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Reprint of: Resolved photometry of Vesta reveals physical properties of crater regolith ☆

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ABSTRACT

During its year-long orbital mission, the Dawn spacecraft has mapped the surface of main-belt asteroid Vesta multiple times at different spatial resolutions and illumination and viewing angles. The onboard Framing Camera has acquired thousands of clear filter and narrow band images, which, with the availability of high-resolution global shape models, allows for a photometric characterization of the surface in unprecedented detail. We analyze clear filter images to retrieve the photometric properties of the regolith. In the first part of the paper we evaluate different photometric models for the global average. In the second part we use these results to study variations in albedo and steepness of the phase curve over the surface. Maps of these two photometric parameters show large scale albedo variations, which appear to be associated with compositional differences. They also reveal the location of photometrically extreme terrains, where the phase curve is unusually shallow or steep. We find that shallow phase curves are associated with steep slopes on crater walls and faults, as calculated from a shape model. On the other hand, the phase curve of ejecta associated with young impact craters is steep. We interpret these variations in phase curve slope in terms of physical roughness of the regolith. The lack of rough ejecta around older craters suggests that initially rough ejecta associated with impact craters on Vesta are smoothed over a relatively short time of several tens of Myr. We propose that this process is the result of impact gardening, and as such represents a previously unrecognized aspect of Vesta space weathering (Pieters et al., 2012). If this type of space weathering is common, we may expect to encounter this photometric phenomenon on other main belt asteroids.

1. Introduction

The Dawn spacecraft has finished its mission at main-belt asteroid Vesta and is on its way to the next target, Ceres. Going through successively lower altitude orbital phases, its instruments mapped the surface with increasing spatial resolution (Russell et al., 2007, 2012). The onboard Dawn Framing Camera (Sierks et al., 2011) has acquired many thousands of images of the surface. In this paper we analyze Framing Camera images to retrieve the photometric properties of the surface, that is, study how the reflectance changes with viewing and illumination angles. The surface reflectance of atmosphereless solar system bodies decreases with increasing solar phase angle. The relation between reflectance and phase angle is termed *phase function* or phase curve. Laboratory studies reveal that the phase function depends on physical properties of the surface. The regolith particles are often considered to be the fundamental light scattering unit of the regolith, with their shape/size distribution and mineralogical composition determining the shape of the phase function. However, the regolith roughness, with which we mean relief on a scale much larger than the particle size, plays at least as important a role (Capaccioni et al., 1990; Shkuratov et al., 2007; Shepard and Helfenstein, 2011), as may do particle internal defects, inclusions, and surface texture (Piatek et al., 2004; Beck et al., 2012).

During an asteroid flyby, only a small fraction of the surface can be observed over a wide range of phase angles. But as an orbiting spacecraft, Dawn observed almost the entire surface repeatedly at a range of illumination conditions, allowing us to reconstruct almost the full reflectance phase function for large parts of the

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surface. Unfortunately, we are unable to characterize a particularly important aspect of the phase function, the *opposition effect*. Any orbit around Vesta that would allow Dawn to make observations at zero phase angle would eventually bring the spacecraft into eclipse, which is a violation of the project flight rules. The opposition effect is a dramatic increase in reflectance towards zero phase angle, first observed for asteroids by Gehrels (1956). Its amplitude and width are thought to be highly diagnostic for the properties of the surface. The fact that Dawn did not observe close to opposition simplifies our analysis considerably, as the rest of the phase function generally has a more regular behavior. In this paper, when we talk about the "phase function", we exclude the opposition effect.

An important tool to describe and interpret phase functions is modeling. The Hapke (1981, 2002) photometric model has been widely used to describe light scattering in particulate surfaces of solar system bodies. Model parameters like "single scattering albedo" and "macroscopic roughness mean slope angle" are often interpreted in terms of physical properties of the regolith. It is recognized that this model can provide excellent fits to observed phase functions, but recent papers have cast doubt on its ability to yield meaningful physical insights (Shepard and Helfenstein, 2007; Tishkovets and Mishchenko, 2010). While Li et al. (2013b) describe the global photometric properties of Vesta in terms of the Hapke model, we do not consider this model the appropriate choice for our analysis. When including the macroscopic roughness term, it is very cumbersome to use. In addition, it contains several terms to describe the opposition effect, which we cannot constrain. Hence, we consider a more simple class of models in which the explicit dependence of reflectance on phase angle is decoupled from the effects of local topography (Kaasalainen et al., 2001; Shkuratov et al., 2011). Well-known examples of functions that describe the effects of local topography are the Lambert, Lommel–Seeliger, and Minnaert scattering laws (Minnaert, 1941).

Earlier studies of the resolved photometric properties of small solar system bodies have all employed the Hapke (1981, 2002) model. Spacecraft that went into orbit around an asteroid were NEAR Shoemaker (visited Eros) and Hayabusa (Itokawa), whereas asteroid flybys were performed by Galileo (Gaspra and Ida), NEAR Shoemaker (Mathilde), and Rosetta (Steins and Lutetia). While these missions have returned a wealth of spatially resolved photometric data, their analyses were mostly concentrated on deriving photometric models that describe the globally averaged properties of the surface. In the case of Gaspra (Helfenstein et al., 1994), Ida (Helfenstein et al., 1996), and Mathilde (Clark et al., 1999), this approach was probably dictated by the limited coverage in viewing and illumination geometries that prevented a spatially resolved photometric modeling to be attempted. Also for Itokawa (Kitazato et al., 2008) and Eros (Clark et al., 1999, 2002) the analysis was limited to generating a globally averaged model. In these cases this may have been guided by the fact that, given the considerable photometric uniformity of both near-Earth asteroids, a global model provided a satisfactory fit to all data. Spjuth et al. (2012), in their study of asteroid Steins, derived the first spatially resolved photometric model for an asteroid. The authors derived spatial maps of some of the Hapke model parameters, namely the single-scattering albedo, the macroscopic roughness parameter, and the single-particle phase function asymmetry factor. In order to overcome the typical instability of the inversion of the Hapke function, mainly due to coupling between the parameters, the spatially resolved parameter maps were derived by solving for each parameter individually, while fixing the remaining parameters to their global average values. The authors did not identify photometric variations larger than 1% on the surface of Steins. The same paper also confirmed photometric variations on the nucleus of comet 9P/Tempel 1 previously identified by Li et al. (2007a). However, Li et al. (2013a) found these variations spurious, resulting from uncertainties in the shape model used. Li et al. (2007b) reported large variations of the Hapke photometric parameters over the surface of another comet, 19P/Borrelly, some of which they related to fan jet activity. In summary, there is evidence for photometric variations over the surface of comets, but not (yet) for asteroids, where it is important to realize that the different physical processes that act on comet and asteroid surfaces may affect their photometric properties in very different ways.

The aim of this paper is two-fold. The first is to find the optimum model to photometrically correct images of Vesta. The term "photometric correction" is often used to simply mean correction for the effects of local topography, but can also include a correction for brightness differences between images taken at different phase angles. The latter can only succeed if the phase angle does not vary too much within a set of images. As the phase function can be very different for different types of terrain, there cannot be a universal correction valid for the entire surface. Our approach of separating the disk function from the phase function is well suited to facilitate photometric correction in each sense. We construct a simple photometric model for the global average of Vesta by combining the best-fit disk function with a polynomial to describe the phase function. The second aim is to investigate the photometric properties of the resolved surface to learn about the distribution of physical properties. We use the best disk function from the previous step to correct images for the local topography, and then proceed to reconstruct the phase functions for large parts of the surface. We model these phase functions by making simple assumptions, and produce maps of the model parameters. By focussing on several terrains with extreme photometric behavior we are able to identify key physical processes active on the surface of Vesta.

2. Photometric modeling

2.1. Methodology

The goal of this paper is to study the physical properties of the surface regolith of Vesta by means of a photometric analysis. This analysis consists of several parts that we summarize here. In Section 4 we derive a photometric model that is most representative for "average Vesta". We limit ourselves to models that can be separated into a *phase function*, which depends on phase angle only, and a *disk function*, which depends on local incidence, emission, and, in some cases, phase angle. The disk function describes how the reflectance varies over the planetary disk at constant phase angle. We evaluate several different disk functions and determine which one works best for Vesta. The phase function describes how the reflectance varies with phase angle. We adopt a polynomial function and determine the coefficients that provide the best fit for the average surface. The data we use for evaluating the performance of our photometric models are Framing Camera clear filter images that were acquired on approach to Vesta, detailed in Section 3. These images have the asteroid filling the FOV, providing all possible combinations of incidence and emission angle, and were acquired at a wide range of phase angles. The clear filter is sensitive in the 400–1000 nm wavelength range, with a peak in responsivity at 700 nm. In Section 5 we use this model to construct a global albedo map from images acquired at the lowest phase angles of the entire Vesta mission. For this, it is necessary to "photometrically correct" the images. There are two aspects to photometric correction: the correction for brightness changes due to local topography within the image, and brightness changes due to differences in phase angle between images. To correct for the