Photometry of powders consisting of dielectric and metallic spheres at extremely small phase angles

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Abstract

We present results of our photometric measurements of three samples of particulate surfaces consisting of dielectric and metallic spheres at extremely small phase angles. Monolayers of the spheres show satisfactory coincidence with the results of Mie-theory calculations. In particular, no opposition effect of the monolayer was found at the phase angle range 0.008 – 1.6° in accordance with Mie theory prediction. On the other hand, thick layers of the spheres reveal the opposition effect at phase angles less than 0.8°. In the case of dielectric spheres the opposition spike is due to the coherent-backscattering effect; whereas, for iron particulate surfaces the main contributor is perhaps the shadow-hiding effect. Measured dependencies do not allow us to separate these effects.

1 Introduction

The motivation of this study is an astrophysical problem: Photometric observations of Kuiper belt objects reveal a prominent brightness opposition spike that is very narrow [1]. These objects are observed at very small phase angles (< 2°) and to reproduce these conditions in a laboratory requires the use of very small angular apertures of the light source and the receiver. Using an old laboratory of our Institute, which had been exploited as an analog processor for Fourier transformation of large images, we have constructed a laboratory laser photometer to study extremely small phase angles; this setup provides measurements in the range 0.008 – 1.6° [2]. This instrument allows us to measure the scattering properties of structural analogs of the surfaces of Kuiper belt objects. First of all it allows studies of the opposition spike effect in a wide physical context. For example, we here compare phase dependencies of intensity for dielectric and metallic small spherical particles that form a monolayer and thick layer in order to study the opposition effect related to the shadowing and coherent backscatter enhancement.

2 Instrument, measurements, and samples

Using the laser extra-small-phase-angle photometer we investigate the opposition effect of complicated surfaces in a vertical and horizontal position in the range of phase angles 0.008 – 1.6°. The extremely small phase angles are feasible due to small linear apertures of the light source (a laser) and receiver (photomultiplier Hamamatsu H5783-01) and the large distance from the light source and detector to the

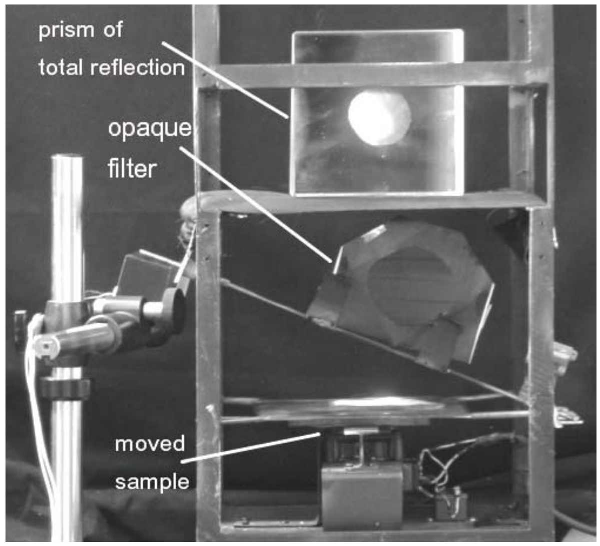

Figure 1: The sample block of the instrument.

scattering surface (samples) that is 25 m. The linear diameter of the apertures is 2 mm. In the laboratory we use a clean-room environment that helps eliminate scattering by dust particles in air, which is very important for small-phase-angle measurements covering a large distance. In these measurements we use a gas monomodal non-polarized laser (50.0 mW) with wavelength 0.658 μm as a light source. All measurements are carried out in full darkness. For light detection we use a pinhole camera, a circular cone with a truncated top [2]. The linear diameter of the samples we use is about 7 cm. A checking procedure includes measurement of the light background from the small totally reflecting prism of the light source that is used in the optical scheme to turn the laser beam. We make this check by bringing the detector aperture to the laser beam (toward minimal phase angles). We change the phase angle by moving the detector block. The block consists of the pinhole camera with the photomultiplier inside and a coaxial guiding spyglass. The spyglass is needed for aligning the sample after a phase-angle displacement of the detector block. Each sample is measured at least twice at increasing and decreasing phase angles. Coincidence of these two dependencies is an indicator of the reproducibility of the measurements. An important verification is to estimate parasitic light scattering by dust in air for low-albedo samples at extremely small phase angles. To test we use as a sample an optical filter that absorbs light at the laser wavelength (Fig. 1). We tilt the filter so the specular reflection is diverted from the detector. Thus we obtain the signal from the dust in air [2]. To avoid problems with speckle pattern we move samples during measurements providing averaging. Figure 1 shows an image of the sample block in the mode allowing measurements of horizontal surfaces; for such measurements a large, totally reflecting prism (10×10 cm) is used to direct the laser beam vertically. The sample is mounted on a moveable spring hanger.

We here study metallic and dielectric materials (Fig. 2). We use two iron powders. One sample consists of small spheres whose average size is 2 μm. The distribution covers a range from a tenth micron to 4 μm. The second sample consists of coarse particles of different sizes whose average is 150 μm, which reveals very complicated surface structure of the particles. The characteristic scale of the particle surface roughness is several microns. The dielectric sample is composed of 1 μm silica spheres (see Fig. 2). We show results of measurements of the samples in Fig. 3. Each point of these phase curves (open circles and crosses) is a result of averaging three measurements. The duration of each measurement is 2 s; at this time the movement of the spring hanger shown in Fig. 1 produces good averaging of the speckle pattern. We measured thick layers of the powders with a thickness ≈ 5 mm. In addition we measured thin (mono) layers that were prepared by drying an alcohol suspension of the particles on a substrate, a dark leatherette with frost coating, that does not have any opposition features. The albedo of the thick layer samples was determined at 1° phase angle and is given relative to the photometric standard Halon [3]. The bright (dielectric) sample shows very high albedo, higher than that of Halon. The iron samples have albedos near 21 % and 32 %, respectively, for the coarse grain sample and the fine sphere powder.

3 Results and discussion

Figure 3a shows that the thick layer sample of silica spheres has a very prominent opposition spike at phase angles less than 1.0°. This spike is related to the coherent backscattering effect that is ubiquitously observed in nature, e.g., [4]. This spike is similar to what was observed for some Kuiper belt objects. The monolayer of the small spheres does not show the opposition effect, and these results are consistent with the Mie theory shown prediction as a solid line; thus, the scatter from the monolayer is dominated by single-particle scattering. For Mie theory modeling we use m = 1.45 + 0i and 3.57 + 4.02i [5], respectively, for dielectric and metallic spheres. It should be emphasized that the monolayer phase curves were calculated with a weighted subtraction of the phase dependence of the substrate.

(a) (b) (c)

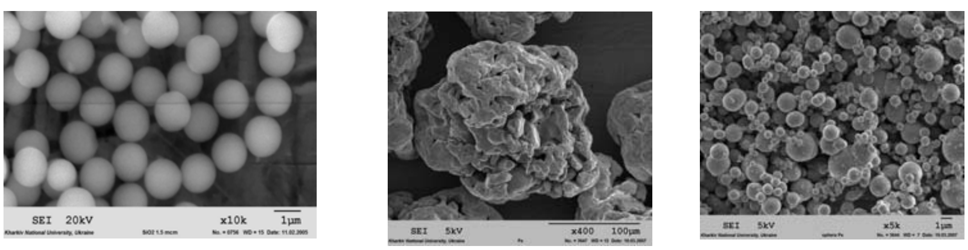

Figure 2: Electron microscope photographs of samples used. Silica spheres with size ≈ 1.0 μm (a), iron powder with coarse particles having complicated surface structure (b), and iron spheres with average diameter 2 μm (c).

(a) (b)

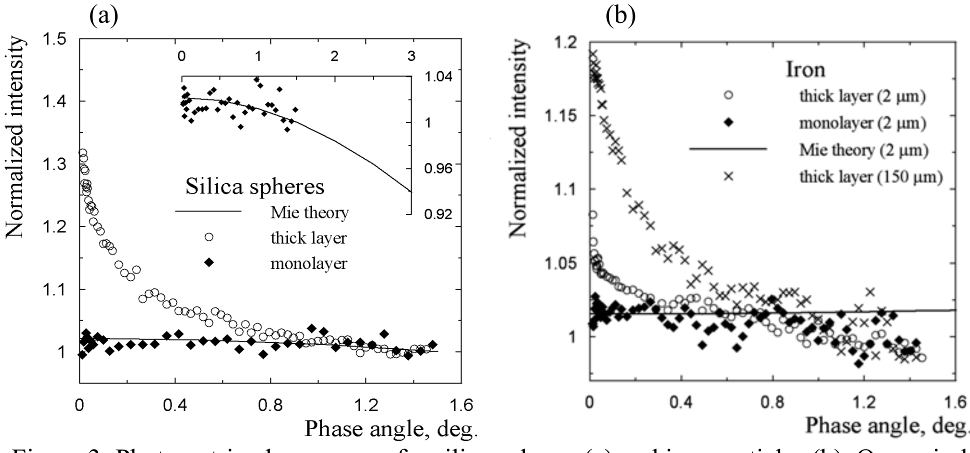

Figure 3: Photometric phase curves for silica spheres (a) and iron particles (b). Open circles and points designate measurements, respectively, for thick and thin layers. Solid lines correspond to calculations with Mie theory. Crosses represent measurements for thick layer of coarse iron particles. All the dependencies are normalized at 1.4°. The insert demonstrate the Mie theory curve at wider range of phase angles.

The sample of coarse iron grains shows a spectacular opposition feature; whereas, the iron sphere sample demonstrates only a small amplitude and very narrow opposition peak starting from 0.2° (Fig. 3 b). The particulate surface consists of coarse iron grains that have two scales of roughness: the first one is produced by the grains and the second one is related to the complicated surface structure of the grains (Fig. 2). It is well-known that surfaces with such a hierarchical structure produce much more prominent shadow-hiding effect than single scale roughness [6]. We suppose that the spike seen in Fig. 3 b for the sample of coarse iron particles is related at least partially to this double-shadowing. This spike also may have a contribution from the coherent backscatter effect. This contribution can be estimated from the phase dependence of the small-sphere sample that forms a non-hierarchical particulate surface. Like in the case of the small dielectric particles, the independent iron spheres reveal a very neutral behavior of brightness over the phase-angle range. This can be seen for monolayer measurements that are in good agreement with the Mie theory.

4 Conclusion

We have initiated research with a new laboratory laser photometer covering an extremely small phase-angle range (0.008 – 1.6°). Our measurements of dielectric and metallic spheres have shown a narrow opposition spike of the samples at phase angle less than 0.8°. From measurements at such small phase angles, we are not able to determine whether the brightness spike is produced by metallic or dielectric surfaces. From comparison of our measurements with the Mie theory we also may conclude that the scattering from a thin layer (monolayer) of particles on a dark substrate is dominated by single-particle scattering at such small phase angles.

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References

[1] I.N. Belskaya, J.L. Ortiz, P. Rousselot, V. Ivanova, G. Borisov, V.G. Shevchenko, N. Peixinho. “Low phase angle effects in photometry of trans-neptunian objects: 20000 Varuna and 1996 TO66.” Icarus 184, 277-284. (2006).

[2] V. Psarev, A. Ovcharenko, Y. Shkuratov, I. Belskaya, G. Videen. “Photopolarimetry of surfaces with complicated structure at extremely small phase angles.” 9th Conference on Electromagnetic and Light scattering by Nonspherical Particles. June 5 – 9, Russia, St. Petersburg, pp. 235-238. (2006).

[3] V. Weidner, J. Hsia, “Reflection properties of pressed polytetrafluoroethylene powder,” J. Opt. Soc. Am. 71. 856-861. (1981).

[4] Yu. Shkuratov, G. Videen, M. Kreslavsky, I. Belskaya, A. Ovcharenko, V. Kaydash, V. Omelchenko, N. Opanasenko, E. Zubko. “Scattering properties of planetary regoliths near opposition”, in: Photopolarimetry in Remote Sensing / Eds. G. Videen, Ya. Yatskiv, and M. Mishchenko. NATO Science Series. Kluwer Academic Publishers, London. pp. 191-208. (2004).

[5] H. Yolken J. Kruger. “Optical constant of iron in the visible region.” J. Opt. Soc. Am. 55, 842-846. (1965).

[6] K. Muinonen, D. Stankevich, Y. Shkuratov, S. Kaasalainen, J. Piironen. “Shadowing effect in clusters of opaque spherical particles.” J. Qunt. Spectrosc. Rad. Transfer. 70. 787-810. (2001).