Optical space weathering on Vesta: Radiative-transfer models and *Dawn* observations

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**A R T I C L E  I N F O**

Article history:
Received 3 June 2015
Revised 3 October 2015
Accepted 10 October 2015
Available online 23 October 2015

Keywords:
Asteroid Vesta
Asteroids, composition
Asteroids, surfaces
Geological processes
Spectroscopy

**A B S T R A C T**

Exposure to ion and micrometeoroid bombardment in the space environment causes physical and chemical changes in the surface of an airless planetary body. These changes, called space weathering, can strongly influence a surface’s optical characteristics, and hence complicate interpretation of composition from reflectance spectroscopy. Prior work using data from the *Dawn* spacecraft (Pieters, C.M. et al. [2012]. Nature 491, 79–82) found that accumulation of nanophase metallic iron (npFe0), which is a key space-weathering product on the Moon, does not appear to be important on Vesta, and instead regolith evolution is dominated by mixing with carbonaceous chondrite (CC) material delivered by impacts.

In order to gain further insight into the nature of space weathering on Vesta, we constructed model reflectance spectra using Hapke’s radiative-transfer theory and used them as an aid to understanding multispectral observations obtained by *Dawn*’s Framing Cameras (FC). The model spectra, for a howardite mineral assemblage, include both the effects of npFe0 and that of a mixed CC component. We found that a plot of the 438-nm/555-nm ratio vs. the 555-nm reflectance for the model spectra helps to separate the effects of lunar-style space weathering (LSSW) from those of CC-mixing. We then constructed ratio–reflectance pixel scatterplots using FC images for four areas of contrasting composition: a eucritic area at Vibidia crater, a diogenitic area near Antonia crater, olivine-bearing material within Bellicia crater, and a light mantle unit (referred to as an “orange patch” in some previous studies, based on steep spectral slope in the visible) northeast of Oppia crater. In these four cases the observed spectral trends are those expected from CC-mixing, with no evidence for weathering dominated by production of npFe0. In order to survey a wider range of surfaces, we also defined a spectral parameter that is a function of the change in 438-nm/555-nm ratio and the 555-nm reflectance between fresh and mature surfaces, permitting the spectral change to be classified as LSSW-like or CC-mixing-like. When applied to 21 fresh and mature FC spectral pairs, it was found that none have changes consistent with LSSW.

We discuss Vesta’s lack of LSSW in relation to the possible agents of space weathering, the effects of physical and compositional differences among asteroid surfaces, and the possible role of magnetic shielding from the solar wind.

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1. Introduction

1.1. Space weathering: Lunar style and a variety of asteroid styles

Space weathering is the name given to the optical, chemical and physical changes that occur when the surface of an airless plane-
tary body is exposed to the space environment. Regolith or soil that has accumulated more of these changes is said to be “more mature.” In the case of the Moon, the returned rock and soil samples and extensive remote sensing data have permitted a reasonably good understanding of space weathering to be developed. Space weathering has strong effects on the optical properties of the lunar regolith. Compared to the spectrum of a freshly powdered lunar rock, a mature lunar soil has a steeper (“redder”) positive continuum slope, reduced overall reflectance, and greatly muted mineralogical absorption bands (e.g., Fischer and Pieters, 1994).

The changes seen in lunar materials are caused by micrometer-to-nanometer-sized blebs and coatings of iron metal on and within regolith grains, produced by reduction of ferrous iron in silicates and vapor deposition during solar-wind ion sputtering and/or micrometeoroid bombardment (Hapke et al., 1975; Pieters et al., 2000; Hapke, 2001). The nanophase metal produced by space weathering is sometimes referred to as npFe0. The relative importance of ion bombardment vs. micrometeoroid bombardment in producing npFe0 is uncertain. The soil maturation trend on the planet Mercury is consistent with accumulation of npFe0, with fresher material being brighter and less red than mature material (Robinson and Lucey, 1997; Robinson and Taylor, 2001; Blewett et al., 2007, 2009; Robinson et al., 2008; Lucey and Riner, 2011). Thus, Mercury appears to undergo lunar-style space weathering (LSWW).

Asteroids, on the other hand, exhibit different styles of space weathering that contrast with that found on the Moon (e.g., Gaffey, 2010). The influence of space weathering on asteroid spectra has long been debated, and figures prominently in the history of the “S-astroid/ordinary chondrite conundrum” (e.g., Bell et al., 1989; Hapke, 2001; Chapman, 2004). The essence of the conundrum is the mismatch between spectra of the most common asteroid type in the inner Main Belt (S-types) and spectra of the most common meteorite type that falls on Earth (ordinary chondrites, OCs). It now appears that lunar-style space weathering can modify OC material to produce an S-type spectrum (e.g., Hapke, 2001). Note that phase-angle effects cause an increase in spectral slope that can mimic the effects of increased space weathering (Sanchez et al., 2012 and references therein). Recent reviews of space weathering that discuss asteroids include Clark et al. (2002), Chapman (2004), Brunetto (2009), Bennett et al. (2013), and Domingue et al. (2014).

Eros (a near-Earth S-type asteroid, ~33 km long) has large variations in reflectance that are consistent with material becoming darker with age. The NEAR spacecraft found that brighter material is exposed on slopes, and accumulations of regolith at the bottom of slopes are darker (Veverka et al., 2000; Murchie et al., 2002). However, these reflectance variations are not correlated with strong changes in color ratios or the strength of the mafic mineral absorption band near 1 μm. The Main Belt S-type Asteroid 243 Ida (~31 km mean diameter) was visited by Galileo and has a surface with color and band depth variations, but very little range in reflectance (Heftenstein et al., 1994; Veverka et al., 1996). Gaspra (mean diameter ~12 km), another Main Belt S-type encountered by Galileo, has color variations such that more mature surfaces have steeper spectral slopes and weaker 1-μm bands.

Asteroid 25143 Itokawa is a sub-kilometer near-Earth S-type asteroid that was extensively investigated by the Hayabusa spacecraft. Itokawa exhibits color and albedo variations analogous to those on Ida (Ishiguro et al., 2007), though with greater contrasts than on Ida. Among the dust-sized samples of Itokawa material returned by Hayabusa are particles that have alteration rims containing nanophase grains rich in iron and sulfur (Noguchi et al., 2011, 2014) and other characteristics that are interpreted to “strongly suggest that solar wind irradiation damage and implantation are the major causes of surface modification and space weathering on Itokawa” (Noguchi et al., 2014). Thus, there is reasonably strong evidence that accumulation of nanophase particles is at least in part responsible for the optical changes related to space weathering of S-type asteroids (both near-Earth and Main Belt), and that the solar wind is a key contributor to the weathering.

Vesta is a large (~525 km diameter) Main Belt asteroid with a surface dominated by basaltic material. Vestan samples have long been available for study, in the form of the howardite–eucrite–dio genite (HED) meteorites (e.g., McSween et al. (2013) and references therein). As noted by Pieters et al. (2000), the ferrous iron content of the minerals in HED meteorites is similar to that of lunar mare basalts; hence there should be the same availability of iron for reduction by space weathering and production of npFe0 on Vesta. However, a longstanding puzzle regarding the spectrum of Vesta is why it resembles that of fresh material (powdered HED meteorites) (McCord et al., 1970), whereas spectra of small Vesta-family objects (spectral type V, also called “Vestoids”) are substantially reddened (Burbine et al., 2001). The timescale for optical alteration of Vesta by solar-wind ion bombardment is estimated to be very short (~10^5 yr, Vettrenza et al., 2006), so Vesta’s relatively fresh-appearing spectrum is unexpected. One possibility (Burbine et al., 2001) is that grain-size differences lead to the more reddened spectrum of the Vestoids (with Vestoids having finer-grained surfaces than Vesta). It has also been suggested that Vesta may have a magnetic field that provides shielding from the solar wind (Vettrenza et al., 2006; Starukhina and McCord, 2012; Fu et al., 2012).

It has been shown that Vesta’s absorption bands are somewhat weaker than those of typical HEDs measured in the laboratory (Hiroy, 1994; Pieters et al., 2011). In addition, the visible spectral slopes of V-types are systematically redder than laboratory spectra of HEDs, similar to the relationship between the spectra of S-types and ordinary chondrite meteorites (e.g., Marchi et al., 2010). However, an important difference between V-types and S-types can be noted. The spectral slope of V-type asteroids decreases with increasing exposure time, where the exposure time is a function of an object’s orbital elements and collisional age (Marchi et al., 2010). This means that the more-exposed V-type objects tend to be bluer, on average, than less-exposed ones. Thus there are a number of open questions related to the nature of space weathering on basaltic asteroids in general and on Vesta in particular.

The Dawn spacecraft orbited Vesta for over one Earth year (Russell et al., 2012). Data collected with the Framing Camera (FC, Sierks et al., 2011) multiband imagers and Visual and Infrared (VIR, De Sanctis et al., 2011) imaging spectrometer have permitted a detailed first look at Vesta’s space weathering processes. The result (Pieters et al., 2012) is that two types of mixing dominate regolith evolution on Vesta. The first type is mixing between eucrite-dominated terrains and more diogenitic materials. The second, more surprising, finding is mixing of exogenic matter possessing spectral and compositional characteristics like that of carbonaceous chondrite (CC) meteorites. Carbonaceous chondrite material is generally of low reflectance, with a flat (shallow) spectral slope from the visible to the near-infrared (e.g., Cloutis et al., 2011a, 2011b, 2012a, 2012b). Hence, the addition of CC-like material as the vestan surface ages causes the reflectance to drop and weakens the prominent pyroxene absorption bands near 1 and 2 μm, without a detectable increase in spectral slope (documented by Reddy et al. (2012a), McCord et al. (2012) and Palomba et al. (2014) using data from Dawn). Vesta’s style of space weathering can thus be described as “darkening, with weakening of absorption bands, but without reddening”. It appears that production of npFe0, which would substantially redder the spectrum, is extremely limited or non-existent on Vesta (Pieters et al., 2012; Blewett
et al., 2013a). The apparent lack of npFe⁰ production on Vesta is in contrast to the situation with Main Belt S-type asteroids, which in general are found to rapidly redden in response to solar-wind exposure (Vernazza et al., 2009). One factor that might explain the difference between Vesta and Main-Belt S-types is that olivine may have a greater susceptibility to space weathering than does pyroxene (e.g., Sasaki et al., 2002, 2003; Vernazza et al., 2006; Loeffler et al., 2009). Thus space weathering could be more efficient on the S-types (Vernazza et al., 2009), which are dominated by olivine and pyroxene, contrasting with the plagioclase–pyroxene assemblage of vestan basalts. Space weathering of the mineral troilite (FeS), which is more abundant in OCs than in HEDs, could also factor into differing space-weathering outcomes.

The Dawn results for space weathering on Vesta give a new appreciation for the role that mixing of foreign material can play in altering the surfaces of asteroids. On the list of factors that influence the type of space weathering exhibited on a given body, exogenous mixing is now included with a body's composition and its location in the Solar System. The location (e.g., near Earth vs. Main Belt), determines the average flux and velocity of impactors (micro and macro) and the solar wind flux. For example, the solar wind and micrometeoroid environments at the Moon and at Vesta's location in the Main Belt are quite different (Matson et al., 1977): The solar wind flux at Vesta is <0.2 of the flux at the Moon (though the average solar wind particles is about the same), whereas the micrometeoroid impact rate is similar to that at the Moon (but the average impact energy of the impacts is ~10% of that at the Moon).

The goals of this paper are to: (A) Explore the effects of LSSW in the presence of CC-mixing, using radiative-transfer model spectra for howardite mineral mixtures. This will help to evaluate the extent to which the presence of low-reflectance material on Vesta could be masking the effects of LSSW. (B) Carry out a survey of the optical effects of space weathering in a wide range of Vesta terrains of contrasting composition. We employ FC multiband image mosaics to provide high spatial resolution, and use spectral parameters as indicators of space weathering style.

2. Data

Dawn FC image data obtained through seven color filters (central wavelengths of 438, 555, 653, 749, 829, 917, and 965 nm) cover nearly the whole surface of Vesta (Russell and Raymond, 2011; Russell et al., 2012), with the exception of areas near the north pole that were not illuminated. Multiband image mosaics were constructed for the 15 Vesta quadrangles defined by Roatsch et al. (2012), sampled at 60 m/pixel. The image data underwent radiometric calibration, stray light correction, and photometric normalization using a digital terrain model (Gaskell, 2012) as described in a series of papers by Schröder et al. (2013a, 2013b, 2014).

3. Radiative-transfer modeling of space weathering on Vesta

As discussed in Section 1, there are questions related to the contrasting optical responses of S-type and V-type asteroids to the space weathering environment, and the extent to which LSSW (accumulation of npFe⁰) takes place on these objects. Reddy et al. (2012a) estimate that the average content of CC-like material on Vesta’s surface is as great as 6%, while some areas rich in dark material could contain 50% CC-like material. These values are consistent with the abundance of CC clasts in HED meteorites (Zolensky et al., 1996; Herrin et al., 2011). In order to assess the extent to which LSSW on Vesta could be masked by the presence of a low-reflectance, CC-like component we constructed model reflectance spectra for a howardite mineral assemblage based upon the radiative-transfer theory of Hapke (1981, 2012). Varying degrees of LSSW were included via the Hapke (2001) model for the spectral effects of npFe⁰. We added a CC component to the spectral mixing models by using a spectrum of the Murchison meteorite.

The details of the spectral modeling are as follows. We employ computer code for the Hapke radiative-transfer intimate-mixing model as implemented by Lawrence and Lucey (2007). The code performs forward modeling, i.e., given a set of modal abundances (for silicate minerals, glass, opaques, and macroscopic metal), the average particle size, the Mg number (Mg#, 100 × the ratio of molar MgO/[MgO + FeO]) and the npFe⁰ abundance, it calculates the bidirectional reflectance at a particular set of illumination, emergence, and phase angles. Our models used the standard photometric geometry of 30° incidence, 0° emergence, 30° phase. To represent typical Vesta surface material, we constructed a mineral assemblage representative of howardite meteorites: 54.7% orthopyroxene, 15.4% clinopyroxene, 29.9% plagioclase, with Mg# = 78, and particle size = 40 μm. The abundances of npFe⁰ modeled were zero, 0.1, 0.7, 1.0 and 5.0 parts per thousand by weight (ppt). Note that the model of Hapke (2001) does not explicitly include the size of the npFe⁰ as a parameter. It was developed for metal particles that are much smaller than the wavelength of the light. As discussed by Lucey and Noble (2008) and Lucey and Riner (2011), the Hapke (2001) model treats npFe⁰ that is in the “small” range (<~50 nm), responsible for both darkening and reddening effects.

The model requires optical constants for the phases in the mixture. Optical constants for pyroxenes are those of Lucey (1998), and those for plagioclase are from Lawrence and Lucey (2007). We employ the iron metal optical constants presented by Cahill et al. (2012). To represent the CC component, we selected a laboratory spectrum for the Murchison carbonaceous chondrite (RELAB spectrum MB-TXH-064/C2MB64, <125 μm particle size). In order to include the Murchison CC component in the model, the spectrum was converted to single-scattering albedo using Hapke’s equations. Models were run with zero, 1%, 3% and 5% content (by weight) of this CC component, both with and without the five levels of npFe⁰ abundance mentioned above.

Model spectra demonstrating the effects of increasing abundances of npFe⁰ are shown in Fig. 1. For comparison, the plot also includes a laboratory spectrum of the Le Teilleul howardite (RELAB spectrum MP-TXH-093-A/CAMP93, <25 μm size fraction). We emphasize that the purpose of these models is not to obtain high-fidelity fits to spectra of HEDs or Vesta (in fact, no fitting was performed), but rather to illustrate the spectral trends that would be predicted for lunar-style space weathering of HED material. The spectra in Fig. 1 exhibit the expected progression associated with LSSW: with increasing npFe⁰, the reflectance decreases, spectra become redder, and the contrast in the pyroxene absorption bands centered near 1 and 2 μm is greatly diminished. Table 1 lists spectral parameters for the model spectra. The 438-nm/555-nm reflectance ratio gauges the spectral slope in the visible part of the spectrum. The 1310-nm/710-nm reflectance ratio is a measure of the near-IR continuum slope. The depth of the mafic absorption band near 1000 nm was measured by fitting a continuum line at 1310 nm and 710 nm, dividing the spectrum by the continuum, and measuring the depth of the band at 910 nm.

Our model spectra for howardite material mixed with a CC component in the absence of LSSW are presented in Fig. 2. The spectral effects of CC mixing on the howardite are similar to those of LSSW in two respects: as the CC content increases, the overall reflectance decreases and the absorption bands become shallower. This progression is also seen in spectra of physical mixtures of HED material with CC material (Cloutis et al., 2013). However, unlike
Figure 1. Bidirectional reflectance spectra computed with Hapke's model illustrating the effects of npFe on a generic howardite mineral assemblage. As the abundance of npFe (labeled in ppt by weight) increases, the overall reflectance decreases, the spectral slope in the visible and the near-infrared increases ("reddens"), and the pyroxene absorption bands centered near 1 and 2 μm become shallower. The thin black line is a laboratory spectrum of the Le Teilleul howardite (RELAB spectrum MF-TXH-093-A/CAMP93). The mismatch in the 2-μm region is related to the limitations of available optical constants for pyroxene and does not affect the interpretations presented here, which involve wavelengths < ~1 μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to help understand the character of model spectra that contain both LSSW and a CC component, we examined several spectral parameters. The ratio of reflectance at a wavelength near the center of the 1-μm pyroxene band to one on the shoulder can provide a proxy for the depth of the band; such a ratio is also a function of the near-infrared continuum slope. The reflectance at a reference wavelength gauges the extent to which space weathering or compositional mixing affects the absolute reflectance of a mixture. Plots of spectral ratios vs. reflectance at a reference wave- 

depth of the band at 910 nm.

The 555-nm filter was employed as the reference reflectance. The 438-nm/555-nm ratio, a measure of the spectral slope in the visible, is sensitive to the reddening effects of npFe and the neutral/opposite effect on the visible spectral slope caused by mixture of CC material with howardite. The plot shows that LSSW and CC mixing lead to differing trajectories in this spectral space: increasing npFe abundance drives spectra toward the lower left portion of the diagram, while an increasing CC component moves material to the upper right.

A view of the observed global spectral character of Vesta and the Moon is provided by the two-dimensional histograms shown in Figure 5. The plot in Figure 5a was produced from a Vesta FC mosaic, trimmed to latitudes 50°N to 70°S to eliminate shadowing and extreme illumination geometries. The lunar plot (Figure 5b) was constructed from Galileo mosaics of the lunar nearside (Belton et al., 1994). The Moon’s compositional dichotomy causes the lunar plot to have two modes, maria and highlands. Vesta’s plot is unimodal, a result of Vesta’s dominantly basaltic surface.

The systematics revealed by the model spectra and the observed visible ratio–reflectance plots for Vesta are analogous to the case of varying ilmenite abundance on the Moon. Ilmenite is a mineral with low reflectance and a relatively flat, mostly featureless spectrum. Lucey et al. (1996, 1998, 2000a) and Blewett et al. (1997) recognized two trends in a lunar visible ratio–reflectance diagram such as Figure 5b: one trend toward the upper left, primarily related to variations in ilmenite abundance in the maria, and another trend toward the lower left that is caused by a combination of maturity variation (i.e., npFe abundance) and variations in the ferrous iron content of the silicates (mostly in the highlands). Hence Vesta’s regolith and the lunar maria can both be thought of as mixtures of basalt with a spectrally neutral, dark, opaque phase (CC material on Vesta and ilmenite on the Moon). Lucey developed a spectral parameter based on the visible ratio–reflectance diagram that is highly correlated with ilmenite abundance and hence TiO2 content (Lucey et al., 1998, 2000a). A complementary parameter is a measure of optical maturity. Although beyond the scope of this paper, a similar approach might permit a CC-abundance and/or an optical maturity parameter to be devised for Vesta. Later in this paper (Section 5), we discuss a simpler parameter in visible ratio–reflectance space, designed to classify the spectral changes associated with regolith maturation in a way that discriminates between LSSW and CC mixing.
4. Examination of spectral behavior related to local maturity and composition

Vesta’s global spectral character as observed by FC (Fig. 5a) is consistent with higher reflectance surfaces tending to have lower 438-nm/555-nm ratio, and areas of lower reflectance have higher ratios. However, it is of interest to examine local spectral behavior to determine if departures from the global trend exist. Any such departures could be the result of unusual compositions, lunar-style space weathering, or other factors. In particular, we search for any differences that could be attributed to (a) variations in mineralogy (i.e., more eucritic vs. more diogenitic material), or (b) the presence of mineralogy that departs from Vesta’s global spectral character as observed by FC (Fig. 5a).

To explore the spectral transition from the fresh, high-reflectance Vibia ejecta to the nearby mature background, an image region of interest (ROI) was defined. This ROI, shown in a location dominated by eucritic material. Areas of differing mineralogy are generally basaltic character. Areas of differing mineralogy are

Any such departures could be the result of unusual compositions, lunar-style space weathering, or other factors. In particular, we search for any differences that could be attributed to (a) variations in mineralogy (i.e., more eucritic vs. more diogenitic material), or (b) the presence of mineralogy that departs from Vesta’s generally basaltic character. Areas of differing mineralogy are interesting because of the apparent greater susceptibilities of olivine to LSSW (see Section 1). Olivine has been identified in localized areas within Vesta’s eastern hemisphere using both VIR (Ammannito et al., 2013b; Ruesch et al., 2014b) and FC (Thangjam et al., 2014), although an alternative to the olivine interpretation involves mixtures of low- and high-Ca pyroxene (Combe et al., 2015). Olivine could be more widespread on Vesta but difficult to detect at lower abundances in mixtures with pyroxene (Beck et al., 2013; Poulet et al., 2015). In this section we analyze visible ratio–reflectance plots for small regions of interest (ROIs) for a range of vestan terrains. The ROIs discussed in this paper were drawn with careful reference to ratio images so that seams between image sets could be avoided. By confining the ROIs to within a single image set, spectral variations or offsets caused by imperfect photometric normalization or residual stray-light effects do not influence the relative distribution of pixels in the ratio–reflectance plots. In addition, the locations of ROIs were chosen to the extent possible, to be on areas of minimal topographical slopes. This was accomplished with the use of digital terrain models and slope maps derived from stereophotoclinometry (Gaskell, 2012).

4.1. A eucritic area near Vibidia crater

Vibia is rayed crater of ~8 km diameter (Fig. 6), located in Vesta’s Av-13 (Tuccia) quadrangle (Roatsch et al., 2012). A geologic map of the Tuccia quadrangle was presented by Kneissl et al. (2014), and a detailed study of the spectral properties as determined with VIR data was done by Zambon et al. (2015). Vibidia formed in Vestalia Terra, a plateau that may represent an ancient piece of the vestan crust (Buczkowski et al., 2014). The lithologic map of Ammannito et al. (2013a) indicates that Vibidia is found in a location dominated by eucritic material. To explore the spectral transition from the fresh, high-reflectance Vibia ejecta to the nearby mature background, an image region of interest (ROI) was defined. This ROI, shown in Fig. 6, represents a traverse from near the crater rim, across the continuous fresh ejecta and crater ray material, and into the mature surroundings. The pixels in the ROI were used to make a

Fig. 2. Bidirectional reflectance spectra computed with Hapke’s model illustrating the effects of a CC component on a howardite mineral assemblage containing no npFe0. As the abundance of CC increases (curves labeled in wt.% CC), the overall reflectance decreases and the pyroxene absorption bands centered near 1 and 2 μm become shallower. However, the presence of increasing amounts of CC causes little change in the spectral slope in the visible or near-infrared. The black line is the laboratory spectrum of the Murchison carbonaceous chondrite (RELAB spectrum MB-TXH-084/C2MB64) used as the CC component in the model spectra.

Fig. 3. Near-infrared ratio–reflectance plot for model spectra computed to explore the combined effects of LSSW and CC mixing on the spectral characteristics of howardite material. The 917-nm/749-nm reflectance ratio is a measure of the depth of the 1-μm (1000-nm) pyroxene band, with higher ratios corresponding to weaker bands. For each of the four CC mixture contents (0, 1, 3, and 5 wt.%), points are plotted for five abundances of npFe0: 0, 0.1, 0.7, 1.0 and 5.0 ppt by weight. Increasing LSSW (greater npFe0 content) causes lower reflectance and lower ratio. Greater mixing with CC material produces lower reflectance but increases in the ratio. Compare with the near-infrared ratio–reflectance plot in Fig. 3.

Fig. 4. Visible ratio–reflectance plot for model spectra computed to explore the combined effects of LSSW and CC mixing on the spectral characteristics of howardite material. The 438-nm/555-nm reflectance ratio is a measure of the spectral slope in the visible portion of the spectrum, with lower values corresponding to steeper (“redder”) slopes. For each of the four CC mixture contents (0, 1, 3, and 5 wt.%), points are plotted for five abundances of npFe0: 0, 0.1, 0.7, 1.0 and 5.0 ppt by weight. Increasing LSSW (greater npFe0 content) causes lower reflectance and lower ratio. Greater mixing with CC material produces lower reflectance but increases in the ratio. Compare with the visible ratio–reflectance plot in Fig. 4.

Fig. 5a. Map of the Tuccia quadrangle was presented by Kneissl et al. (2014), and a detailed study of the spectral properties as determined with VIR data was done by Zambon et al. (2015). Vibidia formed in Vestalia Terra, a plateau that may represent an ancient piece of the vestan crust (Buczkowski et al., 2014). The lithologic map of Ammannito et al. (2013a) indicates that Vibidia is found in a location dominated by eucritic material. To explore the spectral transition from the fresh, high-reflectance Vibia ejecta to the nearby mature background, an image region of interest (ROI) was defined. This ROI, shown in Fig. 6, represents a traverse from near the crater rim, across the continuous fresh ejecta and crater ray material, and into the mature surroundings. The pixels in the ROI were used to make a
behavior is that expected when dark material with a flatter spectral slope is mixed with the fresh crater ejecta, as indicated by the model spectra of Fig. 4. If lunar-style space weathering dominated, the cloud of pixels for the mature area would plot to the lower left of the bright ejecta in Fig. 7, but this is not observed.

4.2. A diogenitic area near Antonia crater

Antonia crater (diameter ~15 km) formed in the southern part of Vesta’s Tuccia quadrangle in an area mapped as Rheasilvia ridge-and-groove material (Kneissl et al., 2014). The mineralogy of the area is some of the most diogenitic on Vesta, as determined by VIR band parameter analysis (Ammannito et al., 2013a). Antonia (Fig. 8a) is a prime example of the “asymmetric” craters that are common on Vesta, ascribed to formation on steep topography. Asymmetric craters have a sharp upslope rim, with loose material covering the downslope rim (e.g., Krohn et al., 2014). Low-reflectance “dark crater material” (Kneissl et al., 2014) is found on and adjacent to Antonia’s southern and eastern rim; the apparent low reflectance of this material may in part result from phase-angle effects (Schröder et al., 2013b).

Ratios of FC images obtained through color filters that sample different portions of the 1-μm mafic mineral absorption band can be used to distinguish between surfaces dominated by eucritic/howarditic material and those richer in diogenite. As discussed by Le Corre et al. (2011), the center of the band in eucrites is at longer wavelengths than in diogenites, with howardites having intermediate band centers. Therefore, the FC 917- and 965-nm filters may be used to discriminate between surfaces that are more eucritic and those that are more diogenitic. Fig. 8b shows a ratio of 917-nm/965-nm; diogenitic material has lower ratio values. Aided by the 917-nm/965-nm image, we defined an image ROI...
on the north rim of the crater, along with spectral end-member locations as indicated in Fig. 8a.

The visible ratio–reflectance plot for the Antonia ROI is shown in Fig. 9. The pixel cloud is approximately bounded by freshly exposed howardite, more mature background howardite, and more mature background diogenite. The freshest diogenite in the scene does not occur within the ROI, but is represented by the ejecta of a small, bright crater to the southeast of Antonia (Fig. 8a). For both diogenite and howardite, the evolution from fresh to mature moves material to the upper left in the diagram (toward lower reflectance, higher 438-nm/555-nm ratio). Thus, similar to the situation at Vibidia (Section 4.1), it appears that the spectral changes associated with aging of the surface at this location are consistent with addition of a CC component.

4.3. Olivine at Bellicia crater

In HED meteorites, abundant olivine is found mostly in diogenites (e.g., Beck et al., 2011), although diogenites with substantial olivine contents are rare (e.g., Thangjam et al., 2014). On Vesta’s surface however, the restricted locations where olivine has been detected are generally in howarditic terrain (Ammannito et al., 2013a, 2013b). As suggested by laboratory laser-pulse simulations (Sasaki et al., 2002), olivine is a more efficient source of npFe⁰ when subjected to micrometeoroid bombardment. Laboratory ion bombardment experiments, simulating the solar wind, have also produced npFe⁰-rich coatings on olivine (Loeffler et al., 2009).

Fig. 7. Ratio–reflectance two-dimensional histogram for pixels in the ROI to the southwest of Vibidia crater (see Fig. 6). The data cloud is coded such that locations with greater numbers of pixels appear in brighter tones. The two squares marked with arrows indicate the spectral coordinates of the endmember bright ejecta and mature background locations shown in Fig. 6. The spectral relationships exhibited here are consistent with the presence of CC material in the mature background.

Fig. 8a. The area near Antonia crater, with FC images taken through 749-, 555-, and 438-nm displayed as RGB. The black box outlines the ROI for which the ratio–reflectance plot in Fig. 9 was constructed. The ROI contains 62,621 pixels. Endmember spectra were extracted for 5 × 5 pixel boxes centered on the tips of the arrows. “D” indicates a diogenite-rich area, area “H” is more howarditic. “FH” and “MH” indicate fresh and mature howardite endmember locations, respectively. “FD” and “MD” are fresh and mature diogenite. The image is a piece of the Vesta Av-13 quad mosaic (Roatsch et al., 2012), which is in Lambert conformal conic projection. The center of the image is at −57.7°S, 158.4°W. North is toward the top.

Fig. 8b. Ratio image 917-nm/965-nm for the same area as 8a. The image is stretched from 0.90 to 0.99 as shown in the greyscale legend. Darker tones correspond to lower ratio values and indicate the shorter-wavelength band centers characteristic of diogenite material.

Fig. 9. Ratio–reflectance two-dimensional histogram for pixels in the ROI adjacent to the north rim of Antonia crater (see Fig. 8). The data cloud is coded such that locations with greater numbers of pixels appear in brighter tones. The squares marked with arrows indicate the spectral coordinates of the endmember locations shown in Fig. 8a. The systematics here are characterized by three-component mixing between howardite, diogenite and the CC component. For both howardite and diogenite, the maturation trajectory is toward the upper left (lower reflectance, higher ratio), consistent with an increasing CC content.
Therefore it is plausible that olivine-rich lithologies on Vesta could exhibit a space-weathering trend that differs from that of Vesta’s dominant plagioclase–pyroxene mineralogy. In order to explore this possibility, we examine FC images for the northern part of Bellicia crater (Fig. 10a). Bellicia (42-km diameter) is the eponym of Vesta’s quadrangle Av-2, which was mapped by Ruesch et al. (2014a). The crater exterior, extending from the rim to a distance of approximately one crater radius, is mapped as “undifferentiated crater material”; the majority of the area of the crater interior walls is also mapped as this unit. Small outcrops high on the wall consist of “bright crater material”, interpreted as fresh, unweathered material. Parts of the floor are occupied by “lobate crater material”, mass-wasted accumulations from topographically higher locations. The lithological map of the area, as determined by VIR band parameters, indicates that howarditic material dominates the surface (Ammannito et al., 2013a).

Olivine has been detected at several of the bright northern wall outcrops (Ammannito et al., 2013b; Thangjam et al., 2014; Ruesch et al., 2014b). The distinctive spectral character associated with olivine in the dominantly howarditic surroundings is highlighted by the 917-nm/965-nm ratio image in Fig. 10b. The long-wavelength center of the olivine 1-μm band produces a high value of the 917-nm/965-nm ratio, and the presence of olivine is confirmed by consideration of the full spectral character with VIR and FC data (Ammannito et al., 2013b; Thangjam et al., 2014; Ruesch et al., 2014b). As expected, the 917-nm/965-nm ratio values for olivine shown in Fig. 10b are greater than those of the howarditic materials, consistent with the analysis of laboratory spectra for HEDs and olivine-bearing materials described by Le Corre et al. (2011).

An image ROI was drawn to sample the spectral character of the fresh olivine-bearing outcrop and the more weathered material derived from mass wasting, as shown in Fig. 10a. A visible ratio–reflectance plot for the ROI is presented in Fig. 11. The relationships exhibited in Fig. 11 can be explained by compositional mixing between the olivine-rich end-member and more howarditic floor material, with additional influence from addition of a CC component. There is no obvious evolution of the surface toward a darker, redder (lower 438-nm/555-nm ratio) state as would be predicted if enhanced npFeO production were occurring because of the presence of olivine.

Fig. 10a. The northern portion of Bellicia crater, with FC images taken through 829-, 917-, and 965-nm filters displayed as RGB. The black box outlines the ROI for which the ratio–reflectance plot in Fig. 11 was constructed. The ROI contains 5054 pixels. Endmember spectra were extracted for 5 × 5 pixel boxes centered on the tips of the arrows. The image is a piece of the Vesta Av-02 quad mosaic (Roatsch et al., 2012), which is in Lambert conformal conic projection. The center of the image is at ~40.6°N, 48.6°E. North is toward the top.

Vesta’s Av-10 quadrangle, named for the ~40-km diameter impact crater Oppia, is a region with generally eucritic mineralogical character (De Sanctis et al., 2012a; Ammannito et al., 2013a, 2013b; Tosi et al., 2015). According to the geological map by Garry et al. (2014), the quadrangle is dominated by three units defined primarily by morphology: “cratered highlands”, “cratered plains” and the “Divalia Fossae Formation”. These units are interpreted to be ancient crustal terrain, the degraded floor of an ancient basin that formed in the cratered highlands, and troughs formed by tectonism in response to the Rheasilvia basin-forming impact, respectively.

The Oppia quadrangle is notable for the strong color variations that are present (De Sanctis et al., 2012a; Reddy et al., 2012b; Le Corre et al., 2013; Tosi et al., 2015). Garry et al. (2014) mapped two color units based specifically on their albedo and FC multiband characteristics, “light mantle material” and “dark mantle material”. These two units are distinctive in the color-composite image of Fig. 12. These units have steeper (redder) spectral slopes in the visible than most of the vestan surface, with the slope of the dark
mantle being greater than that of the light mantle. These materials hence appear as orange and red tones in color-ratio composites made with wavelength bands similar to those often used for Clementine multispectral images of the Moon (Reddy et al., 2012b; Le Corre et al., 2013). The units mapped as light mantle by Garry et al. (2014) were called “orange patches” by Le Corre et al. (2013). The unusual spectral character of the dark and light mantle indicates that material with an atypical composition or physical state is likely to be present. The leading hypothesis for the component with the steep spectral slope is glassy impact melt (Le Corre et al., 2013; Garry et al., 2014). In this scenario, the dark mantle represents impact melt mixed with ejecta (target and/or impactor material); patches of light mantle correspond to deposits of impact melt that has in some cases flowed or ponded. Le Corre et al. (2013) examined images with the highest spatial resolution and found no perceptible texture or morphology differences between the light mantle and the surroundings. Intriguingly, some of the light mantle units associated with Oppia have been found to have a relatively strong absorption feature near 2.8 μm (De Sanctis et al., 2012b; Tosi et al., 2015), indicative of the presence of hydrated material. The light-mantle units to the west of Oppia have the strongest 2.8 μm features. When present, the 2.8-μm absorption band is broad and very asymmetric, which suggests multiple absorption processes due to OH-cation bonds and possibly H–O–H absorptions (Tosi et al., 2015).

It is of interest to evaluate space-weathering and mixing trends associated with the unusual materials in the Oppia quadrangle. To do this, we selected spectral end-members and defined an image ROI for one of the light mantle patches and its surroundings (Fig. 13). The end-members are high-reflectance ejecta from a small (~800-m diameter) crater in the light mantle (#1 in Fig. 13), normal light mantle surface (#2), high-reflectance ejecta from a small crater in the surroundings (#3), and a mature area of the surroundings (#4). The visible ratio–reflectance plot for the ROI and the endmember spectra is in Fig. 14. The ROI does not encompass the fresh-surroundings spectral type, so the pixel cloud exhibits mixing relationships along two lines. The first is between fresh and mature light mantle material, i.e., from end-member #1 to endmember #2 in Fig. 14. This represents the transition from the high-reflectance ejecta of the small light-mantle crater to the background mature surface of the light-mantle patch. The second mixing line in the ROI pixel cloud extends from the mature light-mantle material (#2) to the mature surroundings (#4). This is a result of lateral mixing across the edge of the light mantle patch that is enclosed by the ROI. Regolith maturation within the surrounding material progresses from the fresh end-member (#3) to the mature surface (#4). In both the case of the light mantle and the surroundings, the maturation trajectory is from higher reflectance, lower ratio to lower reflectance, higher ratio, i.e., from brighter and redder to darker and bluer. Thus the space-weathering trends in Fig. 14 are those expected from admixture of a CC component, and are opposite to the trend that would be produced by accumulation of npFe⁰ in lunar-style space weathering.

5. A broader survey of fresh-to-mature spectral change

The pixel scatterplots for the image ROIs discussed in Section 4 permitted us to examine the detailed spectral trends present in areas of specific interest. In this section we conduct a wider survey of space-weathering style across Vesta. We employ a spectral parameter designed to classify the spectral changes associated with regolith maturation in a way that discriminates between LSSW and CC mixing.
The procedure that we followed was to extract pairs of color spectra from the FC image cubes. For each pair, a fresh location was selected, typically on crater ejecta or ray material. A corresponding nearby background surface was identified to represent the mature version of the same type of material. Each extracted spectrum is the average for a 5 \times 5 box of pixels. The images used here have pixel dimensions of 60 m, so the area of a 5 \times 5 box is \approx 9 \times 10^4 m^2. Twenty-one selections were made to represent a wide range of locations around Vesta, and were constrained to generally avoid steep topographic slopes, seams in the FC mosaics, and areas of missing or poor-quality data in either the FC or VIR maps. For each fresh and mature pair, the 555-nm reflectance and the 438-nm/555-nm reflectance were recorded, as listed in Table 2. The latitude and longitude locations for the points are provided in Table 3.

---

**Table 2**

Data for fresh and mature location pairs discussed in Section 5. Names and geographic coordinates for the locations are in Table 3.

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<th>Location number</th>
<th>Quad</th>
<th>Fresh 555-nm refl.</th>
<th>438-nm/555-nm ratio</th>
<th>Mature 555-nm refl.</th>
<th>438-nm/555-nm ratio</th>
<th>VIR wt.% Fe</th>
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**Table 3**

Geographic coordinates* for the fresh and mature locations from Table 2.

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<tr>
<th>Location number</th>
<th>Name</th>
<th>Fresh 555-nm refl.</th>
<th>438-nm/555-nm ratio</th>
<th>Mature 555-nm refl.</th>
<th>438-nm/555-nm ratio</th>
<th>Lat</th>
<th>Long</th>
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* Longitudes are in the “Claudia” coordinate system used by the Dawn team (Roatsch et al., 2012; supplemental material of Russell et al., 2012; Williams et al., 2014), which differs from the system used for Vesta data in the NASA Planetary Data System (Archinal et al., 2011). Positive longitudes listed here = (+PDS longitude) – 150°.

For reference, the iron content for each pair of locations was determined from iron-abundance maps derived from hyperspectral images collected by the Dawn Visual and Infrared (VIR) imaging spectrometer. Ammannito et al. (2013a) used VIR image mosaics to produce maps of the band center of the mafic mineral absorptions near 1 and 2 μm. Le Corre et al. (2013) developed equations for calculating iron abundance (wt.% Fe) based on...
Fig. 15. Illustration of the space-weathering distance parameter for a hypothetical fresh and mature pair. The parameter is the simple Euclidean distance between the fresh point and the corresponding mature point. In case 1, the mature location has a greater ratio value than the fresh location, so the difference (fresh-mature) is positive; this distance is assigned a positive value and corresponds to a change consistent with CC mixing. In case 2, the mature location has a lower ratio value and the difference (fresh-mature) is positive; this distance is assigned a positive value and is consistent with a change caused by LSSW. Compare with the visible ratio–reflectance plot for model spectra in Fig. 4.

The iron content for each pair is the average for a ROI drawn to encompass both the fresh and mature location. The iron values are listed in Table 2. The surface iron content on Vesta does not vary greatly. The values in Table 2 show that the range is less than 1 wt.%, from ~13.0 to 13.8 wt.% Fe. Examination of the iron maps for Vesta quadrangles not represented in Table 2 found that there are a few areas that are slightly below 13.0 wt.% or slightly above 13.8 wt.% Fe. However, data were not extracted for these locations because of a lack of suitable fresh and mature sets, or because of the other data-quality constraints mentioned above.

We employ a spectral parameter that is a measure of distance in ratio–reflectance space as an indicator of the space-weathering trajectory for each of the 21 fresh-mature pairs in Tables 2 and 3. This parameter, illustrated in Fig. 15, is equal to the Euclidean distance from the fresh point to the mature point in a plot of the 438-nm/555-nm reflectance ratio vs. the 555-nm reflectance. This distance represents the extent of the spectral change between the fresh member and its mature counterpart. Further, we give the distance a sign: positive if the change in 438-nm/555-nm ratio (fresh minus mature) is >0, negative if the change in 438-nm/555-nm ratio is <0. As shown in Fig. 15, a positive distance corresponds to movement to the lower left in the diagram, consistent with LSSW (see also Fig. 4). Mixing with CC material causes movement to the upper left in the ratio reflectance plot, producing a negative distance. The three locations strongly suspected to contain olivine (points 4, 5, and 6 in Tables 2 and 3) do not have ratio values that stand out from the other locations examined, suggesting that if unusual (for Vesta) space weathering is taking place it is not detectable with this spectral parameter. This observation is consistent with the region-of-interest analysis for the Bellilca location described above in Section 4.3.

Fig. 16 presents the space-weathering distance parameter for each of the 21 fresh and mature pairs. If material became redder as it matured, as predicted for npFe0 accumulation in LSSW, then the distance parameters shown in Fig. 16 would be positive because the 438-nm/555-nm ratio in mature material would be lower than in fresh material. However, most of the locations have negative distances, consistent with CC-mixing.

Fig. 16 shows that only three of the locations (#11, 16, and 20) have positive distances. For two of these, #11 (Dark ejecta southeast of Oppia) and #20 (Quad 15 dark ray crater), the “fresh” member of the pair is located in low-reflectance material near the rim of a dark-ejecta crater. The corresponding mature member of the pair is located in the higher-reflectance background surroundings (see values for 555-nm reflectance in Table 2). Therefore, the presence of abundant low-reflectance, relatively “blue” CC-like material in the dark ejecta imparts a low 438-nm/555-nm reflectance ratio to the fresh members of these two pairs. As a result, the background surroundings, which contain a substantially lower abundance of CC material, have a higher ratio, and hence the change in ratio (fresh minus mature) is positive. In other words, the mature surface is redder than the fresh surface because of a compositional difference (greater CC abundance in the fresh surface) rather than being evidence of npFe0 accumulation. For location #16 (Sossia N), study of FC color-ratio images for the Av-14 quadrangle indicates that the location that was chosen for the mature background turns out to be within a segment of reddish “dark mantle” ejecta from Oppia crater, which is located to the northeast. Therefore the 438-nm/555-nm ratio for the mature member of the Sossia N pair is lower than that of the fresh member as a result of the presence of this special reddish material at the mature location.

6. Discussion

Our analysis of spectral trends for an array of locations on Vesta has found no case where lunar-style space weathering via accumulation of npFe0 is readily detectable using our method. This suggests that either the conditions that create npFe0 on the Moon do not operate efficiently on Vesta, or that there is some additional unrecognized factor that either protects Vesta from the agent(s) of space weathering or masks the spectral effects of npFe0. As noted in the Introduction, the energy of solar-wind ions is essentially the same at the Moon and at Vesta, though the flux is much lower in the Main Belt. The micrometeoroids that hit Vesta on average are traveling at lower velocities than those that strike the Moon. However, the reddened spectra of Main Belt Vesta-family asteroids (Burbine et al., 2001), the rapid reddening of Main Belt S-type asteroids (Vernazza et al., 2009), and the short predicted timescale for spectral alteration of Vesta by the solar wind (Vernazza et al., 2006) argue that LSSW should take place on Vesta. Complicating the picture, a comparison of visible spectral slope with a theoretical exposure parameter by Marchi et al. (2010) found that on aggregate, more-exposed V-type asteroids have visible spectral slopes that are bluer than less-exposed V-types.

Qualitatively, the presence of the CC component in Vesta’s surface could partially mask the spectral effects of npFe0 accumulation (Fig. 4). Perhaps Vesta itself is large enough to retain substantial CC material during impacts whereas the small Vestoids are not; this could explain why the Vestoids display reddening while Vesta does not. Physical factors such as particle-size effects or phase reddening could also be responsible for the spectral differences between Vesta and the Vestoids. However, evidence from the Kapoeta howardite regolith breccia points to very low production of npFe0 on Vesta rather than CC-masking effects as responsible for the lack of spectral reddening on Vesta. Grain rims containing npFe0 particles have been found in Kappaota (Noble et al., 2011) indicating that LSSW takes place to a small degree on Vesta, but the scarcity of such particles relative to the numbers found in lunar regolith breccias (Noble et al., 2005) suggests that npFe0 production on Vesta is drastically lower than on the Moon. Hence, there could be merit to the hypothesis that Vesta is protected from solar-wind sputtering and implantation by a remnant magnetic field (Vernazza et al., 2006; Starukhina and McCord, 2012). Fu et al. (2012), who reported on paleomagnetism in a eucrite, concluded that Vesta formerly had a global magnetic field.
generated by a core dynamo, and that present-day crustal remnant fields could offer the degree of protection from the solar wind necessary to limit the optical effects of space weathering.

Future work with VIR data could be used to conduct further analysis of space weathering on Vesta. At present, uncertainties in the VIR calibration related to the spectral slope have generally limited analysis to continuum-removed spectra (e.g., Ammannito et al., 2013a, 2013b). By considering the full visible-to-NIR spectral character, including the key parameter of the NIR continuum slope (measured across tangent points on the 1-μm mafic-mineral absorption band, at ~0.7 and 1.3 μm), it should be possible to detect the spectral effects of npFe with greater sensitivity than that achieved with the FC multiband parameterization employed here. Such a study would yield additional insight into the relative roles of CC-mixing and LSSW on Vesta.

As noted by Murchie et al. (2015), Mercury and Vesta are similar in that they are bodies whose surfaces exhibit only narrow variations in the abundance of ferrous iron in silicate minerals, unlike the Moon where there are large differences in iron content between the highlands and the maria. Mercury represents the case where the absolute iron abundance is very low and variations are also small. Vesta has a relatively high abundance of iron with only minor regional and local variations (from more eucritic areas to more diogenitic areas). As a result of having a small range in ferrous iron content, the presence of minor darkening agents plays a key role in reflectance and color variations on both Mercury and Vesta. The identity of the darkening agent on Mercury is uncertain, but recent work suggests that it could be submicroscopic metallic iron (Lucey and Riner, 2011), sulfide minerals (Blewett et al., 2013b; Helbert et al., 2013), or carbon (Peplowski et al., 2015) in the form of graphite (Murchie et al., 2015) or exogenic carbon-bearing material (Bruck Syal et al., 2015). On Vesta, the darkening agent is dominantly exogenic CC-like material. Because Vesta’s surface is basaltic, the spectral effects of a CC component are analogous to variations in ilmenite abundance in the basaltic lunar maria. Ilmenite and CC material both have low reflectance and relatively flat spectra in the visible and near infrared portions of the spectrum. The result of adding either CC-material or ilmenite to a basaltic mineral assembly is to cause the spectrum to become darker and less red.

7. Summary and conclusions

Pieters et al. (2012) carried out an initial assessment of space weathering on Vesta based on observations by the Dawn spacecraft. In the present work, we extend that study by creating radiative-transfer model spectra for space-weathered Vesta material. We examined parameterizations of the model spectra that can be derived from Dawn FC multispectral observations. The visible ratio–reflectance diagram (plot of 438-nm/555-nm ratio vs. 555-nm reflectance) was identified as a means to distinguish the spectral effects of LSSW from those of CC mixing. We also used Dawn FC spectral observations to perform detailed analysis of regolith maturation for a wide variety of vestan localities.

We used FC multiband mosaics to examine the color trends that accompany regolith evolution at four Vesta locations with contrasting composition. The areas examined are locations on the eucritic and diogenitic ends of the compositional range found on Vesta (near Vibidia and Antonia craters, respectively), olivine-bearing materials within Bellicia crater, and one of the enigmatic “light mantle” units northeast of Oppia crater. A separate analysis used a space-weathering parameter derived from FC color data for fresh and mature spectral pairs for 21 locations around Vesta.

The results from these two studies are consistent with the finding of Pieters et al. (2012): as the regolith matures, it becomes darker and “bluer” (i.e., the 438-nm/555-nm ratio increases). This is the spectral trend predicted for addition of CC material to basalts by exogenic mixing, whereas LSSW should lower the reflectance but cause spectra to become “redder” (lower 438-nm/555-nm ratio) as npFe accumulates. Exceptions to the general vestan relationship between fresh and mature material can occur in particular local situations. For example, at craters that expose substantial amounts of CC material, the dark, CC-rich ejecta may be less red than the mature basaltic background. Further, at locations where unusual orange/red material is present as the background, fresh crater material may be bluer than this reddish background.

The lack of obvious LSSW on Vesta continues to be a puzzle, because V-type and S-type asteroids are redder than powdered samples of their respective meteorite analogs. Such reddening is consistent with space weathering by solar-wind ions. While the presence of the bluish CC component in Vesta’s surface could par-
tially mask the reddening effects of npFe\textsuperscript{6+} accumulation, meteorite evidence suggests that npFe\textsuperscript{6+} production on Vesta is indeed very low. Thus there are open questions regarding space weathering on asteroids. The answers may lie in physical or compositional differences between the S- and V-type surfaces, or Vesta's higher surface gravitational acceleration relative to small V-types. Alternatively, perhaps there is merit to the hypothesis that Vesta is protected from solar-wind ion bombardment by a remnant magnetic field.

Acknowledgments

Reviews provided by P. Vernazza and T. Kohout helped us to improve this paper. We are grateful to the Dawn flight, instrument, and science teams for their efforts that led to the successful mission at Vesta and the collection and processing of the data used in this study. D.T.B. thanks Sam Lawrence (Arizona State University) for sharing and collaborating on radiative-transfer code. This work made use of data from the RELAB spectral database at Brown University (http://www.planetary.brown.edu/relab/). The work of D.T.B. and B.W.D. was made possible by NASA Dawn at Vesta Participating Scientist grants (NNX10AR57G and NNX11AC28G, respectively). L.L. is supported by NASA Planetary Data Analysis Program grant NNX14AN16C.

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