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# Radiation pressure forces of fluffy porous grains

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**Abstract.** Based on Mie theory and Maxwell-Garnett effective medium theory (MG-Mie), we have examined a ratio $\beta$ of the radiation pressure forces to the gravity on porous aggregates with fractal structures, which consist of absorbing (graphite or magnetite) or dielectric (silicate) materials. A comparison of $\beta$ by MG-Mie theory with those computed by the discreate dipole approximation (DDA) has shown that when the dust aggregates have rather compact structures and/or the constituent particles are absorbing materials, the values of $\beta$ by DDA theory are reproduced reasonably by MG-Mie theory.

Furthermore, it is found that (i) the higher the porosity, the smaller the value of $\beta$ becomes near the maximum of $\beta$ at a characteristic radius of the aggregate of about 0.1 μm. (ii) For very porous aggregates, $\beta$ does not depend on size in contrast to a remarkable size dependence of $\beta$ for compact spheres. (iii) It would be expected from the MG-Mie theory that regardless of the chemical composition of constituents, $\beta$ of porous grains approaches a constant value, which is close to that for the individual constituent particle, as the porosity increases. Consequently, when the radiation pressure forces are significant in comparison with the gravity, the dynamical behaviour of large fluffy particles with high porosity in the interplanetary space seems to be similar to that of the small compact particles which make up their internal structure.

**Key words:** radiation pressure forces – interplanetary dust – irregularly shaped particles

## 1. Introduction

Radiation pressure forces on dust particles play an important role in the dynamical behaviour of grains in interplanetary space and in cometary atmospheres (e.g. Gustafson 1989; Mukai et al. 1989), as well as in the rings of planets (e.g. Mignard 1984). In addition, recently the radiation forces on particles in dust discs around low-mass main-sequence stars have been examined to study grain removal from such regions (Wolstencroft & Walker 1988), and to estimate the drift velocity of grains relative to the gas (Hecht 1991).

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It is well known that the radiation pressure forces on grains depend strongly on the physical properties of the grains, such as grain size and the optical constants of the grain materials. The dependences of radiation forces on the grain's nature have been studied in detail (see e.g. Burns et al. 1979). Most of these studies, however, have been done under the assumption that the grain is a spherical particle with homogeneous structure, although Voshchinnikov & Il'in (1983) examined the radiation forces on cylindrical dust particles and Gustafson (1989) considered, more generally, those on nonspherical dust grains.

Recent studies on the shape and structure of grains in various environments have suggested a more complex structure of grains. The growth of particles by mutual collisions would tend to produce fluffy porous grains with fractal structure (e.g. Greenberg 1985; Whitten & Cates 1986). Mathis & Whiffen (1989) have even proposed a fluffy aggregate model for interstellar dust particles, consisting of a collection of submicron-sized particles composed of astronomical minerals. Furthermore it has been pointed out that there are many fluffy particles in the collected samples in the upper atmosphere of the Earth (e.g. Brownlee 1978). Therefore it seems to be natural to assume that most of the grain particles existing in the denser region of space are irregularly shaped particles with heterogeneous structure.

How can we estimate the radiation pressure forces on such irregular particles? It seems to be accepted that a fluffy particle with nearly the same geometrical cross section as a compact particle is easily moved by the radiation pressure against the gravity on it, because of a lack of mass inside the fluffy particle. Is this true? To answer this question is the simple motivation of our work.

In the article we examine the radiation pressure forces on fluffy porous grains with fractal structure. A comparison of the resulting forces on such particles with those on spherical grains with homogeneous structure will be done to clear what modification of the previous studies on the dynamical behaviour of spherical dust particles is needed.

## 2. Radiation pressure forces

The radiation pressure force $F_R$ on a grain with a geometrical cross section $A$ is given by

$$F_R = \left(\frac{A}{c}\right)\left(\frac{R_0}{R}\right)^2 \int_0^\infty B_0(\lambda, T)\, Q^*_{PR}(m^*, \lambda)\, d\lambda, \quad (1)$$

where $R$ is the distance of the grain from the central radiation source with a radius $R_0$, and $B_0$ is the Planck function at an effective temperature $T$. The speed of light is $c$ and $\lambda$ is the wavelength of the incident radiation. $Q^*_{PR}$ is the efficiency factor for radiation pressure which value depends on grain size, shape and the optical constants $m^*$ of the grain material. It should be noted that $Q^*_{PR}$ is the efficiency factor for radiation pressure.

The gravitational attractive force $F_G$ on the grain with mass $m$ is defined by

$$F_G = \frac{GMm}{R^2} \tag{2}$$

where $G$ is the gravitational constant and $M$ is the mass of the central radiation source. It is convenient to define a ratio $\beta = F_R/F_G$, i.e.

$$\beta = K\left(\frac{A}{m}\right) \int_0^\infty \lambda^{-5} Q^*_{PR}(m^*, \lambda) \left\{\exp\left(\frac{hc}{\lambda kT}\right) - 1\right\}^{-1} d\lambda, \tag{3}$$

where $K$ is a constant ($=2\pi hc R_0^2/GM$) and $K = 4.55\ 10^{-20}$ in cgs units in the solar system. The $h$ and $k$ denote the Planck constant and the Boltzmann constant, respectively. It should be mentioned that $\beta$ is independent of $R$.

In the following discussion, we will focus our consideration on the value of $\beta$ in the interplanetary space. However, it is easy to apply our results to grains, for example, in dust disks around main-sequence stars by changing the values of $K$ and $T$ in Eq. (3), when the optical thickness is small enough.

## 3. Model for porous grains

Little is known about the physical properties of porous particles existing in space. However, if we assume that the agrregates grew up by sticking following inelastic collisions of constituent particles, such disorderly growth processes may produce porous aggregates with fractal structures (see, e.g. Witten & Cates 1986). We have proceeded computer simulations for collisional coagulation of grains to deduce the nature of fluffy aggregates. The ballistic deposition model (see e.g. Meakin 1987) is applied to simulate the growth of the aggregates with tenuous structures.

We have produced various types of aggregates by three dimensional Monte-Carlo simulation but for simplicity, we deal here with two extreme cases only, which we call ballistic particle-cluster aggregation (BPCA) and ballistic cluster-cluster aggregation (BCCA), respectively. In the case of BPCA, a cluster grows by deposition of single primary particles falling in at random ballistic (linear) trajectories one at a time. All primary particles are spherical, have the same size, and are incorporated into the aggregate with sticking probability = 1. In the case of BCCA, collisions between two clusters of equal mass were simulated step by step to produce larger aggregates. Details of the simulation procedure will be shown in a separate paper (Blum & Kozasa 1992), so we present here only a brief summary of the results.

As shown in Fig. 1, a BPCA cluster has a somewhat more compact structure in contrast to a BCCA cluster with the same number $N$ of the constituent particles (here $N = 16384$). This evidence is clearly confirmed in Fig. 2 where the number of constituent particles (as a measure of the mass of the aggregates) is plotted vs. the normalized radius of gyration $r_g/r_0$, where $r_0$ is the radius of the primary particles, and $r_g$ is given by

$$r_g = \left[\frac{1}{2N^2} \sum_i^N \sum_j^N (\boldsymbol{r}_i - \boldsymbol{r}_j)^2\right]^{1/2},$$

$\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are the position vectors of the $i$-th and $j$-th constituent particles. The structure of fluffy particles is described in terms of the fractal dimension $D$ (e.g. Witten & Cates 1986), which is defined by the relation $N \sim r_g^D$ (Meakin 1987). Our computed results confirm this relation, at least, in $N > 10^2$ and we have found $D = 2.98 \pm 0.02$ for BPCA and $D = 1.93 \pm 0.07$ for BCCA. A value of $D$ close to 3 implies that the aggregates have a somewhat constant density.

As an appropriate description for the actual size of an aggregate, we define the characteristic radius $r$ as $r^2 = (5/3)\, r_g^2$, which represents the radius of a homogeneous sphere with the same radius of gyration as the aggregate. It is convenient to define a porosity $po$ of the aggregate with the characteristic radius $r$ as $po = 1 - (V_{in}/V)$, where $V_{in}$ and $V$ denote, respectively, the total volume of the constituent particles (i.e. $V_{in} = N(4/3)\pi r_0^3$) and the volume of a sphere with a radius $r$ (i.e. $V = (4/3)\pi r^3$). By using the results in Fig. 2, it becomes $po = 1 - \alpha (r/r_0)^{D-3}$, where $\alpha$ is a factor defined as $N = \alpha (r/r_0)^D$ and the value of $\alpha$ depends on the coagulation process. Referring to the results of our numerical simulations, we use, for simplicity, a relation of $\log \alpha = -D/2 + 0.7$ in the following calculations.

We have also derived from these simulations the geometrical cross section $A$ of the resulting aggregates, averaged over three orthogonal directions, as a function of $N$ (see Fig. 3). It is found that for larger values of $N (N > 10^4)$ $A \sim N^\delta$ with $\delta \leqq 0.698$ for BPCA and $\delta \geqq 0.947$ for BCCA. Combining both results shown in Figs. 2 and 3, we obtain $A \sim r^2$ for both, BPCA and BCCA clusters within the uncertainties of our simulation.

## 4. The values of $\beta$ for porous aggregates

### 4.1. $A/m$

If the integration concerning the wavelength in Eq. (3) is constant, $\beta$ varies with $(A/m)$ alone. Since $(A/m) \sim (A/N) \sim r^2/r^D$ in our model for porous aggregates defined in Sect. 3, $\beta \sim r^{-0.98 \pm 0.02}$ for BPCA and $\beta \sim r^{-0.07 \pm 0.07}$ for BCCA, where $r$ denotes the characteristic radius of the aggregates as defined before. It is well known (see e.g. Burns et al. 1979) that $\beta$ for a compact sphere ($\beta_C$) with a radius $s$ is proportional to $(1/s)$ in a range of $s$ larger than at least 0.5 μm. It follows that $\beta/\beta_C$ takes on a nearly constant value for BPCA while $\beta/\beta_C \sim s$ for BCCA, when it is assumed $r = s$. This implies that the importance of the radiation force relative to the gravity on porous aggregates of BCCA type increases with increasing size of the aggregate. Since in the case of $D < 3$ larger fractal aggregates automatically have higher porosity, this conclusion leads to the general concept, noted in the introduction, that sufficiently large fluffy particles are easily blown away by radiation forces than compact ones of comparable size.

Is this result true for "actual" porous aggregates? To examine this question, we have to study the variation of the integral part in Eq. (3) with changing structure of the aggregates.

### 4.2. *Mie theory combined with the Maxwell-Garnett rule*

Several methods were proposed recently to study electromagnetic scattering and absorption by irregularly shaped particles with inhomogeneous structures, e.g. the discrete dipole approximation (DDA) (Purcell & Pennypacker 1973; Draine 1988) and the volume integral equation formulation (VIEF) (Iskander et al. 1989; Hage et al. 1991). The limitation and validity of both methods have been checked in several papers (e.g. Wright 1987;

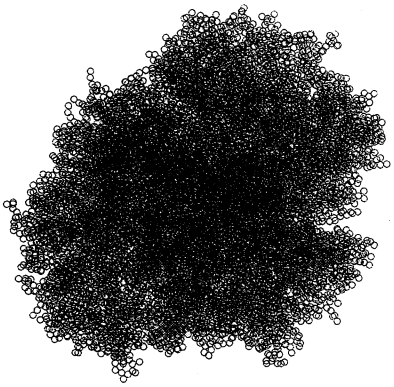

**Fig. 1a.** A particle-cluster aggregate (BPCA) with a number of constituent particles $N = 16384$ used in the calculations, where it is assumed that the constituent particles have the same radii and a sticking probability = 1

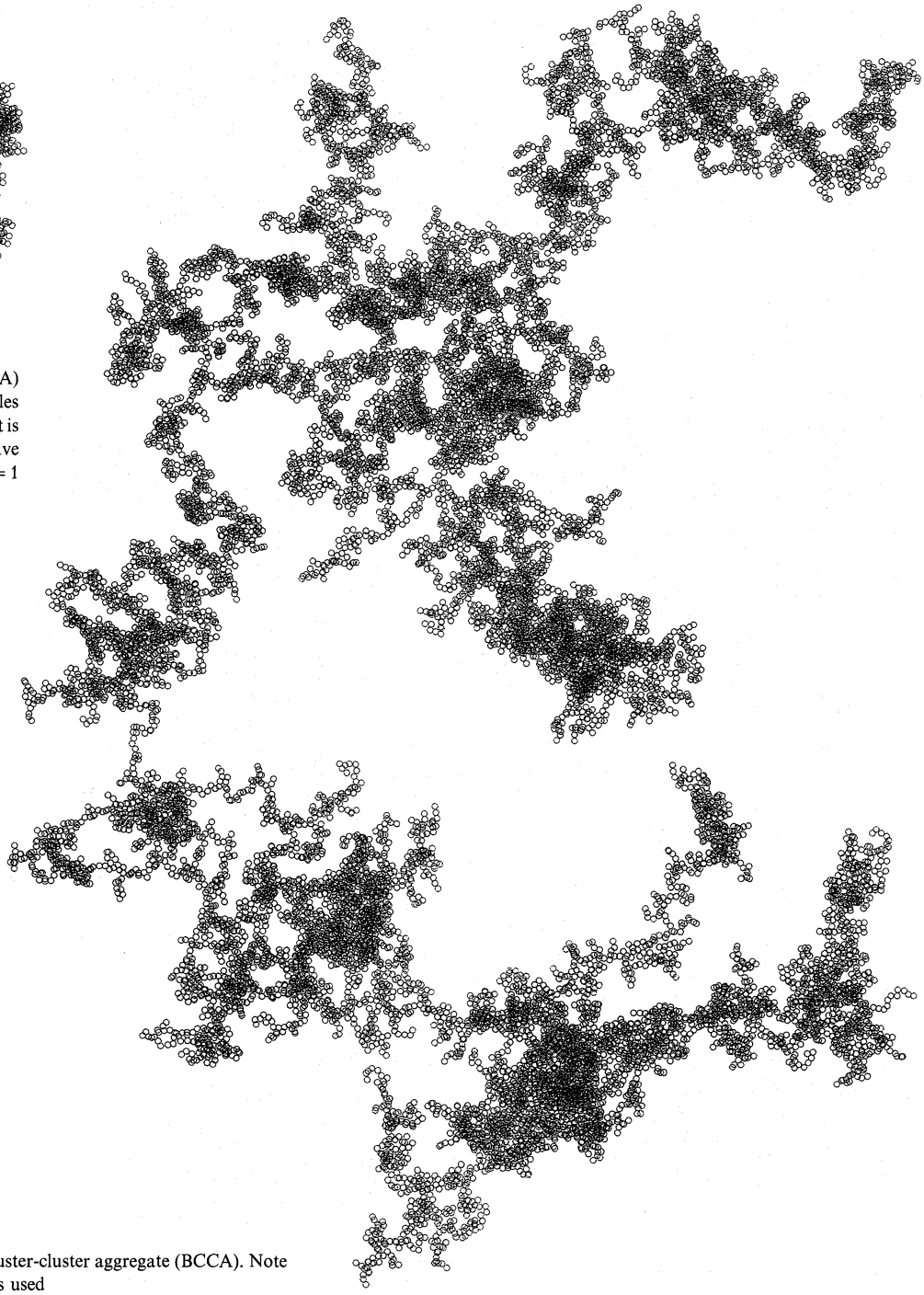

**Fig. 1b.** The same as Fig. 1a, but for a cluster-cluster aggregate (BCCA). Note that the same scale in length as Fig. 1a is used

Bazell & Dwek 1990; Perrin & Lamy 1990). It is known that the computations based on both methods need a large amount of memory in the computer and a long time for proceedings. Therefore if we can get a similar result based on a simple approximation which compares well with that derived by DDA or VIEF, it is certainly preferred for practical use.

Mie calculation with the Maxwell-Garnett approximation (MG) for the effective dielectric function of a composite medium is proposed as one such simple way. That is, representing a porous aggregate by a sphere equal in volume to the characteristic volume of the aggregate, and using an effective refractive index to calculate its optical properties, the scattering/absorption properties of such porous aggregates are readily obtained using standard Mie theory (see e.g. Hage & Greenberg 1990). Some discrepancy in the wavelength dependence of $Q_{\rm abs}$ (the absorption efficiency) between that derived by Mie theory with MG mixing rule and by the DDA has been noted in Bazell & Dwek (1990). On the other hand, Hage & Greenberg (1990) have proved that the Mie theory with the MG rule, taking the vacuum as the "matrix material" and the constituent particles as the "inclusions", gives a

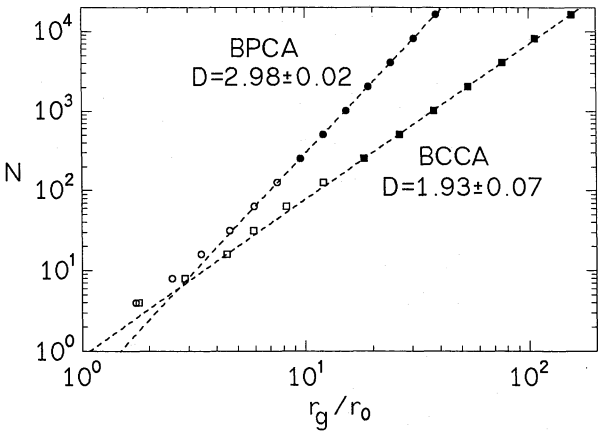


**Fig. 2.** The dependence of the number of constituent particles $N$ on the normalized radius of gyration $r_g/r_0$, where $r_g$ is defined in the text and $r_0$ is the radius of the constituent particle. The results were obtained from averaging ten aggregates resulting from our three-dimensional simulations of ballistic deposition. BPCA and BCCA, respectively, denote the particle-cluster aggregate shown in Fig. 1a and the cluster-cluster aggregate shown in Fig. 1b. $D$ is the slope of each dashed curve and gives the fractal dimension, which was deduced based on the method of least squares by using the data with $N \geq 256$ (filled marks on the panel)

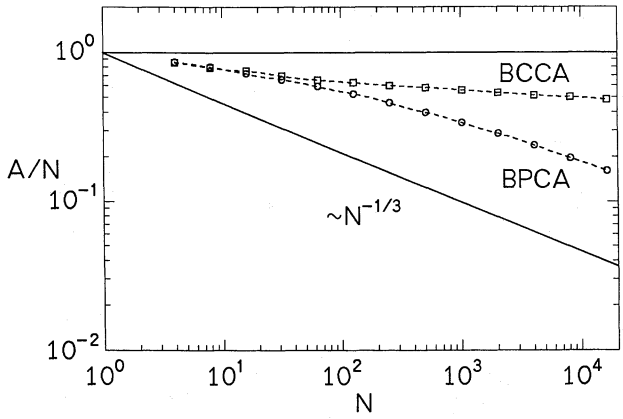


**Fig. 3.** The ratio of the geometrical cross section $A$ to the number of constituent particles $N$ is presented as a function of $N$ for the same resulting aggregates as used in Fig. 2. A is defined in the calculation as the geometrical cross section averaged over three orthogonal directions

very good agreement in $Q_{abs}$ and albedo with those derived by VIEF, as long as the size parameter of the inclusions is sufficiently small compared to the wavelength of interest.

Bazell & Dwek (1990) report a large discrepancy in $Q_{abs}$ between DDA and Mie-MG in the far infrared wavelengths. However, the contribution to $\beta$ in Eq. (3) from such long wavelengths is negligibly small for the aggregates concerned, because the effective temperature is high enough in the solar system. Since radiation pressure forces, in general, are caused by absorption and scattering of incident light on the particle, then we assume that the radiation pressure efficiencies for the porous aggregates modelled here are adequately described to first approximation by the integrated result of $Q_{PR}$ derived by Mie theory with MG mixing rule over the wavelength region of interest ($\lambda = 0.14\,\mu m - 300\,\mu m$).

In general, the average dielectric function $\varepsilon_{av}$ of the inhomogeneous material consisting of a matrix and a single kind of inclusion with the dielectric functions $\varepsilon_m$ and $\varepsilon$, respectively, is expressed by the effective medium theory, e.g. Maxwell-Garnett mixing rule (see e.g. Boren & Huffman 1983) as,

$$\varepsilon_{av} = \varepsilon_m (1 + 3\, f\, F (1 - f\, F)^{-1}), \quad F = (\varepsilon - \varepsilon_m)\,(\varepsilon + 2\varepsilon_m)^{-1}, \tag{4}$$

where $f$ denotes the volume fraction of the inclusions. The limitations of the effective medium theory, such as that the wavelength of the radiation should be large compared to the size of the inclusions, were carefully taken into account in our calculation. In our fractal aggregate model, $\varepsilon_m = 1$ (vacuum), $\varepsilon = m^{*2}$ and $f = 1 - po = \alpha\,(r/r_0)^{D-3}$, where $po$ denotes the mean porosity of the aggregate, as defined in Sect. 3.

In conclusion, we can define $\beta$ for a porous aggregate with fractal structure as

$$\beta = 3.41\ 10^{-4} (\varrho\,\alpha)^{-1}\ (r^{2-D}/r_0^{3-D}) \int_0^\infty \lambda^{-5}\, Q_{PR}\,(m_{av}, \lambda) \cdot \{\exp(2.49/\lambda) - 1\}^{-1}\, d\lambda, \tag{5}$$

where $\lambda$ is in $\mu m$, $\varrho$ denotes the mass density of the constituent particle in units of $g\,cm^{-3}$. We used $T = 5778$ K. Note that we replaced $Q^*_{PR}$ and $m^*$ in Eq. (3) by $Q_{PR}$ derived by Mie theory and $m_{av}$ deduced from Eq. (4), respectively.

### 4.3. Results

In Fig. 4, "homogeneous sphere" means a compact particle with no porosity, for which $\beta_C$ was defined in Sect. 4.1. The optical constants $m^*$ for magnetite and silicate compiled in Mukai (1990) are used to represent the absorbing and dielectric materials. For graphite, we derived $m^*(\lambda)$ based on "1/3–2/3 approximation" in Draine (1988) taking into account the anisotropic optical constants of graphite, which are listed in Draine (1985) for a grain radius of 0.01 μm at a temperature of 300 K. The values of $\varrho$ in Eq. (5) are $5.2\,g\,cm^{-3}$ for magnetite, $2.4\,g\,cm^{-3}$ for silicate, and $2.3\,g\,cm^{-3}$ for graphite. It is well defined (see e.g. Mukai & Mukai 1973) that absorbing (graphite) grains with radii of roughly a few tenths of a micron cannot stay in the interplanetary space, in contrast to no removal of dielectric grains from the solar system.

The values of $\beta$ are also shown in Fig. 4 computed by using Eq. (5) with $r_0 = 0.01\,\mu m$, as a function of an aggregate radius $r$ with different values of $D$, where $r$ denotes the characteristic radius of the aggregate. It should be noted that $\beta$ for $D = 3$ does not strictly correspond to $\beta_C$ because our dust model for porous aggregates gives, at $D = 3$, $f \neq 1$ (this implies $m_{av} \neq m^*$ at $D = 3$) and $\alpha \neq 1$.

In contrast to the estimation given in Sect. 4.1, the value of $\beta$ generally decreases as $D$ decreases near a region of the maximum value of $\beta$ (see Fig. 4). Furthermore, larger porosity, which generally implies a smaller value of $D$ leads to non-dependence of $\beta$ on the size of the aggregate. Furthermore, the value of $\beta$ for such aggregates finally approaches that of the constituent particles ($r_0 = 0.01\,\mu m$). A similar trend has been shown in Greenberg & Hage (1990) when even for large aggregates, the temperature of the aggregate particle rises to the limiting value expected for the individual constituent particles when the aggregate has a sufficiently large porosity. This comes from the fact that a very porous aggregate acts like a "cloud" of its constituent particles; i.e., for higher porosity aggregates, the effective volume for absorption/scattering approaches that of the constituent particle.

From Fig. 4, it is shown that the very porous aggregates consiting of graphite cannot stay in the solar system, even for large

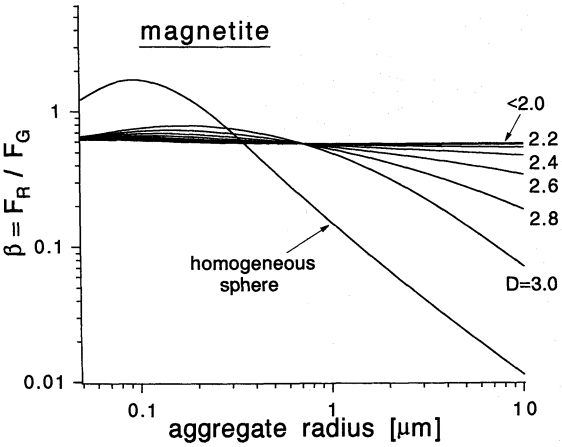


**Fig. 4a.** The ratio $\beta$ of the radiation pressure forces to the gravity on porous aggregates with a fractal dimension $D$, consisting of magnetite constituent particles of the same radii 0.01 μm with a fractal dimension $D$

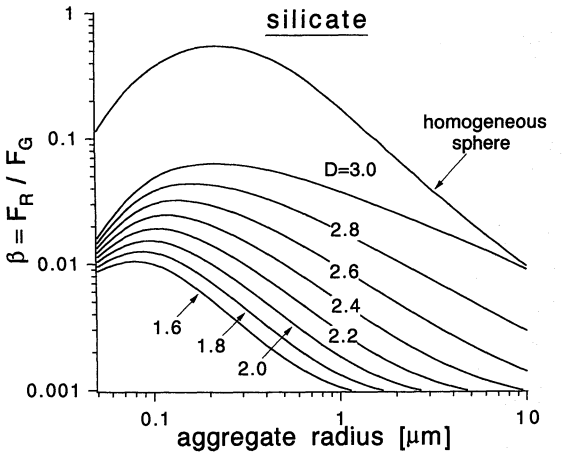


**Fig. 4b.** The same as Fig. 4a, but consisting of silicate particles. Note that the dashed curves with $D \leqq 2.0$ include large uncertainties as will be shown in Fig. 5

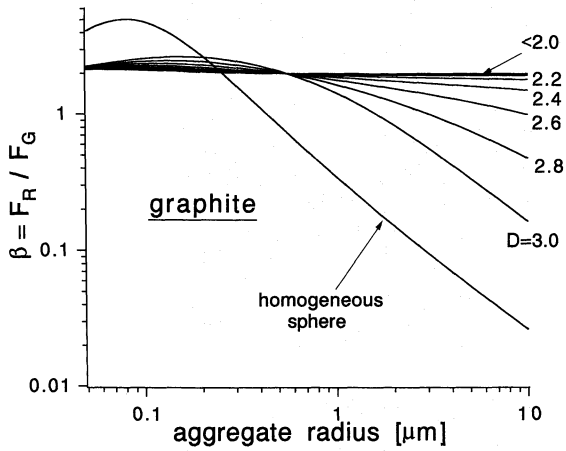


**Fig. 4c.** The same as Fig. 4a, but consisting of graphite particles

aggregates, because even for the individual graphite particle $\beta > 1$. On the contrary, aggregates consisting of silicate or magnetite can always stay in the solar system because $\beta < 1$. It should be noted that a compact magnetite aggregate with $r \sim 0.1$ μm may escape from the solar system. However, as the porosity increases, $\beta$ becomes less than unity and consequently fluffy magnetite aggregates can remain in the solar system, when they consist of smaller individual particles with a radius of 0.01 μm.

The radius of the constituent particle is a parameter in our calculations. In the dust model by Greenberg (1985), it was assumed that the dust consists of aggregates of elongated core-mantle particles with a size of about 0.1 μm. We set, however, $r_0 = 0.01$ μm referring to the discovery of very small grains with $10^{-19}$ kg particle mass in comet P/Halley (e.g. McDonnell et al. 1991). In addition, this value of $r_0$ was chosen to fulfil the limitation on MG mixing rule, i.e. the size of the constituent particle should be smaller than the wavelength of interest, $\lambda > 0.14$ μm. A determination of $r_0$ in real aggregates in space is an important problem in the future in-situ measurements.

### *4.4. Comparison of $\beta$ by MG-Mie theory with $\beta$ by DDA theory*

It is worthwhile to study the limitation of the Mie theory with MG mixing rule. In order to demonstrate the validity of the values of $\beta$ derived by MG-Mie theory obtained in the previous section, we have calculated $\beta$ for the aggregates produced in Sect. 3, based on the discrete dipole approximation (DDA) and compared both results. The numerical code used for the calculations is a modified version of the original program supplied by Draine (e.g. Draine 1988). The details of the DDA calculations will be published elsewhere (Kozasa et al. 1992, in preparation).

We have obtained a ratio of $\beta$ by DDA to $\beta$ by MG-Mie as a function of the total number $N$ of the constituent particles (see Fig. 5). $N = 1024$, which is a maximum value in the present

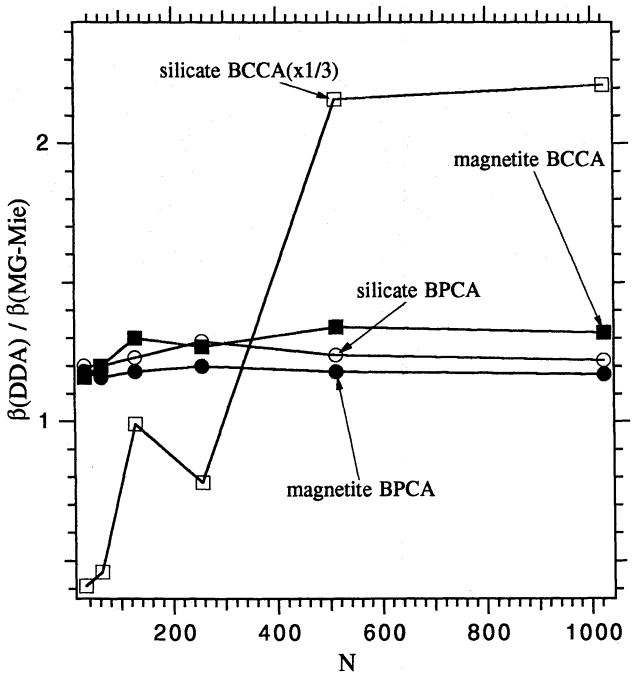


**Fig. 5.** The ratio of $\beta$ computed by DDA to $\beta$ by MG-Mie theories as a function of the total number $N$ of constituent particles consisting of silicate or magnetite, where $\beta$ is the ratio of radiation pressure forces to gravity on porous aggregates defined as BCCA or BPCA in the text. Note the difference in scale for silicate BCCA

calculations due to the limitation of the size of memory, corresponds to a characteristic radius of 0.19 μm for a BPCA and of 0.53 μm for a BCCA. From Fig. 5, we have found that, except for silicate BCCA, other three model calculations show that $\beta$ (MG-Mie) is close to $\beta$ (DDA).

These results suggest that when the dust aggregates have compact structures such as BPCA and/or the constituent particles are absorbing materials, the values of $\beta$ derived by MG-Mie theory give fairly good agreement to those deduced by DDA theory, although our DDA calculations could not cover all the aggregate sizes of interest.

## 5. Conclusions

We have proposed a practical and simple way, based on Mie theory and Maxwell-Garnett effective medium theory, to estimate the radiation pressure forces on porous aggregates with fractal structures represented by a fractal dimension $D$ and a scaling parameter $\alpha$ (see Eq. 5). The resulting values of the ratio $\beta$ of the radiation forces to the gravity on such aggregates are compared with those derived by the discrete dipole approximation (DDA). It is found that the values of $\beta$ by MG-Mie and DDA theories agree well, except for highly porous/fluffy silicate aggregates. Although our comparison does not cover the aggregate sizes of interest due to the limitation of memory of the computer, we could summarize the following new properties: (i) as $D$ decreases, which implies looser structures, $\beta$ decreases near its maximum at a characteristic radius of the aggregate of about 0.1 μm, and (ii) at further increasing porosity, $\beta$ becomes independent of the size of aggregate and finally approaches a constant value deduced for the individual constituent particles. As a result, we may generally conclude that the dynamical behaviour of highly porous aggregates, which is mainly influenced by the radiation pressure forces, is similar to that of the constituent particles.

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