Modeling lunar reflectance spectra

Ye. Grynko,[1] Yu. Shkuratov,[1] and G. Videen[2,3]

[1] *Astronomical Institute of Kharkov V.N. Karazin National University, 35 Sumskaya St., Kharkov, 61022, Ukraine, tel: +38(057)7075063, e-mail: egrinko@hotmail.com*

[2] *Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands*

[3] *Space Science Institute, 4750 Walnut St. Suite 205, Boulder CO 80301, USA*

Abstract

We study the dependence of the reflectance spectra of regolith-like surfaces on the phase angle. A computer model based on the ray optics approximation is used. Our calculations reveal a strong non-monotonous dependence of the spectral slopes on the phase angle. Changing observation geometry also influences the depth of the absorption bands. We also calculate the phase angle distribution of the average path lengths $<L>$ that rays pass through in the medium between the points of entrance and emergence.

1 Introduction

Progress in the remote sensing of planets and their satellites requires better understanding of light scattering by their regoliths. In particular, interpretation of the reflectance spectroscopy data can provide information about chemical and mineral properties of planetary surfaces. There are unresolved questions that should be considered to make this interpretation more accurate. For instance, it is important to estimate contributions of single particles and multiple scattering between particles at different phase angles. Important problems include transforming photometric data to the same illumination/observation geometry of illumination and accounting for the polarimetric effect on spectra.

During photometric observations of a planet with a spacecraft, the illumination and observation conditions change. The principal parameter for characterizing the conditions is the phase angle α. The continuum slope and parameters of the absorption bands can be different for the same portion of a planetary surface, if spectra are taken under different conditions. Examples are spectrophotometric measurements of the Moon, asteroids Eros *in situ* [1] and Itokawa [2]. Although laboratory experiments have been coupled with regolith structure models [3,4], measurements of lunar samples [5], and telescopic observations of the Moon [6], the solution of the problem is not complete. The interpretation of existing space mission data as well as planning future projects warrant more detailed analyses of the role of photometric geometry in the formation of the reflectance spectra.

We here use light scattering computer simulations to study the phase angle and polarimetric effects on lunar spectra. To simulate light scattering in particulate media we use a ray tracing model [7, 8].

2 Computer experiment description

A detailed description of the ray-tracing model used in this study can be found in [7,8]. To generate random particles with irregular shape we use an auxiliary 3-D random Gaussian field (RGF) [7]. The model of the particulate medium is characterized with the following parameters: volume fraction of particles ρ (packing density), the complex refractive index of the material ($m = n + ik$), and the average particle size d. In our samples the sizes of particles are almost the same, varying from 25 to 1500 µm. The

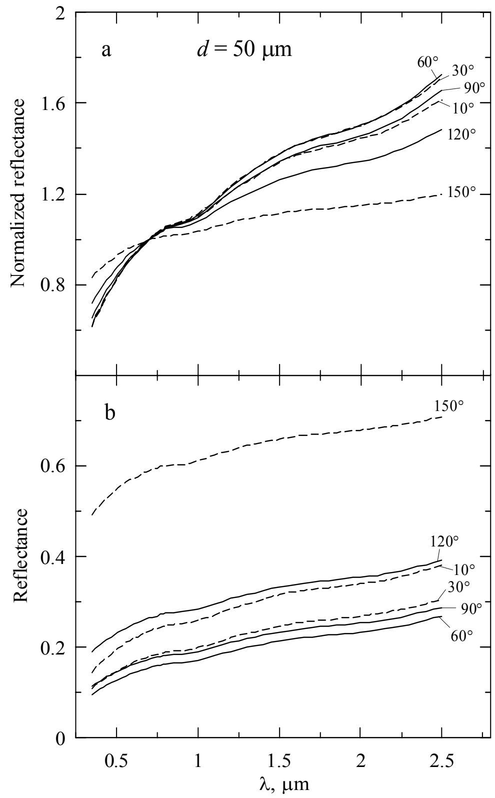

Figure 1: Spectral dependences of reflectance and normalized reflectance at different phase angles for a medium composed of particles d = 50 μm.

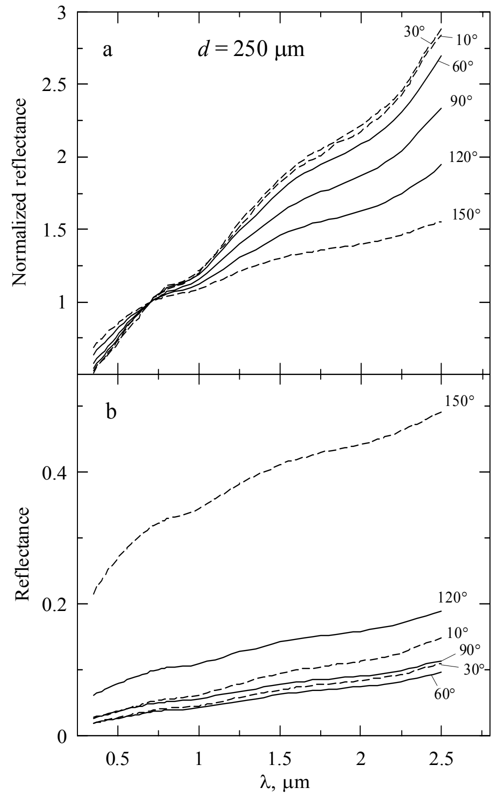

Figure 2: Same as Figure 1 for d = 250 μm.

packing density of particles in all experiments equals to $\rho = 0.1$. Natural powders usually are denser and our algorithm allows packing up to $\rho = 0.4$. However, lower density significantly simplifies simulations and, in general, the parameter ρ plays a secondary role in spectral reflectance (e.g., [9]).

In our ray tracing calculations we used $10^6 - 10^7$ rays. Each ray is traced from facet to facet until it leaves the particulate surface after a sequence of interactions with the particulate medium. At non-zero absorption each ray propagated inside a particle can be absorbed on the way between two facets with probability $\exp(-\tau)$, where $\tau = 4\pi k(\lambda)l/\lambda$, l is the path length between facets, and λ is the wavelength. For $k(\lambda)$ we used an average dependence for lunar mare material obtained from spectral observations of the Moon [9]. The real part n of the complex refractive index is considered as a constant, we use $n = 1.6$.

In order to determine angular scattering characteristics, the phase angle range is divided into a number of angular bins. The number of rays normalized by the solid angle of a given bin is the intensity of scattered light at the bin. The reflectance of a particulate surface at a given phase angle is defined as a ratio of the bin intensities corresponding to arbitrary k and $k = 0$. This simulates comparison with a Lambertian surface. Calculation of reflectance for a set of wavelengths at given photometric geometry provides a spectrum. We made calculations for a fixed incidence angle $i = 70°$ and changing angle of emergence e. Phase angle α varies within 0 – 160°. Scattered intensity is collected in the narrow sector containing a plane perpendicular to the average surface.

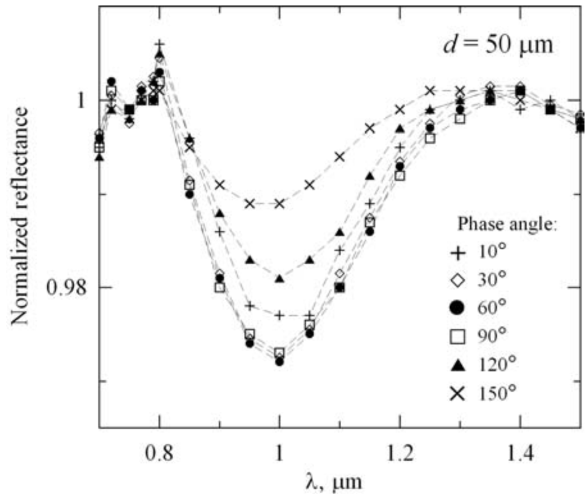

Figure 3: Surface reflectance divided by continuum near the 1 µm absorption feature at different phase angles. The size of constituent particles is d = 50 µm.

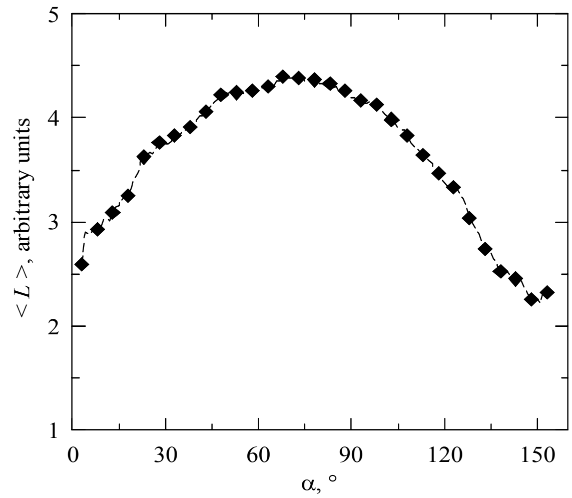

Figure 4: Phase-angle distribution of the average path lengths <L> that rays pass through between the entrance and emergence points of the particulate medium.

3 Results and discussion

Figures 1 and 2 show (a) normalized and (b) absolute reflectance spectra for media consisting of particles with whose average size is 50 and 250 µm measured at λ = 0.7 µm. At first, we note that the surface reflectance becomes lower as particle size increases. This is a widely known effect. The slope of the spectra changes with the phase angle α in all plots. It can be either increasing or decreasing depending on the size of the particles. For a size of 50 µm in the range of phase angles ≈ 0 – 60° the slope increases. This can be attributed to the so called "phase reddening" that is observed for natural surfaces, the albedo of which is higher at larger wavelengths. This was investigated in laboratory experiments (e.g., [3-5, 10]), but has not been adequately studied theoretically before. For particles with sizes larger than ≈ 200 µm the spectral slope decreases monotonously.

The changing illumination/observation geometry also influences the depth of the absorption bands. To illustrate this we plot the spectra divided by the continuum in the wavelength range near the 1 µm absorption feature in Figure 3. We approximated the continuum as a linear function between the band wings. It is seen that beginning from approximately α = 60° the band quickly becomes weaker, and in the range 10° – 120° its depth decreases by a factor of two.

Ray-tracing allows decomposition of the reflected flux into single-particle and multiple-particle scattering components. Our calculations show that for the multiple-scattering component, the spectral slopes are much larger than those for the single-particle-scattering component. The phase dependence of the slopes is monotonous in the case of single-particle scattering and has non-monotonous behavior for the multiple-scattering component.

An explanation can be suggested for the observed behavior of the slope and absorption band. We may consider the total ray path length L in a particulate medium between the points of entrance and emergence from the particulate surface. The intensity of a transmitted ray is proportional to $\exp(-4\pi k(\lambda)L / \lambda)$. The value of L is a function of the phase angle α. These values are different for different orders of scattering. In Figure 4 we show the calculated distribution of $\langle L(\alpha)\rangle$. As one can see, the average ray path length increases in the range 0 – 80°, which corresponds to the increasing spectral slope, reaches a maximum and then decreases at large α.

3 Conclusions

From the results of our ray-tracing simulations we can conclude the following:

1. The results reveal a strong dependence of the spectral slope on the phase angle. It can be either increasing or decreasing depending on the size of particles. The illumination/observation geometry can also influence the depth of the 1 μm absorption band. In the range 10° – 120° its depth decreases by a factor of two.

2. Single and multiple scattering components both appear to be important and play a significant role in the formation of the reflectance spectra and its behavior with phase-angle change. Multiple light scattering is responsible for the non-monotonous phase dependence of the spectral slope.

Acknowledgments

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