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Polarization of cosmic dust simulated with the rough spheroid model

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ABSTRACT

Cosmic dust is a polydisperse mixture of irregular, often aggregated, particles. Previous attempts have tried to simulate polarimetric properties of this dust using aggregate dust models, but it has not been possible to consider particle sizes larger than a couple of microns due to limitations of computer memory and processing power. Attempts have also been made to replace aggregates by polydisperse regular particles (spheres, spheroids, cylinders), but those models could not consistently reproduce the observed photopolarimetric characteristics. In this study, we introduce to the astronomical community the software package developed by Dubovik et al. (2006) for modeling light scattering by a polydisperse mixture of randomly oriented smooth and rough spheroids of a variety of aspect ratios. The roughness of spheroids is defined by a normal distribution of the surface slopes, and its degree depends on the standard deviation of the distribution (which is zero for smooth surface and greater than zero for rough surface). The pre-calculated kernels in the software package allow for fast, accurate, and flexible modeling of different size and shape distributions. We present our results of a systematic investigation of polarization obtained with the rough and smooth spheroid models; we study differences in their phase angle dependence and how those differences change with the particle size distribution. We found that the difference between smooth and rough particles increases with increasing effective size parameter and affects mainly the value and position of the maximum polarization. Negative polarization was found to be typical only for silicate-like refractive indexes and only when the particles have size parameters within 2.5–25. As an example of an application of the rough spheroid model, we made computations for rough spheroids that have a size distribution and composition typical for cometary dust. We found that a mixture of porous rough spheroids made of absorbing material compositionally similar to comet Halley's dust and solid silicate spheroids, dominated by particles of size parameter $5 < x < 20$, can reproduce angular and spectral characteristics of the brightness and polarization observed for cometary dust.

1. Introduction

It is well accepted that cosmic dust of all types (interstellar, circumstellar, interplanetary, cometary, etc.) is a polydisperse ensemble of irregular, mainly heterogeneous and aggregated, particles. Accurate modeling of light scattering by such a complex ensemble of particles, which is required for interpretation of polarimetric observations of cosmic dust, is almost impossible and usually some simplifications have been done to describe the particles. The most common simplifications are the following: (1) presenting the particles by a rather narrow or even monodisperse ensemble of heterogeneous aggregates (e.g., Petrova et al., 2000; Kimura et al., 2003; Zubko et al., 2005; Bertini et al., 2007; Lasue et al., 2009; Shen et al., 2009; Kolokolova and Mackowski, 2012); and (2) considering a polydisperse ensemble of some regular particles, e.g. spheroids (e.g., Kolokolova et al., 2005; Moreno et al., 2007; Voshchinnikov and Das, 2008; Lumme and Penttilä, 2011). The second approach was especially successful when considering terrestrial aerosols as an ensemble of polydisperse and polyshaped (i.e. a mixture of spheroids of a variety of aspect ratios) randomly oriented spheroids (Mishchenko et al., 1997); this model managed to fit both photometric and polarimetric data. However, attempts to apply a similar model to the cometary photopolarimetric data failed to provide a good fit to the observations, especially when both angular (dependence on phase/scattering angle) and spectral (dependence on wavelength) characteristics were considered (Kolokolova et al., 2005).

A recently developed package, which allows simulating light scattering by ensembles of randomly oriented rough spheroids

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with a broad range of size and aspect ratio distributions (Dubovik et al., 2006), opens new opportunities for modeling polarimetric characteristics of cosmic dust. Counting on the roughness of the particles, together with their polyshaped nature, may be a good proxy to simulate an ensemble of irregular particles.

In this paper we describe the rough spheroid package and the computations we performed with it. We focus on studying the degree of linear polarization defined as $P=(I_{\perp-I\|})/(I_{\perp+I\|})$, where $I_\perp$ and $I_\|$ are intensity components parallel and perpendicular to the scattering plane; this is a standard definition of polarization in planetary science and represents the ratio of the Stokes parameters Q/I. We explore how different the polarimetric properties of rough spheroids are from those of smooth spheroids (Section 1); this study includes both prolate and oblate spheroids and particles of different composition. In Section 2 we check if the rough spheroid model can reproduce photopolarimetric properties of cometary dust. We try fitting the whole scope of cometary photopolarimetric data, considering cometary dust as a mixture of porous rough spheroids (representing aggregates) and solid rough spheroids (representing solid particles) to be consistent with the results of studying Stardust mission samples (Flynn, 2008; Rietmeijer, 2008).

2. Rough spheroid model

2.1. Rough spheroid package

We use a software package developed by Dubovik et al. (2006) to study the light scattering properties of randomly oriented spheroids. This package allows computations of light scattering by a mixture of spheroids for 25 logarithmically equidistant axis ratios ranging from 0.3 (oblate spheroids) to 3.0 (prolate spheroids) and 41 size bins covering the size parameter (x) from 0.012 to 625. To cover such a large range of particle dimensions, two complementary methods were used. For $x<30$–60, the simulations were performed using the T-matrix method by Mishchenko et al. (1996). In the case of smooth spheroids, for x exceeding the T-matrix convergence limits, a geometric optics method (GOM) (Yang and Liou, 1995, 1996) was used. In the case of rough spheroids with sizes $x>18$, an improved geometric optics method (IGOM, Yang and Liou, 1998) was used.

In IGOM, the ray-tracing technique is employed to compute the near-field on the particle surface, which is subsequently mapped to the far-field based on an exact electromagnetic integral equation. The reflecting and transmitting directions of an incident ray are determined with respect to the local normal direction based on Snell's law. To account for the surface roughness, the normal of the local particle surface facet is randomly tilted for each incident ray, as suggested by Macke et al. (1996) and Yang and Liou (1998). Fig. 1 illustrates the tilting of a facet. The facet ABCD indicates a facet on a smooth surface whereas AB′C′D′ denotes a tilted facet. In IGOM, for each facet two orthogonal directions on a given smooth facet, for example, the direction along AB and that along AD, are selected a priori as references. The slopes, z_1 and z_2, along the two directions are specified by Gaussian distribution in the form:

$$P(z_1, z_2) = \frac{1}{\pi\sigma}\exp\left[-(z_1^2+z_2^2)/\sigma^2\right] \tag{1}$$

where σ specifies the magnitude of roughness. Based on the distribution in Eq. (1), the two angles shown in Fig. 1 can be randomly specified for an incident ray in the following form:

$$\boldsymbol{\vartheta} = \cos^{-1}[1/(1-\boldsymbol{\sigma}^2\ \ln\ \boldsymbol{\xi}_1)^{1/2}] \tag{2}$$

$$\varphi = 2\pi\xi_2 \tag{3}$$

where ξ_1 and ξ_2 indicate random numbers.

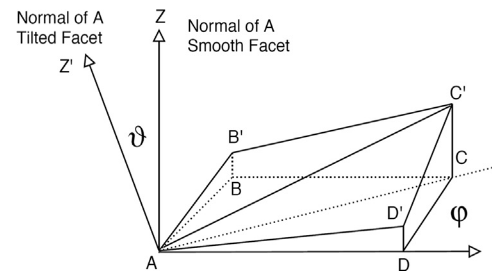

Fig. 1. Schematic diagram illustrating the tilting of a facet for the IGOM technique. The tilts BB′ and DD′ correspond to z_1 and z_2 from Eq. (1).

The preceding method is a highly simplified approach to account for the effect of particle surface roughness on the optical properties. In particular, an unrealistic feature of this approach is that the scale of roughened facets is not involved. A recent study by Liu et al. (2013) employed a roughened sea surface model to rigorously define the particle surface. Their results illustrate that the simplified and rigorous methods lead to similar optical properties. Furthermore,σ=0 – 0.005, 0.005 – 0.05, and 0.05 – 0.2 correspond to slight, moderate, and severe roughness in terms of smoothing the corresponding phase function (Yang and Liou, 1998). It was found that the effects of roughness are negligible for small particles ($x<18$). In such a case the roughness is much smaller than the wavelength and the effects of the particle shape are dominant (Li et al., 2004). For this reason, in this study we only consider the effect of particle surface roughness for $x>18$.

A significant increase of package efficiency to reduce computation time was achieved by creating look-up tables simulated for quadrature coefficients employed in the numerical integration of spheroid optical properties over size and shape. Creating the tables required a significant time (almost one year for smooth spheroids and one more year for rough spheroids); however this has been rewarded by the achieved capability of fast, accurate, and flexible modeling of different size and shape distributions. Currently the kernels cover refractive indexes with a real part that can vary from 1.041 to 1.696 and an imaginary part that can vary from $1\cdot10^{-9}$ to 0.5 for smooth spheroids and from 0.0005 to 0.5 for rough spheroids, and an extension of these ranges is planned by the developers.

2.2. Computations for rough and smooth spheroids

Before suggesting the rough spheroid model for studying light scattering by cosmic dust we checked how efficient it would be to use this model in comparison with the smooth spheroid model. Thus, our first task was a comparison of the results obtained with these two models. This part of our study was also directed to test the package in general by comparing results obtained with it to the results previously obtained for smooth spheroids and published in Mishchenko et al. (2002). This is why we selected the same characteristics of the spheroids as were selected in Mishchenko et al. Specifically, the refractive index was $m=1.53+i*0.008$ (that is rather close to what it should be for silicates), and size distribution was log-normal with an effective variance $\nu_{eff}=0.1$. The effective radius was selected to be $r_{eff}=8.71$ µm. This selection of the effective radius allowed us to consider variations of the size parameter within the most interesting range from 2.2 to 160 that was achieved by varying the wavelength within the whole available range, i.e. from 0.34 µm to 25 µm. The reader may recall that the maximum achieved size parameter in Mishchenko et al. (2002) was 30. In the case of rough spheroids, we considered the roughness with $\sigma=0.2$, which was the maximum roughness available in the package via look-up tables. As was mentioned above, this roughness represents a case of severe