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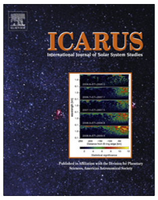

# Comparing Dawn, Hubble Space Telescope, and ground-based interpretations of (4) Vesta

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ABSTRACT

Observations of Asteroid (4) Vesta by NASA's Dawn spacecraft are interesting because its surface has the largest range of albedo, color and composition of any other asteroid visited by spacecraft to date. These hemispherical and rotational variations in surface brightness and composition have been attributed to impact processes since Vesta's formation. Prior to Dawn's arrival at Vesta, its surface properties were the focus of intense telescopic investigations for nearly a hundred years. Ground-based photometric and spectroscopic observations first revealed these variations followed later by those using Hubble Space Telescope (HST). Here we compare interpretations of Vesta's rotation period, pole, albedo, topographic, color, and compositional properties from ground-based telescopes and HST with those from Dawn. Our goal is to provide ground truth for prior interpretations and to help identify the limits of ground-based studies of asteroids in general. The improved rotational period measurement from Dawn is 0.222588652 day (Russell, C.T. et al. [2012]. Science 336, 684–686), and is consistent with the best ground-based rotation period of 0.22258874 day (Drummond, J.D., Fugate, R.Q., Christou, J.C. [1998]. Icarus 132, 80–99). The pole position for Vesta determined by Dawn is 309.03° ± 0.01°, 42.23° ± 0.01° and is within the uncertainties of pole orientation determined by Earth-based measurements (Li, J.-Y. et al. [2011]. Icarus 211, 528–534: 305.8° ± 3.1°, 41.4° ± 1.5°). Similarly, the obliquity of Vesta is 27.46° based on the pole measurement from Dawn and all previous pole measurements put the obliquity within 3° of this value. The topography range from the Dawn shape model is between −22.45 and +19.48 km relative to a 285 km × 285 km × 229 km ellipsoid. The HST range is slightly smaller (−12 km to +12 km relative to a 289 km × 280 km × 229 km ellipsoid) than Dawn, likely due to lower spatial resolution of the former. We also present HST and Dawn albedo and color maps of Vesta in the Claudia (used by the Dawn team) and IAU coordinate systems. These maps serve to orient observers and identify compositional and albedo features from prior studies. We have linked several albedo features identified on HST maps to morphological features on Vesta using Dawn Framing Camera data. Rotational spectral variations observed from ground-based studies are also consistent with those observed by Dawn. While the interpretation of some of these features was tenuous from past data, the interpretations were reasonable given the limitations set by spatial resolution and our knowledge of Vesta and HED meteorites at that time. Our analysis shows that ground-based and HST observations are critical for our understanding of small bodies and provide valuable support for ongoing and future spacecraft missions.

## 1. Introduction

Vesta is one of the most frequently observed objects in the Main Asteroid Belt since its discovery by Heinrich Olbers in 1807. Ground-based color observations of Vesta as early as 1929

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(Bobrovnikoff, 1929) revealed surface albedo/color variations that were attributed to composition. Taylor (1973) noted that Vesta's lightcurve changed depending on viewing geometry, with northern hemisphere and equatorial views showing a single maximum. Degewii (1978) used polarimetry to verify that Vesta's lightcurve is dominated by albedo. The relationship between albedo and polarization and the overlap with the visual wavelength lightcurve suggested that the observed light curve was indeed controlled by albedo variation. Later photometric observations confirmed that hemispherical scale albedo variations dominate the lightcurve rather than shape (Drummond et al., 1988).

Disk-integrated visible wavelength (0.3–1.1 μm) spectral observations of Vesta (McCord et al., 1970) revealed a deep absorption band at 0.9 μm attributed to the mineral pyroxene. Overall spectral shape, and the presence of this pyroxene band, suggested a compositional link between Vesta and the howardites–eucrites–diogenites (HED) meteorites and suggested Vesta as a differentiated object. Rotationally resolved near-IR spectra of Vesta from NASA IRTF suggested that albedo variations might be linked to surface compositional heterogeneity (e.g., Gaffey, 1997; Vernazza et al., 2005; Reddy et al., 2010). Subsequent Hubble Space Telescope (HST) observations confirmed the affinity between compositional variations and albedo units thought to be surface morphological features (Thomas et al., 1997a; Binzel et al., 1997; Li et al., 2010).

In July 2011 the Dawn spacecraft entered orbit around Vesta to begin its yearlong mapping mission (Russell et al., 2012). During this period, the spacecraft mapped the surface of Vesta using its three instruments: Framing Cameras (FC), Visible and Infrared Mapping Spectrometer (VIR), and Gamma Ray and Neutron Detector (GRaND). The Dawn Framing Cameras (FC) are a pair of identical 1024 × 1024 pixel imagers equipped with seven color filters (0.44–0.98 μm) and one panchromatic filter (Sierks et al., 2011) that imaged the surface of Vesta with an angular resolution of 93 μrad/pixel. Only FC2 was used during Vesta mapping phase with FC1 being a backup. Table 1 shows the list of filters along with their central wavelength and band pass. The FC mapped the surface at varying spatial resolution depending on the orbital phase. During approach, three rotational characterization (RC) phases imaged the entire visible surface at 9.07 km/pixel (RC1), 3.38 km/pixel (RC2), and ~487 m/pixel (RC3, RC3B) (Table 2).

Dawn is the first mission to an asteroid that has been profusely studied by ground-based telescopes and HST over many decades. This wealth of knowledge not only helped us understand Vesta prior to arrival of Dawn, but also enabled us to verify the validity of these studies. With over 600,000 asteroids discovered so far, and the ever-increasing cost of robotic exploration of small bodies, sending a spacecraft to many of these asteroids is inconceivable. Dawn presents a unique opportunity to verify and validate ground-based observations of Vesta. In this work we aim to compare ground-based and HST data of Vesta with those from Dawn FC to verify interpretations of albedo units and rotational variations. We also provide maps in three coordinate systems: the original Olbers system based on Thomas et al. (1997a); the Claudia system based on Russell et al. (2012) and used by the Dawn science team; and the IAU coordinate system in which all the Dawn data will be archived on the Planetary Data System (PDS).

**Table 1**
List of FC filters (except clear filter) with their respective band pass width and peak.

| Filter name | Wavelength center (μm) | FWHM (μm) |
|---|---|---|
| F8 | 0.438 | 0.040 |
| F2 | 0.555 | 0.043 |
| F7 | 0.653 | 0.042 |
| F3 | 0.749 | 0.044 |
| F6 | 0.829 | 0.036 |
| F4 | 0.917 | 0.045 |
| F5 | 0.965 | 0.086 |

**Table 2**
Observational circumstances for Dawn data collected at Vesta.

| Orbital phase | Best resolution (m/pixel) | Sub-spacecraft latitude | Distance to Vesta (km) |
|---|---|---|---|
| RC1[a] | 9067 | −32° | 100,000 |
| RC2 | 3382 | −54° | 37,000 |
| RC3 | 487 | −25° | 5200 |
| RC3B | 487 | −25° | 5200 |
| Survey | 252 | 50° to −90° | 2700 |
| HAMO[b] (1) | 61 | 66° to −87° | 660–730 |
| LAMO[c] | 16 | 85° to −90° | 190–240 |
| HAMO (2) | 60 | 85° to −85° | 640–730 |

[a] Rotational characterization.
[b] High altitude mapping orbit.
[c] Low altitude mapping orbit.

## 2. Data sets and processing

Three data sets were used in this paper: ground-based spectral data from Gaffey (1997) and Reddy et al. (2010); HST data from Thomas et al. (1997a), Binzel et al. (1997), and Li et al. (2010); and Dawn FC data from RC1, RC2 and RC3. The best resolution of HST data (38 km/pixel) is compared to the lowest resolution from Dawn during RC1 (9 km/pixel). Data reduction procedures for ground-based data are described in Gaffey (1997), Reddy et al. (2010); and for HST data processing in Thomas et al. (1997a), Binzel et al. (1997) and Li et al. (2010). A detailed description of Dawn FC data processing pipeline is presented in the supplementary materials section of Reddy et al. (2012a). Here we describe processing after the creation of photometrically and spectrally calibrated seven color global mosaics.

HST observations of Vesta at shorter wavelengths show higher contrast in albedo but this is below the wavelength range of Dawn FC filters. The Dawn albedo maps were created by using the 0.75-μm filter data which shows greatest albedo contrast among the FC filters and also has least amount of infield stray light residuals after correction (Reddy et al., 2012a). A global 0.75-μm-filter mosaic was extracted from the seven-color mosaic using IDL ENVI.

In addition to the albedo map, we created a band depth map, and a eucrite–diogenite (ED) ratio map. The band depth map (0.75/0.92 μm) is a single band color-coded map that helps to quantify the 0.9-μm-pyroxene band depth. The ED ratio is an interpretive scheme consisting of a single band rainbow color-coded map that uses the ratio of 0.98 μm and 0.92 μm filters. Diogenite-rich areas are in red and show a deeper 0.90-μm pyroxene band, whereas eucrite-rich areas are in blue (Reddy et al., 2012a). Due to higher iron content in eucrites their 0.9-μm pyroxene band is shifted to longer wavelength and so the eucrite ED ratio is ~1. In contrast diogenites have ED ratio >1 due to their lower iron abundance (Reddy et al., 2012a).

## 3. Evolution of coordinate systems

The evolution of coordinate systems used on Vesta has historically depended on the spatial resolution of data available at that time (Gaffey, 1997; Thomas et al., 1997b; Russell et al., 2012). Typically, ground-based rotational spectral studies of asteroids (e.g., Reddy et al., 2010) used a lightcurve-based coordinate system where near-simultaneous lightcurve observations are used to phase spectral observations (arbitrarily) with the minima of the lightcurve becoming the prime meridian. Gaffey (1997) observed