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Modal mineralogy of the surface of Vesta: Evidence for ubiquitous olivine and identification of meteorite analogue

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A B S T R A C T

The observations of the surface of 4 Vesta by the Visible and Infrared Mapping Spectrometer (VIR) onboard the Dawn spacecraft reveals that its composition is dominated by pyroxenes with olivine in very localized spots. To derive new constraints on the surface composition of the asteroid, we apply a scattering model to VIR reflectance spectra. The model is first calibrated by performing a non-linear deconvolution of laboratory spectra of mineral mixtures and howardite, eucrite, diogenite (HED) meteorites. Abundance estimates of minerals are accurate to within 15–25% for the analyzed samples, while the estimated particle sizes are within the intervals of actual sizes. Grain size effects complicate spectral deconvolution and estimation of modal abundances of samples (both HED and mineral mixtures) that contain olivine. The magnesium-rich olivine detection threshold is 10–20% for large grain sizes (100s μm) and several 10s% for small grain sizes (<50 μm). Major expected minerals (low-calcium pyroxenes, high-calcium pyroxenes, plagioclase and olivine) can provide satisfactory fits of VIR spectra with excellent residuals $\leqslant$1%. Terrains with the strongest low-calcium pyroxene signatures are well representative of diogenites. The best fits of any unit are obtained by including Fo70 olivine at an abundance level of 10–20%, with an uncertainty of ~10%. Olivine is therefore likely to be ubiquitous over the whole surface of Vesta. Olivine is coarser grained (a few hundred μm) than other minerals such as orthopyroxene and clinopyroxene (grain sizes typically smaller than 100 μm). Both the grain size variance and the modal mineralogy are consistent with the lithologic size and mineral distributions of howardites containing olivine phenocryst-bearing melt. These howardites are the best petrologic analogues of Vesta. Such a surface assemblage could be the result of successive melting and mixing processes due to impacts. The compositional view confirms that Vesta underwent major homogenization processes, resulting in a relatively uniform modal mineralogy and explaining the lack of specific olivine enrichment in the Rheasilvia ejecta.

1. Introduction

Asteroid 4 Vesta is widely considered as a differentiated protoplanetary object (Thomas et al., 1997; Russell et al., 2012), and as the parent body of the howardites, eucrites, diogenites (HED) meteorites (McCord et al., 1970; McSween et al., 2013). The differentiation would have resulted in a core, lower mantle, ultramafic upper mantle/lower crust (diogenite-like composition) capped by a basaltic veneer (eucrite-like composition). Spectral investigations from Earth-based telescopes indicated that the vast majority of the surface of Vesta is a mixture of eucrite and diogenite (howardite-like composition) resulting from impact gardening (e.g., Carry et al., 2010). Recent observations by the Visible and Infrared Mapping Spectrometer (VIR) from the Dawn mission confirm that the VIS-near spectra of Vesta are dominated by pyroxene bands consistent with a surface covered by a howardite-like regolith with varying proportions of eucrite and diogenite (Ammannito et al., 2013a, 2013b). Significant amounts of olivine on the surface were predicted by the petrogenic models and the presence of olivine in some diogenite and howardite meteorites (e.g., Pieters et al., 2011). Surprisingly, olivine has not been firmly detected in the areas corresponding to materials excavated by the impact that formed the Rheasilvia basin. The presence of this mineral has been recently reported as isolated patches in the northeastern hemisphere. Most of these small olivine-rich regions are associated with morphologically fresh areas of a few kms in size, such as crater ejecta or brighter slope material (Ammannito et al., 2013b; Ruesch et al., submitted for publication). It is important to note that olivine is difficult to identify at low concentrations in surface material dominated by pyroxene. This left open some unresolved

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questions about surface variations, which we addressed by modeling of the VIR spectral data.

The spatial distributions, abundances, and particle sizes of mineral phases on Vesta have important petrogenetic implications for the formation and evolution of the vestan mantle and crust. Up to now, empirical studies commonly used for interpreting the VIR spectra suffer from the fact that an impossibly large number of laboratory spectra must be generated to account for all the possible mineral assemblages to be found on Vesta. This limited the information on petrology and quantitative mineralogical composition, which could be derived from VIR measurements. The next step in interpreting VIR data is therefore a quantitative retrieval of mineral abundances from the modeling of spectra of selected terrains exposed on the surface. Deconvolving a near-infrared (NIR) reflectance spectrum to mineral abundance in an unambiguous way is difficult, as observed spectra are complex non-linear functions of several parameters such as grain size, abundance, and type of mixture. This requires a good simulation of multiple scattering in a particulate surface. Several models have been developed by Hapke (1981), Douté and Schmitt (1998) and Shkuratov et al. (1999), which have been used to analyze the surface properties of the Moon, Mars, asteroids and planetary satellites. This approach allows us to extend the analysis of VIR spectra beyond the simple recognition of mineral type, by quantifying their abundances thorough a computational exploration of an extensive space of parameters.

In this paper, we use a non-linear spectral mixing method based on the Shkuratov radiative transfer theory. This model can successfully model NIR spectra of basaltic mixtures of granular materials of a wide range of particle sizes and provide modal mineralogy within the uncertainties of the modeling (vol. 5–15% depending on the minerals) (Poulet and Erard, 2004). However, these previous tests were performed on laboratory mixtures that did not well represent the vestan composition, in particular its very diverse pyroxene compositions. Questions and uncertainties thus arise in applying such a modeling approach to complex mixtures of pyroxenes and olivines as revealed by the HED modal mineralogy and to the Vesta spectra because of a lack of textural, space weathering and complete mineralogical data. A validation of the selected modeling approach on a representative sample of spectra including laboratory and HED spectra is therefore required.

A proxy of the compositional diversity of the surface of Vesta is provided by the HED meteorites. They contain a variety of pyroxenes, including orthopyroxenes, low-calcium clinopyroxenes (i.e., pigeonites), and high-calcium clinopyroxenes (Mittlefehldt et al., 1998). Almost all the diogenite rocks are orthopyroxenites, mainly composed of magnesian orthopyroxene crystals, with minor chromite, silica, troilite, metal, and occasionally diopside and plagioclase (Mittlefehldt, 1994). A few olivine-diogenites (also called harzburgites) display significant amount of olivine (up to $\sim$25 vol.%, Beck and McSween, 2010) and are seen as possible mantle lithologies (Sack et al., 1991). It is now widely accepted that all these rocks, including the olivine-diogenites, are cumulates formed at depth (Mittlefehldt, 1994, 2000; Fowler et al., 1995; Barrat, 2004; Barrat et al., 2008; Shearer et al., 2010), while a few samples formed more likely within shallow intrusions (Barrat et al., 2010). Eucrites are mixtures of low- and high-calcium pyroxenes, and abundant plagioclase. Howardites are fragmental and regolith breccias that primarily consist of eucrite and diogenite crystal fragments and clasts. In addition to the silicate variety, localized dark materials were recently found on Vesta's surface, and interpreted to be infall of hydrated carbonaceous material (McCord et al., 2012; Reddy et al., 2012; Prettyman et al., 2012).

After a short description of the modeling technique (Section 2), we evaluate the performance of the modeling of tens of laboratory spectra including those of HED meteorites (Section 3). The deconvolved primary mineralogies are compared to laboratory-measured modal mineralogy to attempt to provide uncertainties on the inferred modal mineralogy and grain size. A specific effort is dedicated to evaluate the detection threshold of olivine in mixtures. On the basis of these applications, the second major objective of this work is to apply the modeling technique to VIR data: (1) inferring the modal mineralogy of selected terrains of Vesta, (2) clarifying the mineral distributions previously identified in various studies based on VIR, (3) identifying possible relationship with the diverse compositions of HEDs.

2. Modeling technique

2.1. Description

Shkuratov et al. (1999) presented an algorithm to derive a non-linear deconvolution of visible and near-infrared reflectance spectra of a particulate sample in the geometric optics framework. This technique, used here, requires four inputs: a spectrum to be modeled, a set of optical constants of minerals, a set of initial conditions for abundances and grain sizes of each mineral and the wavelength range over which to perform the fit. Outputs of a fit are a best fit spectrum, the abundance and the grain size for each mineral used in the best fit model. A root-mean-square (RMS) error value, which is the average error over the entire spectral range, is also calculated to provide an indicator of the quantity of the fit. The RMS value can be used to compare best fits of a given spectrum for various inputs (mineral end-member). The abundances are reported as vol.%, and the fit optimization using a simplex minimization algorithm is performed under the constraint that the sum of the fractions of various minerals be equal to 1.

The Shkuratov model can simulate several types of mixtures (Shkuratov et al., 1999; Poulet and Erard, 2004). The spectra of mineral mixtures and HEDs studied here correspond to granular samples with grain size smaller than 45 μm. Although only preliminary results exist on the texture of the Vesta surface (Hiroi et al., 1994; Capria et al., 2014), the thermal inertia seems to be consistent with pretty fine-sized particles (<10s μm). One specific mixture can be therefore considered: intimate, also commonly called "salt-and-pepper" mixture in which the single scattering albedo is calculated for each component grain and then averaged. A final remark regards to the spectral range over which the fit will be performed. While the VIR/Dawn and laboratory data cover the visible/NIR wavelength range (up to $\sim$2.5 μm), the modeling approach is applied only to the NIR wavelength range (typically from 0.90 to 2.5 μm). The visible part is usually more sensitive to space weathering effects than the NIR range, which are difficult to simulate by a intimate mixture. Although more complex mixtures (such as intra-mixture) could be considered (e.g., Poulet et al., 2009), the implementation of such mixtures increases the complexity of the deconvolution technique at the cost of the computation time and number of parameters. The NIR spectral range is still large enough to encompass the strong and distinct signatures of the major components of Vesta. Finally, one additional free parameter was considered to adjust the continuum spectral slope, whose variations from one spectrum to another one could be due to space weathering effects and/or photometric effects. However, it was found that this parameter was not required and did not improve the quality of the fit.

2.2. End-member selection

The approach used in this study is fully described in Poulet and Erard (2004) and Poulet et al. (2009). Briefly stated, the modeling technique uses a priori choice of end-members known or assumed to be present in the analyzed sample or terrain. We select potential