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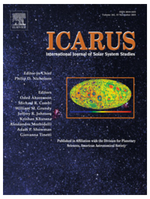

Lithologic variation within bright material on Vesta revealed by linear spectral unmixing

F. Zambon[a,*], F. Tosi[a], C. Carli[a], M.C. De Sanctis[a], D.T. Blewett[b], E. Palomba[a], A. Longobardo[a], A. Frigeri[a], E. Ammannito[c], C.T. Russell[c], C.A. Raymond[d]

[a] INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere, 100, 00133 Rome, Italy
[b] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[c] Institute of Geophysics and Planetary Physics, University of California at Los Angeles, 3845 Slichter Hall, 603 Charles E. Young Drive, East, Los Angeles, CA 90095-1567, USA
[d] NASA/Jet Propulsion Laboratory and California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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ABSTRACT

Vesta's surface is mostly composed of pyroxene-rich lithologies compatible with howardite, eucrite and diogenite (HED) meteorites (e.g., McCord et al. [1970] Science, 168, 1445–1447; Feierberg & Drake [1980] Science, 209, 805–807). Data provided by the Visible and Infrared (VIR) spectrometer, onboard the NASA Dawn spacecraft, revealed that all Vesta reflectance spectra show absorption bands at $\sim$0.9 and $\sim$1.9 μm, which are typical of iron-bearing pyroxenes (De Sanctis et al. [2012] Science, 336, 697–700). Other minerals may be present in spectrally significant concentrations; these include olivine and opaque phases like those found in carbonaceous chondrites. These additional components modify the dominant pyroxene absorptions. We apply linear spectral unmixing on bright material (BM) units of Vesta to identify HEDs and non-HED phases. We explore the limits of applicability of linear spectral unmixing, testing it on laboratory mixtures. We find that the linear method is applicable at the VIR pixel resolution and it is useful when the surface is composed of pyroxene-rich lithologies containing moderate quantities of carbonaceous chondrite, olivine, and plagioclase. We found three main groups of BM units: eucrite-rich, diogenite-rich, and olivine-rich. For the non-HED spectral endmember, we choose either olivine or a featureless component. Our work confirms that Vesta's surface contains a high content of pyroxenes mixed with a lower concentration of other phases. In many cases, the non-HED endmember that gives the best fit is the featureless phase, which causes a reduction in the strength of both bands. The anticorrelation between albedo and featureless endmember indicates that this phase is associated with low-albedo, CC-like opaque material. Large amounts of olivine have been detected in Bellicia, Arruntia and BU14 BM units. Other sites present low olivine content ($<30\%$) mostly with a high concentration of diogenite.

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1. Introduction

1.1. Early knowledge of Vesta

The first spectral study of Vesta dates back to Bobrovnikoff (1929). McCord et al. (1970) compared Vesta spectra with the meteorite Nuevo Laredo, inferring a relation between Vesta and pyroxenes. Pyroxenes are characterized by the presence of two crystal field absorptions, centered approximately at 0.9 and 1.9 μm (McCord et al., 1970), due to ferrous iron (Fe^{2+}) in octahedral sites (e.g., Burns, 1993). Consolmagno and Drake (1977) suggested a possible link between Vesta and eucrite meteorites, and Feierberg and Drake (1980) proposed that Vesta is a mixture of howardite and eucrite. Studies by Lupishko et al. (1988) show a clear inverse correlation between the polarization and brightness of Vesta, correlated with the west–east dichotomy. Hubble Space Telescope (HST) observations between 1994 and 1996 confirmed this inference by highlighting the geological differences on the asteroid (Binzel et al., 1997). Moreover the identification of the prominent impact basin at the south pole (now named Rheasilvia) corroborates the hypothesis that Vesta is the parent body of the howardite, eucrite and diogenite (HED) meteorites (Thomas et al., 1997). In addition, the disk-integrated mid-infrared spectra of Vesta have shown the presence of minor constituents as olivine, feldspar, and chromite (Donaldson Hanna and Sprague, 2009). Studies by Li et al. (2010) revealed that the vestan surface can be

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* Corresponding author: Tel.: +39 06 45488210, +39 06 49934210; fax: +39 06 45488188.

E-mail address: francesca.zambon@iaps.inaf.it (F. Zambon).

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divided into several geological units (more specifically, regions of lithologic variation), in particular, eucrite-rich and diogenite-rich units, as well as slightly weathered and freshly exposed units. Shestopalov et al. (2010) concluded that the global diversity of Vesta might be caused by variations of non-basaltic source sediments enriched by dark rocks, spinel group minerals, or even chondritic-like material. Moreover, they showed that certain vestan units contain olivine abundances of several volume percent.

1.2. The Dawn era and Vesta's lithologies

Dawn entered orbit around Vesta in July 2011 (Russell and Raymond, 2011), and enabled many discoveries during about one year of observations. For the first time, Dawn acquired data of Vesta's surface at high spatial resolution, allowing for production of complete geological and lithological maps (De Sanctis et al., 2012a; Williams et al., 2014). Dawn's Visible and Infrared (VIR) imaging spectrometer (De Sanctis et al., 2011) provided high spectral resolution data covering the majority of Vesta's surface at varying spatial scales. The spatial resolution of the VIR maps ranges from ~800 m/pixel in the Survey phase to ~180 m/pixel in the HAMO and HAMO-2 phases (see Table 1 of Zambon et al. (2015)).

Vesta is the parent body of the HED meteorites. HEDs encompass a large variety of igneous rocks, similar to basalts, cumulate gabbros, orthopyroxenites and igneous brecciated mixtures (Mittlefehldt et al., 1998). Diogenites are coarse-grained cumulates that originated in a plutonic layer deep in the crust (Beck and McSween, 2010; McSween et al., 2013, 2011; Mittlefehldt et al., 1998). The mineralogy of diogenites is dominated by orthopyroxenes (from 87% to 99%); all diogenites contain $< 5\%$ chromite and some contain olivine, typically at contents $< 10\%$ (McSween et al., 2011). Eucrites occur as basaltic or cumulate rocks. They are dominated by Ca-poor pyroxenes and plagioclase, with minor amounts of metal, troilite, chromite, ilmenite, and silica (Mayne et al., 2010; McSween et al., 2011). Eucrites are believed to have crystallized as lavas on the surface or within relatively shallow dikes and plutons (McSween et al., 2011). Basaltic eucrites contain Fe-rich pyroxenes, whereas cumulate eucrites are predominantly unbrecciated and their chemistry is similar to basaltic eucrites, but richer in Mg (McSween et al., 2011; Mittlefehldt et al., 1998). Howardites are brecciated achondrites, principally mixtures of eucrite and diogenite clasts, and reflectance spectra of howardites have pyroxene band center positions intermediate between those of eucrites and diogenites (McSween et al., 2011; Mittlefehldt et al., 1998). Impact mixing of eucrite and diogenite has produced the polymict breccias and howardites.

Eucrite, diogenite and howardite lithologies are present on Vesta's surface, as revealed by VIR data (Ammannito et al., 2013a; De Sanctis et al., 2012a) augmented by Dawn Framing Camera images (Reddy et al., 2012b) and Gamma Ray And Neutron Detector data (Lawrence et al., 2013; Prettyman et al., 2014, 2011, 2013). Recently, many papers on the analysis of Vesta's surface composition using Dawn data have been published (e.g., Ammannito et al., 2013a; De Sanctis et al., 2013b; Ruesch et al., 2014; Le Corre et al., 2013; Reddy et al., 2013; Thangjam et al., 2013). The crust of Vesta is dominated by howardite enriched in eucrite (De Sanctis et al., 2012a; 2013b). A few outcrops of diogenite are present in localized areas in the south polar region, corresponding to the rim of the large impact basin Rheasilvia. Large areas of diogenite-enriched howardite have also been identified in the northern hemisphere (longitude 0°–90°E) and are interpreted to consist of Rheasilvia ejecta (Ammannito et al., 2013a; De Sanctis et al., 2012a).

Ammannito et al. (2013a) suggested a high content of olivine (50–80 vol.%) in the area of Bellicia (lat 40°N, lon 40°E) and Arruntia craters (lat 40°N, lon 70°E), highlighting the presence of lithologies different from that of typical HEDs. Others 11 sites containing much smaller amounts of olivine (located up to 39°S latitude) have also been identified by Ruesch et al. (2014), and six other new olivine-rich regions were proposed by Palomba et al. (2015), almost all located at latitudes below 28°N. Dark material units on Vesta were discussed by Jaumann et al. (2012), McCord et al. (2012), Reddy et al. (2012a), and Palomba et al. (2014). Hydrated mineral phases were shown to be correlated with this low-reflectance material (De Sanctis et al., 2012b), confirming that the dark material can be attributed to the presence of a carbonaceous chondrite (CC)-like component delivered by impacts.

1.3. Bright material units: A slice of fresh material

The spectral analysis of the bright material units reveals that they are generally characterized by greater band depths than their surroundings. Most bright units have a howardite rich-eucrite, composition, with some exceptions such as the bright unit called "BU15" in Zambon et al. (2014).

BM units could represent pristine material that has been recently exposed on the surface, and thus contains less carbonaceous-chondrite-like contamination introduced by impact mixing than other areas of Vesta (see Zambon et al., 2014 for more detail). To be consistent with Zambon et al. (2014), we follow the same classification of the BM units, as described by Mittlefehldt et al. (2012). The abbreviation CWM stands for crater wall material, SM means slope material, and RM refers to radial material. The spectral analysis employed in Zambon et al. (2014) to derive Vesta's lithologies is based on selected spectral parameters, namely band center (BC), band depth (BD) and band area ratio (BAR).

The goal of our work is to use linear spectral unmixing to automatically identify the main lithologies of specific regions and determine their semi-quantitative mixing coefficients, including identification and mapping of mineralogical phases other than the spectrally dominant pyroxenes. The mixing coefficients depend on various effects, such as, the grain size, the abundance of the mineralogical phases present in the scene, and the scale at which the components are mixed (i.e., macroscopic vs. intimate; Combe et al., 2008). Since the grain size on Vesta, at the VIR spatial scale, is quite homogeneous (< 25–$45\ \mu\text{m}$) (Hiroi et al., 1994; Palomba et al., 2014; Zambon et al., 2014), we can assume that the grain size does not substantially affect our derived mixing coefficients. Thus the unmixing results principally depend on the abundance of the mineralogical phases and on the type of mixing.

Unmixing methods are useful for understanding the composition of a surface (e.g. Bioucas-Dias et al., 2012; Keshava and Mustard, 2002; Pieters and Englert, 1993). Mixing models can be either linear or non-linear. In the linear case, the spectrum of a region can be considered the area-weighted average of the endmembers present (Bioucas-Dias et al., 2012; Hapke, 2012; Singer and McCord, 1979). The endmembers can be extracted from the scene, or can be reference spectra of plausible analogue phases. The endmembers are generally assumed to represent the different components, which are the fundamental constituents of the scene, so that each pixel in the scene can be modeled as a linear combination of the endmembers (Bioucas-Dias et al., 2012).

The case of non-linear mixing arises when light is scattered by multiple materials in the scene. Scattered light interacts with more than one endmember, and the resulting spectrum is a non-linear combination of the components. Models for non-linear mixing require comprehensive information on the expected minerals, such as scattering coefficients, particle sizes, and optical constants (e.g., Hapke, 1981; Shkuratov et al., 1999). Here we use linear unmixing as a first step in order to derive additional information on the composition of Vesta's surface.

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