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Light scattering from regolith containing powdered alumina: an analogue for asteroid surface scattering

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Abstract

The laboratory studies of the light scattering behavior of the powdered samples are important tools to characterize the physical conditions and compositions of the planetary and asteroid surfaces, since these are covered with layers of fine dust grains called regolith layers. A laboratory based observation enables us to know the light scattering property of the regolith like samples with known compositions and other physical parameters. The data obtained from the experiment can be compared with the existing in situ data or may be analyzed with the help of various theoretical models for the better understanding of the light scattering from regolith. In this work we have performed laboratory based photometry of the light scattered from the surface of powdered alumina (Al_2O_3) having particle diameter of 0.3μm. The data are fitted by a surface scattering model originally suggested by Hapke. Instead of using empirical Henyey Greenstein phase function, which is generally used with Hapke formula, the albedo and phase function may also be taken from a theoretical single particle model. This approach will help us to the determination of single particle properties from surface scattering phase curves. For the primary treatment and simplicity Mie theory has been used as the single particle theory in this case. It depends only on the size parameter X(=2ð(radius/wavelength)) and complex refractive index (n,k) of the material. Since the absorption coefficient (k) for alumina is known to be very low but not exactly zero, the best fit to the experimental data was obtained by least square technique by varying k. Also, by this treatment unknown absorption coefficient of alumina is obtained. Finally, the intensity-particle size behavior (discussed in detail in Deb and Sen 2010) of alumina has been tested by using this retrieved value of k with respect to data collected by other workers.

Keywords : Light scattering, Powdered alumina, Asteroid surface scattering

Introduction

The study of the light scattering property of the powdered materials is known to be an important tool to characterize the physical and compositional properties of asteroids, since the asteroids are known to be covered with finely grained materials known as regolith layers (Hapke 1993). Therefore, laboratory based experiments on the asteroid surface analogues are important so that the in situ data can be compared with these and the theoretical models can also be tested.

In our previous work (Deb and Sen 2010, henceforth paper-1), we have seen that the Hapke formula (Hapke(1993)) and Mie theory (Van de Hulst (1957)) together describes the intensity versus particle size behavior of low absorbing materials very satisfactorily and is hardly dependent on the shape of the regolith grains. However the study included only two low absorbing materials. Data collected by Nelson (2000) for alumina sample could not be tested due to its unknown value of absorption coefficient.

In this work, first we generate the laboratory based photometric data at large phase angles for the plane surface containing powdered alumina (Al_2O_3) with 0.3μm particle diameter and at laser wavelength 632.8nm (Red). The particle size and

wavelength are such that Mie theory can be used to describe the particle phase function and albedo (further discussed in section 4). Then, the Mie theory and Hapke formula have been used to fit the data obtained from the experiment, by least square technique by varying the unknown absorption coefficient k of alumina. Finally, the accuracy and significance of the analysis are tested with the help of intensity versus particle size plot (I-D curve) for alumina sample using the retrieved value of k, to match with the experimental data reported by Nelson (2000).

Instrument and sample

The experimental part was carried out with the help of a goniometric device (Fig. 1) at the Department of Physics, Assam University, Silchar, India. It consists of two metal arms having a common horizontal axis of rotation. The sample surface is placed lying along the axis of rotation of the arms with the help of three translation stages (for X-Y-Z movement of the sample). A miniature goniometer acts as a tilting device to the sample. The two arms can be rotated by $\pm 90^0$ from the zenith direction and a tilt up to $\pm 20^o$ can be given to the sample tray, with respect to the plane containing the incident ray and emergent ray. A He-Ne laser at 632.8nm as the source of light and a CCD (make: SBIG, ST-6) camera as the detector are mounted on the two arms such that their axes are perpendicular to the horizontal section of the respective arms (Fig. 1). The sample is placed at the common intersection of the axis of rotation and axes of the source and detector. A diffuser was placed in front of the CCD to kill the laser speckles produced by the coherent laser beam on scattering from a rough surface McKechnie *et al.* 1976.

The sample used in the present experiment is powdered alumina (Al_2O_3) with 0.3μm particle diameters. The powdered sample was taken in a sample tray and the bottom of the tray was stroked gently on a table to make the sample surface nearly plane. At this stage, the surface roughness of the sample was quite high. To prepare a smooth surface, the sample surface was pressed by a smooth metal spatula so that the sample surface obtains its smoothness. The thickness of the prepared sample was about 6.2 mm and the porosity was found to be 0.88. The porosity P was measured with the help of the relation Sakai *et al.* 2005:

$$P = 1-(m/\tilde{n}V) \quad (1)$$

where, m denotes the mass of the powdered sample, V denotes its volume (obtained after pressing) and $\tilde{n}$ is the bulk density of the material, which is 3.9 g/c.c for alumina.

Measurement and data collection

The tilt angle of the sample was set fixed at 0^o for simplicity to begin with. The detector angle or emergent angle (e) was also kept fixed at -45^o (anticlockwise) from the zenith. The angle of incidence (i) was varied from 0^o to 63^o in steps of 9^o (which is equivalent to rotation by 5 divisions of the circular scale attachment). Thus the phase angle (g) was varied from 45^o to 108^o.

The image of sample surfaces were recorded at every angle of incidence in the form of FITS image. As the field of view of the detector was larger than the laser spot, geometrical correction ($\cos i/\cos e$) was necessary to calculate the intensity values from the detector counts. The background and dark correction were also done for each observation. The reflectance values were calibrated by using $BaSO_4$ pressed surface (a standard Lambert surface), at the condition of incidence angle 0^o and detector angle -45^o. The experimental errors are less than 10%.

Results and analysis

(i) Phase curve

The bidirectional reflectance($r(i,e,g)$), which is the ratio between the reflected light intensity (I) to the incident irradiance (J), measured for the alumina sample are shown in Fig. 2 as a function of phase angles. These data are theoretically fitted with the help of Hapke formula along with Mie theory as the single particle theory in a similar way as it was done in our previous work (please see paper-1).

Though we have used Mie theory as the single particle theory, it is hardly expected that, the particles of alumina are smooth and homogeneous spheres. But, Pollack and Cuzzi (1980) suggested that the Mie theory may be used to calculate the scattering properties of *equant* irregular particles also, but with X< 5. In this case X value is 1.49 for particle diameter D = 0.3μm and wavelength of the incident light ë = 632.8nm. Therefore we expected that, in this case the Mie theory could be applied with Hapke formula to calculate the bidirectional reflectance values up to a considerable accuracy.

The refractive index of alumina at 632.8 nm is n = 1.766 (Gervais 1991), and absorption coefficient 'k' is known to be very small, but not known accurately. We have varied the unknown parameter 'k' to fit the laboratory data. The data was fitted by least square technique and the best fit to the data was obtained for k = 0.000009. We do not claim at this stage that, the value of k retrieved from this analysis is very accurate, since there are features like porosity and roughness which were neglected during the treatment. The accuracy and significance of the analysis done in this subsection can be realized from the analysis done in the next subsection

(ii) *I-D* curve

A detailed laboratory based study on the opposition effect by powdered alumina surface was performed by Nelson (2000) using alumina samples at 13 different particle diameters ranging from 0.1 to 30.09μm. Since, the study was confined within opposition region only, the maximum phase angle under consideration was as low as 5°. But, it can be clearly realized from the plots of their data, apart from very small phase angles, the phase curves are parallel to each other, so that the ratio of the reflectances (i.e. relative intensities) at a given phase angle will practically remain unchanged up to phase angles much larger than 5° also.

Now, it was shown in our previous work (please see paper-1), the relative dependence of intensity on particle diameter at a constant phase angle of about 25-30° (on the *I-D* curve) obtained by using Mie theory and Hapke formula, agrees with the experimental results for the weakly absorbing materials. It has also been shown that, the nature of the curve depends strongly on the absorption coefficient k. Since the absorption coefficient of alumina was not known accurately, we could not test the *I-D* curve for alumina. As told in paper-1, the parameters B_0 and h should be correctly known, if phase angle is small (less than about 15°). Since, only the typical vales of these two parameters have been used in our analysis (accurate values being unknown), we have plotted the theoretical *I-D* curve for alumina at a larger phase angle g = 20°. The curves are plotted for three distinct values of k = 0.0001, 0.000009 and 0.000001, which are shown in Fig. 3. The natures of the curves are quite distinct from each other. It can be clearly seen that, the experimental data by Nelson (2000) at g = 5° fits much efficiently with the theoretical curve for k = 0.000009 which was found from the phase curve fitting in previous subsection. The trends for other values of k are quite distinct from the trend of the experimental data. This consolidates the accuracy of the analysis done in the previous subsection. Also, it again confirms the applicability of the analysis done in our previous work (paper I) in case of low absorbing materials.

Conclusion

(1) We found that, the theoretical fit to the large phase angle experimental data is quite satisfactory (Fig. 2) for reflectance studies from a regolith surface using Hapke's model with Mie theory. The features like porosity and roughness were neglected in this treatment, and therefore accurate fitting is not expected. Moreover, particles are hardly smooth spheres, which may also introduce uncertainty in the result. But, it is evident from the analysis that, the phase curves of the regolith like samples with grain sizes comparable to the wavelength of incident radiation can be very efficiently studied at large phase angles using theoretical phase functions like Mie theory in Hapke model to retrieve the single particle features like grain size and/or composition. If the particle diameter D >> ë, Mie theory is unable to describe the phase function of the irregular

particles (Hapke (1993)). Therefore, in such cases applicability of other numerical or theoretical phase functions for irregular particles with Hapke formula may be tested.

(2) From this study we also derived the not so known absorption coefficient *k* of alumina up to a considerable degree of accuracy.

(3) This study again shows that, in case of low absorbing materials, the intensity versus particle size behavior can be very efficiently simulated with the help of Hapke formula and Mie theory, and *I-D* curve is hardly affected by the irregular shape of the individual grains.

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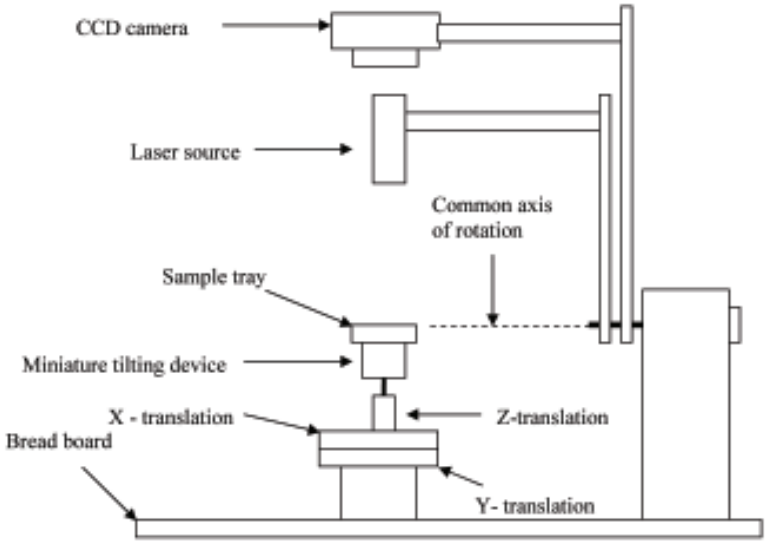

Fig. 1. The schematic diagram of the Goniometric device used in the experimental part (side view).

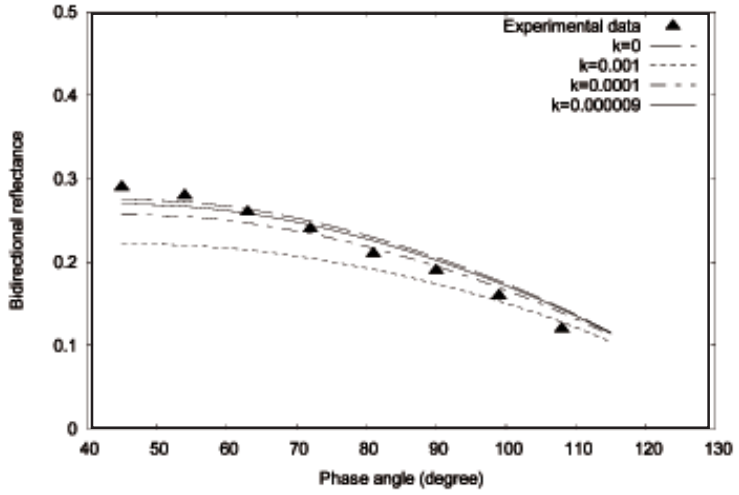

Fig. 2. The points indicate experimental data for Alumina sample (D=0.3ì m) at ë=0.633 ìm. The X coordinates of the points represent the phase angle g in degrees at fixed e=45° and at zero tilt. The theoretical curves are obtained by using Hapke formula with Mie theory at same wavelength. The best fit was obtained for k=0.000009.

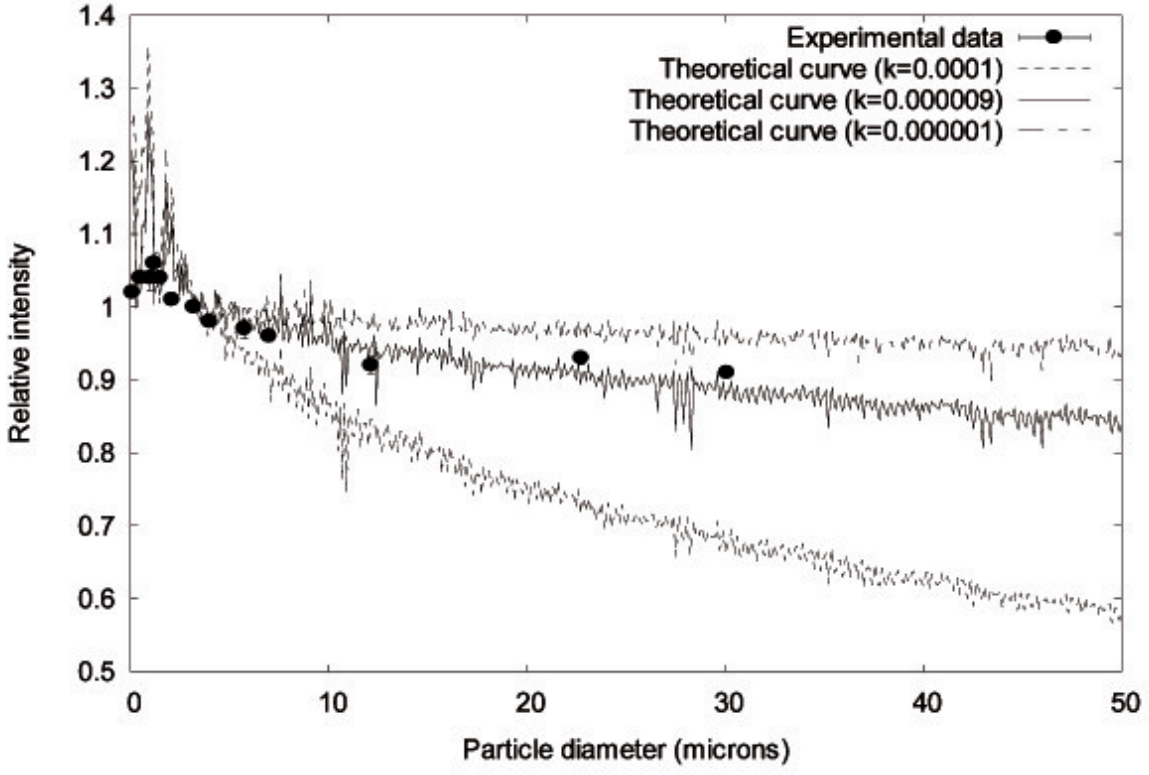

Fig. 3. The points indicate experimental data for Alumina sample at ë=0.633ìm taken from Nelson et al. 2000. The X coordinates of the points represent the average particle diameters. The theoretical curves are obtained by using Hapke formula with Mie theory at same wavelength and at i=0°, g=20°. The intensity values are relative to the respective values at D=3.2ìm.

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