PHOTOMETRIC MODELING OF PARTICULATE SURFACES : A NEW RADIATIVE TRANSFER APPROACH.

A. F. Cheng[1], D. L. Domingue[2], [1]JHU-APL, Maryland, USA (andrew.cheng@jhuapl.edu), [2]Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson AZ 85719-2395 (domingue@psi.edu).

Introduction: The Hapke models of reflectance from particulate surfaces are widely used to analyze spacecraft data and have been tested by comparisons with laboratory goniometer data. Previous work has shown, based on these tests, that Hapke models can be fitted accurately to data, but fitted photometric parameters are not uniquely correlated to the physical properties of the sample. We propose that the Hapke (1981) model [1] can be used to describe particulate surface reflectance, without the later corrections for opposition effect, surface roughness, or porosity. These effects can be described by choosing an appropriate functional form for the scattering phase function, instead of correcting the reflectance model so that it is no longer a radiative transfer (RT) solution. We propose that opposition effects, roughness, and porosity effects can be treated by fitting a single scatter albedo and phase function within the framework of RT modeling. We test this RT modeling approach with laboratory datasets previously analyzed with Hapke models to determine if a better correlation can be made between model parameter values and sample physical properties. We find that four-photometric parameters (single scatter albedo and three parameters of a double Henyey-Greenstein phase function) are able to describe the data and to be interpretable in terms of sample bulk physical properties, bearing in mind that the single scatter albedo and phase function parameters are themselves correlated and influenced by the angular coverage of the observations. We suggest that geometric albedo is a more robust measure of surface reflectivity and spectral dependence, as it is less unaffected by viewing geometry and by porosity.

Radiative transfer models: The surface brightness seen in reflected light is dependent on viewing and illumination geometry. Photometric modeling is used to correct imaging and spectral data for effects of varying geometries and also to infer surface physical properties. A widely used approach to photometric modeling has been developed by Hapke, starting from an approximate RT solution [1], with later modifications [2,3] that incorporated corrections for opposition effects (such as from shadow-hiding and coherent backscatter mechanisms), surface roughness, and porosity. With these corrections, the photometric models are modified from RT solutions. The corrections involve up to 6 parameters in addition to those associated with the single scatter albedo and the scattering phase function. These latter parameters are in principle sufficient to characterize surface scattering properties and to determine an RT solution.

Shepard and Helfenstein [4,5] have demonstrated with experimental measurements from the Bloomsburg University Goniometer (BUG) that Hapke photometric parameters are not uniquely interpretable in terms of surface physical properties, although the modified Hapke models fit data accurately. Helfenstein and Shepard [6] have also discussed issues with Hapke modeling, especially the modified post-1981 versions, and noted that obtaining unique fits to planetary data is often difficult owing to the many photometric parameters. Combinations of surface physical properties such as albedo, roughness, and porosity are combined within each photometric parameter. The promise of reliably assessing physical properties of regolith via photometry has not been realized.

Objectives and Approach: In the present work, we develop a new approach to photometric modelling based on the Hapke (1981) model, with new forms for the phase function, and with support from accurate RT solutions using the numerical quadrature method of Cheng and Domingue [7]. We report initial results using this new photometric model to analyze an extensive laboratory dataset from the BUG, the same data used in [4] to test Hapke models. In future work we will also report tests with spacecraft data.

The Hapke (1981) model with no opposition correction and no roughness correction is

$$\frac{I}{F} = \frac{w}{4}\frac{\mu_0}{(\mu_0+\mu)}\left[p(\Theta) + \frac{1+2\mu}{1+2\mu\sqrt{1-w}} \times \frac{1+2\mu_0}{1+2\mu_0\sqrt{1-w}} - 1\right]$$

which gives the radiance factor, conventionally written I/F. Here I is the scattered intensity (or radiance), and πF is the incident solar flux (or irradiance). The single-scatter albedo w is the fraction of energy scattered. The angular distribution of scattering is given by the phase function $p(\Theta)$ where Θ is the scattering angle between the incident and the scattered rays, and where μ, μ_0 are cosines of emission and incidence angles, respectively.

The double Henyey-Geenstein form is adopted

$$p(\cos\Theta) = \frac{(1-c)(1-b^2)}{(1+2b\ \cos\Theta+b^2)^{3/2}} + \frac{c(1-d^2)}{(1+2d\ \cos\Theta+d^2)^{3/2}}$$

for the phase function $p(\Theta)$, where our innovation is to remove constraints conventionally placed on the three parameters (b, c, d). We will impose only $0<c<1$ and $b<d$, removing any restriction on the sign of b. If both b and d are positive, there are two backscatter terms, where one is used for opposition, and the other for broad backscatter. Alternatively, $b < 0$ and $d > 0$ are

allowed, in which case *b* describes a forward scatter lobe and *d* describes a backscatter lobe.

We wish to find the minimum set of photometric parameters (as few as possible) that would be able to determine an RT solution and to describe experimental data. In the following, we consider Hapke-RT models with only the 4 parameters (*w*, *b*, *c*, *d*).

Tests with experimental data: We fitted these 4-parameter Hapke-RT models to BUG measurements [4] of hematite and Blackbird clay acquired at three wavelengths (450 nm, 550 nm, and 750 nm). The samples analyzed included packed (low porosity) and a loose (high porosity) states. Good model fits were found, similar in quality to those in [4]. Our objective, however, is not only to find a photometric model that describes data well, but to find one whose retrieved photometric parameters can be better related to sample physical properties.

The dramatic effect of porosity is shown in Fig. 1. The I/F increases up to four-fold for packed vs. loose clay as seen in forward scatter direction. Each point in Fig. 1 shows the I/F ratio at a single measurement geometry.

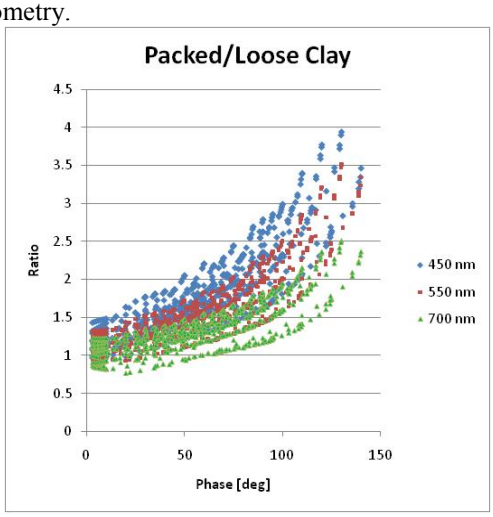

Figure 1. Ratio of I/F for packed clay versus loose clay

Porosity effects can be described in the 4-parameter Hapke-RT models. Fig. 2 shows inferred phase functions for the nine BUG datasets. that the scattering phase functions are shown to be fairly independent of wavelength. The packed clay (BCP) is strongly forward scattering; the other samples (loose clay: BCL, and hematite: HEM) are backscattering. We found that the best-fit Hapke-RT models for BCP yield phase functions so anisotropic that the Hapke (1981) model is no longer an accurate RT solution, when compared with accurate quadrature solutions. We constrained the Hapke fits for BCP to (*w*, *b*, *c*, *d*) values such that Hapke models remain within ~15% of accurate, numerical RT solutions.

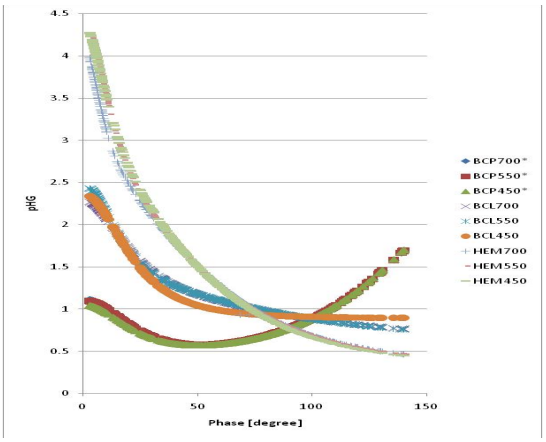

Figure 2. Phase functions from fitting of 4-parameter Hapke models to BUG data [4]. BCP packed clay; BCL loose clay; HEM hematite.

Even with only 4 photometric parameters, and with the extensive angular coverage of BUG data (which is rarely if ever matched by spacecraft data), difficulties were encountered for BCP in the unique retrieval of photometric parameter values. This study suggests that the effects of single scatter albedo *w* may not be separable from anisotropy (*b*, *c*, *d*), given limitations in angular coverage. However, the geometric albedo is proving to be much more stable against porosity states than either *w* or Bond albedo, and may be preferable to describe spectral dependence (Fig. 3).

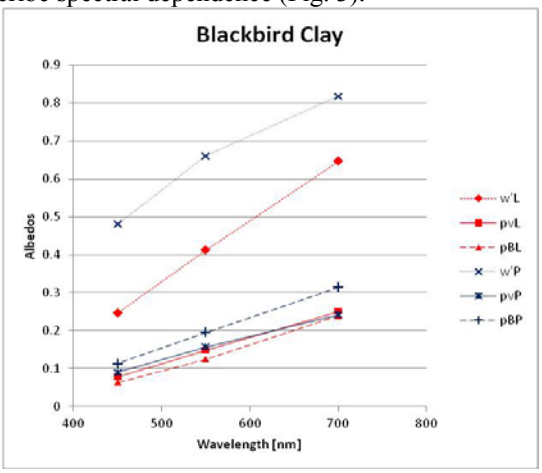

Figure 3 Albedos, packed clay (…P) vs. loose clay (…L), where pv is geometric albedo and pB is Bond albedo. The pvL and pvP are almost identical.

References: [1] Hapke B (1981) JGR 86, 3039. [2] Hapke B (1984) Icarus 59, 41. [3] Hapke B (2008) Icarus 195, 918. [4] Shepard M and P Helfenstein (2007) JGR 112, 3001. [5] Shepard M and P Helfenstein (2011) Icarus 215, 526. [6] Helfenstein P and M Shepard (2011) JGR. [7] Cheng A and D Domingue (2000) JGR 105, 9477.