DIFFERENTIATION OF ASTEROID 4 VESTA: CORE FORMATION BY IRON RAIN IN A SILICATE MAGMA OCEAN

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Introduction: Geochemical observations of the eucrite and diogenite meteorites, together with observations made by NASA's Dawn spacecraft while orbiting asteroid 4 Vesta, suggest that Vesta resembles H chondrites in bulk chemical composition, possible 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, with a composition of 73.7 weight % Fe, 16.0 weight % S, and 10.3 weight % Ni. 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 [2-5]. The combination of the melting phase relationships for the silicate and metal phases [6-8], together with the moderately siderophile element concentrations together require that complete melting of the metal phase occurred (T> 1350 °C), along with substantial (>40%) melting of the silicate material. Thus, core formation on Vesta occurs as iron rain sinking through a silicate magma ocean.

Stage 1: Metal-only melting (T=940-1100 °C)

Melting in the Fe-FeS system begins at the eutectic temperature of 988 °C [6], although inclusion of a small amount of Ni will lower the eutectic temperature to ~940 °C [9]. This is below the silicate solidus, so initial melting consists of metal-sulfide only. Liquid iron in solid silicate has a high dihedral angle and thus 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 % [10, 11]. However, for Vesta's Fe-S composition, only about 40% of the total metal phase, or 3-4 volume % of Vesta, melts prior to the onset of silicate melting. Thus, metal segregation to form a core does not occur prior to the onset of silicate melting.

Stage 2: Metal and Silicate melting (T=1100 to 1350 °C)

The onset of silicate melting occurs between 1100 and 1150 °C for a ¾ H + ¼ CM composition [7, 8]. From this point until completion of metal melting at 1350-1400 °C [6], both metal and silicate melt simultaneously. At the time at which the metal phase is fully molten, the silicate phase will be at about 40% partial melt [7, 8]. Silicate melt is capable of efficiently migrating along grain boundaries (Darcy flow) [12]. However, it is necessary to consider the behavior of both the silicate and metal melts before understanding how differentiation proceeds.

The likely initial size of melt droplets is set by the size of the kamacite and troilite grains in the solid metal. The mean observed grain sizes in several H6 chondrites is 35±10 μm (kamacite) and 25±8 μm (troilite) [13]. At the viscosities that are relevant when the silicate melt fraction is less than 40%, the Stokes flow velocities for such small metal-sulfide drops are less than 10^{-6} m/year (**Figure 1**). Thus, at this stage of evolution, the metal liquid is unable to efficiently segregate from the silicate liquid and we must consider the evolution of the mixed silicate + metal liquid relative to the solid matrix. Because the molten metal-sulfide is immiscible in the silicate liquid, it effectively forms an emulsion of 20-50 micron metal drops in the silicate liquid.

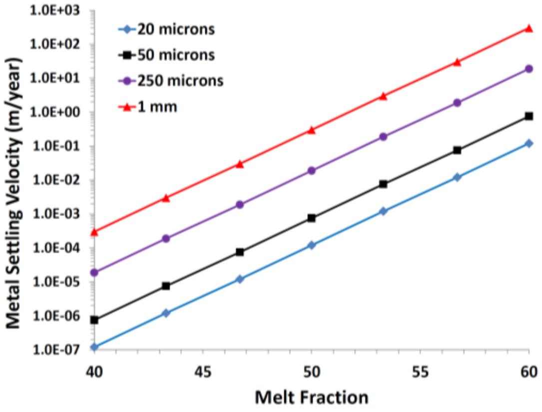

Figure 1: Stokes flow velocities for metal drops of the indicated diameters as a function of silicate mass fraction in a silicate magma ocean on Vesta.

Early in stage 2, the overall liquid density is dominated by the liquid metal, and as a result, the liquid is negatively buoyant with respect to the bulk (silicate + metal) solid. As silicate melting proceeds, the silicate liquid gradually begins to dominate the overall liquid density. However, even when metal melting is complete, the liquid phase is still slightly negatively buoyant compared to the solid. As a result, we disagree with the assertion that silicate magma is efficiently removed from the mantles of differentiating asteroids [12]; this assertion is correct for a pure silicate melt but is not correct for a combined silicate + metal liquid phase. Our preliminary buoyancy calculations are based on the average densities for the metal and silicate liquid and solid phases. More rigorous calculations, which take into effect the changes in the composition (and thus density) of the silicate solid and liquid as melting proceeds, are currently being developed and may modify the point at which the silicate + metal liquid achieves positive buoyancy. This is important for the thermal evolution and possible continued melting of Vesta. Aluminum is concentrated in plagioclase, which fully enters the melt at low melt fraction. So long as the liquid is negatively buoyant relative to the bulk solid, there will be continued heating of the deep interior of Vesta by radioactive decay of ^{26}Al. However, once the liquid is positively buoyant, it will rapidly separate to the near-surface by Darcy flow [14], which limits the subsequent radioactive heating and melting that is possible in the deep interior of Vesta.

Stage 3: Chemical equilibration between silicate and metal liquids and separation of liquid from residual silicate solids (T>1350 °C)

As long as the liquid remains negatively buoyant, there will continue to be radioactive heating of the deep interior by ^{26}Al, allowing the silicate to continue melting. At melt fractions above 40 %, the liquid viscosity begins to drop sharply, and at melt fractions above 60% the viscosity is similar to the pure liquid viscosity [15]. Once the liquid becomes positively buoyant, it will quickly separate from the crystalline mush by Darcy flow. 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 (< 1 day), so the observed concentrations of moderately siderophile elements in the eucrites are easily achieved.

Stage 4: Metal drop collisional growth and core formation by "iron rain"

Due to the relatively low viscosity of the silicate magma at this stage of the evolution (~10^7 Pa-s for 40% silicate partial melt, ~10 Pa-s for > 60% silicate partial melt), the silicate magma ocean will be strongly convecting. Over most of this range, convection will be in the soft turbulent regime. Solomatov estimated that the characteristic convective velocity for a terrestrial magma ocean is 10 m s^{-1} [16]; scaling to Vesta conditions gives a characteristic velocity of ~1 m s^{-1} (or $3 \cdot 10^7$ m/yr). At small metal drop sizes, the small Stokes flow sinking velocity (**Figure 1**) is overwhelmed by the magma ocean's convective flow. 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 will be comparable to the characteristic magma ocean convective velocity and the metal drops will sink through the silicate magma ocean to form a core. A mechanical stability analysis indicates that drops of this size are stable against break-up due to viscous forces applied to the metal drop [17]. In the spirit of [18, 19], we refer to this mode of core formation as iron rain. The speed with which metal drops grow in size 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 isotopic systematics [20, 21].

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