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The contamination of the surface of Vesta by impacts and the delivery of the dark material

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ABSTRACT

The Dawn spacecraft recently observed the presence of dark material, which in turn proved to be associated with the presence of OH and H-rich material, on the surface of Vesta. The source of this dark material has been almost unanimously identified with the low albedo asteroids, likely analogous to the carbonaceous chondrites found on Earth, that impacted on Vesta over its lifetime. However, it is still a matter of debate whether the delivery of the dark material is associated with a few large impact events, to micrometeorites or to the continuous, secular flux of impactors on Vesta. The "continuous flux" scenario, in particular, predicts that a significant fraction of the exogenous material accreted by Vesta should be due to non-dark impactors likely analogous to ordinary chondrites, which instead represent only a minor contaminant in the Howardite–Eucrite–Diogenite meteorites. In this work, we explored the "continuous flux" scenario and its implications for the composition of the vestan regolith, taking advantage of the data from the Dawn mission and the Howardite–Eucrite–Diogenite meteorites to constrain the contamination history of Vesta. We developed a model for the delivery of the exogenous material to Vesta and verified how the results it supplies are sensitive to the different parameters we consider. We calibrated the flux of impactors predicted by our model with the number of dark craters observed inside the Rheasilvia basin and we tested the assumptions on the impact conditions by studying the formation of Cornelia crater and of its dark deposits with a hydrocode simulation. We used our calibrated model to show that the "stochastic events" scenario and the "micrometeoritic flux" scenario are just natural consequences of the "continuous flux" scenario. We then used the model to estimate the amounts of dark and hydroxylate materials that were delivered on Vesta since the Late Heavy Bombardment and we showed how our results match well with the values estimated by the Dawn mission. We finally used our model to assess the amount of Fe and siderophile elements that the continuous flux of impactors would mix in the vestan regolith: concerning the siderophile elements, we focused our attention on the role of Ni. The results we obtained are in agreement with the data available on the Fe and Ni content of the Howardite–Eucrite–Diogenite meteorites and can be used as a reference frame in future studies of the data from the Dawn mission and of the Howardite–Eucrite–Diogenite meteorites. Our model cannot yet provide an answer to the conundrum of the fate of the missing non-carbonaceous contaminants, but we discuss some possible reasons for this discrepancy with the otherwise coherent picture described by our results.

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1. Introduction

The Dawn spacecraft recently observed the presence of dark material on the surface of Vesta (McCord et al., 2012; Reddy et al., 2012) and the dark material proved, in turn, to be associated with H-rich material (Prettyman et al., 2012) and OH (De Sanctis et al., 2012a). While the source of this dark material has been almost unanimously identified with the carbonaceous chondrites, particularly the CM and CR chondrites that have been observed as clasts inside the Howardite–Eucrite–Diogenite (HED) family of meteorites (see McCord et al., 2012; Reddy et al., 2012; Prettyman et al., 2012; De Sanctis et al., 2012a for more in-depth discussions), the actual delivery scenario is still debated.

McCord et al. (2012) linked the delivery of the dark material to the flux of low albedo impactors associated with the collisional history of Vesta since the Late Heavy Bombardment. Reddy et al. (2012) also associated the delivery of the dark material to impacting asteroids: however, instead of a continuous flux, these authors proposed that the delivery could be due to a few large, low-velocity impact events (at least two), one of these being responsible for the formation of the Veneneia basin. As an alternative possibility, Reddy et al. (2012) proposed that the dark material could be delivered by micrometeorites. As these authors pointed out, however, the micrometeoritic flux since the Late Heavy Bombardment is too low to account for the observed amount of dark material on Vesta. As the flux of dark micrometeorites was likely orders of magnitude more intense during the Late Heavy Bombardment, Reddy et al. (2012) suggested that the ancient meteoritic flux could have significantly contributed to the total budget of the dark material together with the impacts of low albedo asteroids.

In discussing the detection of OH in the spectral features of Vesta, De Sanctis et al. (2012a) linked its presence in the vestan regolith either to low-velocity impactors or to the micrometeoritic flux. These authors argued against a more or less continuous flux of OH-carrying impactors and favored instead a temporally limited delivery, possibly located in the more ancient past of Vesta (De Sanctis et al., 2012a). In discussing the distribution and setting of H-rich materials and studies of carbonaceous chondrite clasts in howardites, Prettyman et al. (2012) pointed out instead that the H content in the vestan regolith plausibly rules out a single, isolated impact or a temporally limited enhancement of the meteoritic flux as possible sources. These authors argued that the concentration and distribution of H suggests on the contrary an accumulation over time from numerous impactors and asteroidal dust (Prettyman et al., 2012).

In this work we will focus on the role of asteroidal impacts on Vesta in delivering the dark material, and the OH and H-rich material detected by the Dawn spacecraft. The “stochastic events” and the “micrometeoritic flux” scenarios discussed by Reddy et al. (2012) and De Sanctis et al. (2012a) are not necessarily in contrast with the “continuous flux” scenario discussed by McCord et al. (2012). As already noted by McCord et al. (2012), in the case of a continuous flux of impactors about half of the dark material would be delivered by a handful of large asteroids and an even larger contribution would be associated with stochastic events like the one responsible for Veneneia basin. Moreover, the “continuous flux” scenario naturally incorporates the “micrometeoritic flux” scenario. The “continuous flux” scenario, however, predicts that the dominant fraction of the exogenous material accreted by Vesta would be due to non-dark impactors (see e.g. McCord et al., 2012), likely analogous to ordinary chondrites. These contaminants have been detected only in marginal quantities in the HED family of meteorites (Lorenz et al., 2007), raising the conundrum of their fate.

The aim of this work is to address the problem of the contamination history of Vesta by providing a quantitative assessment of the amounts of the different exogenous materials delivered in the “continuous flux” scenario. To achieve this goal, we improved the model we first used in McCord et al. (2012) and refined the calculations performed there to estimate the flux of impactors and the amount of dark material delivered on Vesta since the Late Heavy Bombardment. We tested the assumptions on the average impact velocity and angle by studying the formation of Cornelia crater with a hydrocode simulation and verifying that the distribution of the dark material inside the crater is satisfactorily reproduced by the remnants of the impactor material in the simulation. We extended our physical model to allow the assessment of the amounts of OH and H-rich material and of non-dark exogenous material delivered to Vesta. Concerning the latter class of contaminants, we focused on the role of Fe and of Ni, which we used as our tracer for the siderophile elements based on the results of Warren et al. (2009). We finally compared our results with the findings of the Dawn mission (De Sanctis et al., 2012a; De Sanctis et al., 2012b; McCord et al., 2012; Prettyman et al., 2012; Reddy et al., 2012; Yamashita et al., 2013) and discussed their implications for the composition of the vestan regolith in light of our current understanding of the HED family of meteorites (e.g. Zolensky et al., 1996; Lorenz et al., 2007; Warren et al., 2009).

2. Method

As we mentioned previously, our delivery scenario is based on the one we first employed in McCord et al. (2012). As such, it uses the intrinsic impact probability of Vesta together with a description of the temporal evolution of the population of the asteroid belt to statistically assess the number and sizes of the impactors on the asteroid. Using these values together with scaling laws for the retention efficiency of Vesta, it is then possible to estimate the amount of exogenous material accreted by the asteroid.

Following McCord et al. (2012), we used our current understanding of the present-day fraction of dark and non-dark asteroids to constrain the amount of potential carriers of dark material among the projectiles hitting Vesta. However, with respect to McCord et al. (2012) we also used the available information on the composition of the different classes of meteorites to try to quantitatively assess the amounts of the different materials delivered to the asteroid that could be measured by the Dawn mission.

In the following sections we will describe in detail all the aspects of our model. Before proceeding, we must point out that some of the observational parameters (e.g. the fraction of dark asteroids) and of the theoretical results (e.g. the mass fraction of the impactors that remains on Vesta) we used to build our model are still poorly constrained. As a consequence, in the model we considered different possibilities for these parameters in order to assess how much our results are affected by these uncertainties.

2.1. Temporal evolution of the asteroid population and flux of impactors on Vesta

In their work, McCord et al. (2012) analytically estimated the flux of dark impactors on Vesta based on the present day population of bodies with $D \geqslant 1$ km in the asteroid belt (see Table 1 and Bottke et al. (2005a)).

The authors took into account the depletion in the population of asteroids that should have occurred across the last 3.5 Ga due to chaotic diffusion (estimated to be of a factor 2, Minton and Malhotra, 2010) by assuming a constant decay (i.e. a linear decrease) in the number of asteroids over time. From the point of view of the total number of impacts (but not from that of their temporal distribution), this is equivalent to assuming a population constant in