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Example of dark and bright material: An example of the occurrence of bright and dark material on Vesta, revealed by Dawn, is shown in Fig. S1.

Calibration of VIR data: The entire VIR IR data set from late Approach, Survey and High-Altitude Mapping (HAMO) orbits was processed. First, VIR raw data in Digital Numbers (DNs) were calibrated into radiance (Level 1b) following the usual steps of dark current subtraction, flat-field correction and multiplied by the response function of the instrument. Then, for the purpose of spectral analysis, radiance was converted to I/F by using a Lommel-Seeliger photometric model (Eq. 1);

$$I/F = \frac{\pi I}{S} d^2 \frac{\cos i + \cos e}{\cos i} \times f(\alpha) \qquad \text{Eq. 1}$$

where d is the distance from the Sun to Vesta in AU, I is the surface spectral radiance measured by VIR in $W.m^{-2}.sr^{-1}.\mu m^{-1}$, S is the irradiance (or solar flux) from the sun in $W.m^{-2}.\mu m^{-1}$, I and e are the incidence and emergence angles respectively, based on the topography of Vesta derived from the shape model[1]

The albedo analysis at 1.7 µm included all the steps above, completed by a conversion from I/F to reflectance R, such as R = I/F × f(α), by means of an order-2 polynomial phase function correction (Eq. 2) in order to better account for the effects of multiple scattering, The empirical phase function is of the form:

$$f(\alpha) = a\alpha^2 + b\alpha + c \qquad \text{Eq. 2}$$

where α is the phase angles.

Finally, the corrected images were registered to a global latitude/longitude grid[8] and mosaicked (Fig 1)

The accuracy of the photometric correction is improving as the spatial resolution of the shape model is increasing. The relevance of this standard Lommel-Seeliger correction is limited where the incidence angle is higher than 80° and on areas with shadows, mostly at high, northern latitudes, because indirect illumination occurs due to multiple reflections (adjacency effects).

Origins of dark and bright material: A list of possible origins of the dark material (DM) includes either endogenic, freshly exposed mafic material or impact melt, or exogenic, infall of carbon-rich material[1,2]. We examined each of these possibilities. No unequivocal observational evidence has been found so far for near-surface flows or intrusions of volcanic material[1], and no late energy source within Vesta has been identified to create them. Vesta was previously melted, but HEDs indicate that it cooled and solidified early in its history, and no younger igneous rocks occur in the extensive HED collections[19].

A more plausible source of DM is shock-melted material formed by high-velocity impacts. Impact melts are common on Solar System objects, especially airless bodies such as the Moon. Such materials occur as sheets and flows on the surface and may be covered by ejecta from subsequent nearby impacts[24], and there is abundant evidence of such deposits on Vesta[1]. However, reflectance spectra for impact melted silicates would likely have at least a subdued Fe^{++} glass or distorted pyroxene absorption. Yet another possible source of DM is vestan material excavated from below the regolith (the gardened surface layer). This origin requires strong regional differences in subsurface composition, because the uncontaminated vestan mafic silicate material composing most of the regolith, when broken up, would look very much like the bright material (BM): high reflectance with a strong pyroxene absorption. However, the apparent pervasive melting and differentiation of Vesta early in its evolution and the global, relatively uniform bulk mineralogy consistent with this model suggested by the Dawn measurements[12] argue against strong lateral compositional differences. Also, material formed deep within a differentiated silicate object would be more mafic (rich in Mg and Fe), would show at least some mafic mineral absorptions and would not have the mineralogy of basalt generated near the surface.

Another possible source of DM is the impactors themselves. Many of the objects in the asteroid belt are postulated to be carbonaceous chondrite-like (CC) objects[24] in that they have low albedos and increasing reflectance toward longer wavelengths with little or no specific absorptions. This term refers to a class of meteorites that are carbon-rich and have much lower reflectance and weak or non-existent mafic mineral absorptions compared with the basaltic material composing most of Vesta's surface. Relatively low-velocity impacts by these objects likely result in the preservation of parts of the impactor as blocks[14] or finer materials[26].

Dark material and carbonaceous chondrites: First, we point out that the association of CC meteorites with the classes of dark asteroids is not completely proven. The problem is that there is no strong and unique spectral feature available in CC material that could be identified in asteroid spectra. It is a widely but not universally accepted hypothesis that at least several of these classes of dark asteroids are the source of cc meteorites. Thus, we proceeded to assess the quantitative viability of the scenario linking Vesta dark material to the carbonaceous meteorites and to asteroid classes thought to be the source of this material. We analytically estimated the amount of carbonaceous material that could have been delivered on Vesta across its history and focused on the last 3.5 Ga, i.e. from the end of the most violent phases of the evolution of the asteroid belt and of the Solar System [22, 24].

We based our evaluation on the present size-frequency distribution of the asteroid belt as estimated by Bottke et al.[27]. According to Minton and Malhotra[22], the population of large (D >

30 km) bodies in the asteroid belt declined by a factor two over the considered time span due to chaotic diffusion of the asteroids into orbital resonances with the giant planets. According to these authors, the depletion rate of smaller bodies could have been even higher, since Yarkovsky drift should increase the number of bodies affected by the resonances. In order to make a first, conservative estimate of the delivery of carbonaceous chondrite-like material to Vesta, we assumed a depletion of a factor two for all bodies with diameter greater than 1 km taking place at a constant rate across 3.5 Ga. This is equivalent, in terms of the total number of collisions, to integrate a constant population enhanced by a factor 1.5 respect to the present one.

O'Brien et al.[29] used the techniques developed by Bottke et al.[36] to assess the intrinsic impact probability on Vesta (P_i = 2.72x10^{-18} km^{-2} yr^{-1}) and the velocity distribution of the impacting bodies. Svetsov[37] used hydrocode simulations to derive scaling laws for the fraction of the impactor's mass retained by the target body as a function of the impact velocity and the escape velocity of the target body. We used the impact velocity distribution estimated by O'Brien et al. [35] and the scaling law for impact velocities $V_i < 15$ km s^{-1} from Svetsov[25] to compute the velocity-weighted average retained mass $M_r = 0.4658 m_i$, where m_i is the mass of the impactor.

We then used the number of observed C, D and P type asteroids and the number of all spectrally classified asteroids in the asteroid belt from the JPL Small-Body Database Search Engine[1] to estimate the ratio (F_d = 0.2148) of potential carriers of dark material among all the impactors on Vesta. In the limits of the assumptions made, we estimated that Vesta would be hit by about 300 of these asteroids with diameter between 1 and 10 km. Dark asteroids whose diameter varies between 10 and 25 km have impact probabilities with Vesta varying respectively between 60% and 10%. If we compute the cumulative probability associated to these stochastic events, Vesta should have undergone one collision with these asteroids with diameter in this size range in the last 3.5 Ga.

The amount of dark material delivered on Vesta by the estimated 300 impacts depends on the average density of the impacting bodies. If we conservatively assume an average density equal to the lower bulk density measured among the different classes of carbonaceous chondrites (d = 2120 kg m^{-3}, i.e the density of CI meteorites[26]) the delivered amount of dark material is M_{dm} = $3x10^{18}$ g. If, instead, we consider an average density d = 2742 kg m^{-3} [27], the amount of dark material increases to M_{dm} = $4x10^{18}$ g. Note that the average density values of carbonaceous chondrites vary roughly between 2600 and 2800 km m^{-3} depending on the considered subset of meteorites and whether a simple or weighted mean is computed.

These amounts of dark material, if uniformly distributed on a spherical body with radius equal to the mean radius of Vesta R_V=262.7 km, would cover the surface with a blanket 1.2-1.7 m thick. Interestingly, on average the stochastic impacts of bodies between 10 and 25 km in diameter would delivered about the same amount of dark material as the previously discussed 300 impacts, thus increasing the thickness of this hypothetical blanket to 2.5-3.4 m.

There is little information on the fate of projectiles in hypervelocity impacts: in particular, we presently ignore how much of the delivered dark material would be in the form of solid fragments or frozen melt. The existing literature mainly focuses on the case of impacts of iron meteorites on Earth[34,35], so they investigate the fate of stronger materials, which requires higher pressures and temperatures to melt or sublimate. However, the impact velocities considered in those studies (12-20 km s^{-1}) are generally higher than the ones that characterize impacts on Vesta (2-10 km s^{-1} [23]). Further, C type asteroids generally have relatively high porosity values, so the associated shock pressures should be lower and thus would favor the survival of large fractions of the impactors as solid fragments or melt droplets.

The delivered dark material should therefore be in the form of a mixture of solid fragments and melt, the exact ratio depending on the impact angle, the impact velocity and the strength and porosity of the material composing the impactor. If we use the case of the Meteor Crater in Canyon Diablo[35] as a terrestrial analogue, the dark material would be distributed downrange with respect to the impact direction and with an angular dispersion of <30° [28]. Both solid fragments and frozen melt droplets would be expected to cover the interior of the crater and should also concentrate just beyond the crater rim, roughly between 1 and 2 crater radii[35]. The area affected by the dark material could extend to about 4 crater radii but lower densities of the dark material[35] would characterize this outer region.

Using the scaling laws from Holsapple & Housen[36] for impacts on basalt material and assuming an average impact angle of 45° and an average impact velocity of 4.75 km s^{-1} [29], impactors ranging in diameter between 1 and 10 km would produce craters whose diameter would vary between roughly 9 and 90 km. Assuming ballistic trajectories[37] for the fragments of the impactor, the highest concentrations of dark material would be associated to ejection velocities ranging respectively between 30 and 75 m s^{-1}. The fraction of material ejected with velocities higher than 100 m s^{-1} would disperse over the whole surface of Vesta and mix with the existing vestan regolith.

If we make the simplifying assumption that the dark material should be concentrated inside the crater and in the downrange cone of impactor's ejecta (angular width of 30°, length 4 crater radii), we can estimate that the affected surface area would be about 27% of the surface of Vesta. If we focus only on the higher-density regions of the impactor's ejecta, equivalent to the inside of the crater plus a cone of angular width of 30° and length of 2 crater radii, the affected surface area would be about 15% of the surface of Vesta. If we assume an average depth-to-diameter ratio of 0.2 for craters smaller than 30 km and of 0.18 for larger craters[38], the dark material would penetrate the crust of Vesta to depths locally varying between ~1.5 and 15 km.

The craters and ejecta blanket produced by the more abundant non-carbonaceous asteroids (the ratio is about 4:1 with respect to carbonaceous asteroids) over the same time span can be estimated to affect a total area of the same order of magnitude as the surface of Vesta. They would therefore bury the dark material deposited by earlier impacts, reducing the affected surface area and mixing it with the indigenous material of the Vestan surface. As a consequence, however, dark material should be present with varying concentrations in the crust of Vesta up to depths of about 15 km.

It is worth noting that the cumulative surface area affected by the craters and the associated ejecta blanket produced by all impactors on Vesta (i.e. both carbonaceous and non-carbonaceous) becomes lower than the surface of Vesta if we consider only the flux of impactors over about the last 2 Ga. As a rule of the thumb, therefore, the dark material present on the surface of Vesta should include the amount deposited over the past 2 Gad, which would affect about 10-13% of the surface of Vesta, plus an undefined fraction of older dark material incorporated in the vestan regolith.

Finally, stochastic impacts of asteroids with diameter between 10 km and 25 km would produce craters ranging between 100 km and 200 km in diameter and 20 km and 40 km in depth. While dedicated hydrocode simulations are needed to assess the effects of these impacts, the dark material they could supply would in principle affect the surface of Vesta on a global scale.

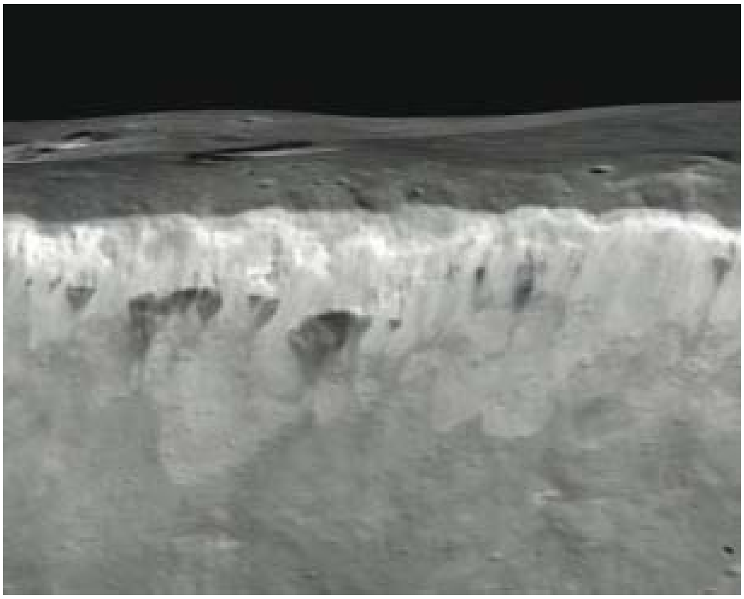

Figure S1 Example of dark and bright material. The NASA Dawn spacecraft[11], the first to visit and orbit Vesta, revealed localized dark and bright surface materials, as in this Framing Camera images. Here dark and bright materials occur as outcrops near the top of the wall of Marcia crater (5.50˚N, 184.16˚E). Cover picture candidate?

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