LIGHT SCATTERING BY SOLAR SYSTEM DUST: THE OPPOSITION EFFECT AND THE REVERSAL OF POLARIZATION

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1. Introduction

The opposition effect and the reversal of linear polarization, or negative polarization, at small phase angles have been almost universally observed in light scattered from atmosphereless solar system bodies (e.g., Seeliger 1887, Lyot 1929). Recent investigations have indicated that both phenomena can be qualitatively understood as resulting from a common physical mechanism: coherent multiple backscattering (Shkuratov 1989, Muinonen 1989). These findings have cast doubt on the hitherto accepted explanation that mutual shadowing alone is responsible for the opposition effect, and for the first time offer an acceptable interpretation of the polarization reversal near opposition. As for interplanetary dust, the coherent backscattering mechanism contributes both to the Gegenschein and to the almost certainly existing negative polarization branch (Roosen 1970, Lumme and Bowell 1985).

In the following, theoretical results supporting the coherent backscattering explanation are briefly presented. As future work, we suggest modeling light scattering by a particulate medium to include the first, second and, if necessary, higher orders of scattering in the range below the typical particle size.

2. Coherent Backscattering Mechanism

The mechanism of second-order coherent backscattering is illustrated in Figure 1, in which an electromagnetic plane wave with wave number k is scattered at two scattering centers separated by a distance d. The scattering centers can be individual particles, subparticles in an aggregate particle, or cracks or other optical inhomogeneities.

The phase difference between the wave components that propagate in opposite directions (cyclic passage) determines the interference. In the backward direction (at phase angle $\alpha = 0°$), the phase difference is always zero and the two paths of propagation coincide. This leads to constructive interference and coherent second–order backscattering. For non–zero phase angles, the interference varies from constructive to destructive depending on kd and the orientation of the system. Coherence also occurs in scattering orders higher than the second. Phase reddening and the color opposition effect can also be explained by this mechanism, since it predicts a narrower opposition effect for shorter wavelengths.

Negative polarization near opposition can be understood by calculating the phase difference in the yz–plane in the two scattering geometries shown in Figure 1. Since first–order scattering is predominantly positively polarized (e.g., Rayleigh scattering, Fresnel reflection), the scattering centers sufficiently far from each other interact mainly with the electric field vector perpendicular to the plane defined by the Sun and the scattering centers. The

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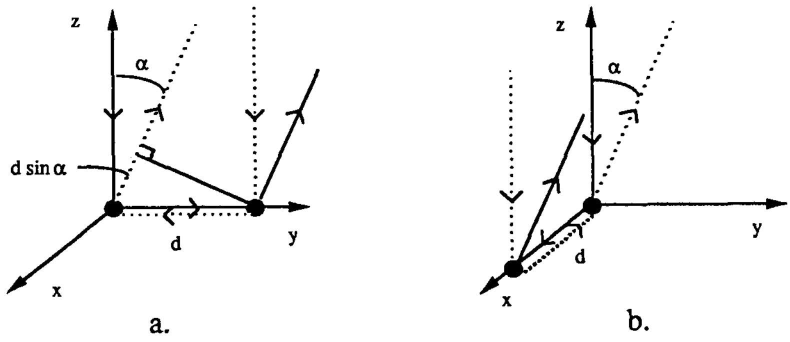

Fig. 1. Interference in second–order scattering (Muinonen 1990a). The wave components propagating in opposite directions (solid and dotted lines) interfere constructively at opposition ($\alpha = 0°$). For non-zero but small phase angles, the interference favors negative polarization: *(a)* in the yz–plane, in the scattering geometry leading to positive polarization, the interference depends on the phase difference $\delta = kd \sin \alpha$; but *(b)* the interference is always constructive in the geometry causing negative polarization.

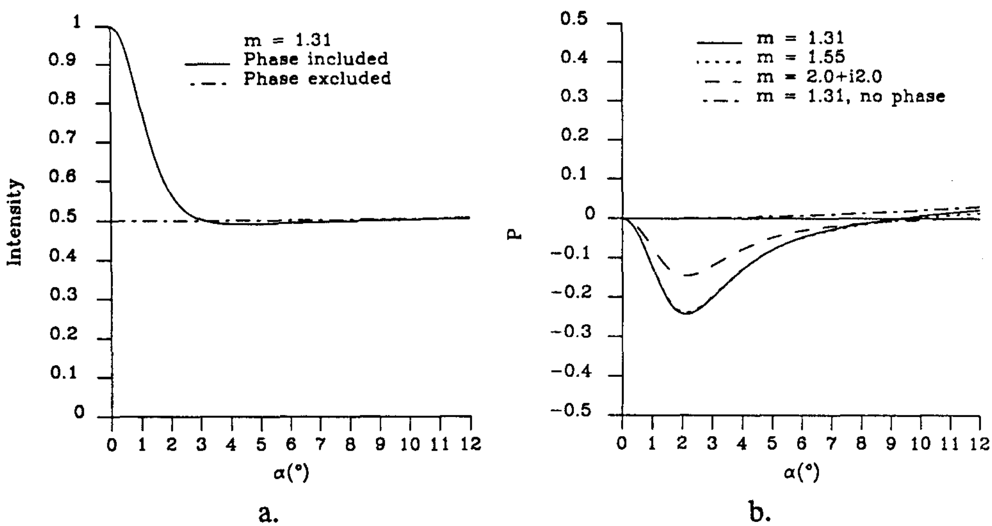

Fig. 2. Second–order reflection including and excluding the phase. Both *(a)* backward enhancement and *(b)* polarization reversal follow when the phase is included. The spherical elements (radius R) touch each other, $\kappa = 1/10k$ in an exponential size distribution $n(R) = \kappa \exp(-\kappa R)$, and m is the refractive index.

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observer in the yz–plane will measure positive polarization from the geometry in Figure 1(a) and negative polarization from that in Figure 1(b). However, positive polarization undergoes a phase difference $\delta = kd \sin\alpha$, whereas the phase difference for negative polarization is zero at all phase angles (scattering centers in the xy-plane). Isotropic averaging over positions of the scattering centers will result both in an increase in brightness and in a reversal of polarization near the backward direction (at exactly zero phase angle the polarization goes to zero).

The simplest two–particle scattering problem is that of two electric dipole scatterers (Muinonen 1989). The backscattering enhancement and reversal of polarization are clearly present in second–order scattering, but due to the small scattering cross section, the phenomena do not show up in total scattering. The contribution due to multiple scattering increases when the other dipole scatterer of the previous calculation is replaced by a dielectric halfspace (Muinonen et al. 1990), and a quantitative confirmation is obtained for the backscattering peak and polarization reversal in total diffuse scattering. Finally, the second–order external reflection from two spherically curved surface elements indicates why the phase has to be included in the study of a close–packed medium (Muinonen 1990b). Figure 2 shows the results from horizontal isotropic averaging, both including and excluding the phase, for normal incidence. Neither the backscattering peak nor polarization reversal follows from calculations, in which phase is excluded.

3. Modeling Regoliths and Fluffy Particles

As shown above, coherent backscattering arises from inhomogeneities at scales of about a few microns. Spheres are known to exhibit the glory effect which, however, is due to a different interference mechanism. Both the regolith and interplanetary dust particles are believed to have sizes between 10 μm and 100 μm, which is larger than the typical range of coherence phenomena. This suggests a model in which, in the first approximation, scattering between the particles can be treated using geometric optics, although wave optics phenomena must be accounted for when calculating the single–particle phase function.

For planetary regoliths we can now assume

$$I_p(\mu_0, \mu, \psi) = \frac{1}{4}\varpi_0 P_p(\alpha)\, \mu_0 R_1(\mu_0, \mu, \psi)\, F + \mu_0 R_M(\mu_0, \mu, \psi)\, F \qquad (1)$$

for the perpendicular and parallel polarizations (subscripts $p \to \perp$ and $p \to \|$). In this model, μ_0 and μ are the cosines of the angles of incidence and emergence, ψ is the azimuth, α the phase angle, πF the incident solar flux density, ϖ_0 the single–particle albedo, and P_p is the single–particle phase function. The single and multiple reflection coefficients R_1 and R_M can be calculated from the geometric optics approximation as by Lumme et al. (1990), who generalized the classical radiative transfer theory, replacing the planar interface with a stochastic process. If the surface roughness tends to zero then $R_1 = S(\alpha)/(\mu_0 + \mu)$ which is the classical Lommel–Seeliger law corrected for the mutual shadowing function S.

As described earlier, we have calculated P_p for two extreme cases: when the scattering centers are very small or very large compared to the wavelength. It is, however, conceivable that the elements are on the order of 1 μm in the case of closely packed fluffy particles. Modeling this kind of situation could be done, as a first step, by the rigorous theory of two interacting spheres as formulated by Bruning and Lo (1971).

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4. Discussion

At present, no valid theoretical model exists for quantitative analysis of the observations of the opposition effect and polarization reversal. We suggest that modeling could be initiated by studying dark particulate media using radiative transfer theory, including the effects of coherent multiple backscattering, mutual shadowing, and shadowing due to surface roughness.

Based on our calculations, we conclude that the width of the branch of negative polarization depends mainly on the size of the inhomogeneities, their distribution in the regolith, and on the refractive index. The observed negative branch can be ascribed to inhomogeneities on the order of 1μm. The mechanism predicts broader negative branches for larger refractive indices, in which case more energy is concentrated on low orders of scattering. This agrees well with observations.

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