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Application of multiple photometric models to disk-resolved measurements of Mercury's surface: Insights into Mercury's regolith characteristics

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ABSTRACT

Photometric analyses are used to standardize images obtained at a variety of illumination and viewing conditions to a common geometry for the construction of maps or mosaics and for comparison with spectral measurements acquired in the laboratory. Many models exist that can be used to model photometric behavior. Two of the most commonly use models, those of Hapke and Kaasalainen–Shkuratov, are compared for their ability to standardize MESSENGER images of Mercury. Analysis of the modeling results shows that photometric corrections using the Kaasalainen–Shkuratov model provides significantly less contrast between images acquired at large differences in emission angle. The contrast seen between images acquired at large differences in either incidence and phase angle is smaller with the Hapke model based corrections, but not significantly better than that provided by the Kaasalainen–Shkuratov model. Photometric studies are also used to infer scattering properties of the surface regolith. The quantitative correlation between photometric model parameters and surface properties is questionable, but laboratory studies do indicate general correlations and trends between parameters and sample properties that allow for comparisons between surfaces based on photometric modeling. Based on comparisons with the Moon and several asteroids that have been observed by spacecraft, the photometric analyses presented here are interpreted to indicate that Mercury's regolith is smoother on micrometer scales and has a narrower particle size distribution with a lower mean particle size than lunar regolith. Grain structures of regolith particles from Mercury are inferred to be different than those of the Moon or those asteroids observed to date. Mercury's regolith may contain a component compositionally distinct from lunar regolith.

1. Introduction

Photometry is defined here as the variation in reflection as a function of lighting geometry, specifically the incidence angle of incoming irradiance (from the surface normal), the emission angle of outgoing radiance (from the surface normal), and the phase angle (the angle between the incident and reflected rays of light). Variations in reflectance are influenced by the properties of the reflecting surface, and in the case of rocky planetary bodies, properties of the surface regolith. Models of spectrophotometric behavior (photometric behavior as a function of wavelength) attempt to predict the scattering properties of regolith, which are affected by texture and composition. With knowledge of the scattering properties, these models are used to predict reflectance at a given illumination and viewing geometry. However, commonly it is the inverse problem that interests planetary scientists: with no a priori knowledge of the regolith scattering properties (1) can a model accurately predict how the surface reflect lights at an unmeasured geometry given knowledge of how it reflects light for a subset of possible incidence and emission angles, and (2) can regolith scattering properties be derived by modeling photometric observations that only partially cover possible illumination and viewing geometries?

A model that can accurately predict (within 2–5% relative accuracy) the reflectance of a surface at an unmeasured geometry, based on measurements that cover only a subset of possible incidence and emission angle values, is invaluable for standardizing imaging data to a common illumination and viewing geometry. This "photometric standardization" or "photometric correction"

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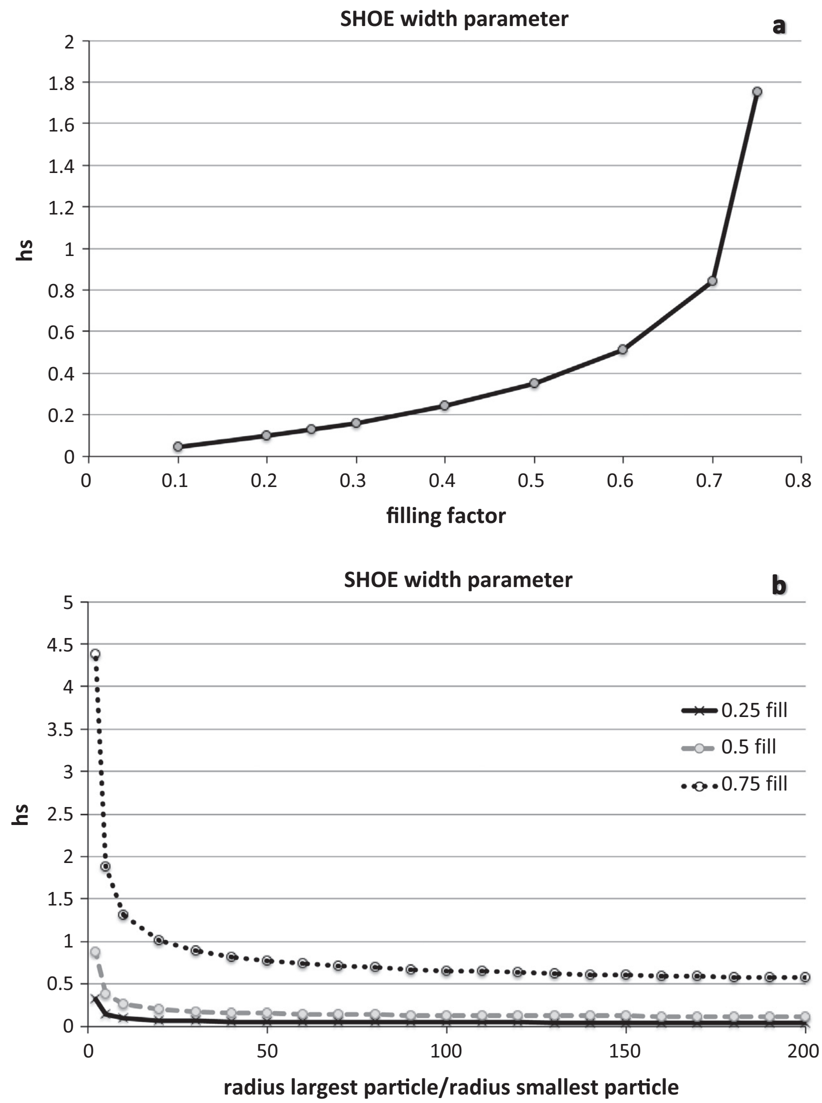

Fig. 1. (a) The variation in the shadow-hiding opposition effect width as a function of regolith filling factor (1–porosity), assuming a regolith comprised of equant particles larger than the wavelength of the observing light with a narrow size distribution. (b) The variation in the shadow-hiding opposition effect width as a function of the ratio of the radius of the largest to smallest sized particles for a range of filling factor values (black, solid line: $\phi = 0.25$; gray, dashed line: $\phi = 0.5$; black, dotted line: $\phi = 0.75$).

to a standard illumination and viewing geometry enables the construction of reflectance maps from images taken at varying geometries, the comparison of surface spectral reflectance from one region to another observed under different geometries, and interpretation of composition based on laboratory measurements taken at geometries different from the planetary observations.

A model that can accurately translate a set of reflectance measurements acquired at different geometries into a prediction of regolith physical properties provides a tool for understanding the structure and evolution of the regolith. These properties include, but are not limited to, single-scattering albedo (ratio of amount of light scattered to the amount of light both scattered and absorbed), grain size and shape, porosity, and surface roughness. Measurement of such properties would enable comparisons of regolith across the surface of an object, correlation of regolith properties with geologic terrains and processes, and comparison of regolith between Solar System bodies.

The structure of planetary regoliths vary on multiple spatial scales, from geologic units of meters to kilometers in scale to grains and clumps of grains on the order of micrometers to centimeters in size. The optical characteristics of the regolith material also strongly affect the reflective properties of the regolith and may vary within and between grains (Shkuratov et al., 2011). These characteristics include, but are not limited to, complex indices of refraction, inclusions (providing non-uniformity in scattering and absorption, affecting the scattering mean free path and direction), and grain size (affecting the scattering mean free path and direction). Photometric models that attempt to correlate photometric properties with regolith properties are thus inevitably complex and contain numerous parameters, making the uniqueness of the modeling solution difficult to assess. Empirical formulas with fewer parameters are therefore usually used when the goal is to determine a photometric correction and not to decipher the properties of the regolith. However such empirical formulas may not be more accurate.

Using images acquired by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's Mercury Dual Imaging System (MDIS), the MESSENGER project has produced and delivered to the Planetary Data System (PDS) a global eight-color mosaic (Domingue et al., 2011, 2015). Although the images in the mosaic were photometrically corrected, there are obvious residuals in images acquired at large incidence and emission angles (Domingue et al., 2015). Therefore in this paper we investigate: (1) which models provide a photometric correction