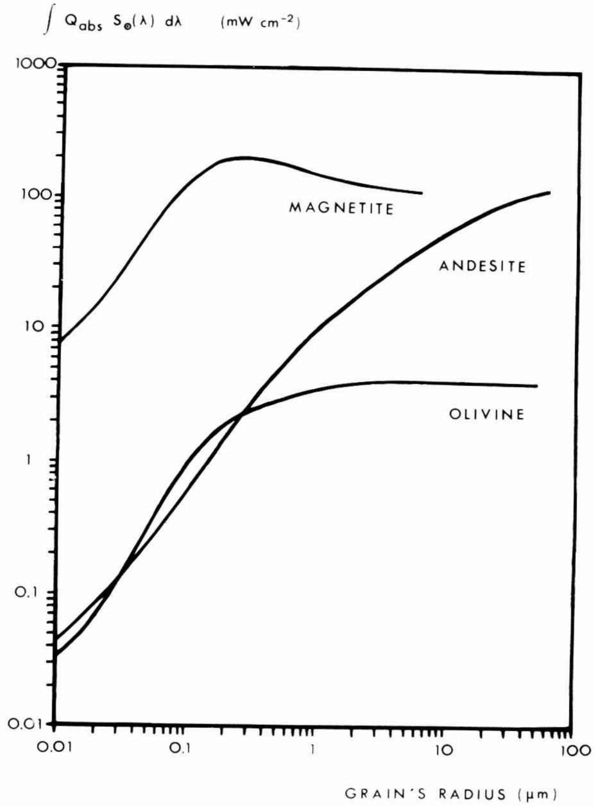

Fig. 5. Energy absorbed per unit area by interplanetary dust grains of different materials as function of grain size

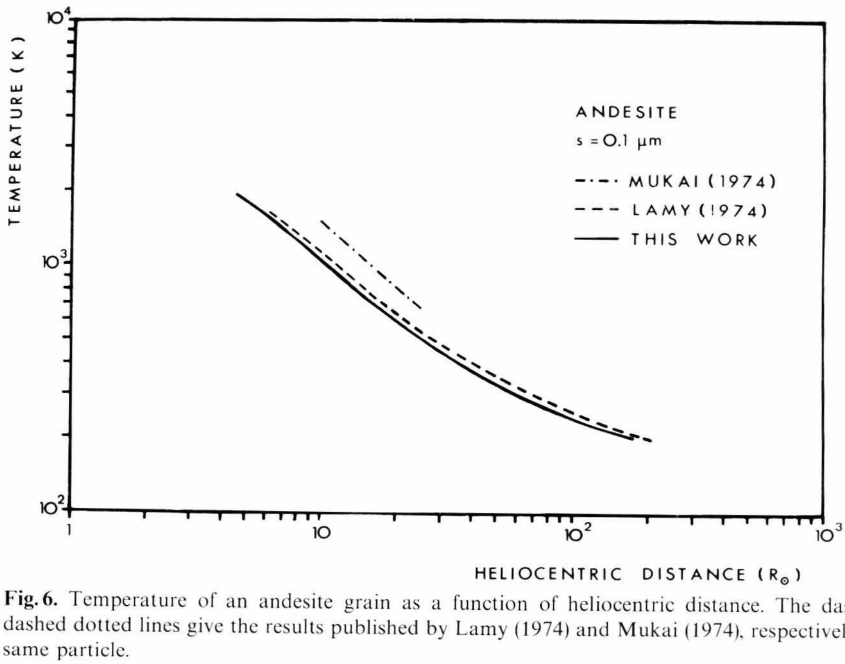

Fig. 6. Temperature of an andesite grain as a function of heliocentric distance. The dashed and dashed dotted lines give the results published by Lamy (1974) and Mukai (1974), respectively, for the same particle.

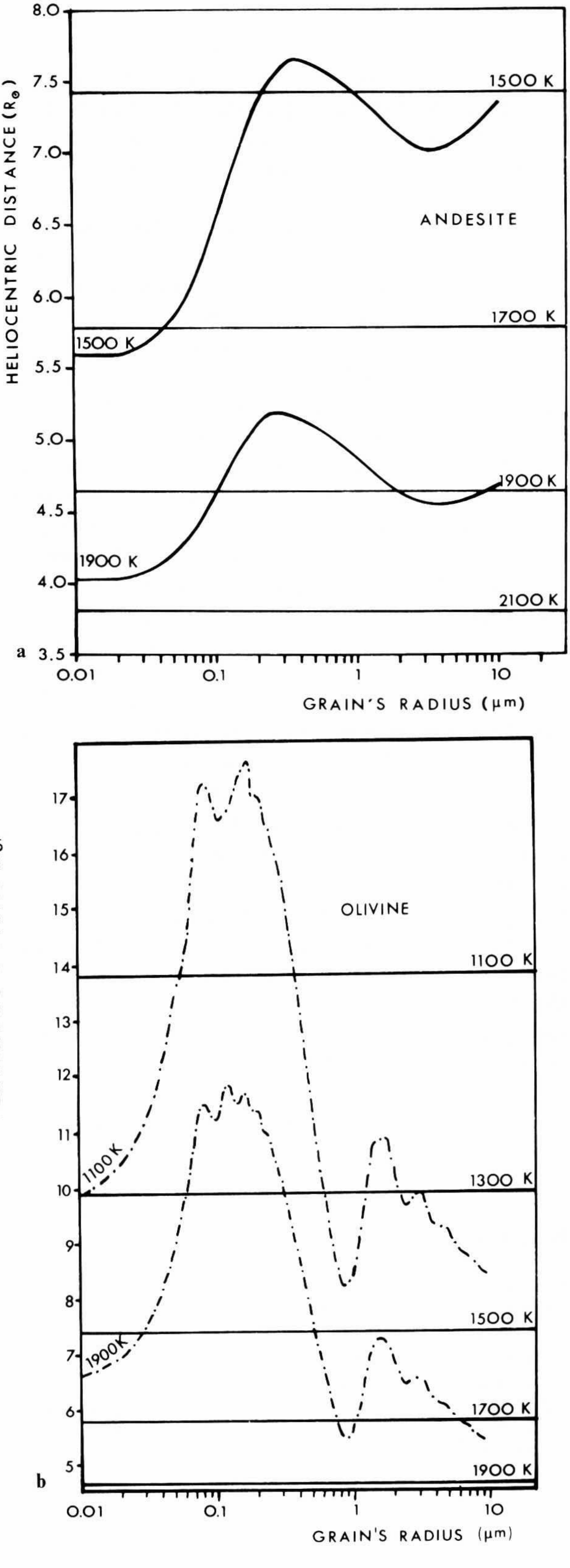

Fig. 7a and b. Temperatures of andesite and olivine grains in units of K are shown as functions of grain radius and heliocentric distance (in solar radii [$R_\odot$]). The straight parallel lines denote black body temperatures at each distance

This equation is very easy to solve for R; we therefore take T_g as the parameter and evaluate the corresponding distance from the sun for a grain with the chosen temperature. The integral on the left-hand side of the equation gives the amount of energy per unit area absorbed by the particle. The dependence of this quantity on the size and the material of the particles is demonstrated in Figure 5.

The temperature of a 0.1 μm andesite particle as a function of its distance from the sun (in solar radii $R_\odot$) is plotted in Figure 6. For comparison values given by Mukai et al. (1974) and Lamy (1974) are also included in the diagram. The slight differences in the results are due to the higher accuray in our computations and to the accurate values for the whole solar energy spectrum, whereas Mukai und Lamy take for certain intervals of the wavelengths a black body approximation for this spectrum (cf. Schwehm, 1976).

To give an idea what the temperature distribution looks like, we have plotted in Figure 7a and b the isothermals for andesite and olivine spheres as a function of grain radius. The distance from the sun, where the particle takes a distinct temperature is given in solar radii. The straight parallel lines give the distances, at which a black body would assume the temperatures indicated. If one takes into account the wavelength dependence of the refraction indices the temperature distribution becomes much more complicated than in the case of a black body approximation (temperature variations of the refraction indices were not considered). The two curves for 1500 K and 1900 K, respectively, give the distance from the sun at which a grain of a certain size will have this temperature, e.g. a 0.01 μm particle has a temperature of 1900 K at 4.0 $R_\odot$ from the sun, a 0.3 μm particle already at 5.2 $R_\odot$, but a 10 μ grain is again colder and reaches this temperature at 4.7 $R_\odot$.

Much more striking is the temperature behaviour of olivine, where the deviation from a black body approximation is very significant (Fig. 7b). In this case the general statement given by Lamy (1974), that the heliocentric distance corresponding to a given temperature tends to increase with increasing grain radius, does not account for the important variation in the temperature distribution for the submicron grains. In the case of olivine heating is most effective for the same size range for which the force due to radiation pressure is highest. This fact plays an important role in the discussion of the orbits and lifetimes of submicron particles and for the existence of a dust free zone around the sun.

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