Dark material on Vesta from the infall of carbonaceous volatile-rich material


Localized dark and bright materials, often with extremely different albedos, were recently found on Vesta’s surface1,2. The range of albedos is among the largest observed on Solar System rocky bodies. These dark materials, often associated with craters, appear in ejecta and crater walls, and their pyroxene absorption strengths are correlated with material brightness. It was tentatively suggested that the dark material on Vesta could be either exogenic, from carbon-rich, low-velocity impactors, or endogenic, from freshly exposed mafic material or impact melt, created or exposed by impacts. Here we report Vesta spectra and images and use them to derive and interpret the properties of the ‘pure’ dark and bright materials. We argue that the dark material is mainly from infall of hydrated carbonaceous material (like that found in a major class of meteorites and some comet surfaces3–5), whereas the bright material is the uncontaminated indigenous Vesta basaltic soil. Dark material from low-albedo impactors is diffused over time through the Vestan regolith by impact mixing, creating broader, diffuse darker regions and finally Vesta’s background surface material. This is consistent with howardite–eucrite–diogenite meteorites coming from Vesta.

Vesta has a mean diameter of 525 km and is the second-most massive object in the main asteroid belt of our Solar System, smaller than Ceres and similar to Pallas. These three bodies form a separate class of intact objects in the asteroid belt that have experienced planetary processes, such as thermal evolution powered by short-lived radio-nuclides incorporated at the time of accretion. This process in general results in mineralogical alteration due to heating, and differentiation, with denser materials sinking towards the centre. In contrast, most other main-belt asteroids seem to be pieces of collisionally disrupted objects. Although subdued albedo differences on global6 and broadly regional7 scales were known to exist from telescopic observations, localized and intense dark and bright occurrences were not anticipated (see Supplementary Information).

We used photometrically uniform near-global albedo spectral image mosaics constructed from the Dawn11 Framing Camera and

**Figure 1 | Locations of dark and bright material.** Mapped occurrences of local dark- and bright-material locations (points) are shown here plotted on a 1.7-μm albedo map derived from VIR images. The albedo mosaic also exhibits broad low-albedo regions, especially between about 70° and 220° longitude, near which the localized dark-material points tend to cluster, suggesting a causal relationship. Bright- and dark-material local examples tend not to be uniformly distributed or correlated with each other. For this base map, the entire VIR infrared data set from late Approach, Survey and High-Altitude Mapping orbits was converted into reflectance and mosaicked.
represents mixing between dark and bright materials. At this resolution, the broad global distribution represents surface area fraction (not globally and in detail, a product of Vesta’s igneous past. Dark (Fig. 3). The pyroxene signature clearly dominates Vesta’s spectra to be distinct from dark material on a local scale, but globally at this resolution these albedo classes form a continuum distribution with a peak at the global average albedo. This suggests a mixing of dark and bright materials to produce the range of Vesta surface materials.

The visible and infrared mapping spectrometer (VIR) to demonstrate that dark and bright materials are distributed non-uniformly and are uncorrelated (as seen in Fig. 1), suggesting different origins. Unlike bright material, some dark material also occurs over larger areas with more diffuse boundaries.

Investigation of the 1.7-μm albedo frequency distribution at the spatial scale of 1 km per pixel surprisingly showed it to be unimodal, lacking any special albedo classes (Fig. 2). The bright material appears to be distinct from dark material on a local scale, but globally at this resolution these albedo classes form a continuum distribution with a peak at the global average albedo. This suggests a mixing of dark and bright materials to produce the range of Vesta surface materials.

We compared VIR spectra for dark and bright material (Fig. 3). The pyroxene signature clearly dominates Vesta’s spectra globally and in detail, a product of Vesta’s igneous past. Dark material has weaker apparent absorptions. We then applied a Multiple-Endmember Linear Spectral Unmixing Model to derive the spectrum of each of Vesta’s surface materials within each VIR pixel, using the fewest possible spectral endmembers. We found that the VIR spectra could be modelled using the weighted sum of only two spectral endmembers, called ‘bright’ and ‘dark’ materials in Fig. 3. The modelled dark-material endmember spectrum shows no absorption bands, with a reddish slope that flattens towards longer wavelengths. The modelled bright-material endmember spectrum shows the classic, strong pyroxene 2-μm band and the expected pyroxene continuum shape. Our conclusion is that, for the most part, Vesta’s surface material can be thought of as having two spectral components—the dark and bright endmember spectra—in different proportions. This is consistent with the mixing-process hypothesis and suggests that the dark spectral component is the agent diluting the pyroxene spectral signature. The identity of the bright endmember is probably the intrinsic Vesta basaltic soil, rich in unaltered, crystalline pyroxenes. This relationship between bright and dark materials is further supported by the strong correlation of the 1-μm pyroxene absorption band strength with albedo from analysis of the Framing Camera colour data and shown here (Fig. 4). We note that the dark-material spectrum is very similar to that of carbonaceous chondrite material, such as is found in a major class of meteorites (the carbonaceous chondrites).

Regions of Vesta where the residuals from the spectral mixing analysis are largest (but still small) have some of the strongest pyroxene signatures. These represent the best opportunity to study intrinsic Vesta material, for example, at some apparent impact structures that may be sampling ejecta from the Rheasilvia basin near the south pole. Suggestions for the origin of discrete areas of dark material include indigenous sources (such as opaque-rich lava flows and impact melts) as well as contamination from exogenous material (delivered from foreign, impacting bodies). A search of Dawn VIR spectra for OH spectral features near 3 μm was made, prompted by the discovery of OH and H₂O in the lunar surface. A 2.8-μm absorption was found and its analysis indicates that the dark material appears to be relatively enriched in OH (Fig. 5). Carbonaceous chondrite meteorite material often contains 10–20% OH-bearing hydrated minerals, whereas none of the other suggested dark-material sources contain

**Figure 2** | Frequency distribution of albedos. The global distribution of albedos at 1.7 μm, derived from the infrared global base map (Fig. 1) at a spatial resolution of about 1 km. The curve represents surface area fraction (not number of pixels). At higher resolutions this distribution would develop smaller peaks at each extreme of brightness, representing individual dark- and bright-material locations. At this resolution, the broad global distribution represents mixing between dark and bright materials.

**Figure 3** | Reflectance spectra of dark and bright materials. the resulting residual is shown as a dashed black line. The residual shows no distinctive features and overall is near the noise level of the VIR data, suggesting successful modelling. (The feature near 1.44 μm is a calibration artefact.) b, c, Similar examples for intermediate and brighter materials nearby. The weighting factors are given on the plots and the mixture spectrum is calculated as the weighted sum of dark + bright. This analysis was performed at several other areas with similar results, before we successfully modelled the entire mosaic shown in Fig. 1.
The strength of the 1-\(\mu\)m pyroxene absorption, measured by the ratio of reflectance at 0.75 \(\mu\)m to that at 0.92 \(\mu\)m, is strongly correlated with the reflectance in the continuum (0.75 \(\mu\)m), shown here for three example regions. Data from points are from the framing camera. Greater ratio values correspond to stronger absorption bands. Dark (black filled circles) and bright (black open circles) areas cluster near the extremes of the plot, while background material (grey open circles) appears near the middle of this apparent mixing line. Dark material points are from Cornelia crater (9.3\(^\circ\)S, 225.5\(^\circ\)E), background material is from an area located between 5\(^\circ\)S–17\(^\circ\)N, 320\(^\circ\)E–356\(^\circ\)E and the bright material is from Tuccia crater (40\(^\circ\)S, 197\(^\circ\)E) in the Claudia coordinate system used by Dawn. If the entire surface of Vesta were treated here, rather than only example areas, the three clusters of points would merge into a continuum from least to greatest reflectance.

Figure 4 | Correlation of pyroxene absorption with material reflectance. Two-dimensional scatter plot from global observations of Vesta by VIR show a diffuse anti-correlation of the OH-related 2.8-\(\mu\)m-absorption band depth and Vesta’s reflectance at 1.7 \(\mu\)m (Fig. 1). The OH signature is correlated with the dark material in Vesta’s surface.

Figure 5 | Correlation of OH spectral absorption with material reflectance. The strength of the 1-\(\mu\)m pyroxene absorption, measured by the ratio of reflectance at 0.75 \(\mu\)m to that at 0.92 \(\mu\)m, is strongly correlated with the reflectance in the continuum (0.75 \(\mu\)m), shown here for three example regions. Data from the framing camera. Greater ratio values correspond to stronger absorption bands. Dark (black filled circles) and bright (black open circles) areas cluster near the extremes of the plot, while background material (grey open circles) appears near the middle of this apparent mixing line. Dark material pixels are from Cornelia crater (9.3\(^\circ\)S, 225.5\(^\circ\)E), background material is from an area located between 5\(^\circ\)S–17\(^\circ\)N, 320\(^\circ\)E–356\(^\circ\)E and the bright material is from Tuccia crater (40\(^\circ\)S, 197\(^\circ\)E) in the Claudia coordinate system used by Dawn. If the entire surface of Vesta were treated here, rather than only example areas, the three clusters of points would merge into a continuum from least to greatest reflectance.

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**Supplementary Information** is available in the online version of the paper.

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