# THERMAL EVOLUTION ON ASTEROID 4 VESTA IN THE MAGMA OCEAN REGIME

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**Introduction:** Geochemical observations of the eucrite and diogenite meteorites indicate that their parent asteroid has differentiated to form a crust, mantle, and core, which is consistent with observations made by NASA's Dawn spacecraft of asteroid 4 Vesta. Eucrite and diogenite petrology is best explained by solidification of the crust from a magma ocean constituting 60-70% of Vesta's silicates [1], or 1425-1475 °C. The abundances of moderately siderophile elements (Ni, Co, Mo, W, and P) in eucrites require that essentially all of the metallic phase segregated to form a core prior to eucrite formation and likely reached a temperature of 1450-1575 °C [2]. These observations provide important constraints of the thermal evolution of the eucrite parent body (likely Vesta, but alternative models exist [3, 4]). The high inferred temperature indicates that convective heat transport must have been important during part of Vesta's thermal evolution.

**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, $\rho$ 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 $\Gamma_L$ is the melt production rate. The radioactive heat production is time dependent and includes contributions from both $^{26}Al$ (dominant) and $^{60}Fe$. Melting includes both the silicate phase based on the melting phase relationships for H and CM chondrites and for the metal phase based on melting in the Fe-S-Ni system, consistent with the current best estimate of Vesta's bulk composition [5].

Nu in equation 1 is the Nusselt number and incorporates the effects of convective heat transport using a parameterized convection model; Nu >> 1 implies that convective heat transport dominates over thermal conduction. This approach has been widely used to model the thermal evolution of Mars and other terrestrial planets [e.g., 6]. Nu is a power law function of the Rayleigh number, which measures the vigor of thermal convection. The power law constants are determined from laboratory and numerical studies of high Ra mantle convection [7]. A crucial factor here is the very strong dependence of viscosity on melt fraction [8, 9], particularly near the rheologically critical melt fraction of about 30%.

Prior thermal models for Vesta have either neglected the role of convective energy transport on the thermal evolution [10-12] or assumed that convective heat transport only becomes important when the melt fraction exceeds 50% [13-15]. 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. Nu exceeds 100 at 20% melt fraction, emphasizing the dominant role of convective heat transport even before the rheologically critical melt fraction is reached.

**Results**: Successful models must reach interior temperatures of at least 1450 °C to satisfy petrological and geochemical constraints [1, 2]. $^{182}Hf$-$^{182}W$ isotope systematics for the eucrites imply a core formation age on Vesta of ~1 Ma after CAI formation [16]. In order to satisfy both the temperature and age constraints, our models require that Vesta's initial $^{26}Al/^{27}Al$ ratio was at least $2\text{-}3 \cdot 10^{-5}$ (~50% of the canonical Solar System value [17, 18]) and that it completed accretion within about 0.4 million years after CAI formation.

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