A&A 407, L5–L8 (2003)
DOI: 10.1051/0004-6361:20030967

Astronomy
&
Astrophysics

Optical properties of cometary dust

Constraints from numerical studies on light scattering by aggregate particles

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Received 16 May 2003 / Accepted 24 June 2003

Abstract. Optical observations of cometary dust have revealed that the solar radiation scattered by the dust has common characteristics in the phase-angle and wavelength dependences of intensity (including albedo) and polarization, irrespective of the properties of the parent comets. We present numerical calculations on light scattering by clusters of spheres showing that all of these common optical properties are reproduced by large aggregates consisting of optically dark submicron grains. Our model neither invokes any averaging of the results over size and/or composition of the aggregates nor needs to specify the configuration of the constituent grains. The refractive indices used in this model are consistent with a mixture of silicates, metals, and carbonaceous compounds with the element abundances of cometary dust.

Key words. comets: general – interplanetary medium – meteors, meteoroids – polarization – scattering

1. Introduction

Cometary grains are found to have common characteristics in their light-scattering properties, regardless of differences in the properties of their parent comets, such as nucleus size and activity. These findings were confirmed by the recent apparitions of bright comets, which have greatly enhanced the number of optical data for light-scattering properties of dust grains in the comae. The common characteristics derived from optical observations of the scattered light can be summarized as follows (see Gustafson & Kolokolova 1999; Hanner 2003; Kolokolova et al. 2004):

1. The intensity of scattered light is a smooth function of phase angle with a weak increase toward small phase angles, a strong, broad rise toward large phase angles, and a relatively flat profile at intermediate phase angles.
2. The scattered-light intensity increases with wavelength and this red color does not significantly change with phase angle.
3. The dependence of the linear polarization on phase angle is well represented by a bell-shaped curve with a maximum value of 10–30% around the phase angle $\alpha = 90{-}100°$. At phase angles smaller than 20–30°, the linear polarization turns to negative values with a minimum of approximately −2%.
4. The spectral gradient of polarization (polarimetric color) is positive and increases with phase angle, at least, for α within 10–90°.
5. The geometric albedo is low, $A_\mathrm{p} < 0.06$ at $\alpha = 0°$.

These light-scattering properties of cometary dust can be used to characterize the mineralogical and morphological nature of the dust. Previous attempts to model cometary dust properties were restricted to explaining only a part of these observational features (see, e.g., Mukai et al. 1987; Mukai & Mukai 1990; Lumme & Rahola 1994; Xing & Hanner 1997; Yanamandra-Fisher & Hanner 1999; Petrova et al. 2000; Kimura 2001). In this Letter, we report the first successful model that reproduces all the main light-scattering properties of cometary dust.

2. Model

It is shown that fractal clusters of submicron grains could have the intensity and polarization curves similar to those observed for cometary dust (Levasseur-Regourd et al. 1997; Lumme et al. 1997; Kimura 2001). We consider two types of fractal aggregates consisting of identical spherical particles: (1) BCCAs, which are formed under the Ballistic Cluster-Cluster Aggregation process, and (2) BPCAs, which are formed under the Ballistic Particle-Cluster Aggregation process (see Mukai et al. 1992; Kitada et al. 1993). The two coagulation processes are used simply to describe highly porous aggregates (BCCAs) and relatively compact aggregates (BPCAs).

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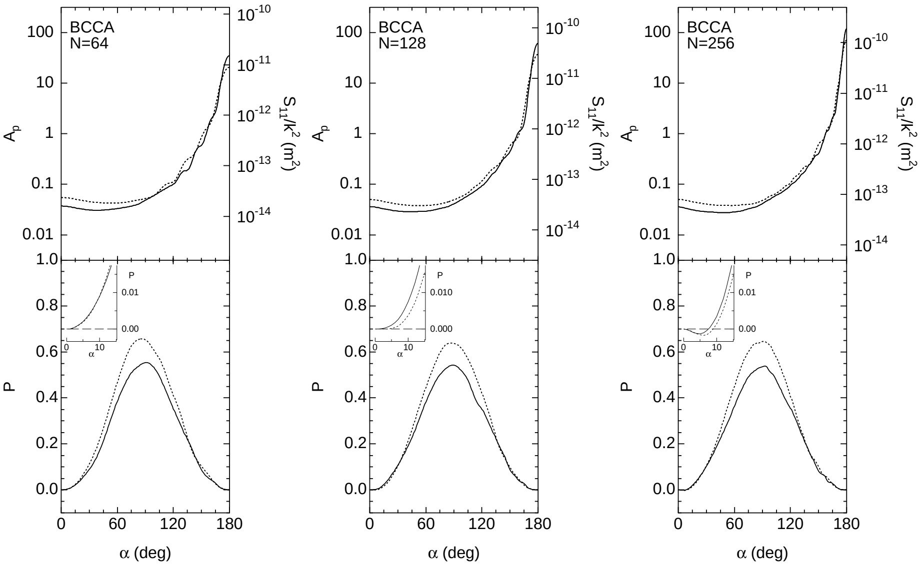

Fig. 1. The geometric albedo A_p and polarization P for randomly oriented BCCA particles consisting of optically dark submicron grains. The geometric albedo is also described using the corresponding values for S_{11}/k^2 where S_{11} and k denote the $(1, 1)$ element of the scattering matrix S_{ij} and the wave number, respectively. Solid lines are the numerical results for the wavelength $\lambda = 0.45$ μm and dotted lines are those for $\lambda = 0.60$ μm. Dashed horizontal straight lines in the upper left corner of each lower panel are plotted to illustrate $P = 0$. The number of constituent particles in the aggregate is set to be $N =$ 64 (left panel), 128 (middle panel), or 256 (right panel).

We set the radius of the monomers to $a_\mathrm{m} = 0.1$ μm, which is found to give better results in comparison to other monomer's sizes. The radius $a_\mathrm{m} = 0.1$ μm was also inferred by Greenberg & Hage (1990) from their arguments for grain temperature and has long been used for modeling cometary dust (e.g., Li & Greenberg 1998). In addition, this is comparable to the average size for the constituent grains of interplanetary dust particles (IDPs) collected in the stratosphere (Brownlee et al. 1980). The number N of the monomers is $N = 64$, 128, or 256 where the largest number $N = 256$ is the limitation of our computational resources for the selected refractive index, radius, and configuration of monomers. As a result, the aggregate with $a_\mathrm{m} = 0.1$ μm has a radius of $a_\mathrm{V} = 0.400$, 0.504, or 0.635 μm where a_V is the radius of a volume-equivalent sphere. Note that a_V has been commonly used to describe the radius of an aggregate in light-scattering calculations, but differs from the radius of an aggregate used by Greenberg & Hage (1990), Mukai et al. (1992), and Li & Greenberg (1998).

The constituent particles (monomers) are assumed to consist of a mixture of silicates, metals, and carbonaceous materials that is consistent with the composition of the dust in comet Halley (Jessberger et al. 1988). We hypothesize one third of carbonaceous materials in the form of organic refractory and two thirds of carbonaceous materials in the form of amorphous carbon based on a comparison of the nitrogen abundance between Halley's and interstellar dust (see Kimura et al. 2003). Let silicates, iron, and organics refractory be embedded in amorphous carbon so that we can estimate the average refractive index of the mixture using the Maxwell-Garnett mixing rule (Bohren & Huffman 1983). The refractive indices of silicates, iron, organics refractory, and amorphous carbon are taken from Laor & Draine (1993), Johnson & Christy (1974), Li & Greenberg (1997), and Rouleau & Martin (1991), respectively. To study the spectral dependence of our results, we use two wavelengths $\lambda = 0.45$ and 0.60 μm, which are close to the effective wavelengths of blue- and red-band filters. Taking into account the elemental abundances of Halley's dust, we obtain the average complex refractive index of $m = 1.88 + i\,0.47$ at $\lambda = 0.45$ μm and $m = 1.98 + i\,0.48$ at $\lambda = 0.60$ μm from the volume filling factors of silicate 31.76%, iron 2.56%, and carbonaceous materials 65.68%.

Our choice of the radius, number, and refractive index of monomers is not arbitrary, but is based on extensive and careful calculations with a comprehensive survey of the parameters within our computational capabilities. We caution the readers that the choice of the parameters should not be taken as a unique set to reproduce the observational results nor the best one.

We assume that the orientation of cometary grains is random and calculate the intensity of scattered light and the degree of linear polarization for randomly oriented grains as a function of phase angle at the two wavelengths mentioned above. The intensity is proportional to S_{11}/k^2 where S_{11} denotes the $(1, 1)$ element of the scattering matrix S_{ij} and k is the wave number, $k = 2\pi/\lambda$ (Bohren & Huffman 1983). Here we present the intensity using the geometric albedo defined as $A_\mathrm{p} = \left(S_{11}/k^2\right)(\pi/G)$ where G denotes the geometric cross section (Hanner et al. 1981). The degree of linear polarization is given by $P = -S_{12}/S_{11}$ where S_{12} is the $(1, 2)$ element of the scattering matrix. The values of S_{11} and S_{12} are calculated by the superposition T-matrix method (TMM), which is a powerful technique to compute orientationally averaged scattering matrix elements for a cluster of spheres (Mackowski & Mishchenko 1996).

3. Results and discussion

Figures 1 and 2 show the numerical results for BCCA and BPCA particles on geometric albedo A_p (upper panels) and linear polarization P (lower panels) as a function of phase angle. The right axis in each upper panel gives A_p in unit of S_{11}/k^2. Solid curves indicate the results for $\lambda = 0.45$ μm and dotted curves indicate those for $\lambda = 0.60$ μm.

Aggregate-size dependences: The results for $N = 64$, 128, and 256 given in the left, middle, and right panels, respectively,

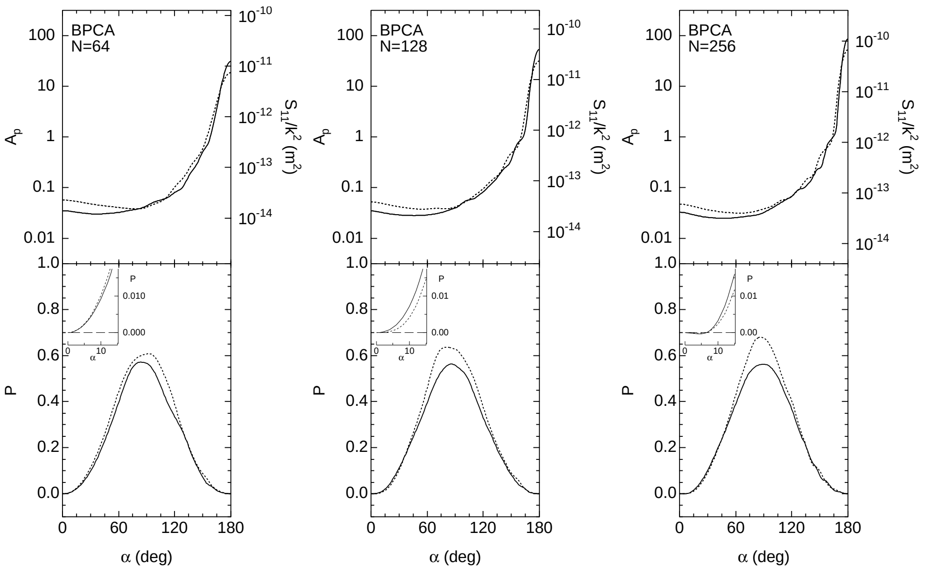

Fig. 2. Same as Fig. 1, but for BPCA particles.

clearly demonstrate the similarity in the light-scattering properties for aggregates of different sizes. The weak size dependency results most likely from the fact that we use a large number of monomers having submicron size and highly irregular configurations. This contrasts with the results from the majority of previous modeling, which often had to employ averaging numerical results over various sizes or compositions to erase unfavorable features of single grains with small sizes and/or regular shapes. Our results indicate that a size distribution of aggregates, even if taken into account, does not drastically change the light-scattering characteristics of an ensemble of the aggregates.

Aggregate-structure dependences: A comparison of Figs. 1 and 2 illustrates that the numerical values for the BPCAs are not significantly different from those for the BCCAs. Note that even the minor differences may disappear as soon as we consider an ensemble of various BCCAs and BPCAs, instead of a single BCCA and a single BPCA. This implies that the morphology of cometary grains is of minor importance for their light-scattering properties in the optical wavelength range, in accord with the conclusion by Kimura (2001). As far as the optical properties of fractal aggregates are concerned, our conclusions are not restricted to a particular aggregate shape.

Phase-angle dependences: The geometric albedo, which we use as a measure for the intensity of scattered light, is a smooth function of phase angle with a slight increase toward small phase angles and a significant enhancement toward large phase angles. While the value at $\alpha = 180^\circ$ rises with increasing N, the geometric albedo at small phase angles is almost independent of N and structure. Consequently, the low geometric albedo of cometary dust at small phase angles does not provide information on the overall size nor structure of the aggregates, but on their chemical composition.

The polarization has an overall bell-shaped curve with a maximum around phase angle $\alpha \approx 90^\circ$. Although the polarization curve is not strongly dependent on N over the whole range of phase angle, a close look at the curves as seen in the upper left corner of each lower panel shows that a shallow negative branch at small phase angles gradually grows with N. We expect the validity of this tendency in the linear polarization for larger aggregates to be confirmed with a large computing facility in the future. In previous studies, the negative polarization has often been attributed to optically bright grains such as large dielectric particles, although the low albedo has ruled out a predominance of optically bright grains. Here we suggest that the presence of negative polarization at small phase angles is characteristic not only of optically transparent materials, but also of large aggregates.

Wavelength dependences: Our numerical calculations reveal that the intensity and polarization of aggregates have red color over wide ranges of phase angle. Within the phase-angle range of 0–90°, the color is approximately constant and the polarimetric color increases with phase angle as observed for cometary dust. The spectral variations of refractive indices significantly influence the color of intensity and polarization (Kolokolova & Jockers 1997). The color as well as the shape of intensity and polarization curves are also sensitive to the absolute magnitude of the refractive index. The refractive index used for the presented calculations is high and increases with increasing wavelength. This is typical for optically dark materials that also contribute to lowering the albedo by increasing the absorptivity in the optical wavelength range. It should be noted that, because of carbon being an abundant element in cometary dust, aggregates consisting of carbonaceous materials alone could provide results similar to those presented in this paper. If the monomers were, on the other hand, composed exclusively of silicates, or contained a substantial amount of ices, we would not find satisfactory results, owing to their low refractive indices. It is the use of optically bright materials that prevented previous models from reproducing the observed low albedo together with the observed spectral variations in the intensity and linear polarization.

Constraints on the properties of cometary dust: Although our model needs further improvements to obtain quantitative fits, we would like to emphasize the fact that the model achieves, for the first time, simultaneous qualitative agreements to all the observed optical characteristics of cometary dust listed in the introduction. Our results also put the following constraints on the cometary dust models (feasible parameter ranges are given in parentheses):

1. The observed optical characteristics altogether limit the size of constituent particles to the submicrometer range ($a_\mathrm{m} \approx 0.1\,\mu$m).
2. The wavelength dependences of intensity and polarization, and the low geometric albedo require optically dark materials whose refractive index commonly increases with wavelength ($\mathrm{Re}(m) \geq 1.9$, $\mathrm{Im}(m) \geq 0.1$, $\mathrm{d}\,|m|/\mathrm{d}\,\lambda > 0$).
3. The presence of negative polarization at small phase angles indicates the overall size of aggregates to be large compared with the visible wavelength ($a_\mathrm{V} > 0.6\,\mu$m).

Our model also provides the mineralogically and morphologically proper image of cometary dust. Namely, a mixture of silicates, metals, and carbonaceous materials is in agreement not only with the composition of Halley's dust, but also with the composition of IDPs (Rietmeijer 1999; Jessberger et al. 2001). Furthermore, aggregates of optically dark submicron grains are typical of IDPs, although their origin has not been fully understood. We can conclude that large aggregates consisting of more than hundreds of optically dark submicron grains are highly descriptive of typical cometary dust.

Acknowledgements. We thank Daniel Mackowski, Kirk Fuller, and Michael Mishchenko for making their TMM code available, and an anonymous referee for his/her constructive comments. This research has been supported by the German Aerospace Center *DLR* (Deutschen Zentrum für Luft- und Raumfahrt) under the project "Kosmischer Staub: Der Kreislauf interstellarer und interplanetarer Materie" (RD-RX-50 OO 0101-ZA).

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