THE OPTICAL PROPERTIES OF INTERPLANETARY DUST

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ABSTRACT. After briefly evaluating the observations of the Zodiacal Light and F-corona, we review the laboratory results on the light scattering by dust particles and the various theories which have been recently proposed. We then discuss the optical properties of the dust with emphasis on the phase function, the polarization, the color, the albedo and the local enhancement in the Gegenschein.

1. Optical observations of interplanetary dust and deduced properties

The present review is concerned with the light scattered by interplanetary dust that is wavelengths below approximately 3 μm; beyond, the observed brightness is dominated by thermal emission. The observations relevant to the optical properties of the dust grains are essentially the all-sky brightness and polarization encompassing the ultra-violet, the visible and the near-infrared.

No new major observations have been obtained since the previous colloquium of this series (Marseille, 1984). We therefore limit ourselves to a brief summary of the present situation.

At 1 AU, the survey of the visible brightness and polarization of the zodiacal light by Dumont and Sanchez (1975, 1976) remains the most complete and reliable source of data (see also the tabulations by Levasseur-Regourd and Dumont, 1980 and by Fechtig et al., 1981). The axisymmetric, non-spherical model of the F-corona obtained by Koutchmy and Lamy (1985) bridges nicely to the Dumont-Sanchez data along the ecliptic and meridian directions, the combination of the two sources resulting almost in an all-sky map.

As pointed out by Lamy and Perrin (1986), these results look very reasonable on one hand but are in conflict with other good-quality data on the other hand. A good example is the brightness of the anti-solar point, the center of the Gegenschein, which ranges from 150 to 250 S_{10}(V). Progress in the absolute photometry and polarization are still needed and the forthcoming results from the COBE satellite will make a significant contribution in this direction. Outside the visible, the situation is far less satisfactory as we have only limited coverages in the ultra-violet - see Cebula and Feldman (1982) and Lillie (this volume) - and the near infrared-red (Leinert and Grün, 1991, for a recent review). Polarization data in these spectral ranges are especially meager.

Inside 1 AU, visible brightness and polarization measurements of limited spatial coverage have been obtained by the Helios space probes (Leinert et al., 1982). Outside 1 AU, the Pioneer spacecrafts have secure extended spatial brightness measurements out to a distance of 3 AU (Toller and Weinberg, 1985).

A.C. Levasseur-Regourd and H. Hasegawa (eds.), Origin and Evolution of Interplanetary Dust, 163–170.

This observational material is classically analyzed to produce the volume scattering function $\psi(\theta)$ and its associated polarization p(θ) which characterizes the scattering phase function of a unit volume of interplanetary dust, the spectral variation of the intensity I(λ) - that is the color - and of the polarization p(λ) and the albedo. These quantities are amenable to confrontations with laboratory measurements and theoretical calculations and provide direct information on the optical properties of the grains.

Retrieving $\psi(\theta)$ and p(θ) implies a transformation from the spatial coordinates (elongation, latitude) to the scattering angle. This is the so-called inversion technique which has been pioneered by Dumont (1973). It allows to get rid of the integral over the spatial distribution and to obtain $\psi(\theta)$ and p(θ). Note that these quantities still include the integral over the size distribution. The inversion effort may be broadly divided into three main streams:

i) inversion limited to the plane of the ecliptic (Dumont and Sanchez, 1975; Leinert et al., 1976);

ii) all-sky inversion attempted by Schuerman (1979) and Buitrago et al. (1980) and successfully carried out by Lamy and Perrin (1986) who further realized the inversion at several heliocentric distances;

iii) local inversion allows to retrieve $\psi(\theta)$ at specific spatial locations with minimal uncertainty (Dumont, 1973; Dumont and Levasseur-Regourd, 1988).

Note that the all-sky inversion gives also access to the three-dimensional distribution of interplanetary dust.

2. Light scattering by dust particles

We now review the situation and progress in the field of light scatering by dust particles from the points of view of experimental measurements and theoretical treatments.

The group at Bochum University headed by the late R. Giese has been very active in experimental work, both in the visible and microwave domains, pertaining to interplanetary dust. Laser (λ = 0.633 μm) scattering measurements on single particles of diameter 30 to 80 μm performed by Weiss-Vrana (1983) have been pursued and extended by Killinger (1987). The diameter range has been increased to 20-200 μm, the laser was upgraded to allow multi-color measurements (λ = 0.476, 0.568 and 0.647 μm) and the coverage in scattering angle has been extended to 170°. This effort resulted in a wealth of high quality data which should be the basis for better understanding the scattering by complex particles. The investigation also includes grains extracted from various meteorites (Allende, Murchison) which are particularly suitable for interplanetary dust studies. An interesting finding of Killinger (1987) is the color dependence of the phase function: as expected, the diffraction lobe is colorless but a strong color effect appears at large scattering angle. This behaviour was also found by Bliek and Lamy (1988) in a totally different experiment where a jet of dust particles whose size distribution extends from 1 to 40 μm is illuminated at five different wavelengths (0.447 to 0.829 μm). The microwave facility at Bochum University has also produced significant results in the field of light scattering by complex e.g. Zerull et al. (1977). More recently Gustafson et al. (1989) has started to investigate porous aggregates of small spheres having dimensions of a few wavelengths. These authors experimentally obtained the phase function, the linear and cross polarization and also attempted to solve theoretically the problem. Another microwave facility located at the University of Florida at Gainesville has concentrated on different types of particles (e.g., ellipsoids, cylinders, cubes...) which are less appropriate to the interplanetary dust situation (Schuerman, 1980).

The field of theoretical investigations of light scattering by complex particles has been quite active in recent years. An exhaustive review is beyond the scope of the present article as the developments are further highly specialized and technical. One widespread approach which has also been actively pursued by us starts with the classical electrodynamics equation for the electric field **E** interacting with a dust praticle

$$\nabla \times (\nabla \times \mathbf{E}) - n^2 k^2 \mathbf{E} = 0 \qquad (1)$$

where k is the wave number (= $2\pi/\lambda$) and n, the complex index of refraction (a tensor in the most general case). The solution of equation (1) is given by the integral equation

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_o(\mathbf{r}) + k^2 \int_V G(\mathbf{r}-\mathbf{r}') \, [n^2(\mathbf{r}') - 1] \, \mathbf{E}(\mathbf{r}') \, d\mathbf{r}' \qquad (2)$$

where **E(r)** is the total field at the point **r** (inside or outside the particle), $\mathbf{E}_o(\mathbf{r})$ is the incident field at the point **r** and G is the Green function which describes the field at the point **r** resulting from the interaction of an unit incident field with an element of matter dr', i.e. an "elementary particle" in the framework of the classical electrodynamic theory. The integral in equation (2) extends over the volume V of the particle. Depending upon the particular case (small or large particles) and the corresponding approximations which can be introduced in the expression of the Green function, one ends up with different practical solutions. The above elements of matter dr' are dipoles, so the discrete dipole approximation (DDA) as first introduced by Purcell and Pennypacker (1973) is obtained. This is well adapted to small particles as the number of dipoles remain within computer capabilities. For larger grains, one may consider larger, non-dipolar, elements of matter and solve for their complex mutual interactions as performed by Grim and Greenberg (this volume). One may also recover, the so-called eikonal solution (Chiappetta, 1980). All these solutions lead to intensive calculations often requiring large, vectorial computers. The DDA is well adapted to handle inhomogeneous or porous particles as impurities are modeled by different dipoles while porosity is simply modeled by voids. An example of a highly rough and porous particle is given in Fig. 1 and compared with spheres (Mie solution) of equivalent mass or equivalent cross-section. One notes important differences, both for the phase function and the polarization. The approach of effective medium has been introduced in particular for large particles for which the DDA becomes impractical. However, we have shown (Perrin and Lamy, 1990) that this application requires very stringent conditions or leads to large uncontroled errors. So one should be excessively cautious when using it.

3. Interpretation and discussion

3.1. THE VOLUME SCATTERING FUNCTION

As introduced in section 1, the volume scattering function $\psi(\theta)$ obtained from inversion of observational data represents the phase function of a unit volume of interplanetary dust. Basically, it can be expressed by

$$\psi(\theta,\lambda) = \frac{c}{k^2} \int F(\theta,\lambda,s)\, S(s)\, ds$$

where the integral extends over the size distribution S(s). Fig. 2 gives our nominal solution (Lamy and Perrin, 1986) characterized by a broad diffraction lobe, a shallow minimum in the interval 80-120° and a broad backward enhancement by a factor 2. We further found that the shape of $\psi(\theta)$ does not vary with heliocentric distance d while its magnitude varies as $d^{-0.3}$. This implies that the albedo increases as d decreases, a result confirmed by local inversion (Dumont and Levasseur-Regourd, 1988). It is interesting also to emphasize that the absolute value of $\psi(\theta)$ at 1 AU is fully compatible with the measured differential spatial density of interplanetary grains.

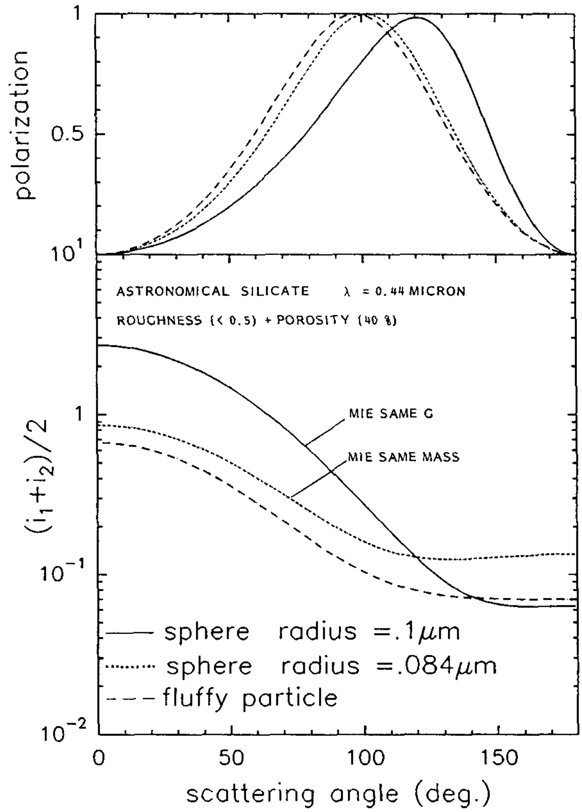

Fig. 1: The DDA result for the phase function and polarization of a highly rough and porous silicate particle of 0.1 μm radius (broken line) and comparison with the Mie result for spheres of equivalent mass (dotted line) and equivalent cross-section (solid line)

3.2. THE BACKSCATTERING SPIKE

A careful observation of the Gegenschein reveals a narrow spike (Maucherat et al., 1986) which has unfortunately escaped attention, in particular in the low resolution photometric scans. This spike has a width of approximately 1.5° to 2.5° and bears a direct ressemblance to the backward spike found in observations of several asteroids. An important point is that it is not correlated with the negative branch of polarization (see below) which extends over 15° to 20°. It may be connected with a fundamental aspect of optics known as the principle of weak localization. Among several mechanisms which may be invoked to explain this phenomenom, it seems that multiple effects (reflection, scattering) produced by the roughness of interplanetary grains is the most plausible.

3.3. THE POLARIZATION FUNCTION p(θ)

When inverting separately the two polarized components of the brightness of the zodiacal light, we retrieve the polarized components of the volume scattering function and finally, the polarization function p(θ) which is therefore also "integrated" over the size distribution. p(θ) is displayed in Fig. 2 and exhibits a broad maximum in the interval 70-100° reaching 0.29, and two negative branches: one in the backscattering domain which is not well defined since the observations themselves are not sufficiently accurate (the inversion angle is about 168°); and a second branch in the forward direction with an inversion angle of approxiamtely 22°. Overall, the polarization values decrease with decreasing heliocentric distance as $d^{0.3}$.

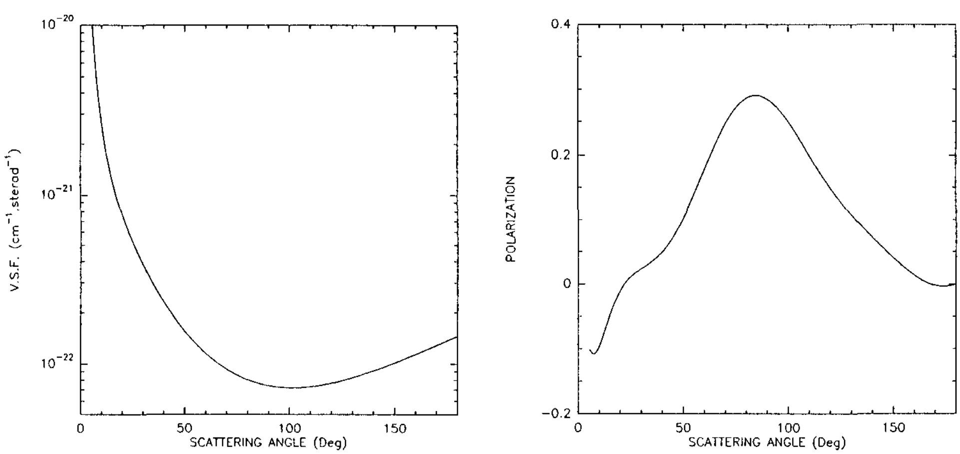

Fig. 2 The volume scattering function and its polarization at 1 AU

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3.4. INTERPRETATION

As already hinted in the above sections, the behaviour of both $\psi(\theta)$ and $p(\theta)$ are best explained by **rough**, moderately absorbing dust grains. It must be emphasized that other explanations such as those obtained by the Mie theory, i;e., assuming spherical grains, require restrictive, not to say unrealistic, assumptions. Furthermore, the simultaneous presence of two negative branches of polarization (if confirmed) cannot be explained by this theory but is present in laboratory results on irregular grains (Killinger, 1987). Also, on the basis of these results, the behaviours of both $\psi(\theta)$ and $p(\theta)$ are well compatible with a mixture of Allende matrix and Murchison grains. However, this must be taken as a trend since the laboratory data are for single grains, i.e., not integrated over a size distribution. But this points to a very coherent view of the zodiacal cloud. Finally, the decrease of $p(\theta)$ and the increase of albedo as the heliocentric distance decreases are probably connected to a change in size distribution resulting from catastrophic collisions among interplanetary grains and the loss of absorbing material such as organic material.

3.5. THE COLOR OF THE ZODIACAL LIGHT

As a presentation of the observational results may be found in the review of Grün and Leinert (1991), we limit ourselves to discussing the various aspects of this question following a more detailed investigation (Perrin and Lamy, 1989). First, it must be understood that the color index of the zodiacal light deduced from brightness measurements at different wavelengths depends upon the elongation, while the color ratio for light scattered by dust grains is intrinsec since it involves the scattering cross-section. The two indices are equal only in the limit of zero elongation when, furthermore, the spatial density varies as r^{-1}. Second, the widespread view that the presence of small grains implies a blue color is incorrect as this results from the Rayleigh law which is strictly never obeyed. This is due to the variation of the refractive index with wavelength and the large values of its complex part exhibited by all materials in the ultra-violet. This is of course confirmed by a simple Mie calculation for spherical grains. Third, the color depends upon the amplitude of grain roughness with respect to wavelength: small amplitudes lead to reddening while large amplitudes lead to blueing. Finally, the very observation of the brightness of the zodiacal light as a function of elongation introduces an intrinsec color effect, either reddening or blueing; this theoretical prediction is supported by actual observations.

3.6. THE ALBEDO

Following the work of Hanner et al. (1981), the albedo $Ap(\theta)$ of a single dust grain is well defined as a function of its total intensity function $i(\theta)$ and its geometric cross-section. As a consequence, the albedo depends upon the scattering angle, the wavelength and the size of the grain as proved by laboratory measurements (Killinger, 1987; Giese et al., 1986). To derive the albedo from observed intensities which are integrated over the size distribution and along the line-of-sight certainly is an hopeless task. As we have proposed for cometary grains (Lamy et al., 1987), a reasonable approach may be to find an acceptable fit to the volume scattering function $\psi(\theta)$ - from the point of view of composition and scattering theory - and to compute the albedo in restricted size intervals, typically $\Delta s/s = 0.1$. It can be shown from theoretical considerations that the method which combines visible and infrared brightnesses and which was devised for asteroids does not apply at all to dust particles. Finally, the method relying on the slope of the negative branch of polarization calibrated for rough surfaces and used for determining the albedo of planetary objects again completely fails for dust particles (Lamy, in preparation). A sound approach to the question of the albedo of interplanetary dust is probably to measure the phase function of collected IDP.

4. Conclusion

In our opinion the situation of the observations of the zodiacal light is somewhat paradoxal. On the one hand, the set of available data, in particular from the Pioneer and Helios space probes have not been fully interpreted to reach a synthesis of the properties of interplanetary dust. On the other hand more data are needed, especially polarization data, as well as a better photometric accuracy. The forthcoming COBE data will partly fill this need but the inner zodiacal light remains poorly known. The next solar eclipse and the SOHO mission may help remedy this situation. Direct determinations of the spatial density of dust using impact detectors are also needed to help obtain the volume scattering function from inversion. The Galileo, Ulysses and Cassini missions should provide this information. A better understanding of the optics of complex dust particles has been achieved in recent years thanks to both laboratory measurements and theoretical work. Overall it appears that we now have a coherent understanding of the zodiacal light as rough grains of mostly meteoritic composition satisfy most if not all observational constraints.

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