PHOTOMETRIC AND POLARIMETRIC OPPOSITION EFFECTS OF SIMULATED PLANETARY REGOLITHS

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We present results from simultaneous photometric and polarimetric laboratory measurements of samples that have different microcrystalline structures and albedos. The studies were conducted using the Kharkiv Observatory laboratory polarimeter at a wavelength of 0.65 μm and phase angles covering $0^\circ\!.1 - 3^\circ\!.5$. This polarimeter was calibrated with a comparable instrument at JPL NASA. Surfaces formed by smoked deposits of MgO and carbon soot show similar prominent negative branches of polarization with minima near $2^\circ\!.0$ and depths near 1%, despite the fact that they have extremely different albedos and brightness opposition effects. The results for carbon soot allow to predict a narrow negative polarization branch for some dark asteroids. A strong particle-size dependence of the negative polarization parameters for powdered dielectric surfaces was found. Particle-size separates of Al_2O_3 (0.1, 0.5, 1, 7, and 12 μm) with almost the same albedo were studied. For grain larger than 1 μm the depth of negative polarization does not exceed 0.2%. It is maximal (0.8%) for the 0.1 and 0.5 μm fractions. The angular width of the opposition spikes of all the separates are very similar. These data are important to interpret photometric and polarimetric opposition effects of icy satellites of outer planets and bright asteroids.

INTRODUCTION

Many bright airless Solar System bodies exhibit two phenomena observed near opposition: opposition brightening and negative linear polarization. These effects are observed over both narrow ($< 2^\circ$) and wide (2°–20°) ranges of phase angles. Photometric and polarimetric opposition effects, both with very narrow angular widths, are observed in Saturn rings, some icy satellites of outer planets (*e.g.*, Europa, Titania), and also bright asteroids. The photometric and polarimetric opposition effects accompany each other in laboratory experiments as well as in planetary observations. Characteristic opposition effects are illustrated by photometric observations of Harris *et al.* (1989) and polarimetric measurements (Rosenbush *et al.*, 2000) of the asteroid 64 Angelina (see Figs. 1 and 2). To date, most planetary studies suggest that the strength of the photometric opposition effect and the depth of the negative branch of polarization are correlated with one another – surfaces with strong photometric opposition effects often exhibit larger negative polarizations than surfaces with weak photometric opposition effects. Their simultaneous occurrence is predicted by coherent backscatter enhancement theory (*e.g.*, Shkuratov, 1985; Muinonen, 1990; Mishchenko, 1993).

Most laboratory studies of the photometric and polarization opposition effects cover a wide range of phase angle with the minimum angle extending down to a few degrees in phase. However, measurements of both effects at phase angles smaller than a few degrees are very rare. For instance, polarimetric measurements at phase angles $< 1^\circ$ were first carried out by Lyot (1929), but included only a sample of smoked deposit of MgO. To better understand the photometric and polarimetric opposition effects and to interpret available telescopic and anticipated (*e.g.*, Cassini) spacecraft observational data, more laboratory measurements of regolith simulants are necessary. In this paper we present first results of such measurements for samples that exhibit different albedos and microstructure.

EQUIPMENT AND SAMPLES

To study the phase dependence of the degree of linear polarization from light scattered by samples of simulated regolith, we used the Kharkiv Astronomical Observatory laboratory photometer-polarimeter (Shkuratov *et al.*, 1999). This instrument allows us to measure the reflectance and degree of linear polarization at phase angles covering $\alpha = 0.^{\circ}1 - 3.^{\circ}5$. In this study, we used only one spectral band 0.65 μm. All measurements were done at a standard observation/illumination geometry such that the samples were viewed by the detector at normal emission angle and motion of the light source changes the incidence and phase angles. Sample albedo was determined relative to a Halon reflectance standard at $\alpha = 2^{\circ}$. The estimated accuracy of our measurements is 0.05%, including random and systematic errors. The Kharkiv photometer-polarimeter was calibrated against a comparable JPL NASA instrument (Nelson *et al.*, 1999). Table 1 provides a description of our laboratory samples. We studied smoked-deposits of MgO and carbon soot (*i.e.*, samples with extremely different albedo), ultra-disperse powdered SiO_2, and particulate size-separates of Al_2O_3 powder. Results of our preliminary studies are presented in Figures 1 and 2.

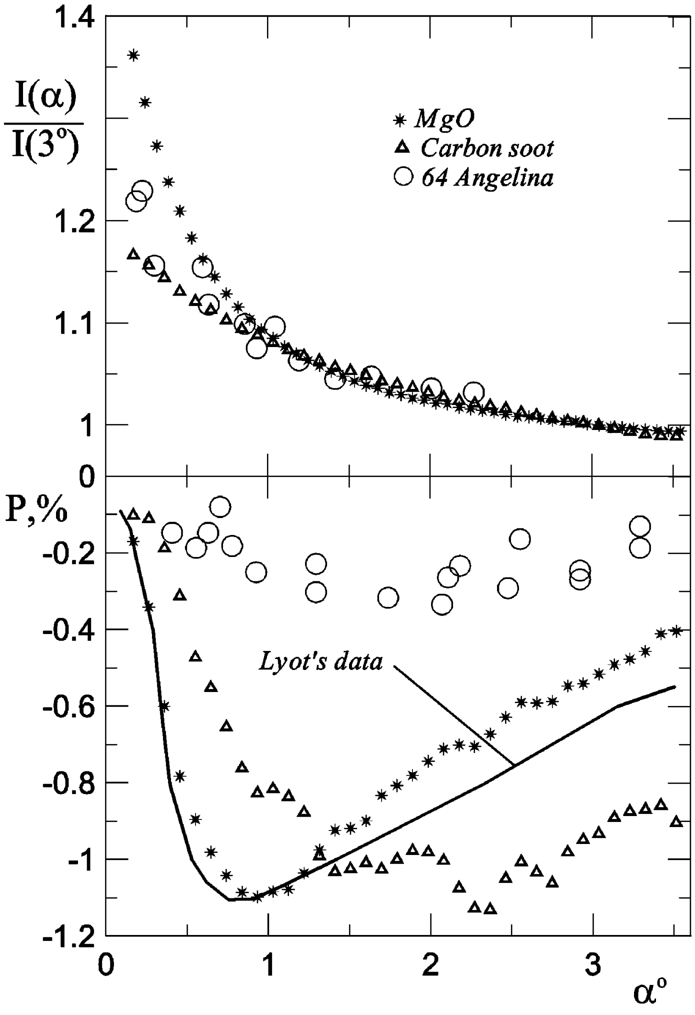

Figure 1: The photometric and polarimetric opposition effects for the asteroid 64 Angelina (the opposition spike is obtained after removal of a linear component of the phase curve) and for carbon soot and MgO smoked deposits. Lyot's (1929) data are presented by line

RESULTS AND DISCUSSION

Figure 1 shows the phase dependences of brightness and the degree of linear polarization for smoked surfaces that exhibit different albedo, MgO and carbon soot. The strengths of the photometric opposition effects clearly depend on albedo: The opposition spike for bright MgO is about 20% stronger than for dark soot deposits. Because coherent-backscatter enhancement relies upon the presence multiply-scattered light, the observed behavior is consistent with its occurrence in our samples. However, in this example, photometric and polarimetric effects

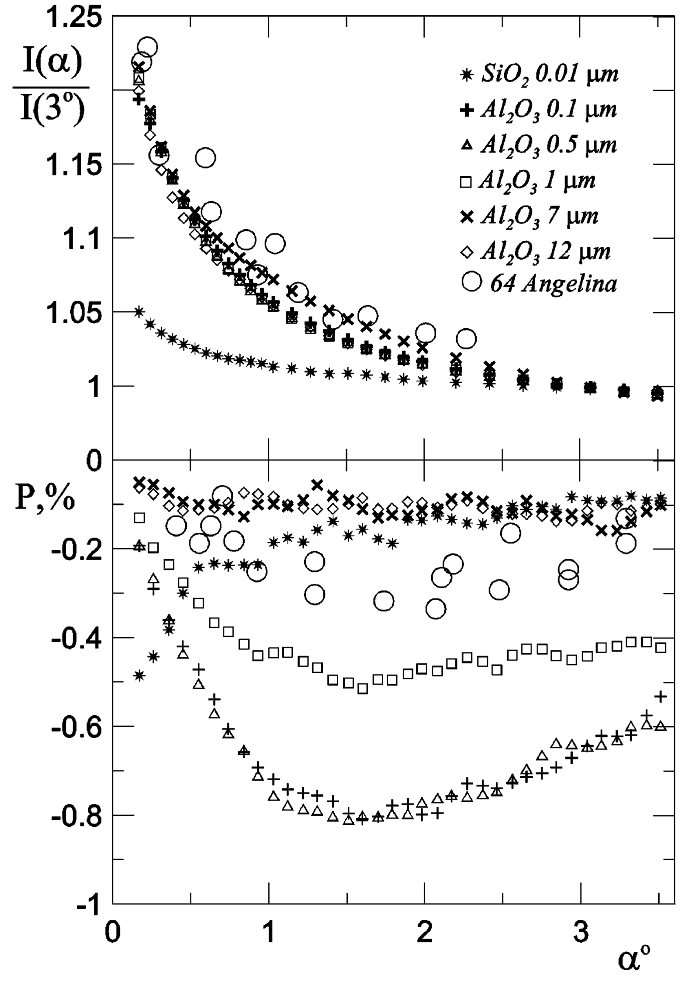

Figure 2: Phase dependence of brightness and polarization degree for nanodisperse powder of SiO_2 and for Al_2O_3 separates with different size of particles. Data for the asteroid 64 Angelina are also given here

are not strictly correlated with one another, in contrast to what might be expected if coherent-backscatter is responsible for the negative polarization and the brightness opposition effects. Figure 1 shows that while both samples clearly exhibit different brightness opposition surges they each have similar negative polarization branches. The results for carbon soot allow to expect a narrow negative polarization branch for some dark asteroids, if they have fluffy submicron structure of the surface. Figure 1 also allows a comparison of our measurements of smoked-MgO to those of Lyot; the dependences are almost the same. Some mutual deviations are likely related to differences in preparation of the samples. Note also that the depth of the negative branch of polarization for the samples and asteroid 64 Angelina is very different.

Figure 2 shows the photometric and polarimetric behavior of SiO_2 powder with very small particles that are only a few nanometers in size. This sample exhibits an extremely narrow negative polarization branch. While the plot can be seen to approach a definite minimum as phase angle decreases to $0\overset{\circ}{.}1$, our experimental measurements do not extend downward to small enough phase angles to observe the polarization as it becomes zero. The nanodisperse SiO_2 powder appears to exhibit no significant brightness opposition spike over our measured phase angle range.

A strong particle-size dependence in the negative polarization branch for powdered dielectric surfaces was found (see Figure 2). Particle-size separates of Al_2O_3 (0.1, 0.5, 1, 7, and 12 μm) with almost the same albedo were studied. For grain-sizes larger than 1 μm the depth of the negative polarization does not exceed 0.2%. It is maximal (near 0.8%) for the 0.1 and 0.5 μm fractions. The brightness phase dependencies of the samples are remarkably similar. The angular-width of the opposition spike is slightly broader for the 4 μm fraction than for the other size-fractions. Our measurements of Al_2O_3 particle-size separates thus provide an additional example

Table 1: Characteristics of samples

name	albedo at 2°, %	particle size, μm
MgO	98	< 1
soot	3	< 1
SiO_2	98	~ 0.01
Al_2O_3	100	~ 0.1
Al_2O_3	100	~ 0.5
Al_2O_3	97	~ 1
Al_2O_3	95	~ 7
Al_2O_3	95	~ 12

for which the photometric and polarimetric opposition effects are not strictly correlated. Among measured samples, only the 1 μm fraction of Al_2O_3 yields both photometric and polarimetric opposition effects that are more or less mutually comparable to those of 64 Angelina. We note that qualitatively similar results with polarimetry of Al_2O_3 powders have been obtained by Geake and Geake (1990). However, they were able to measure only at phase angles larger 1° and they did not study the photometric properties of the samples.

In summary, we have found laboratory examples of samples whose photometric and polarimetric behaviors do not strictly follow to the coherent backscatter enhancement model. In particular, the photometric and polarimetric opposition effects are not neither correlated among bright and dark samples of the same particle microstructure structure and in the case of particle-size separates of Al_2O_3.

CONCLUSION

1. We have found examples for which both photometric and polarization opposition effects are not strictly correlated to one another, contrary to the predictions of coherent-backscatter theory. In particular, MgO and carbon soot smoked-deposits have closely matching negative polarization branches, but exhibit different photometric behavior at small phase: a prominent opposition spike for MgO and comparatively small surge in the case of soot.

2. Surfaces composed of particles having a characteristic structure scale on the order of a wavelength of light reveal the negative polarization at the range $0.^\circ1 - 3.^\circ5$. This effect disappears at larger structure scales. The negative polarization branch is transformed to a very asymmetric one for fluffy surfaces consisting of nanometer-sized (Rayleigh) particles and the brightness opposition spike becomes too narrow to be measured in our experiments ($< 1°$).

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