THERMAL EVOLUTION AND CORE FORMATION ON ASTEROID 4 VESTA IN THE MAGMA OCEAN REGIME

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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, indicate that Vesta has differentiated to form a crust, mantle, and core [1, 2]. Eucrite and diogenite petrology is best explained by solidification of the crust from a magma ocean constituting 60-70% of Vesta's silicates [3], or a temperature of ~1550 °C. 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 formation and likely reached a temperature of 1450-1575 °C [4, 5]. These observations provide important constraints on Vesta's thermal evolution. The high inferred temperature indicates that convective heat transport must have been important during part of Vesta's thermal evolution. In this study, we model Vesta's thermal evolution in the magma ocean regime.

Method: We model the thermal evolution of Vesta using the time-dependent, one dimensional (radial) thermal conduction equation in spherical geometry:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{Nu\, k}{r^2}\frac{\partial}{\partial r}(r^2\, \partial T/\partial r) + \rho H(t) + L_f \Gamma_L \quad (1).$$

Here, T is temperature, t is time, r is radius, ρ is density, c_p is specific heat, k is the thermal conductivity, H is the radioactive heat production, L_f is the latent heat of melting, and Γ_L is the melt production rate. The radioactive heat production is time dependent and includes contributions from both ^{26}Al (dominant) and ^{60}Fe. We include uncertainties in the initial concentrations of the radioactive isotopes in the model and discuss their effects in the Results section. Melting includes both the silicate phase based on the melting phase relationships for H and CM chondrites [6, 7] and for the metal phase based on melting in the Fe-S-Ni system [8], consistent with the current best estimate for Vesta's bulk composition [9].

Nu in equation 1 is the Nusselt number and incorporates the effects of convective heat transport using a parameterized convection model; this approach has been widely used to model the thermal evolution of Mars and other terrestrial planets [e.g., 10]. Here, Nu = a Ra^b, where Ra is the Rayleigh number, which measures the vigor of thermal convection. The constants a and b are determined from laboratory and numerical studies of high Ra mantle convection [11]. $Ra=\rho g \alpha \Delta T d^3/(\eta\kappa)$, where g is the gravitational acceleration (using the value at mid-depth in the body as a representative average value), α is the thermal expansion coefficient, ΔT is the temperature difference between the top and bottom of the convecting layer, d is the depth of the convecting layer, and κ is the thermal diffusivity. η is the viscosity, which includes the effects of melt on the viscosity [12].

Our model differs from previous models for the thermal evolution of Vesta in two important ways. First, prior models have either neglected the role of convective energy transport on the thermal evolution [13-15] or assumed that convective heat transport only becomes important when the melt fraction exceeds 50% [16-17]. However, Vesta reaches the critical Ra and begins convecting at about the same time that silicate melting begins, and our model therefore incudes convective heat transport beginning at that point. Second, based on the low density of silicate liquids, it has commonly been assumed that crusts form quickly on asteroids [18]. This is an important issue for the thermal evolution, because Al partitions into the crust at temperatures only slightly above the mantle solidus [19]. This would remove the major heat source from the interior of Vesta and thus truncate heating at relatively low melt fraction and resulting in just a shallow magma ocean [16]. However, the small initial size of metal grains in the likely precursors of Vesta (25-45 microns, [20]) inhibits early separation of the silicate and metal liquid phases. The combined silicate + metal liquid suspension is too dense to rise to the surface of Vesta until a later stage in the evolution, which we have termed the "iron rain" model for differentiation of Vesta [21]. As a result, ^{26}Al is retained in the interior of Vesta for a longer period of time, allowing for formation of a deep magma ocean.

Results: Both the maximum internal temperature and the timescale for core formation are strong functions of the radioactive heating rate and in particular are sensitive to the initial abundance of ^{26}Al. The Solar System's initial ^{26}Al abundance has been a much disputed value in recent years. Some studies support a canonical value of $^{26}Al/^{27}Al \sim 5\cdot 10^{-5}$ [22-

25], whereas other studies favor distinctly lower values [26, 27]. It is possible that the initial value varied with location in the solar nebula [24, 28, 29].

In order to reach interior temperatures of 1450-1575 °C, which are required by petrological and geochemical constraints [3, 5], our models require that the initial concentration of ^{26}Al in Vesta was about 2-3·10^{-5}, or 40-60% of the canonical value initial Solar System value. A larger initial Solar System value is possible if there was a moderate delay between the formation of CAIs and the accretion of Vesta. For example, if the initial ^{26}Al abundance was the canonical value of 5·10^{-5} and Vesta accreted 0.7 Ma after CAIs (~1 half-life of ^{26}Al), the initial ^{26}Al abundance in Vesta would be 2.5·10^{-5}, resulting in a peak interior temperature that is consistent with the petrologic and geochemical constraints.

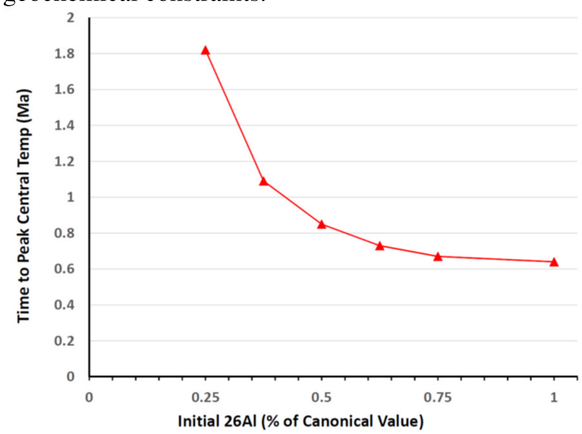

Figure 1: The time from initial accretion of Vesta to the maximum central temperature as a function of the initial abundance of ^{26}Al. Initial ^{26}Al is expressed as fraction of the canonical initial Solar System abundance of 5·10^{-5}.

An additional constraint on these models comes from the time at which Vesta's core formed. As an initial approximation for the core formation time, Figure 1 uses the time to peak central temperature. The time to peak central temperature is 0.6 to 0.8 Ma for initial ^{26}Al exceeding 50% of the canonical Solar System value. Recent ^{182}Hf-^{182}W isotope systematics for the eucrites favor a core formation age on Vesta of ~1 Ma after CAI formation [30]. The results in Figure 1 are inconsistent with this if the initial ^{26}Al is less than about 40% of the canonical Solar System abundance. On the other hand, if there was a brief (0.1-0.3 Ma) delay in Vesta's accretion after CAI formation, then the results in Figure 1 are consistent with the Hf-W core formation age for initial ^{26}Al at the time of Vesta accretion in the range 0.4-0.6 of the canonical Solar System value. This result is consistent with our inference derived from the peak formation temperature.

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