



Detection of serpentine in exogenic carbonaceous chondrite material on Vesta from Dawn FC data



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ABSTRACT

The Dawn mission's Framing Camera (FC) observed Asteroid (4) Vesta in 2011 and 2012 using seven color filters and one clear filter from different orbits. In the present paper we analyze recalibrated HAMO color cubes (spatial resolution ~ 60 m/pixel) with a focus on dark material (DM). We present a definition of highly concentrated DM based on spectral parameters, subsequently map the DM across the Vestan surface, geologically classify DM, study its spectral properties on global and local scales, and finally, compare the FC in-flight color data with laboratory spectra.

We have discovered an absorption band centered at $0.72 \mu\text{m}$ in localities of DM that show the lowest albedo values by using FC data as well as spectral information from Dawn's imaging spectrometer VIR. Such localities are contained within impact-exposed outcrops on inner crater walls and ejecta material. Comparisons between spectral FC in-flight data, and laboratory spectra of meteorites and mineral mixtures in the wavelength range $0.4\text{--}1.0 \mu\text{m}$, revealed that the absorption band can be attributed to the mineral serpentine, which is typically present in CM chondrites. Dark material in its purest form is rare on Vesta's surface and is distributed globally in a non-uniform manner. Our findings confirm the hypothesis of an exogenic origin of the DM by the infall of carbonaceous chondritic material, likely of CM type. It further confirms the hypothesis that most of the DM was deposited by the Veneneia impact.

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1. Introduction

The Framing Camera, FC2,¹ onboard the Dawn mission (Russell et al., 2012) has imaged the entire visible surface of Asteroid 4 Vesta from different orbits in 2011 and 2012. The FC is equipped with one clear (panchromatic) and seven color filters, covering the wavelength range between 0.44 and $1.0 \mu\text{m}$ (Sierks et al., 2011). Vesta was mapped from Survey, HAMO (High-Altitude Mapping) and LAMO (Low Altitude Mapping) orbits at spatial resolutions of ~ 250 m/pixel, ~ 60 m/pixel, and ~ 20 m/pixel, respectively.

The surface of Vesta as imaged by FC is unlike any asteroid visited so far. Albedo and color variation are the most diverse among the objects in the asteroid belt (Reddy et al., 2012b). Low albedo features were among the most prominent units appearing during Dawn's approach to Vesta. Subsequently, terrains rich in low albedo material, termed "dark material" (DM), have been identified in several geologic settings (Reddy et al., 2012a; McCord et al., 2012; Jaumann et al., in press): (1) associated with large impact craters, e.g. outcropping at crater walls and present in ejecta blankets, (2) as flow-like deposits or rays, and (3) dark spots. FC color spectra (Reddy et al., 2012a) and spectra acquired by the visible and near-infrared spectrometer VIR (De Sanctis et al., 2013) indicate that DM, which is mixed with materials indigenous to Vesta, is spectrally similar to carbonaceous chondrite meteorites (CC)

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¹ Dawn carries two redundant cameras FC1 and FC2.

and thus possibly of exogenic origin, i.e. due to the infall of carbonaceous volatile-rich material (Prettyman et al., 2012). It was shown (Reddy et al., 2012a) that band depth and albedo of DM are identical to those of the carbonaceous chondrite xenolith-rich howardite Mt. Pratt (PRA) 04401. Laboratory mixtures of Murchison CM2 carbonaceous chondrite and basaltic eucrite Millbillillie show close similarity of band depth and albedo to DM (e.g., Reddy et al., 2012a). The presence of exogenous carbonaceous chondrite meteorite clasts in HED (howardite, eucrite, diogenite) meteorites is well documented and thus a further indication for its presence on Vesta (e.g. Buchanan et al., 1993; Zolensky et al., 1996). Clasts in HED meteorites are primarily composed of a phyllosilicate matrix (mostly serpentine), with Fe–Ni sulfides, carbonates, hydrated sulfates, organics, and Fe³⁺-bearing phases, and inclusions of olivine, pyroxene, relict chondrules and calcium–aluminum-rich inclusions. Although some of these clasts have been heated and dehydrated during impact (~400 °C), a majority is still hydrated, escaping metamorphism (Vilas and Sykes, 1996), and contain H₂O- and/or OH-bearing phases (Zolensky et al., 1996). Aqueous alteration products may include magnetite, which has been identified on asteroids (Yang and Jewitt, 2010) in the orbital environment of Vesta. This implies the presence of hydrated minerals, as confirmed by VIR at ~3 μm (De Sanctis et al., 2012). Further observational data for Vesta indicate that darker terrains are associated with enhanced hydrogen abundance (Prettyman et al., 2012). Besides the theory that DM on Vesta is the result of infall of carbonaceous chondritic material, two other hypotheses have been put forward (McCord et al., 2012; Jaumann et al., 2012; Williams et al., 2013): basalt flows (dikes/sills) that were shattered and redistributed by impacts, and impact melt produced by large impacts. While we have no conclusive evidence for preserved basaltic lava flows from FC data, morphological evidence for impact melt on Vesta exists (Denevi et al., 2012; Le Corre et al., 2013). Recently, Palomba et al. (in press) have discussed DM on Vesta based on VIR data and concluded that all DM shows similar spectral properties, dominated by pyroxene absorption features. They also found a positive correlation between low albedo and an OH band, centered at 2.8 μm, confirming the conclusion of the existence of exogenic carbonaceous chondritic material.

Our detailed investigation of the Vestan surface revealed for the first time the presence of an absorption feature at ~0.7 μm for several DM localities, when inspected at high FC spatial resolution. In the following, we describe the distribution and the context of DM sites showing the lowest reflectivities on Vesta. The origin and characteristics of candidate materials are also described. When comparing spectra of possibly related meteorites, and the range of spectral variations found for DM on Vesta, a significant coincidence is indicated. We are also aiming to identify relationships within the color variations on Vesta.

2. Data processing and method

Framing Camera images exist in three standard levels: 1a, 1b and 1c. The data stream received on the ground (level 0) is converted to PDS format images (level 1a) that contain unprocessed, uncalibrated digital values from 0 to 16,384 DN (14 bit). Level 1a data is converted to level 1b as radiometrically calibrated PDS-compliant images (unit μW/(cm² sr nm)). All FC color images are affected by a stray light component, the so-called “in-field” stray light (Kovacs et al., 2013). This ghost signal, which leads to absolute errors of up to ~10%, needs to be removed from each science image by a deconvolution process, leading to level 1c data, which is the final image data product. In order to correct for the ghost signal, a stray-light removal algorithm based on laboratory data has been developed (Kovacs et al., 2013). The stray light removals are

scene- and filter dependent and its residual systematic error is: 0.438 μm filter – 2.0% (11%), 0.555 μm – 2.0% (3.0%), 0.653 μm – 2.5% (5%), 0.749 μm – 3.0% (4.0%), 0.829 μm – 3.0% (9%), 0.917 μm – 2.5% (7%), 0.965 μm – 2.5% (6%); whereby the numbers in brackets are the typical errors before stray light removal. After stray-light removal, level 1c data is converted to reflectance (*I/F*) by dividing the observed radiance by solar irradiance from a normally solar-illuminated Lambertian disk.

The stray-light corrected level 1c *I/F* data is used for processing in our ISIS pipeline. ISIS (Integrated Software for Imagers and Spectrometers; Anderson et al., 2004) is a UNIX-based program developed and maintained by USGS. ISIS performs the photometric correction of the FC color data to standard viewing geometry (30° incidence and 0° emission angle) using Hapke functions (e.g., Hapke, 1981). Starting values for the Hapke input data were taken from Li et al. (2013) and Helfenstein and Veverka (1989). They were then optimized for inter-image and spectral consistency. The former is achieved by minimizing photometrically induced seams in color mosaics, and the latter by comparison of the corrected images obtained at different illumination angles. Initially, both proved to be met by Li et al.’s (2013) data, but because of local deviations from the global model, they are not fulfilled simultaneously. Since the transition from HED type to ‘pure’ DM is continuous, no ‘normal’ is available for the local photometric correction. Therefore a set of parameter values has been adopted which emphasizes the invariability of the radiance data to the range of incidence and emission angles covered by the FC data, and is applied in the photometric correction. The resulting reflectance data are map-projected in several steps, and co-registered to align the color frames, creating color cubes for analysis. A detailed description of the FC data processing pipeline is presented in Reddy et al. (2012b). Note that the photometric parameters used by Reddy et al. (2012b) are slightly different from the one employed in our study as stated earlier. For the present analysis, FC color data from HAMO and HAMO_2 orbits were used, whose spatial resolution is about ~60 m/pixel. Higher resolution data from LAMO orbits (~20 m/pixel) were used to identify details of the morphological context, and for separating DM from shadowed regions. The color mosaics generated by the ISIS pipeline were analyzed using ENVI and ArcGIS software. In order to assess the uncertainty of the individual color bands, smooth, homogeneous areas on Vesta have been photometrically analyzed. We conclude that for a 4 × 4 pixel sized area, the relative statistic error is ±0.4% in all bands. This error propagates into the spectral ratios accordingly. Not included are the effects caused by local deviations from the global photometric model connected with the differences in composition. Therefore the total error may be somewhat higher, in particular in areas of steep slopes. HAMO data is taken for the spectral analysis and hence integrated over areas of inhomogeneous material. Since the different materials show non-linear variations in the individual bands, such integration may introduce weight errors. For the photometric correction of our FC data and the visualization of the results, we used the Vesta shape model (gaskell_vesta_20130522_dem.cub) derived from FC clear filter images by Gaskell (2012). All maps are produced in the Claudia System used by the Dawn science team (Reddy et al., 2013).

3. Description of dark material

Dawn FC discovered dark material (DM) on Vesta during its approach phase in 2011. These enigmatic surface features, in the form of low albedo units, are unevenly distributed across the Vestan surface (see Fig. 3). Reddy et al. (2012a) describe specific locations of DM in the ejecta blanket of the crater Marcia and its inner wall. Prominent deposits were also found in the inner crater walls

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