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Disk-resolved photometry of Vesta and Lutetia and comparison with other asteroids

Andrea Longobardo [a,*], Ernesto Palomba [a], Mauro Ciarniello [a], Federico Tosi [a], Maria Cristina De Sanctis [a], Fabrizio Capaccioni [a], Francesca Zambon [a], Eleonora Ammannito [b], Gianrico Filacchione [a], Carol A. Raymond [c]

[a] INAF Istituto di Astrofisica e Planetologia Spaziali, via Fosso del Cavaliere, 00133 Rome, Italy
[b] UCLA, 90095 Los Angeles, CA, USA
[c] California Institute Technology JPL, 91109 Pasadena, CA, USA

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A B S T R A C T

Photometry of asteroids gives fundamental information about their spectral and physical properties. The aim of this work is two-fold: (1) to calculate phase functions of Vesta and Lutetia in the visible spectral range; and (2) to compare photometric properties of all the asteroids visited by space missions, as inferred from disk-resolved photometry.

The phase functions of Vesta and Lutetia have been retrieved by performing a statistical analysis on data provided by the VIR–Dawn and the VIRTIS–Rosetta imaging spectrometers, respectively. The approach is based on the empirical procedure defined in Longobardo et al. (Longobardo, A. et al. [2014]. Icarus 240, 20–35).

The Vesta phase functions have been calculated at two wavelengths, one outside (0.75 μm) and one inside (0.95 μm) the pyroxene absorption band at 0.9 μm. The steepness of the phase function at 0.75 μm decreases from dark to bright regions, due to the increasing role of multiple scattering. Otherwise, the phase function at 0.95 μm results in uniformity across Vesta surface, since darkening agents are spectrally featureless and their influence at wavelengths inside the pyroxene absorption band is negligible. Moreover, it is, on average, steeper than the phase functions at 0.75 μm, due to the more important role of single scattering at 0.95 μm.

The Lutetia phase function is instead constant across the surface due to the homogeneous spectral properties of this asteroid.

The obtained photometric curves (reflectance versus phase angle) of Vesta and Lutetia have been then compared with those retrieved in previous works on asteroids visited by space missions. Differently from comparisons of disk-integrated phase functions of asteroids performed in previous works at low phase angles (lower than 25°), this work restricts to asteroid observations that are disk-resolved and occur at solar phase angles between 20° and 60°.

The S-type asteroids (Gaspra, Ida, Eros and Annefrank) show similar photometric curves.

The phase functions found in bright material units on Vesta are similar to those found for Steins (E-type in the Tholen taxonomy, Xe-type in the Bus one), suggesting a photometric analogy between achondritic surfaces. The latter are brighter and with a flatter phase function with respect to chondritic surfaces: we argued that this behavior is driven by optical properties of asteroid surfaces (e.g. albedo, role of multiple scattering) rather than by physical ones (e.g. grain size, roughness).

Dark material units on Vesta show an intermediate behavior between achondrites and the C-type Mathilde, confirming once again that these regions are characterized by mixtures of HED and carbonaceous chondrites.

While a clear anti-correlation is observed between reflectance and steepness of phase function for V, S and C asteroids, Lutetia shows an anomalous photometric behavior, presenting both a low reflectance and

* Corresponding author. Fax: +39 0649934384.
E-mail address: andrea.longobardo@iaps.inaf.it (A. Longobardo).

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a flat phase curve, and hence cannot be grouped with other spectral classes here considered. This behavior is similar to some X-type asteroids ground-observed at low phase angles and is consistent with a chondritic composition of its surface.

1. Introduction

1.1. Relation between asteroids photometry and spectral class

The behavior of reflectance as a function of illumination and observation geometry, through the incidence (i), emission (e) and solar phase (φ) angles, carries information on the scattering properties of the surface materials. In turn, scattering properties are related to optical and physical properties of the materials comprising the surface (Hapke, 2012; Lumme and Boweel, 1981). Physical parameters affecting the scattering properties are regolith grain size (e.g., Gaffey et al., 1993; Pommerol and Schmitt, 2008; Sanchez et al., 2012) and surface roughness (e.g., Capaccioni et al., 1990; Shkuratov et al., 2007; Shepard and Helfenstein, 2011), while optical properties concern albedo and transparency (Hapke, 2012; Lumme and Boweel, 1981). Moreover, the study of this behavior on spectral data may reveal wavelength-dependent photometric trends, such as phase reddening (e.g., Sanchez et al., 2012; Schröder et al., 2013) or photometric behavior of absorption bands (e.g., Reddy et al., 2012a; Longobardo et al., 2014), giving further insights into surface composition and role of multiple and single scattering.

Photometric analysis is a fundamental process of data reduction, since a comparison between images and spectra taken at different illumination conditions makes sense only after a photometric correction, i.e. after the removal of influence of illumination and viewing angles, avoiding misinterpretation of photometric effects (e.g. color variations, absorption band shallowing, darkening) as compositional information about surface materials.

Furthermore, Belskaya and Shevchenko (2000) showed that magnitude-phase angle dependence gives the possibility of discerning different asteroid classes (in particular they considered the Tholen, 1989, taxonomy) by means of their phase curve.

Their study is focused on ground-based observations of asteroids belonging to different spectral classes, and therefore the inferred photometric parameters concern large-scale properties of asteroid surfaces. Belskaya and Shevchenko (2000) put in relation the geometric albedo of asteroids p_V, inferred from their magnitude in the V-band, and the phase coefficient b, defined as the slope of the V magnitude vs phase angle curve between 10° and 25°. They found the empirical relation $b = 0.013 - 0.024 \log p_V$, i.e. low-albedo asteroids show steeper phase curves (larger b) whereas large albedo is associated with low phase coefficient. In the b vs $\log p_V$ scatterplot, high albedo (and low phase coefficient) boundary is occupied by E-type asteroids (classified as Xe-type in the Bus and Binzel, 2003, taxonomy) whereas on the opposite extreme (low albedo and high phase coefficient), P, C and F type asteroids are located. Finally, G, M and S spectral classes present an intermediate visual albedo and phase coefficients.

The Earth-based observations of the ESA Rosetta targets Steins and Lutetia, preceding the nominal Rosetta mission to the Comet Churyumov–Gerasimenko, revealed that albedo and phase coefficient of the E-type Steins (Dotto et al., 2009) are in agreement with asteroids belonging to the same spectral class. Otherwise, even if Lutetia is thought to have a composition similar to C-type asteroids (Coradini et al., 2011), its global photometric parameters are not representative of C class and in general of studied meteorites (Belskaya et al., 2010). Moreover, Belskaya et al. (2010) concluded that Lutetia probably shows heterogeneous surface properties, which may be related to surface morphology.

However, disk-resolved photometry can give further insights into physical and optical properties of asteroids as well as on their taxonomy, since it allows the characterization of not only the asteroid as a whole, but also of different terrains of the asteroid surface. This is particularly useful in the case of asteroids showing a large range of composition and albedo. Vesta is the asteroid with the largest albedo variations (Reddy et al., 2012b; Schröder et al., 2013; Longobardo et al., 2014) and a disk-resolved photometry allowed us to reveal the optical variations across its surface (Schröder et al., 2013; Longobardo et al., 2014).

In this work, we define photometric parameters describing disk-resolved phase curves (Section 3), that are obtained on a phase angle range much wider and centered toward larger angles (20–60°) than the ones allowed from ground-based observations. This makes it possible to give additional information on asteroid photometry. The Vesta and Lutetia disk-resolved phase curves are retrieved in Section 4 by applying the statistical approach defined in Longobardo et al. (2014) on data provided by the VIR–Dawn and the VIRTIS–Rosetta mapping spectrometers, respectively. Photometric parameters have been then calculated on disk-resolved phase curves of other asteroids visited by space missions retrieved in previous works. Results are given in Section 5. A comparative analysis is then performed, between ground-based and disk-resolved phase curves, between photometric parameters of the analyzed asteroids, and, when possible, between disk-resolved phase curves obtained at different wavelengths (Section 6). Conclusions of this analysis are given in Section 7.

1.2. Introduction to Vesta and Lutetia

The NASA Dawn mission, which orbited around Vesta from 16 July 2011 to 5 September 2012 (Russell et al., 2012, 2013), improved our knowledge of this asteroid, previously based only on ground-based and Hubble Space Telescope observations (e.g. McCord et al., 1970; Gaffey, 1997; Binzel et al., 1997).

The science allowed by Dawn is based on hyperspectral images provided by the Visible and InfraRed (VIR) mapping spectrometer (De Sanctis et al., 2011), on color images provided by the Framing Camera (FC; Sierks et al., 2011a), and on the elemental composition maps obtained by the Gamma Ray and Neutron Detector (GRaND; Prettyman et al., 2011).

The mission has confirmed the relation between Vesta and the HED (howardite–eucrite–diogenitic) basaltic achondrites clan (McSween et al., 2011, 2013; Russell et al., 2012; McCord et al., 1970; De Sanctis et al., 2012a, 2013), as inferred from the unambiguous observation of the two pyroxene absorption bands, centered at 0.9 μm (BI) and 1.9 μm (BII), respectively.

Vesta is the asteroid showing the largest variation in composition, spanning the range from diogenitic to eucritic (with presence of a few olivine deposits, e.g. Ammannito et al., 2013; Palomba et al., 2015), and albedo, with the presence of dark and bright patches on its surface (Reddy et al., 2012b), generally not associated to geologic units (Longobardo et al., 2015). Spectral analyses revealed that bright terrains are composed substantially of Vesta unaltered soil (Zambon et al., 2014), whereas dark terrains are composed of a mixture of HED and a dark contaminant (McCord