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COBE/DIRBE Studies of Scattering By Interplanetary Dust

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Abstract. The high photometric quality and full-sky coverage in the COBE DIRBE datasets make possible detailed studies of the interplanetary medium. This paper presents a preliminary derivation of the infrared scattering phase function of interplanetary dust. The ultimate purpose of these investigations is to use the DIRBE observations to constrain the composition, size and structure of interplanetary dust grains.

1. Introduction

The COBE Diffuse Infrared Background Experiment (DIRBE) has produced the first full-sky survey, between solar elongation angles $\epsilon = 64^\circ$ to 124°, of the intensity and polarization of the diffuse sky from 1.25 μm to 3.5 μm (Boggess et al. 1992). The principal source of diffuse radiation is the zodiacal light. Its visible phase function shows strong forward scattering and moderate backscattering, characteristic of slightly absorbing silicates (Hong 1985). Yet Berriman et al. (1994) argued that the infrared color and polarization still allow for a substantial proportion of absorbing material. Clearly, the infrared phase function itself is required to probe the nature of the scattering grains. This paper presents a preliminary derivation of the scattering phase function in the ecliptic plane at 1.25 μm and 2.2μm, where thermal emission from interplanetary dust is very likely negligible.

2. Intensity Of The Scattered Light

The scattered zodiacal light must be separated from interstellar emission and from the emission of discrete sources. The results described here use data averaged over the interval 1990 Jan 1-7, when the Galactic Center was behind the line of sight through the Sun and the interstellar emission supplied no more than a few percent of the near-infrared light in the ecliptic plane.

The scattered intensity, $Z_\nu(\epsilon)$, was found from the peak value of an analytic fit to the variation of the observed intensities with ecliptic latitude at fixed ϵ (Vrtilek and Hauser 1995). These "slices" were fitted every 5° in elongation to generate the run of $Z_\nu(\epsilon)$ with ϵ, along the zodiacal cloud's symmetry plane projected on to the sky. In practice, the data were fitted with the sum of this empirical function and a Galactic template, to subtract the small contribution of unresolved starlight and interstellar emission. Each value of Z_ν may be subject to a systematic error of up to 10% due to systematic calibration errors in the Galactic template. Bright discrete sources were removed by an iterative scheme that weighted residual intensities from the fit inversely with their magnitude. The sources eliminated in this way supply on average ≈15% of the total light at 1.25 μm and 2.2 μm.

The resulting scattered intensities in the ecliptic plane at 1.25 μm and 2.2 μm decline steadily by roughly 50% across the 64° to 124° elongation range scanned by DIRBE, compared with ≈ 35% in the visible (Dumont and Sanchez 1976).

3. Derivation of the Phase Function

The purpose of the analysis is to determine the scattering phase function of the grains and their spatial distribution that give rise to the variations of intensity with elongation described in Section 2.

The volume averaged phase function $\Phi(\Theta)$ is related to $Z_\nu(\epsilon)$ via:

$$Z_\nu(\epsilon) = \frac{K}{\sin^{\gamma+1}\epsilon} \int_\epsilon^\pi \Phi(\Theta) \sin^\gamma \Theta \; d\Theta \qquad (1)$$

where Θ is the scattering angle, and the number density, n, is assumed to vary with distance r (in AU) from the Sun according to a power law with index γ, $n = n_o r^\gamma$, where n_o is the number density at the Earth. The normalization factor K incorporates n_o and the volume averaged albedo. While this formulation assumes incorrectly that the plane of symmetry of the cloud coincides with the ecliptic plane, it is adopted to allow comparison with Hong's (1985) results. (Essentially the same results were, in fact, found when the infrared intensities derived in the ecliptic plane were used rather than the peak values).

Derivation of Φ involves transforming equation (1) from spatial to scattering coordinates. Two methods widely applied in the visible, inversion and *parameterization, have been applied to the DIRBE data.*

3.1. The Inversion Method

The phase function is obtained simply by differentiating equation (1), so that $\Phi(\Theta)$ is found from measurements of $\partial Z/\partial\epsilon$, itself easily determined from quadratic fits to $Z_\nu(\epsilon)$ *vs.* ϵ. The confusion noise due to faint stars inherent in $Z_\nu(\epsilon)$ limits the accuracy with which $\partial Z/\partial\epsilon$ can be found to ≈10% (beyond the systematic error already described). This imprecision will, over the DIRBE elongation range, accommodate phase functions ranging from those with strong backscattering to those with no backscattering. Direct inversion affords no useful constraints on the infrared scattering function.

3.2. Parameterization of the Phase Function.

Parameterization is the only practical method applicable to the DIRBE data. Following Hong (1985), $\Phi(\Theta)$ is parameterized with the sum of three Henyey Greenstein functions, $\phi(\Theta, g)$:

$$\Phi(\Theta) = \sum_{k=1}^{3} w_k \phi(\Theta, g_k); \quad \phi(\Theta, g) = (1 - g^2)/[4\pi(1 + g^2 - 2g\cos\Theta)^{3/2}] \quad (2)$$

where $g = <cos\Theta>$ is an "asymmetry factor" ; the sum of the relative weights of each function, w_k, is normalized to unity. The corresponding parametric form of equation (1) has been solved with the Levenberg-Marquardt non-linear least squares fitting technique to give the g's, w's and the power-law index γ directly. Unfortunately, the parameters γ, g_1, and w_1 were found to be correlated. Consequently, the optimum solution was found from Monte Carlo simulations, and taken to be the solution giving the minimum value of χ^2. By contrast, Hong (1985) assumed γ=1 to obtain a closed-form value of the integral in equation (1), and showed how to generalize Φ for arbitrary γ.

3.3. Results of Parametric Fitting

Table 1 presents the parametric solution for 0.5 μm using the data of Dumont and Sanchez (1976) used by Hong (1985) between ϵ=45° to 140°and β=0°, and compares it with Hong's solution derived from the same data. The solutions in

Table 1. Parametric Solutions for the Scattering Phase Function.

λ (μm)	γ	K	w_1	w_2	g_1	g_2	g_3
0.5[a]	1.0±0.1	3.8±0.5	0.65±0.06	0.34±0.06	0.60±0.05	-0.20±0.05	-0.80±0.10
0.5[b]	1.0[c]	4.6	0.665	0.330	0.70	-0.20	-0.81
1.25	1.40±0.05	8.4±0.3	0.62±0.05	0.37±0.05	0.68±0.05	-0.20±0.03	-0.75±0.30
2.2	1.45±0.05	5.2±0.3	0.52±0.05	0.45±0.05	0.65±0.05	-0.16±0.02	-0.80±0.30

[a]This work
[b]Hong
[c]assumed

Table 1 bring to light the following results:

- At 0.5 μm, our results agree with Hong's. This demonstrates the validity of our parameterization technique.
- From 0.5 μm to 1.25 μm, K increases by a factor of 1.8, after accounting for the Solar spectrum. Therefore:
- either the albedo increases with wavelength, as also proposed by Matsuura et al. (1995), or different populations of grains, with different number

density distributions, are important in diferent bands. There is another alternative. While the thermal emission that predominates at $\lambda \geq 5$ μm would supply <0.0001% of the light at 1.25 μm for T=250 K (Berriman et al. 1994), emission from small, hot grains cannot be unequivocally eliminated.

- The value of γ found in the infrared is consistent with that measured directly by Hannner et al. (1976). The small difference between the visible and infrared values may suggest that different populations of grains contribute in each band.

- Within the uncertainties of the parameters, the phase function shows no strong dependence on wavelength.

4. Conclusions

The parameterization method holds much promise for deriving the near-infrared scattering properties of interplanetary dust. The parameterization used in this initial study does, however, suffer from correlations between parameters. We are therefore investigating different parametric forms of the phase function, with more nearly independent terms. Forms involving the sum of three exponential terms appear very promising. Other refinements will include taking account of the geometry of the symmetry plane of the zodiacal cloud.

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