EPSC Abstracts
Vol. 6, EPSC-DPS2011-1841, 2011
EPSC-DPS Joint Meeting 2011

Phase Reddening as Observed in the Laboratory

S.E. Schröder (1), Y. Grynko (2), A. Pommerol (3), and H.U. Keller (4)
(1) Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany (schroder@mps.mpg.de), (2) Universität Paderborn, Germany, (3) Physikalisches Institut, Universität Bern, Switzerland, (4) Technische Universität Braunschweig, Germany

1. Introduction

The reflectance spectrum of atmosphereless solar system bodies is known to depend on phase angle. This phenomenon is called phase reddening, because the spectrum is usually (but not always) observed to become redder with increasing phase. It has been found for a variety of solar system bodies, like the Moon and asteroids [1, 2]. Past laboratory (goniometer) experiments on regolith simulants show reddening at low phase angles, but, surprisingly, bluing at larger phase angles [3, 4]. We have performed our own experiments. Using the Bern PHIRE goniometer [5] we measured phase reddening for particulate samples of three common rock types. Apart from attempting to corroborate earlier findings, we aim at investigating phase reddening in a systematic fashion. We interpret our findings with the help of dedicated geometric optics simulations.

2. Past experiment

In [3] the reflectance of silicate powders, sorted for particle size, was measured using a goniophotometer. Color (expressed as R/B) was found to depend on albedo, and hence particle size. Phase reddening (increase in R/B) was observed up to a certain phase angle ($30°$-$50°$, depending on sample), but phase bluing beyond that. The authors argued that the average optical path length increases with increasing phase angle, but that the blueing beyond is due to the domination of scattering at the surface at large phase angles.

3. Our experiment

Goniometer measurements were performed on particulate samples of three different rock types: basalt, granite, and lime stone. For each type we selected three samples of different particle sizes in the range of 10-2000 μm. One additional basalt sample was a fine powder, which, when sprinkled, would spontaneously build structures on the surface on a scale of 0.1 mm. We thoroughly characterized each sample with both an optical and scanning electron microscope (Fig. 1).

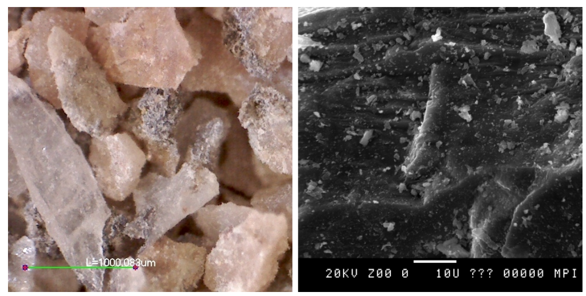

Figure 1: Micrographs of the granite 500-630 μm particle size sample. **Left**: Optical microscope image (scale bar 1000 μm). **Right**: Scanning electron microscope image (scale bar 10 μm).

We measured phase curves over the $5°$-$130°$ range at four different wavelengths. A “color ratio” can be constructed by dividing these phase curves. We consider four color ratios: 1000 nm / 800 nm, 800 nm / 600 nm, 600 nm / 500 nm, and 500 nm / 400 nm. We show an example of our results in Fig. 2. For samples of semi-transparent particles we confirm that, if the reflectance spectrum increases from the small to the large wavelength in a particular ratio (e.g. 600 nm / 500 nm), the color ratio as a function of phase angle has an “arched” shape. We also identify persistent reddening at higher wavelength ratios (e.g. 1000 nm / 800 nm), seemingly unrelated to spectral shape. The basalt powder measurements, both sprinkled and pressed, revealed that the presence of the aforementioned microscopic structures destroys the arch and leads to persistent reddening.

4. Geometric optics simulations

Some of the explanations for phase reddening put forward in the literature can be tested with geometric

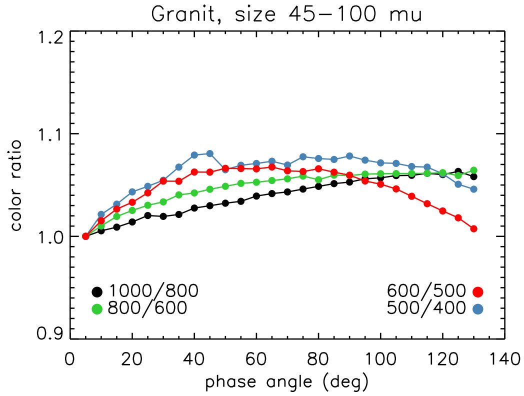

Figure 2: Phase reddening for a granite sample of particle size 45-100 μm ($\iota = 60°$, curves normalized at $\varphi = 5°$). Wavelength ratios in the legend are in nm.

optics simulations [6]. In the particular case of 10 μm-sized basalt particles our simulations reproduce the arch shape for low wavelength ratios, where the reflectance spectrum of basalt increases towards the larger wavelengths (Fig. 3). This dependence is determined by different total path lengths of the ray propagation in the medium at different phase angles. However, the persistent reddening for high wavelength ratios (where the spectrum becomes non-monotonous) is not explained in the geometric optics approximation.

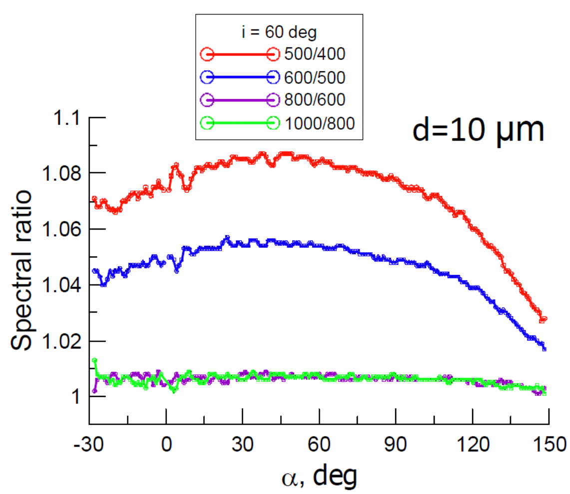

Figure 3: Geometric optics simulations for a surface of 10 μm basalt particles. Wavelength ratios in the legend are in nm.

5. Summary and Conclusions

We measured phase curves for samples of different particle sizes of common rock types at different wavelengths, and constructed ratios to study phase reddening. Our experiments, supported by simulations, confirm one peculiar aspect of phase reddening (the arched shape of the ratio), and reveal it to be a geometric optics effect. Another aspect (persistent reddening at larger wavelengths) remains puzzling. The presence of microscopic structures on the surface destroys the arch, a finding that enables us to relate spacecraft observations of solar system bodies (e.g. [7]) to regolith properties. These structures may form naturally on regolith surfaces exposed to space. As such we do not expect to see the arch shape for asteroid surfaces, a prediction relevant to Dawn observations of Vesta.

Acknowledgements

Samples were kindly provided by L. Moroz. F. Goesmann helped us operating the SEM. This work received support from the OSIRIS project.

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