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Shallow Magma Ocean on Vesta and Implications for the HEDs

Wladimir Neumann, Doris Breuer, and Tilman Spohn
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany (wladimir.neumann@dlr.de)

The asteroid 4 Vesta is widely held as a differentiated object and as the parent body of the HED meteorites. However, the origin of the HEDs, which is closely linked to the differentiation processes, is still a subject of debate. In particular, various differentiation scenarios have been proposed (e.g. partial melt[1] and residual melt[2,3] scenario) to explain the process of HEDs' formation. Here we present results of numerical calculations of the early thermo-chemical evolution of Vesta, placing constraints on the possible differentiation scenario and on the occurrence and depth of the Vestan mantle magma ocean. We use a numerical heat conduction code[4] that considers accretion, compaction, melting, associated changes of the material properties, partitioning of ^{26}Al, advective heat transport, differentiation by porous flow, and effective cooling of a magma ocean by convection. We show that partitioning of ^{26}Al and its transport with the silicate melt is crucial for the formation of a magma ocean. Previous models that neglect this effect[5,6,7] infer a whole-mantle magma ocean beneath a solid crust. We show that in contrast to these models a deep magma ocean does not form if partitioning of ^{26}Al is considered: Radioactive nuclides are enriched in the melt and relocated towards the surface. Due to the over-production of the radiogenic heat in a shallow layer, the melt fraction increases rapidly above a critical melting threshold (here we assume 50 % of melt) for which the rheology is dominated by the liquid phase, i.e. a magma ocean forms. For formation times of Vesta $<$1.5 Ma relative to the CAIs, a thin shallow convecting magma ocean with a thickness of 1 to a few tens of km is obtained, above which a basaltic crust forms. The lifetime of the magma ocean is $\approx O(10^5)$ years and convection is accompanied by the extrusion of ^{26}Al at the surface. The interior differentiates from the outside inward with a mantle which is depleted in ^{26}Al and a core which forms within $\approx$0.3 Ma. The lower mantle experiences a maximal melt fraction of 45 % suggesting a harzburgitic to dunitic composition. These findings strongly depend on the silicate melt viscosity – the higher the viscosity, the lower the migration velocity and the thicker the magma ocean. For basaltic melts derived from chondritic material, viscosities of $\approx$1-100 Pa s have been proposed[8]. For 1 Pa s, we obtain a 1 km thick magma ocean with a lifetime of $O(10^5)$ a, which crystallises rapidly. For 10 Pa s, the thickness increases to $\approx$10 km and the lifetime is prolonged to 1 Ma. In the extreme case of 100 Pa s, the magma ocean even extends to the depth of $\approx$100 km. Core, mantle and crust from almost simultaneously, and the melt fraction in the mantle remains below 50 %. Our results suggest that previous models of Vesta (which neglect partitioning of ^{26}Al and/or convection) overestimate the temperature in the interior and thus the amount of partial melting[5,6,7]. Thus, our results contradict the idea of a deep magma ocean on Vesta, but support the formation of non-cumulative eucrites by percolation of early partial melt while diogenites and cumulate eucrites form by rapid crystallization of a shallow magma ocean. This is consistent with the rapid time scale for magma ocean crystallization of Al-free diogenites[2]. Silicate melt viscosity values of up to 100 Pas suggest that the shallow magma ocean can be up to 100 km deep. A few tens of km thick shallow magma ocean would in fact be consistent with the assumption of Vesta's crust having an average thickness of 35-85 km with an upper eucritic and a lower orthopyroxene-rich layer[9].

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