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Optical measurements of chemically heterogeneous particulate surfaces

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ABSTRACT

We experimentally study light scattering by particulate surfaces consisting of two high-contrast materials. Using the Finnish Geodetic Institute field goniospectropolarimeter, reflectance and degree of linear polarization are measured in dark volcanic sand, bright salt (NaCl) and bright ferric sulfate ($Fe_2(SO_4)_3$); and in mixtures of bright and dark components. We found that the light-scattering response monotonically changes with volume ratio of dark and bright components. In contrast to previous finding, we do not detect an enhancement of the negative polarization amplitude in two-component high-contrast mixtures. Two-component mixtures reveal an inverse correlation between maximum of their linear polarization and reflectance near backscattering, the so-called Umov effect. In log–log scales this inverse correlation takes a linear form for the dark and moderate-dark samples, while for the brightest samples there is a noticeable deviation from the linear trend.

1. Introduction

Remote sensing is intended for studying objects that, for some reason, cannot be reached directly. An important case is the passive remote sensing that is based on interaction of sunlight with a target. This approach is widely exploited in astronomical applications due to large distances from the observer to objects of interest. However, passive remote sensing also is important in terrestrial applications, for example, in atmospheric, oceanic, soil, and vegetation studies (e.g. [1–4], and references therein). Characteristics of the sunlight scattered from these objects having different origin are governed by their physical and chemical properties and conditions.

Analysis of the light-scattering response measured in an unknown target requires a comparison with well-characterized reference samples. In this sense, laboratory measurements are quite useful for validation of the retrievals. Laboratory studies of light scattering by particulate surfaces have been carried out for long time and resulted in numerous findings (e.g. [5–15]).

Geake and Dolfus [6] attempted to link the laboratory optical measurements and astronomical observations; they excellently demonstrated the value of the laboratory measurements to interpret the observations. Their work incorporates laboratory optical measurements of rocks and

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powder samples, meteorites, lunar samples delivered by Apollo space missions, along with astronomical observations of Mercury, Mars, Moon, and other solar system objects. These efforts resulted in some fundamental discoveries. For instance, comparison of optical measurements of the lunar samples with astronomical observations of the Moon has proven that its surface is entirely covered with regolith and has no significant amount of bare rocks. Furthermore, comparison of the light-scattering response from the lunar samples with astronomical observations of the planet Mercury, also suggested presence of a regolith surface.

A program of comprehensive laboratory investigation of light scattering by particulate surfaces was conducted at the V.N. Karazin Kharkov National University, Ukraine (e.g., [7,8,10,13]), which revealed a number of interesting phenomena. One of them corresponds to the phenomenon of the negative polarization in high-contrast two-component mixtures [7], and it also is in focus of the present study.

Phenomenon of the negative polarization is observed in the scattering of sunlight by particulate surfaces at small phase angles $\alpha \approx 0$–$30°$ note, the phase angle is a supplementary angle to the scattering angle θ, so $\alpha = 180° - \theta$. While the incident solar radiation is unpolarized, the scattered light acquires partial linear polarization that is quantified with the degree of linear polarization P as follows [16]:

$$P = \frac{I_\perp - I_{||}}{I_\perp + I_{||}}. \quad (1)$$

Here $I_\perp$ and $I_{||}$ stand for intensity of the scattered light that is polarized perpendicular to the scattering plane and in the scattering plane, respectively. The scattering plane is the plane that includes the source of light, the detector, and the sample. Thus, the negative polarization simply implies that $I_\perp < I_{||}$. It is important to emphasize, the negative polarization is systematically detected in particulate surfaces having different composition and texture. For more details on this phenomenon, we refer reader to review [17].

Shkuratov and Ovcharenko [7] investigated light scattering by a bright powder of MgO and a dark powder of Fe_2O_3. The amplitude of the negative polarization in these significantly different samples was found to be remarkably similar, $|P_{min}| \approx 0.6$–0.7%. However, mixture of these two materials revealed the negative polarization whose amplitude is about two times larger compared to the pure components, $|P_{min}| \approx 1.2\%$. The authors concluded that the increase of the negative polarization results from mixing high-contrast components. On the other hand, this conclusion is based on a sole set of the constituent materials that, apparently, raises certain doubt concerning how common is this effect in other high-contrast mixtures. The principal goal of the present work is to address this issue. We also would like to note other studies of light scattering by two-component mixtures (e.g., [9,11]); however, they do not address to the effect of enhancement of the negative polarization in high-contrast mixtures.

We investigate three types of pure powders, two of them, salt (NaCl) and ferric sulfate ($Fe_2(SO_4)_3$) are bright in appearance, whereas another one, volcanic sand, is dark. Study on light-scattering properties in mixtures of materials with significantly different brightness has numerous terrestrial and cosmic applications. For instance it is of high practical interest in remote sensing of purity of snow. It also can be applied to analysis of astronomical observations. For example, recent observations of dwarf planet Pluto with *New Horizon* probe [18] have revealed that the Pluto's surface consists of dark and bright areas with plausible mixing of these substances in boundary region.

We consider two types of mixtures: (1) salt–volcanic sand and (2) ferric sulfate–volcanic sand. It also is important to note that analysis in [7] is limited to the phase angles $\alpha \leq 60°$. However, we extend analysis toward the range of large phase angles, up to $\alpha \leq 120°$ that permits investigation of the phenomenon of the positive polarization, i.e., $I_\perp > I_{||}$. This makes it possible to investigate the so-called *Umov effect* in high-contrast mixtures. Note, the Umov effect refers to an inverse correlation between amplitude of the positive polarization and reflectance in a particulate surface; therefore, it is a powerful tool for passive remote sensing, e.g., [19].

2. Instrumentation and experiment description

The measurements were carried out with the Finnish Geodetic Institute field goniospectropolarimeter FIGIFIGO [20]. FIGIFIGO allows measurement of the reflectance and linear polarization of the target, both in the laboratory and in the field conditions. The scheme of the optical setup in the laboratory is presented in Fig. 1. In the experiment a halogen lamp is used as a light source. The lamp light is collimated by the parabolic mirror and directed to the target by a plane mirror. The zenith angle of incident light was set to 52°. The phase angle dependence of the polarization is measured with the detecting optics placed on a motor-driven moving arm. Line of sight of detector is parallel to the moving arm. Field of view at the location of sample has an extent of about 10 cm when zenith angle is equal to 0° at larger zenith angles it spans an elliptical area with the major axis being up to 30 cm. Distance from sample to the detector lens is 150 cm. The moving arm has capability to decline from the normal to sample surface for angles from −70° to 70° that corresponds to phase angle spanning the range from −18° to 122°. A calcite Glan–Thompson prism is used as a polarizer, covering the full spectral range with better than 1% accuracy. To measure all linear polarization states, the prism was rotated. The fore-optics is connected to an ASD FieldSpec Pro FR 350–2500 nm spectroradiometer by an optical fiber. For the spectrometer calibration, a Labsphere Spectralon 99% is used as a white reference.

For the laboratory experiments the system is mounted on a rotating ring, which allows measurement of reflectance and polarization from the target at controlled azimuth angles. The presented measurements have been obtained in the principal plane, which is fixed by the source light direction and the surface normal; in other words, the surface normal lies within the scattering plane. To improve signal-to-noise ratio and estimate the error of the measurements, each target was measured several