**The Photometric Properties of Vesta and the Implications.** Jian-Yang Li[1], B.J. Buratti[2], C.M. De Sanctis[3], B.W. Denevi[4], M. Hoffmann[5], A. Longobardo[3], S. Mottola[6], A. Nathues[5], V. Reddy[1], C.T. Russell[7], S.E. Schröder[6], [1]Planetary Science Institute, jyli@psi.edu, [2]Jet Propulsion Laboratory, California Institute of Technology, [3]Istituto di Astrofisica e Planetologia Spaziali, INAF, Rome, Italy, [4]Johns Hopkins University, Applied Physics Laboratory, [5]Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany, [6]Deutsches Zentrum für Luft- und Raumfahrt (DLR), 12489 Berlin, Germany, [7]Institute of Geophysics and Planetary Physics, University of California Los Angeles.

**Introduction:** The visual geometric albedo of 0.38 [1, 2] makes Asteroid Vesta the brightest rocky body of its size in the solar system. All other large planetary bodies in the solar system that are brighter than Vesta have mostly icy surfaces. For the less than 1% of asteroids that are brighter than Vesta, all are much smaller and considered collisional fragments from their parent bodies. Ample evidence suggests that Vesta, instead, is a protoplanet that failed to accrete to a full-sized planet, and has an ancient surface that retains the impact records over the past four billion years [e.g., 3, 4]. Li et al. [1] performed a detailed global photometric analysis of the surface of Vesta in the visible wavelengths using the images collected by the Framing Camera (FC) onboard NASA's Dawn spacecraft during its year-long stay in orbit around Vesta. We will summarize the photometric properties of Vesta, and discuss the implications of both our understanding of the photometric properties of Vesta and asteroids in general, and the photometric modeling of solar system rocky bodies. Vesta shows relatively large and interesting variations in its local photometric properties [e.g., 5, 6]. In this paper, we shall restrict ourselves to the globally averaged photometric properties. We note that some hypotheses we proposed in this paper can be further tested with in-depth, comparative studies of the photometric variations on the highly heterogeneous surface of Vesta in the future.

**Photometric Properties of Vesta:** Based on Li et al. [1], the albedo of Vesta is about twice as high as that of average S-type asteroids, and shows a strong dependence on wavelength from its pyroxene composition [7, 8]. Other than albedo, the globally averaged photometric properties of Vesta are similar to those of S-type asteroids. The wavelength dependence of those photometric parameters is weak between 0.4 and 0.98 µm wavelengths. The Hapke photometric roughness of Vesta is 18º. The histogram of the albedo distribution of Vesta at a pixel size of 1 km is single peaked, with a full-width-at-half-maximum of 17% of the average albedo, compared to the total range of albedo >4x wider. Models from FC data suggest similar or slightly stronger phase reddening as compared to Eros, an S-type near-Earth asteroid with a mean dimension of 17 km [9]. However, previous ground based observations and laboratory measurements of HED meteorites suggested the same trend but twice as strong phase reddening [10].

**Implications:** While the physical interpretations of photometric behavior, especially under the Hapke's theoretical framework, are still under debate and further laboratory investigation [e.g., 11], comparisons between different objects are still revealing. The albedo of Vesta puts it between the generally darker rocky and the generally brighter icy bodies. It is therefore also informative to consider the implications in terms of photometric modeling.

*Phase Function:* It is interesting to note that, despite the nearly 2x albedo difference, the single-particle phase function of Vesta is similar to that of average S-type asteroids [1]. However, dark, primitive type asteroids have steeper phase functions than Vesta, and brighter, icy satellites have comparable or shallower slopes. Based on McGuire and Hapke [12] and Souchon et al. [13], the single-scattering phase functions of Vesta and S-type asteroids are most consistent with irregular, rough, and opaque solid or hollowed particles that have a large fraction of internal impurity, but not consistent with smooth or transparent particles. The similar disk-averaged phase functions of large and ancient Vesta and various small, possibly fragment S-type asteroids indicate that phase function of asteroids seems to be independent of their average surface ages.

*Hapke Roughness Parameter:* The exact physical meaning of Hapke's roughness parameter is not clear. Some laboratory studies [14] suggested that roughness parameter is determined by the smallest structures that cast shadows. In the visible wavelengths, almost all asteroids, and even comets, that have been carefully modeled with disk-resolved data have roughness parameters within a range of 15º-30º [1, 15]. This fact seems to suggest that, despite the vastly different surface morphology of these objects, the small-scale (<mm) macroscopic structures of all solar system objects are similar. If this conclusion is true, then it further suggests that photometric roughness is dominated by small-scale regolith processes, such as micrometeorite gardening, rather than large-scale impacts. Or, alternatively, the small range of modeled roughness values compared to the possible full range (0º-60º) could suggest that the Hapke model itself is not very sensitive to roughness at all.

*Multiple Scattering:* Li et al. [1] estimated that, even for the relatively high single-scattering albedo of Vesta (~0.5 at 550 nm), multiple scattering accounts for only up to 30% of the total reflectance, which in turn still linearly depends on single-scattering albedo within ±30% of the average albedo. The majority of rocky bodies in the solar system are darker than Vesta. Therefore, this result for Vesta validates the approach that uses photometricaly corrected reflectance maps to approximate albedo maps by assuming a linear relationship between reflectance and various albedos for most rocky bodies.

In addition, Li et al. [1] compared Hapke model using an isotropic multiple scattering approximation and that partially accounting for anisotropic multiple scattering [c.f. 16], and reported that the level of multiple scattering for Vesta does not generate appreciable deviation between the two models. Although this result could be due in part to the large photometric variations on the surface of Vesta that hide the effect of multiple scattering, it still suggests that the effect of anisotropic multiple scattering can be ignored in the photometric modeling of almost all rocky bodies.

*Phase Reddening:* The similar phase reddening effect for Vesta compared to Eros is consistent with the similar photometric properties of Vesta with average S-type asteroids and the similar characteristics in their visible spectrum. But it is a puzzle that the phase reddening measured from FC data appears to be much weaker than those observed from the ground and measured for HED meteorites [10]. Assuming that all instruments are well inter-calibrated, then the discrepancy must lie on their different spatial resolutions and the associated geometric characteristics: Ground-based observations are hemispheric in scale, with the total flux integrated at a particular phase angle but over the whole range of incidence and emission angles in the illuminated and visible part of the surface. FC data used in Li et al. [1] have a field-of-view (FOV) of ~200 km, with relatively limited range of relatively low emission angles in each pixel. While laboratory measurements essentially eliminate all of the variations in the scattering geometry, the samples are artificially prepared and might have different photometric properties from the natural surface on Vesta.

Recent studies suggest that multiple scattering could cause phase reddening [17]. The fraction of multiple scattering is higher at higher phase angles [e.g. 1]. The overall increasing albedo of Vesta with wavelength means that at longer wavelength, increasing multiple scattering will result in a relatively shallower phase function, resulting in phase reddening. We suggest that the high emission angle areas on Vesta included in ground-based, disk-integrated data might be the cause of stronger phase reddening observed as compared to FC data. Hapke model calculations showed that the relative contribution of multiple scattering increases with phase angle faster near the limb/terminator than the center of disk (low emission angles). We plan to compare the phase reddening observed from the ground with those derived from FC data with the full disk of Vesta in the FOV and with the highest resolution data with 20 km FOV to quantitatively assess this explanation.

**Conclusions:** The similar phase functions and Hapke photometric roughnesses of Vesta and many S-type asteroids might be an indication that the globally averaged photometric properties are probably not sensitive to geologic processes of the overall surface. If photometric properties are affected by any global scale geologic processes, then the "photometric equilibrium" might be reached in a much shorter time scale than geologic time scale. This conclusion is similar to that suggested by Li et al. [15] with the study of similar photometric properties of cometary nuclei and the comparisons with dark type asteroids.

The phase reddening behavior of Vesta seems to be consistent with a multiple scattering origin of phase reddening, although we cannot rule out any other possible causes. On the other hand, the level of multiple scattering on Vesta is not sufficiently strong to cause an appreciable non-linear effect in photometric modeling. Since the albedo of Vesta is higher than most rocky bodies, the above conclusions about multiple scattering should be applicable to most rocky bodies in the solar system.

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