CHARACTERIZATION OF MERCURY'S REGOLITH WITH MULTIPLE PHOTOMETRIC MODELS.

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Introduction. Photometric modeling is used to standardize imaging or spectral observations to a common illumination and viewing geometry. Such standardization is important in the construction of maps and mosaics that are built from images acquired under different illumination and viewing conditions. Photometric correction is also important in the examination of color or spectral observations and their comparison with laboratory mineral measurements, as it is rare for either telescopic or spacecraft color and spectral measurements to be acquired at standard laboratory illumination or viewing conditions.

Another use of photometric models is the derivation of regolith properties from the model parameters. Photometric models have been used to place constraints on porosity, roughness, and regolith grain characteristics such as size and structure.

This study applies two classes of photometric models in an effort to ascertain the model that provides the most robust photometric standardization for the construction of maps and mosaics for Mercury. Characteristics of the regolith are derived from both models and compared with similar modeling results from the Moon and those asteroids encountered by spacecraft.

The Models. Several photometric models, and variations on these models, have been used to study reflectance from planetary surfaces as a function of illumination and viewing geometry. The most common model currently in use is that derived by Hapke [1-7] and is based on geometric optics and the equations of radiative transfer. This model incorporates expressions and parameters to account for surface roughness, porosity, grain scattering properties, and two mechanisms ascribed to the formation of the opposition surge, the shadow-hiding opposition effect (SHOE) and the coherent backscattering opposition effect (CBOE). Another model that has been applied to Vesta and the Moon is that described by Kaasalainen et al. [8] and Shkuratov et al. [9]. Their model (hereafter referred to as the Kaasalainen-Shkuratov model) has been used to derive photometric corrections to Dawn images of Vesta [10] and telescopic observations of the Moon [9]. The strength of this model is in the separation of effects due to phase angle (the angle between the incident and reflected rays of light) from those due to incidence and emission angles (which are measured from the surface normal and thus depend on local topography).

This study examines the application of three variations of the Hapke model and six variations of the Kaasalainen-Shkuratov model to disk-resolved measurements of Mercury's surface. The three Hapke model variations include: (1) a model with a term for surface roughness, a term for the SHOE, but no terms for the CBOE or surface compaction; (2) a model with terms for surface roughness and surface compaction, but no opposition terms; and (3) a model with terms for surface roughness, both opposition terms, and surface compaction. The six Kaasalainen-Shkuratov model variations include five models with a phase function that has no opposition terms and a sixth version with a phase function that includes the opposition terms. The five models that do not incorporate the opposition terms in the phase function each contain a different expression for the disk function: (1) a Lommel-Seeliger expression, (2) a parameter-free Akimov disk function based on lunar studies [9], (3) a combined Lommel-Seeliger and Lambert law expression, (4) a Minnaert function, and (5) a single-parameter Akimov disk function [9]. The sixth Kaasalainen-Shkuratov model uses the single-parameter Akimov disk function.

Quality of Fit. Three tests of fit quality were performed with the modeling results. The first test utilizes χ^2 values derived from the model solutions, where χ^2 is defined by

$$\chi^2 = \sum_{i=1}^{N} \sqrt{(r_{measured} - r_{model})^2} \Big/ N$$

and where $r_{measured}$ is the observed reflectance, r_{model} is the reflectance calculated from the model, and N is the number of data points. Each model was fit to the MESSENGER Mercury Dual Imaging System (MDIS) data with a grid search (in which all parameters were varied simultaneously) that minimized the value of χ^2. The three Hapke model variations and four of the six Kaasalainen-Shkuratov model variations passed this quality test. The Kaasalainen-Shkuratov model variations with the Lommel-Seeliger and Minnaert disk functions did not pass this test.

The second fit test is termed the reflectance ratio analysis. The reflectance ratio is defined as the ratio of the measured reflectance to the reflectance predicted by the model. A perfect fit of the model to the data would produce a reflectance ratio of unity. Of the seven model variations that passed the first test, no single model clearly describes the photometric measurements better than the remainder. All of these models generally performed well, with many of the reflectance ratio values falling within 2% of a perfect solution. Examination of the reflectance ratio values as a function of wavelength, incidence angle, and emission angle provided a guide for selecting among model variations for each model, but not among the models. The Hapke model selected by this test was the first model described: the model with a term for surface roughness, a term for the SHOE, but no terms for the CBOE or surface compaction. The Kaasalainen-Shkuratov model selected by this test was the third model described: the model with the phase function with no opposition terms and a combined Lommel-Seeliger and Lambert law for the model disk function.

The final fit test is applied to those models that pass the χ^2 test and reflectance ratio analysis. In this test, seams between MDIS eight-color images acquired with large differences in incidence or emission angle are examined to see if one model provides a more seamless mosaic than the other. This final test is in progress as of this writing.

Ability of the Models to Assess Surface Properties. In some tests of the Hapke model there has been qualitative agreement between the model parameters and the sample characteristics [11–13], but these results have been dependent on the form of the model used in the test and on the angles sampled (excluding observations taken at large incidence and emission angles and measurements within the opposition surge). Other tests have shown poor quantitative correlation between Hapke model parameters and sample properties [14,15], but once again, this outcome is dependent on the form of the model used in the test. There has been no unambiguous proof of the correlations between Hapke model parameters and regolith properties of natural soils in their natural environment. Thus, at best, comparisons between different planetary surfaces can provide insight, but the quantitative measures derived from the Hapke model should be interpreted in a comparative sense and not as an absolute measure of any surface characteristic.

The Kaasalainen-Shkuratov model has not been as closely scrutinized as the Hapke model in terms of correlating parameters with specific surface characteristics. Thus the results from this model should also be interpreted in a comparative sense and not as an absolute measure of any surface characteristics.

Implied Surface Characteristics. On the basis of comparisons with the Moon and several asteroids that have been viewed at close range by spacecraft, the photometric analyses presented here indicate that Mercury's regolith is smoother on micrometer scales than the lunar regolith. This inference derives from comparisons between both Hapke modeling and Kaasalainen-Shkuratov modeling results from the Moon [16, 17, 9] and the models of Mercury from this study. Both types of models include parameters related to surface topography, and these parameters show values for Mercury that differ from those for the Moon.

The regolith soil grains show a different particle size distribution on Mercury from that on the Moon; in particular, the distribution is narrower and has a lower mean particle size. This inference is made from comparisons of porosity determinations from Hapke modeling results for the Moon [16, 17] and asteroids [18–23] with results for Mercury from this study. Grain structures of regolith particles on Mercury are also different from those on either the Moon or those asteroids viewed by spacecraft to date. The grain structure differences are based on comparisons of single-particle scattering functions from the Hapke models for a variety of solar system objects (including our modeling results for Mercury) with correlations between single-particle scattering function properties derived form laboratory measurements with particle characteristics [24].

Examination of the normal albedo from the Kaasalainen-Shkuratov modeling results for the Moon [9] and Vesta [10] along with the single-scattering albedo properties derived from the Hapke modeling results for the Moon [16, 17] and a variety of asteroids [18–23] show differences from the normal albedo and single-scattering albedo for Mercury that can be attributed to differences in composition as well as structure. The spectral properties of both the normal albedo and the single-scattering albedo are correlated to both composition and structure (in terms of inclusions and mineral phase changes). This spectral comparison between solar system objects leads to the conclusion that Mercury's regolith differs compositionally from the lunar regolith, a result in agreement with findings from MESSENGER's X-Ray Spectrometer and Gamma-Ray Spectrometer [25, 26].

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