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Vesta thermal models

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Abstract. Vesta thermal evolution and structural models are compared. These models, based on decay of ^{26}Al, ^{60}Fe and long-lived radionuclides (^{40}K, ^{232}Th, ^{235}U and ^{238}U), differ for the delay in injection (Δt_d) of ^{26}Al by the nebula in which Vesta was formed. In all models we can see the pristine formation of a metallic core followed by the differentiation of silicatic mantle and we can observe the evolution of the crust. This is in preparation of the Dawn mission that will provide us with constraints on the crust thickness and composition of the crust and underlying mantle.

Key words. Vesta – thermal modeling – radioactive decay

1. Introduction

Vesta is a large Main Belt asteroids, the second most massive after Ceres. Spectroscopic studies suggest that Vesta is the parent of the HED (Howardite−Eucrite−Diogenite) (Gaffey 1997) meteorites: this would make Vesta one of few bodies in the Solar System of which we have samples available. Vesta is particularly interesting because it is differentiated since it has a metallic core (mostly iron), an overlying rocky olivine mantle and a basaltic crust. Ghosh and McSween (Ghosh & McSween 1998) summarize Vesta chemical and thermal evolution into three stages: 1) radiogenic heating and consequent formation of the iron core; 2) subsequent heating of the mantle until crust formation; 3) subsequent heating and cooling. After the crust formation Vesta underwent an intense collisional resurfacing as shown by the presence of a large crater in the south pole: it should be stressed that Vesta is the only (known) intact asteroid that underwent these geological processes. The importance of studying the thermal evolution of Vesta is linked to understanding the processes of core and crust formation in protoplanetary bodies so it can be considered a good model for the primordial stages of the terrestrial planets.

2. Thermal Model

The thermal models adopted are considered "instantaneous" for the neglecting of the accretion time of Vesta and differ for the delay in injection of ^{26}Al by the nebula in which Vesta was formed. Heat sources considered are ^{26}Al, ^{60}Fe and long-lived radionuclides, although the main contribution is provided by the ^{26}Al.

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We fix the radius equal to 270 Km and the total mass to 2.75×10^{20} Kg. The initial temperature (that is also the surface temperature) is fixed to 200 K.

When melting temperature of Fe-FeS is reached the differentiation, due to permeable flow (Yoshino et al. 2003), and subsequent core formation occur. The migration velocity of molten metal is given by:

$$v = \frac{K_D}{\mu} g \Delta\rho, \tag{1}$$

in which $\mu = 0.005$ Pa sec is the viscosity of molten iron, $\Delta\rho$ is the density contrast between the molten metal and solid silicate, g is the gravity, $\Phi = 0.1$ is the porosity (Yoshino et al. 2004) and K_D is the permeability of the silicate medium defined as:

$$K_D = \frac{r_g^2 \Phi^2}{200}, \tag{2}$$

being $r_g = 10^{-3}$ m the grain size of silicate medium. Considering Vesta initially composed partly silicatic (0.77%) and partly metallic (0.23%), we solve numerically (using a finite-difference method in 1D radial direction with donor-cell scheme) the following set of differential equations (Nield et al. 2006):

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_f \boldsymbol{v} \cdot \boldsymbol{\nabla} T = \boldsymbol{\nabla} \cdot (K_m \boldsymbol{\nabla} T) + H \tag{3}$$

$$\frac{\partial C}{\partial t} + \boldsymbol{v} \cdot \nabla T = \nabla \cdot (D_m \nabla C). \tag{4}$$

In the eq.3 it is assumed the local thermal equilibrium (so $T_s = T_f = T$ in which s stands for solid and f for fluid), taking averages over the volume of an element. The term H represent the heat production by radionuclides decay per unit volume. The terms $(\rho c)_m = (1 - \Phi)(\rho c)_s + \Phi(\rho c)_f$ and $K_m = (1 - \Phi)K_s + \Phi K_f$ represent the overall heat capacity and thermal conductivity respectively. Following (Ghosh & McSween 1998), we use "windows" of temperature in which the entire latent heat for metal and silicate melting is assumed to be expended (Ghosh & McSween 1998). In eq.4 C represents the concentration of silicate component and $D_m = 10^{-6} m^2 s^{-1}$ is the diffusion coefficient. The heat provided by the ^{26}Al is expressed as (Castillo-Rogez et al. 2007):

$$H_{Al} = \rho C [^{26}Al]_0 H^* e^{-\lambda t}, \tag{5}$$

in which ρ is the density of the silicate component, λ is the decay constant and H^* is the specific power production. The heat provided by the decay of ^{60}Fe and long-lived radionuclides is treated similarly.

3. Results

We consider four different scenarios (Model 1-4 in following), characterized by a time delay $\Delta t_d = 0$, $\Delta t_d = 0.25 T_{1/2}^{Al}$, $\Delta t_d = 0.50 T_{1/2}^{Al}$ and $\Delta t_d = 1.50 T_{1/2}^{Al}$, respectively. Obviously, the smaller the delay the greater the intensity of radioactive sources. The general trend of the temperature profile shows an almost linear increase in temperature within the first 150 km, a plateau region in the zone between 150 and 250 km in which a maximum temperature is reached and finally in the last region (>250 km) a rapid decrease. The mean innovation of this model respect Ghosh and McSween (1998) (Ghosh & McSween 1998) is the movement of the silicate component during the differentiation from the the forming core to the mantle region: this fact is important because the silicate component drags the ^{26}Al that is the main energy source so the temperature increases with the radius. The decrease in temperature in the outer part of the body is due to the irradiation of the energy at the surface. During the evolution, due to the change in density, the moment of inertia depart from the value (0.4) characteristic of an uniform sphere. When the core formation stops (about after 1.4 Myr) the migration of metallic part to the center of the body ceases and the problem becomes an heat diffusion one. Fig.1 shows the profile temperature (at a fixed time) from Vesta accretion for four models considered. Fig.2 shows the inner composition profile for Mod. 3 at t = 10 Myr. Fig.3 shows the mean heat flow in the first 100 Myr for Mod.3 and finally Fig.4 shows the behavior of the maxi-

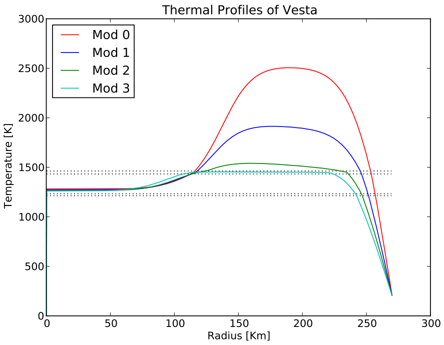

Fig. 1. Thermal profiles of Vesta for the different models analyzed at t = 5 Myr. The dotted lines represent the temperature "windows" in which the entire latent heat for metal and silicate melting is assumed to be expended.

mum temperature as a function of time in the first 100 Myr for Mod.3.

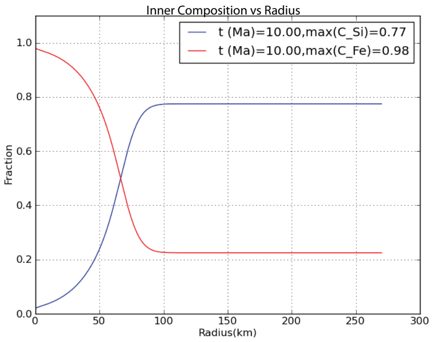

Fig. 2. Example of inner composition profile (for Mod. 3 at t = 10 Myr).The intersection between the concentration of the metallic component (in red) with the silicatic one (in blue) gives an estimate of the core radius.

4. Conclusions

In all the models it is possible to observe the pristine formation of a metallic core followed by the differentiation of a silicatic mantle and the formation and evolution of the crust. In all cases the temperature reaches the melting

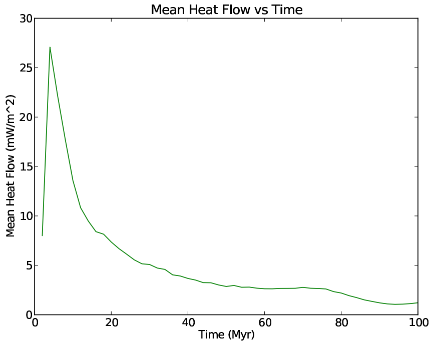

Fig. 3. Mean heat flow for Mod. 3 in the first 100 Myr.

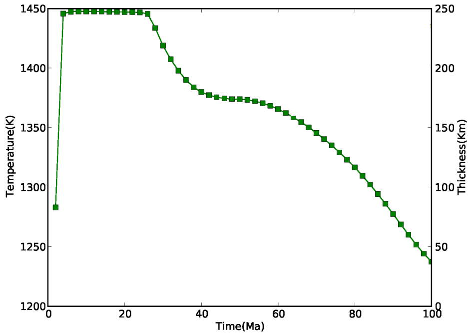

Fig. 4. The behavior of maximum temperature as a function of time for Mod. 3 in the first 100 Myr.

temperature of the silicate implying a complete fusion. The first two models (1 and 2) are slightly unrealistic for the high maximum temperatures and for the very high mean heat flow (much greater than the Earth one). The thickness of the crust is determined by the intersection, that moves in the time, between the temperature profile with the isothermal of the melting temperature of Fe-FeS: this is another difference with Ghosh and McSween (1998) because they fixed this point in their models. The contribution of long-lived radioactive elements does not change the qualitatively thermal history but it only contributes in the delay of the cooling of the body. This fact means that Vesta did not experience other differentiation events and for this Vesta appears substantially the same body of 4.5 Gyr ago. This peculiarity makes Vesta the oldest differentiated body in the Solar System of which we have sample materials. Currently we are testing the possibility to introduce other radioactive heat source (i.e. ^{25}Mn) and to consider impact with other bodies as additional sources of energy. Furthermore we are developing models in which we account for the accretional heat.

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