WAVELENGTH DEPENDENCE OF THE ZODIACAL LIGHT

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ABSTRACT. We calculated the scattering cross section of an ensemble of large, convex, randomly oriented particles with a slight surface roughness. If the roughness structure is described by an exponential correlation function, the degree and angular dependence of the zodiacal light reddening are well reproduced by our model.

1. INTRODUCTION

The observations in the last 20 years and especially the experiments on Helios 1 and 2 appreciably improved our knowledge of the interplanetary dust, and there is a consensus about the essential properties of those dust particles that produce most of the visual zodiacal light: they are much larger than wavelength and show up a very irregular structure. These irregularities lead to shadowing and multiple scattering at the surface of the particles, effects which cause the "Gegenschein" and the low polarization values.

Several particle models have been suggested, and most of them are based on geometrical optics (Mukai et al., 1982; Schiffer and Thielheim, 1982; Perrin and Lamy, 1983); that means that the radii of curvature of the surface irregularities are assumed to be much larger than wavelength. In spite of this restriction these model particles can very well reproduce the essential features of the zodiacal light, and so they possibly represent a rather realistic description of a great part of the interplanetary dust.

But scattering models based on geometrical optics lead to wavelength independent scattering - if we neglect the wavelength dependence of the refractive index for the moment. The measurements carried out on the Helios space probes, on the other hand, show a slight reddening of the scattered intensity with respect to the solar spectrum, and this reddening decreases with increasing elongation; moreover the degree of polarization becomes lower with increasing wavelength (Leinert et al., 1981). A similar type of reddening has been found for other atmosphereless bodies of our planetary system. It should, however, be emphasized that not all zodiacal light observations support the evidence of this

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colour effect.

As a reddening in the visual range of the spectrum cannot well be explained by a wavelength dependent refractive index (Röser and Staude, 1978), we suspected that it might be produced by the surface structure of the particles, and we shall show in the following that a slight surface roughness, a roughness structure of the order of wavelength and smaller, can in fact explain the observed colour effects; this slight roughness might be superposed on the large irregularities mentioned above.

2. THE PARTICLE MODEL

In order to simplify the calculations we constructed a model particle which shows up only the slight surface roughness. This model does not represent a realistic interplanetary dust particle, because the large irregularities are neglected, but it is sufficient for a discussion of colour effects. Our model consists of an ensemble of large, convex, randomly oriented particles with a slightly rough surface. The material is slightly absorbing so that light refracted into the particles will not escape - so only the reflected component has to be considered. The particles are assumed to be so large that results for light reflection from planar rough areas may locally be applied to the surface of the particles.

The problem of light reflection from slightly rough planar areas can be solved in form of a perturbation expansion, the so-called Rayleigh-Rice-approach (Lord Rayleigh, 1907; Rice, 1951). Given the rough plane and the incident plane wave, the refracted and the reflected light are expanded in plane waves, and the coefficients of these terms are determined by the perturbed boundary conditions. Explicit results are then obtained as an expansion in hk (k: wavenumber, h: mean height deviation of the roughness structure), as shown here for the reflected electric field:

$$\vec{E}_r = \vec{E}_r^{(0)} + \vec{E}_r^{(1)} + \vec{E}_r^{(2)} + \dots ,$$

and if h is much smaller than wavelength, we may neglect terms of higher than second order in hk.

Averaging the intensity over the statistical properties of the surface then gives, up to the second order in hk,

$$\langle|\vec{E}_r|^2\rangle = |\vec{E}_r^{(0)}|^2 + \langle|\vec{E}_r^{(1)}|^2\rangle + 2\,\mathrm{Re}\,\vec{E}_r^{(0)}\cdot\langle\vec{E}_r^{(2)}\rangle^* .$$

The first term represents the light reflected from a smooth surface, the second is the incoherent contribution produced by the roughness, and the third term is the coherent component - it is for the most part negative and represents the intensity diminution of the zero order term. Explicit expressions have been given e.g. by Barrick and Peake (1967) and Valenzuela (1967).

The decisive quantity, which has most influence on the scattering behaviour, is the correlation function $\rho(r)$ of the roughness structure; for a rough surface $z=f(x,y)$ $(\langle f\rangle=0)$ we have

$$\langle f(x,y)\; f\,(x+\Delta x,\; y+\Delta y)\rangle = h^2\, \rho(\sqrt{(\Delta x)^2+(\Delta y)^2}) \qquad \text{with} \quad \rho(0) = 1,$$

where the bracket denotes the average over (x,y). In the following we choose an exponential function for $\rho(r)$:

$$\rho(r) = \exp(-r/l)$$

l is called the correlation length of the roughness structure.

These results can now be applied to the surface of our model particles. Here we make use of a well known theorem which states that the scattering pattern of large, convex, randomly oriented particles is identical with the scattering pattern of a large sphere with the same surface conditions. So for calculating the reflected light we may assume our model particles to be spherical.

3. RESULTS AND DISCUSSION

Calculations yield, for unpolarized incident light and a dielectric constant $\varepsilon = 5$, the curves in Figs. 1 and 2 for intensity and polarization of the reflected light as a function of the scattering angle Θ; the infinite value of the parameter kl corresponds to a perfectly smooth surface (Schiffer and Thielheim, 1984).

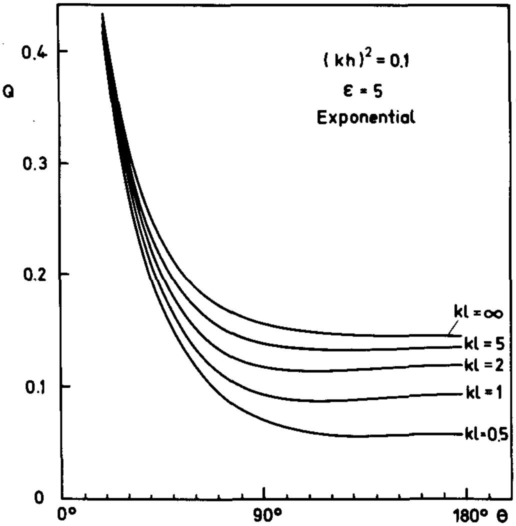

Figure 1. Scattering cross section of a slightly rough sphere.

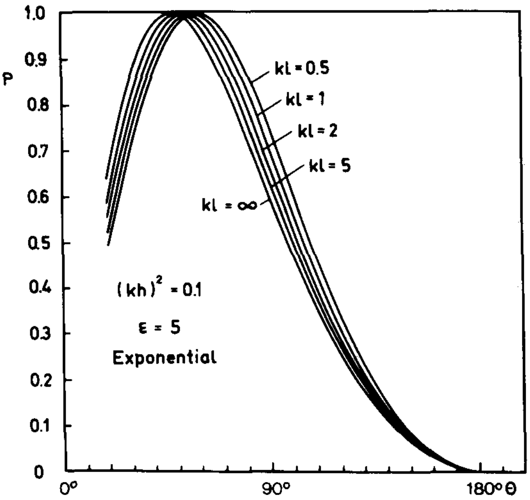

Figure 2. Polarization curve of a slightly rough sphere.

These plots show that stronger roughness, that means smaller l, reduces the reflectivity of the surface and shifts the polarization maximum to larger scattering angles.

Fig. 3 shows the wavelength dependence of the scattered intensity between 4000 and 8000 Å for several scattering angles, a dielectric constant $\varepsilon = 2.25$, and a correlation length l = 5000 Å; the curves have been normalized to 1 for $\lambda = 4000$ Å. Obviously the scattered light is reddened for all scattering angles.

For a comparison with measurements we calculated the ratio of intensities at visual and blue wavelengths as a function of the elongation, as measured by Helios. For achieving this we have to integrate our results

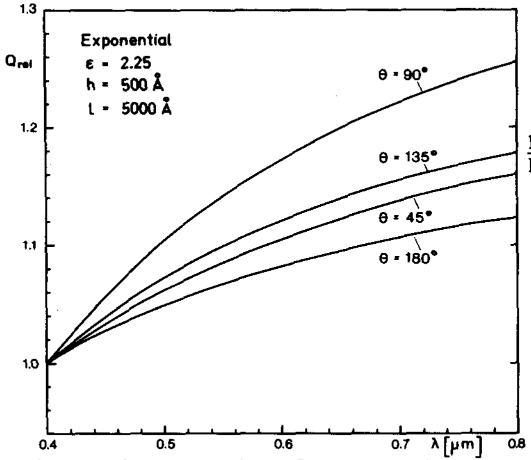

Figure 3. Normalized scattering cross section as a function of wavelength for several values of the scattering angle θ.

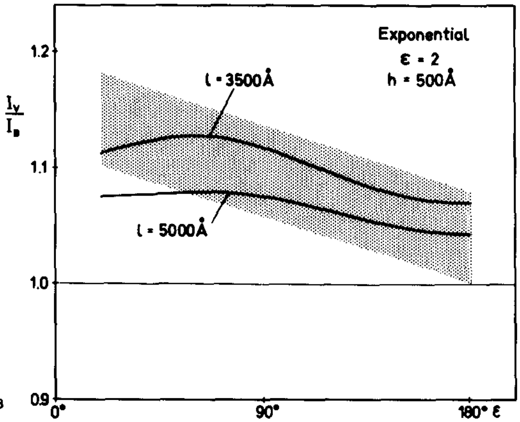

Figure 4. Ratio of intensities at wavelengths λ_V = 5290 Å and λ_B = 4250 Å as a function of elongation; shaded area: range of measured data.

over the line of sight, and assuming a particle density proportional to $R^{-1.3}$ (R: distance from the sun) we obtain curves as shown in Fig. 4; the shaded area indicates the range of the measured data. One may conclude that the observed reddening of the zodiacal light can well be produced by slight surface irregularities of the type considered here.

However, we so far neglected the strong roughness, which is certainly the dominant type of irregularity for the interplanetary dust particles. But closer inspection shows that this strong roughness, since it does not lead to wavelength dependent effects, does not change these curves appreciably. So particles with a composite surface combining both roughness types possibly represent a realistic model of the zodiacal light particles.

The superposition of both roughness types also provides an explanation of the observed flattening of the polarization curve with increasing wavelength: the polarization values are in this model mainly determined by the light scattered multiply at the surface of the particle, which is an effect of the strong type roughness; enhanced multiple scattering leads to smaller polarization values. When the reflectivity of the surface increases for larger wavelengths, this especially enhances the multiply scattered intensity and so leads to a further flattening of the polarization curve.

Maybe the observed reddening of the scattered light from other atmosphereless objects of the planetary system can at least in part be explained by a slight surface roughness of the type considered above - it seems plausible that bodies exposed to the environment of the solar system exhibit a similar microstructure of their surfaces.

Question (Zerull): Does your theoretical approach also reduce the polarization reversal, or could it be modified to do this?

Answer (Schiffer): No, our model does not lead to negative polarization values near backscattering, at least not for dielectric materials. We believe the polarization reversal to be an effect of the strong type roughness.

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