# CORE FORMATION ON ASTEROID 4 VESTA: IRON RAIN IN A SILICATE MAGMA OCEAN

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Geochemical observations of the eucrite and diogenite meteorites, together with observations made by NASA's Dawn spacecraft, suggest that Vesta resembles H chondrites in bulk chemical composition, possibly with about 25% of a CM-chondrite like composition added in [1]. For this model, the core is 15% by mass (or 8 volume %) of the asteroid. The abundances of moderately siderophile elements (Ni, Co, Mo, W, and P) in eucrites require that essentially all of the metallic phase in Vesta segregated to form a core prior to eucrite solidification [2, 3].

Melting in the Fe-Ni-S system begins at a cotectic temperature of ~940 °C [4, 5]. Only about 40% of the total metal phase, or 3-4 volume % of Vesta, melts prior to the onset of silicate melting. Liquid iron in solid silicate initially forms isolated pockets of melt; connected melt channels, which are necessary if the metal is to segregate from the silicate, are only possible when the metal phase exceeds about 5 volume % [6, 7]. Thus, metal segregation to form a core does not occur prior to the onset of silicate melting.

Silicate melting begins at 1100-1150 °C [8], and silicate melt can efficiently migrate along grain boundaries by Darcy flow. However, the ability of silicate melt and liquid metal drops to segregate depends on the metal drop size. The likely initial size of melt droplets is set by the size of the kamacite and troilite grains in the solid metal. The mean grain sizes in several H6 chondrites are 35±10 μm (kamacite) and 25±8 μm (troilite) [9]. The initial Stokes flow velocities for such small metal-sulfide drops are less than $10^{-6}$ m/year. At this stage of evolution, the metal liquid is unable to efficiently segregate from the silicate liquid. The molten metal-sulfide is immiscible in the silicate liquid and effectively forms an emulsion of 20-50 micron metal drops in the silicate liquid. Due to the small initial size of the metal drops, the timescale for achieving chemical equilibrium between liquid metal and liquid silicate is very short, so the observed concentrations of moderately siderophile elements in the eucrites are easily achieved.

Due to the relatively low viscosity of the silicate magma at high melt fraction (~$10^7$ Pa-s for 40% silicate partial melt, ~10 Pa-s for > 60% silicate partial melt), the silicate magma ocean will convect in the soft turbulent regime [10]. At small metal drop sizes, the Stokes flow sinking velocity is overwhelmed by the magma ocean's convective flow, keeping the metal suspended in the magma ocean. However, there will be a spectrum of metal drop sizes, and larger drops sink more rapidly than smaller drops. Thus, there will be collisions among the metal drops, resulting in gradual growth of the drops to larger sizes. Once the metal drops reach ~10 cm in diameter, their Stokes velocities are comparable to the magma ocean convective velocity and metal can sink as iron rain through the silicate magma ocean to form a core (**Fig. 1**). Metal drops of this size are stable against break-up due to viscous forces applied to the metal drop [11]. We are modeling drop growth with a bubble coalescence model [12]. The speed with which metal drops grow is likely to be the rate-limiting step for the formation of the core and thus the efficiency of this process may be constrained by Hf-W isotopes [13, 14].

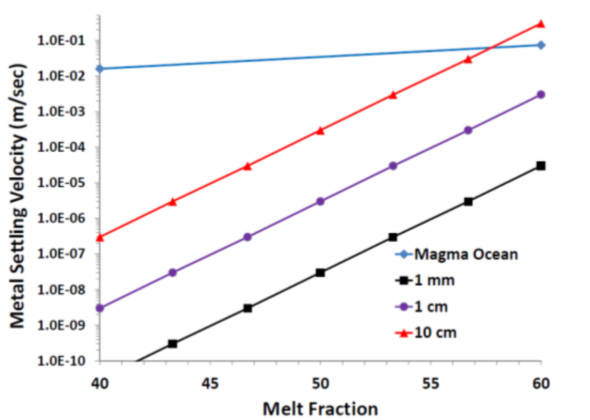


**Figure 1:** Magma ocean convection velocity (blue) and metal sinking velocities for several different size metal drops as a function of silicate melt fraction in a magma ocean.

**References:** [1] Toplis et al., *Meteoritics Planet. Sci.* 48, 2300-2315, 2013. [2] Righter and Drake, *Meteoritics Planet. Sci.* 32, 929-944, 1997. [3] Steenstra et al., *Geochim. Cosmochim. Acta* 177, 48-61, 2016. [4] Fleet, *Rev. Mineral. Geochem.* 61, 365-419, 2006. [5] Ghosh and McSween, *Icarus* 134, 187-206, 1998. [6] Walte et al., *Earth Planet. Sci. Lett.* 305, 124-134, 2011. [7] Cerantola et al., *Earth Planet. Sci. Lett.* 417, 67-77, 2015. [8] Jurewicz et al., *Geochim. Cosmochim. Acta* 59, 391-408, 1995. [9] Guignard and Toplis, *Geochim. Cosmochim. Acta* 149, 46-63, 2015. [10] Solomatov, *Treatise on Geophysics*, vol. 9, pp. 91-119, 2007. [11] Rubie et al., *Earth Planet. Sci. Lett.* 205, 239-255, 2003. [12] Black and Manga, *JGR Planets* 121, 944-964, 2016. [13] Kleine et al., *Geochim. Cosmochim. Acta* 68, 2935-2946, 2004. [14] Touboul et al., *Geochim. Cosmochim. Acta* 156, 106-121, 2015.