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Impact contamination on asteroid Vesta throughout the history of the Solar System

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Abstract

Asteroid Vesta, one of the targets of the NASA mission Dawn, is the source of the HED family of meteorites and one of the most ancient body for which we possess samples. The collisional history of its basaltic crust extends over the whole life of the Solar System. Here we report the results of a series of investigations of the role of impacts in shaping the composition of Vesta's crust by delivering exogenous contaminants since the time such crust was still in a molten state, highlighting how Vesta is a unique laboratory to study impact contamination and how it provides powerful constraints to investigate the early history of the Solar System.

1. Asteroid Vesta and the Dawn mission

Impacts are an ubiquitous process in the life of planetary systems and play a major role in shaping the evolution of their planetary bodies. Their effects are both destructive and constructive: they cause a loss of endogenous material from the impacted body while at the same time delivering new exogenous material to it through the fragments of the impacting one. The balance between these two effects will determine the final composition and appeareance of the impacted body and of its surface. The NASA mission Dawn explored asteroid Vesta between 2011 and 2012 [1, 2] and confirmed Vesta's basaltic crust as the source of the Howardite-Eucrite-Diogenite (HED) family of achondritic meteorites [3, 4]. Members of the HED family possess some of the oldest formation ages among the known meteorites (e.g. [5, 6]), making Vesta the most ancient planetary body for which we possess samples. The data provided by the Dawn mission revealed that the basaltic crust of Vesta globally survived the whole collisional history of the asteroid [5]. Dawn's observations revealed the presence of dark material on Vesta's surface [7], which proved to be associated with H-rich material [4] and OH [3] and was identified as exogenous in origin [7, 3, 4]. The same data revealed few scattered patches of olivine-rich terrains (see [10] and references therein), a material generally associated to the interior of differentiated planetary bodies, on Vesta's apparently intact surface. In parallel, laboratory analyses of the HED meteorites constrained the limited presence of water within Vesta's otherwise volatile-poor primordial crust [8] and the possibile signature of the late accretion of Vesta's crust in the form of an overabundance of highly-siderophile elements [6], materials that should be mainly segregated in Vesta's core. We explored whether all these observed features could be linked to the role of impacts in shaping Vesta and what they could tell us about the history of the Solar System [13, 14, 9, 15].

2. Secular impact contamination of Vesta's surface

We create a collisional model based on statistical methods to evaluate the average flux of impactors on Vesta over the last 4 Gyr of life of the Solar System taking into account the secular depletion of the asteroid belt [7, 9, 10]. The collisional model incorporated scaling laws [18, 9] and the results of impact simulations [10] performed with the hydrocode SOVA [17, 18, 14, 19] to estimate the the contamination by exogenous materials delivered by the different classes of asteroids [9, 10]. The collisional model was calibrated using the number of dark material units within the 1 Gyr-old Rheasilvia's crater [9] and successfully reproduced it as resulting from the impacts of carbonaceous asteroids [9]. The collisional model was then used to estimate the global delivery of water-rich material by carbonaceous hydrated asteroids, obtaining results in good agreement with the measurements of the GRaND instruments onboard Dawn [9], and the enrichment in high-siderophile elements of regolithic howardites with respect to the mixture of eucrites and diogenites from which they originate, obtaining again a good match to laboratory data [9]. Finally, the collisional model was used to verify whether the olivine-rich terrains on Vesta's surface could result from exogenous deposits left by olivine-rich impactors like A-type asteroids instead of being excavated from Vesta's interior [10]. Impacts of this rare type of asteroid proved indeed capable of creating the required number of olivine-rich terrains [10], while impacts of the more numerous but less olivine-rich S-type asteroids would not create global olivine signatures on Vesta's surface in agreement with Dawn's data [10].

3. Ancient impact contamination of Vesta's crust

The ancient formation ages of HED meteorites reveal that Vesta's formation predates that of the giant planets in the Solar System (e.g. [15] and references therein). The formation of giant planets was shown to trigger a phase of dynamical and collisional excitation of the surrounding planetesimals both in the Solar System [11, 12] and in circumstellar disks [16] even in absence of planetary migration. The formation of Jupiter, in particular, was shown to result in an early bombardment on asteroid Vesta while its crust was still molten [11, 15]. We investigated whether the data provided by Dawn and the HEDs on the composition of Vesta's crust and its enrichment in water and highly-siderophile elements could constrain its collisional evolution and, consequently, the migration of Jupiter [15]. We combined N-body simulations with statistical methods to estimate the impact fluxes on Vesta during Jupiter's formation for different migration scenarios and planetesimal populations [11, 13, 14, 15]. We used impact simulations with the hydrocode SOVA [17, 18, 14, 19, 15] to assess the outcomes of the impacts. Our results show that the global survival of Vesta's crust to impacts can be used to rule out violent collisional scenarios characterized by numerous high-energy impacts [15]. The abundances of water and highly-siderophile elements in HEDs, instead, appear to be sensitive to the extent of Jupiter's migration and to the size frequency distribution of the planetesimals respectively [15]. The joint use of these three constraints from Vesta results in a powerful tool to quantitatively compare different formation and migration scenarios for Jupiter and the giant planets [15].

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