Radiation pressure on porous micrometeoroids

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Abstract. We discuss the importance of the porosity for radiation pressure forces acting on micrometeoroids. Assuming different morphologies and material compositions of micrometeoroids, we show that an increase in the porosity changes the slope of the β-value, defined as the ratio of the radiation pressure force to the solar gravitational force, as a function of particle size. It reduces the β-value of small grains and enhances the value for large grains. Consequently, the lifetime of grains against the Poynting-Robertson drag force tends to be less influenced by their size and is shortened for large grains. We give simple equations to describe the β-value and the Poynting-Robertson lifetime of large grains as a function of their size and porosity.

1. Introduction

After micrometeoroids are ejected from their parent bodies, they instantaneously suffer from the solar radiation pressure. Therefore the radiation pressure force plays an important role in the evolution of meteoroids and micrometeoroids in the solar system (Burns et al., 1979). It determines which particles are ejected in hyperbolic orbits and which particles drift into the inner solar system due to Poynting-Robertson effect. Also the amount of the drift force and hence the Poynting-Robertson lifetime depends on the radiation pressure force.

Analysis of micrometeoroids trapped in the earth's atmosphere has shown that some particles contain pores and some can be described as an agglomeration of many small grains (Brownlee, 1985). We therefore study the effect of dust porosity on the radiation pressure force and its consequence for the Poynting-Robertson lifetime.

2. Method of computing

We define β as the ratio of radiation pressure force to solar gravitational force acting on a particle. The solar gravitational force $F_{\rm G}$ at distance r from the Sun is given by $F_{\rm G} = GM_{\odot}m/r^2$, where G is the gravitational constant, $M_{\odot}$ is the solar mass and m is the grain's mass. The radiation pressure force $F_{\rm R}$ is calculated by $F_{\rm R} = (S/c)\,C_{\rm pr}$, where S, $C_{\rm pr}$ and c are the integrated solar irradiance at distance r from the Sun, the radiation pressure cross section averaged over the solar irradiance and the speed of light, respectively. We average the cross section over wavelengths of 0.14–300 μm using the solar radiance compiled in Mukai (1990). Note that the ratio β is a dimensionless parameter independent of

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heliocentric distance r because both the solar gravity and the radiation pressure are proportional to r^{-2}.

The solar radiation pressure on a homogeneous spherical particle moving in a bound orbit around the Sun includes not only a direct force $F_{\rm R}$ in the radial direction from the Sun but also a decelerating tangential force known as the Poynting-Robertson effect. This tangential force is given by $F_{\rm R}\,(v/c)$, where v and c indicate the speed of the particle and light, respectively, and causes the gradual drift of particles towards the Sun. However depending on shape and orientation of the particle, the direct force $F_{\rm R}$ of the radiation pressure has in general also a component perpendicular to the radial vector from the Sun (van de Hulst, 1981). Although a certain orientation of the particle may enhance the importance of the perpendicular component (Voshchinnikov & Il'in, 1983), we hereafter limit our consideration only to the radiation pressure forces acting on randomly rotating particles.

Because the radiation pressure cross section $C_{\rm pr}$ depends on the shape and structure as well as the size and material composition of the particle, estimates of $C_{\rm pr}$ need light-scattering theory appropriate to the particle morphology. We shall consider two types of porous micrometeoroids: fluffy aggregates and porous spheres.

Fluffy aggregates. We apply ballistic particle-cluster aggregation (BPCA) and ballistic cluster-cluster aggregation (BCCA) of identical spherical monomers to model fluffy aggregates (Kitada et al., 1993). The mass m of a fluffy aggregate is determined by $m = (4/3)\pi {a_0}^3 N\rho$, where a_0 is the radius of the monomers, N is the number of the monomers, and ρ is the bulk density of the constituent material. According to Kimura & Mann (1998), the radiation pressure cross sections for the fluffy aggregates are computed by the discrete dipole approximation (DDA), which is powerful and flexible method to deal with light scattering by irregularly shaped particles (Draine & Flatau, 1994). We set $a_0 = 0.01\ \mu$m and replace the monomers by single dipoles whose polarizability is determined by the a1-term method suitable to a cluster of spherical monomers (Okamoto & Xu, 1998). Computational resources limit the size range of evaluation into $a_{\rm m} < 0.13\ \mu$m, where $a_{\rm m}$ is the radius of a mass-equivalent sphere described as $a_{\rm m} \equiv N^{1/3} a_0$ for the aggregates.

Porous spheres. We regard a porous sphere as being composed of material and pores (i.e. vacuum) whose sizes a_0 are smaller than the wavelength of consideration: $a_0 \leq 0.01\ \mu$m. The mass m of a porous spherical grain is expressed as $m = (4/3)\pi a^3 (1 - po)\,\rho$, where a and po are the geometric radius and porosity of the grain, respectively. Mie theory, which is the exact solution of Maxwell's equations for a homogeneous sphere, enables us to compute the radiation pressure cross section for a homogeneous spherical grain if the refractive index of the homogeneous medium is given (van de Hulst, 1981). In order to investigate the dependence of porosity on the radiation pressure force acting on the porous spheres, we therefore substitute the effective refractive index of the composite material into the Mie calculations once the effective refractive indices of the

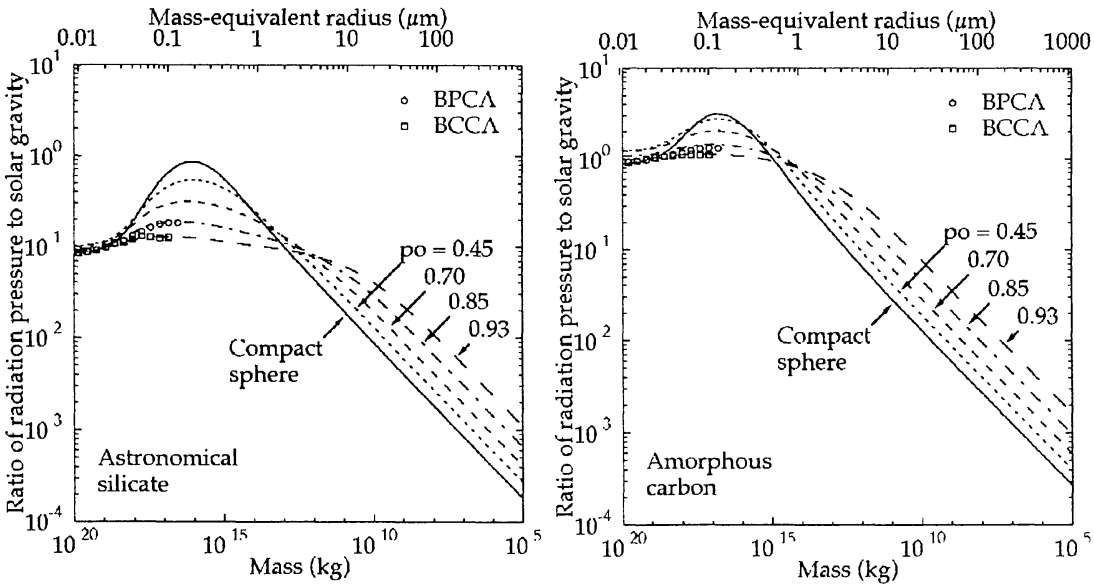

Figure 1. The β-ratio of micrometeoroids with different porosity vs. dust mass. Left panel: astronomical silicate; right panel: amorphous carbon.

composite medium is derived by the Bruggeman theory. Although Mie theory is valid for arbitrary sized particles, we limit our consideration to the size range of $a_{\rm m} \leq 1000$ μm, where the mass-equivalent radius $a_{\rm m}$ of the porous sphere is given by $a_{\rm m} \equiv (1 - po)^{1/3} a$.

3. Numerical results

Figure 1 shows the size dependence of the β-ratio for porous grains as well as compact grains (solid curve). The dotted, short-dashed, dash-dotted and long-dashed curves are the ratios for porous spheres with the porosity of 0.45, 0.70, 0.85 and 0.93, respectively. The circles and squares indicate the β-ratios for the BPCA and BCCA grains. The left panel indicates porous grains composed of astronomical silicate (Laor & Draine, 1993) having bulk density $\rho = 3.3 \times 10^3$ kg m^{-3} and the right panel those of amorphous carbon (AC1) with $\rho = 1.85 \times 10^3$ kg m^{-3} (Rouleau & Martin, 1991).

As the porosity of the porous spherical grains increases, the β-ratio approaches the value for tiny ($a_{\rm m} \sim a_0$) grains. Consequently, an increase in the porosity flattens the peak of the β-ratio at $a_{\rm m} \sim 0.1$ μm and enhances the ratio for large ($a_{\rm m} >> 1$ μm) grains. Grains composed of different material show the same tendency, while the absolute magnitude depends on the material composition.

The β-ratios for the BPCA and BCCA are well represented by those of porous spheres with high porosity $po \approx 0.85$ and $po \approx 0.93$, respectively. The β-ratio of a very fluffy aggregate is almost the same as the value for the constituent monomer.

4. Discussion

We have shown that the β-ratios for highly porous grains in the radius range $a_{\rm m} \leq 1$ μm approach those of constituent grains in the limit of $po \rightarrow 1$. It is worthwhile noting that the β-values for constituent grains may depend on the radius a_0. Accordingly the β-values of a very highly porous grain may be expressed as $\beta \approx \beta_0$ near the peak, where β_0 is the β-value for a compact spherical grain having the radius a_0.

The high β-values for large porous grains result from the fact that light scattering by large grains falls in the geometrical optics regime. Namely the radiation pressure cross section for a large porous grain with porosity po is just its geometrical cross section πa^2, which is $(1-po)^{-2/3}$ times larger than that of a compact spherical grain ($po = 0$) with the same mass. Therefore the β-values for large porous grains with porosity po can be given by $\beta \approx \beta_{\rm c}(1-po)^{-2/3}$, where $\beta_{\rm c} = 9.0 \times 10^{-4}\rho^{-2/3}m^{-1/3}$ (in mks unit) is the β-ratio for compact spherical grains having the same mass.

Applying these results to micrometeoroids, the Poynting-Robertson lifetime τ at distance R is proportional to the inverse of the β-ratio, that is, $\tau = 400R^2\beta^{-1}$ years with R in AU. Because the dependence of the β-ratios on the size is very weak for highly porous micrometeoroids in the radius range $a_{\rm m} \leq 1$ μm, the Poynting-Robertson lifetime becomes independent of mass m for $po \rightarrow 1$. On the other hand, the Poynting-Robertson lifetime τ for large porous micrometeoroids with porosity po can be given by $\tau \approx \tau_{\rm c}(1-po)^{2/3}$, where $\tau_{\rm c}$ is the Poynting-Robertson lifetime for a compact spherical particle having the same mass. Consequently the Poynting-Robertson lifetime for large porous micrometeoroids is shorter than that for compact spherical grains.

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