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Photometry of particulate mixtures: What controls the phase curve?

C. Pilorget [a,*], J. Fernando [b,c], B.L. Ehlmann [a,d], S. Douté [e]

[a] Division of Geological and Planetary Sciences, Caltech, Pasadena, CA 91125, USA
[b] Université Paris-Sud, GEOPS, UMR8148, Orsay 91405, France
[c] CNRS, Orsay 91405, France
[d] Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, USA
[e] Institut de Planétologie et d'Astrophysique de Grenoble, Grenoble 38041, France

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ABSTRACT

The amplitude and angular distribution of the light scattered by planetary surfaces give essential information about their physical and compositional properties. In particular, the angular variation of the bidirectional reflectance, characterized through the phase curve, is directly related to the grain size, shape and internal structure. We use a new radiative transfer model that allows specifying the photometric parameters of each grain individually to study the evolution of the phase curve for various kinds of mixtures (spatial, intimate and layered), mimicking different situations encountered for natural surfaces.

Results show that the phase curve evolution is driven by the most abundant/brightest/highly anisotropic scattering grains within the mixture. Both spatial and intimate mixtures show similar trends in the phase curves when varying the photometric parameters of the grains. Simple laws have been produced to quantify the evolution of these variations. Layered mixtures have also been investigated and are generally very sensitive to the photometric properties of the top monolayer.

Implications for the interpretation of photometric data and their link with the phases identified by spectroscopy are examined. The photometric properties of a few planetary bodies are also discussed over a couple of examples.

These different results constitute a new support for the interpretation of orbital/in situ photometric datasets.

1. Introduction

As solar light penetrates into a surface, it is partially reflected back by interaction with its constituents and structures. The amplitude and angular distribution of this signal, as well as its evolution with the wavelength of light give essential information about the physical and compositional properties of this surface. Models have been developed and experimental work has been performed to better understand how the surface properties affect the light scattering (e.g. Hapke, 1981, 1984, 1986, 2002, 2008; Hapke and Wells, 1981; Douté and Schmitt, 1998; Shkuratov et al., 1999; Stankevich et al., 1999; Mishchenko et al., 1999; Stankevich and Shkuratov, 2004; Shkuratov and Grynko, 2005; Pilorget et al., 2013). In particular, it has been shown that analysis of the amplitude and angular distribution of the scattered light at a single wavelength (typically in the visible) constrains: (1) the absorptivity of the medium (at this wavelength), (2) the size, shape and internal structure of the grains and (3) the spatial organization of the grains. Key parameters include the single scattering albedo, phase function, surface roughness, opposition surge and porosity. Photometry has therefore been used for decades to characterize the surface of the Moon (e.g. Helfenstein and Veverka, 1987; Shkuratov et al., 1999, 2011; Hapke et al., 2012), asteroids (e.g. Helfenstein and Veverka, 1989; Helfenstein et al., 1994, 1996; Domingue et al., 2002; Newburn et al., 2003; Hillier et al., 2011) and planets (e.g. Veverka et al., 1988; Johnson et al., 2006a,b; Jehl et al., 2008; Fernando et al., 2013, 2014).

In particular, the angular variations of the scattered signal, characterized through the phase curve, are directly related to the grains' size, shape and internal structure (McGuire and Hapke, 1995; Grundy et al., 2000; Grynko and Shkuratov, 2003; Shepard and Helfenstein, 2011; Souchon et al., 2011; Hapke, 2012). These grain properties are therefore critical for interpreting the geological and climatic processes that were or are currently occurring on the parent body. However, little is known about what controls the overall phase curve in a natural sample made of different grains with specific composition, phase function and grain size dis-

* Corresponding author.
E-mail addresses: cpilorge@caltech.edu (C. Pilorget), jennifer.fernando@u-psud.fr (J. Fernando), ehlmann@caltech.edu (B.L. Ehlmann), sylvain.doute@obs.ujf-grenoble.fr (S. Douté).

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tribution. Here, we use numerical modeling to simulate the radiative transfer within different kinds of mixture, and analyze the variations of the scattering behavior, in particular the angular variations of the signal, characterized by the phase curve.

Our main objectives are:

1. To study the evolution of the bidirectional reflectance for different kind of mixtures (spatial, intimate and layered), and particulates (complex index of refraction, size and phase function).
2. To quantify the evolution of the observed phase curve (i.e. the angular and amplitude variations of the bidirectional reflectance) with these parameters and derive simple laws when possible.
3. To determine which particulates control the overall phase curve.
4. To discuss the implications for the interpretation of photometric data.

2. Model description

The radiative transfer model from Pilorget et al. (2013) is used to perform the different simulations. The model simulates light scattering in a compact granular medium using a Monte–Carlo approach. The wavelength of the light is set to 750 nm. The approximation of geometric optics is assumed, which is a reasonable assumption for grain sizes greater than a few microns here. The physical and compositional properties of the sample are specified for each grain individually, thus allowing simulation of different kinds of heterogeneities/mixtures within the sample. Radiative transfer is then calculated using a ray tracing approach between the grains and probabilistic physical parameters such as a single scattering albedo and a phase function at the grain level. All scattering orders are taken into account. The incidence angle is set to an intermediate value of 45°. The bidirectional reflectance is then computed for different geometries covering the entire upper hemisphere.

Because geometric optics is assumed, the diffraction peak of each particle taken individually can be neglected in the case of a compact granular medium (Hapke, 1993). The single scattering albedo is calculated for each grain using Hapke (1993) and thus is a function of the complex index of refraction of the material, the grain size and the potential inclusion of internal scatterers. A two-lobe Henyey–Greenstein phase function, as a function of phase angle, β, is attributed to each grain in the model. It can be expressed as follows:

$$p(\beta) = \frac{1+c}{2}\frac{1-b^2}{(1-2b\cos\beta+b^2)^{3/2}} + \frac{1-c}{2} \times \frac{1-b^2}{(1+2b\cos\beta+b^2)^{3/2}} \quad (1)$$

with $0 \leqslant b < 1$ and $-1 \leqslant c \leqslant 1$. Here, β is equal to 0 if the photon is scattered backward and equal to 180 if the photon is scattered forward. The first term describes a back scattered lobe and the second term a forward scattered lobe. The parameter b describes the angular width of each lobe, whereas the parameter c describes the amplitude of the back scattered lobe relative to the forward. Thus, a positive value of c indicates that the particle is predominantly back scattering, and a negative value implies a forward scatterer (see Fig. 1). This phase function is commonly used for photometric studies and parameters b and c have been derived for various planetary bodies (e.g. Domingue and Hapke, 1992; Domingue and Verbiscer, 1997; Fernando et al., 2013; Sato et al., 2014).

Two-compound mixtures are assumed in what follows. A systematic analysis of the influence of each compound's phase function on the overall phase curve for given grain size distributions, compositions and spatial organization is performed, using the b and c parameters. Several prior studies had shown that for natural particles, the parameters b and c describe a "L shape" in a c vs. b diagram: c tends to increase as the internal structure of the grains is filled with internal scatterers and b tends to decrease for rougher grains (e.g. McGuire and Hapke, 1995; Souchon et al., 2011; Hapke, 2012). We test in what follows realistic values of parameters b and c with regards to these constraints. The single scattering albedo is also affected by the roughness and the internal structure of the grains but is computed independently of the phase function in the framework of this study in order to highlight the effect of each parameter separately. Here, the single scattering albedo is calculated for each grain using Hapke (1993) analytical expressions.

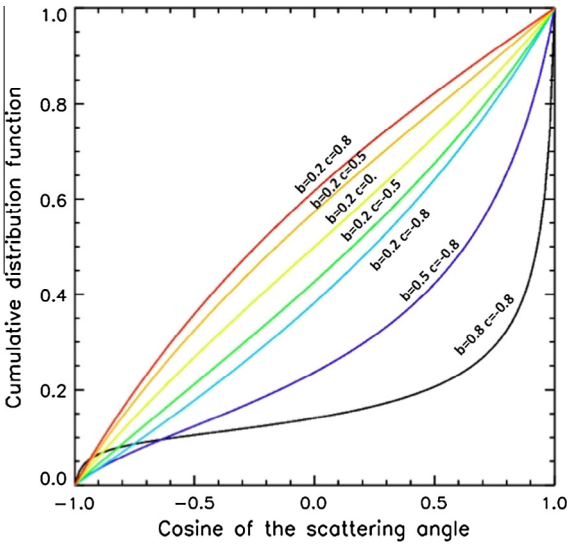

Fig. 1. Cumulative distribution function for different two-lobe Henyey–Greenstein phase functions. Parameters b and c were chosen following McGuire and Hapke (1995).

Simulation results with mixtures are then inverted by fitting the phase curves with the ones of pure homogeneous samples with given single scattering albedo and phase function parameters (parameters ω, b and c). Uncertainties are estimated to be within the ±0.02 range for the parameter c, ±0.03 for the parameter b and ±0.02 for the single scattering albedo ω. In what follows, the derived photometric parameters are designated ω', b' and c'.

3. Results

3.1. Spatial mixtures

Spatial mixtures are mixtures where the areas occupied by the different compounds are segregated. The photons therefore only interact with one of the compounds (except when close to the boundary). The resultant number of scattered photons in a specific direction is equal to the sum of the photons scattered by each fraction of the sample in this direction. The overall phase curve is therefore a linear combination of the phase curve of each fraction of the sample. In a first series of tests, we simulate the radiative transfer in a sample made of two compounds, A and B, in a spatial mixture (or "checkboard"). Both fractions are set to have the same grain size distribution (log-normal law centered on 70 μm with ≈72 volume% between 50 and 110 μm) and the same material (complex index of refraction $n = 1.4 + 2.10^{-4}$i). With these parameters, the single scattering albedo of each fraction is estimated to be 0.68 ($\omega_A = \omega_B = 0.68$). Each grain belonging to fractions A and B