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Composition and mineralogy of dark material units on Vesta

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ABSTRACT

Vesta is the asteroid with the largest albedo variation among the known rocky Solar System objects and shows a widespread occurrence of dark material (DM) and bright material (BM) units. In the first observation phases by the Dawn spacecraft, two main extensions of low albedo areas were identified on Vesta and found to be closely correlated with carbonaceous, OH-rich, material. In this work we use the hyperspectral data provided by the VIR-Dawn imaging spectrometer onboard Dawn to detect and analyze individual, well-defined, dark material units. We define DM units assuming a relative criterion, i.e. reflectance lower than the surroundings. By coupling visible and infrared images of the same area we are able to select real dark material units, discarding false detections created by shadowing effects. A detailed final catalogue of 123 dark units is presented, containing the geographical parameters and the main spectral characteristics for each unit. Independently of the geological context of the dark units, all DMs show similar spectral properties, dominated by the pyroxene absorption features, as is the average spectrum of Vesta. This finding suggests a similar composition, with the presence of darkening agents that also weaken pyroxene band depths. The majority (90%) of the DM units shows a positive correlation between low albedo and an OH band centered at 2.8 μm, confirming the hypothesis that the darkening agents are carbonaceous chondrites, probably delivered by low-velocity impacts of primitive asteroids. A comparison with laboratory spectra allows us to better constrain the size and the composition of the darkening agents. These DM areas seem to be made of eucritic material. The regolith grain size seems to be nearly constant around an average value of 25 μm, and is quite homogenous at least in the first hundreds of meters beneath the Vesta surface, suggesting similar processing mechanisms for both DM and BM.

1. Introduction

Prior to 2011, our knowledge of Vesta was derived from space-based and ground-based telescopic observations: visible and near-IR spectroscopy have shown that the surface of Vesta exhibits absorption features indicative of basaltic minerals, similar in composition to the howardite–eucrite–diogenite (HED) family of basaltic achondrite meteorites, leading to the conclusion that Vesta was the most plausible candidate to represent the HED parent body (e.g., McCord et al., 1970; Gaffey, 1997; Binzel et al., 1997).

Ground-based and Hubble Space Telescope (HST) images of Vesta have revealed that the surface is not covered with uniform material, but instead exhibits local color and albedo variations of 10–20% (e.g. Gaffey, 1997; Binzel et al., 1997; Li et al., 2010).

In July 2011 NASA's Dawn spacecraft entered into orbit around Vesta for a year-long mapping phase (Russell et al., 2007, 2012) during which the real nature of the asteroid was unveiled, making remarkable discoveries that strongly improved understanding of the origin and evolution of the Solar System and its building blocks (Russell et al., 2012; De Sanctis et al., 2012a; Jaumann et al., 2012; Prettyman et al., 2012).

During the first year of orbit around Vesta, the Dawn spacecraft took color and hyperspectral images of Vesta by means of the Framing Camera (Sierks et al., 2011) and the Visual and InfraRed

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spectrometer (VIR) (De Sanctis et al., 2011) and mapped the surface elemental composition at regional spatial scales by means of the Gamma Ray and Neutron Detector (GRaND) (Prettyman et al., 2011).

Dawn confirmed that Vesta has a composition spanning from the eucritic to the diogenitic, and found a strong dichotomy between the southern and northern hemispheres and between eastern and western hemispheres (Ammannito et al., 2013a; De Sanctis et al., 2012a; Reddy et al., 2012a).

The VIR spectrometer showed that there are considerable regional and local albedo and compositional variations across the asteroid, and that diogenitic components are concentrated mainly in the southern region, particularly matching the Rheasilvia impact basin (De Sanctis et al., 2012a; Ammannito et al., 2013a; McSween et al., 2013).

Furthermore, it has been observed that Vesta is the asteroid with the largest known albedo variations (Reddy et al., 2012a; Li et al., 2013; Prettyman et al., 2012; Denevi et al., 2012). Surface brightness is not uniform, and bright and dark material units (hereafter tagged as BM and DM units) are observed at local scale (Jaumann et al., 2012; McCord et al., 2012; Palomba et al., 2013; De Sanctis et al., 2013; Zambon et al., 2014). DM units are non-randomly distributed across Vesta's surface and often are associated with specific geo-morphological features (Jaumann et al., 2014). Typically DM units are associated with impact features and likely consist of ejecta materials, both inside and outside craters. However, they are also associated with soil movements and mass wasting. In addition to DM units, a broad low-albedo region that extends from 90° to 200° longitude and 64°S to 16°N latitude was observed on Vesta (Jaumann et al., 2014). The characteristics of this region are compatible with the presence of a darkening agent finely mixed with the original Vesta regolith. A plausible explanation is that this material was delivered to Vesta by low-albedo (probably carbonaceous) asteroids over time and that subsequent impact gardening created a mixed layer to depths between one and several kilometers (McCord et al., 2012). An alternative hypothesis is that the dark material is delivered by small carbonaceous chondrite (CM type) particles up to at least centimeter size over a limited time span (De Sanctis et al., 2012b). This event may have delivered CM material during the early evolution of Vesta (after differentiation and crust formation), which upon subsequent cratering may have mixed into the regolith. A major impact may also have produced an uneven distribution. The two scenario can be considered the two endmembers of the continuous flux scenario, discussed in Turrini et al. (2014), according to which bot large stochastic events and micrometeoroid flux can have been occurred onto the Vesta surface.

The carbon-rich, low-velocity impactors discussed in all the scenarios would deposit hydrated compounds onto the dark areas on Vesta, which in fact show a weak but well-defined OH spectral feature at 2.8 μm (De Sanctis et al., 2012b; McCord et al., 2012). Combining seven color Framing Camera images of a representative DM unit samples with laboratory data show a close relationship between DM areas. The broad low albedo areas seems to confirm the possibility that DM originated in a low-velocity (<2 km/s) carbonaceous body during the formation of the 400 km diameter Veneneia basin (Reddy et al., 2012b). This scenario seems to be supported by the recent global distribution found by the Framing Camera, in which many DM units are concentrated in the northern parts of the Veneneia impact basin (Jaumann et al., 2014).

A possible alternative and endogenic source for dark material on Vesta is represented by freshly exposed mafic material or impact melt, created or exposed by impacts, both rich in opaque phases and volcanic units (McCord et al., 2012).

The scope of this paper is to identify and map the locations of dark material units on the surface of Vesta using VIR data. Assuming that the dark materials are more concentrated near their source on the surface, we focused on the detection of areas that combine local extrema of low albedo and high surface temperature. This analysis led us to build a taxonomic catalogue of the different types of deposits, to study the general spectral property trends and individual peculiarities of the low-albedo materials, and to consider all the postulated sources for the darkening. The hypotheses of delivery of carbonaceous chondrites, as well as opaques, or impact-shocked materials will be compared in detail.

The possible causes of darkening such as the grain size variation, the presence of carbonaceous chondrites, impact-shocked materials or opaque rich compounds, are discussed in Section 2. In Section 3 we give an overview of the spectral data used and define the spectral parameters suitable to analyze the mineralogy of DM. We present the methodology adopted to detect DM and their classification in Section 4, whereas in Section 5 we discuss the composition and origin of DM, offering endogenic sources as alternatives (or as complementary) to the exogenic carbonaceous sources or other opaque rich materials. Finally, conclusions are given in Section 6.

2. Darkening agents

There are many agents that can darken a Vis–NIR spectrum that can be at the origin of the DM units on Vesta: grain size, carbonaceous chondrite materials, opaques and metals.

2.1. Regolith grain sizes

It is well known that a general decrease in reflectance is observed with increasing grain size (Adams and Filice, 1967; Clark et al., 1992). For example, on Mars, low albedo regions typically consist of coarse-grained (mm size) regolith whereas bright regions are formed by fine-grained (μm size) dust (Ruff and Christensen, 2002). This behavior is also observed in several laboratory spectra of different materials (e.g. Cloutis et al., 2013). Similarly, and especially in pyroxenes, the increase in grain size will deepen both Band I and Band II and result in band saturation which is achieved for ~100 μm (Cloutis et al., 2013).

2.2. Carbonaceous rich material

Among common asteroidal materials, carbonaceous chondrites are some of the darkest. Here, the major opaque darkening phases are represented by magnetite and various carbonaceous phases. The carbonaceous phases refer to material that is rich in carbon. It is fine-grained, finely dispersed and intimately associated with phyllosilicates (Mason, 1962; Pearson et al., 2002; Garvie and Buseck, 2004; Kebukawa et al., 2010; Clemett et al., 2010). As a result, in spite of its low overall abundance (a few percent) it is very effective at darkening the reflectance spectra of carbonaceous chondrites (Gaffey, 1976). Decreasing petrologic grade (from 3 to 1) follows a change in the basic mineralogy from anhydrous to hydrous silicates.

Generally, darker carbonaceous chondrite spectra are correlated with bluer spectral slopes: a behavior most consistent with an increasing abundance of fine-grained magnetite and/or insoluble organic material (IOM). There are many examples of carbonaceous chondrite clasts in howardites, typically with abundances up to 5 vol.% (Zolensky et al., 1996), although one sample (PRA 04401) shows an abundance as high as 60 vol.% (Herrin et al., 2011; Cloutis et al., 2013).