TIME SCALES OF ACCRETION AND DIFFERENTIATION OF VESTA Formisano M.[1,2], Federico C.[1,3], Coradini A.[1], Turrini D.[1], Capaccioni F.[1]
[1]IAPS - INAF, Via Fosso del Cavaliere 100-00133 Roma, Italy; michelangelo.formisano@ifsi-roma.inaf.it; [2]Università di Roma "La Sapienza", Piazzale Aldo Moro 5, I-00185 Roma, Italy, [3]Dip. di Scienze della Terra - Università degli Studi di Perugia, 06123 Perugia, Italy

Introduction: Vesta is the only intact primordial asteroid in the Solar System showing an internal differentiated structure as the one of the Moon and Mars and for which we have rock samples. The evidence of the differentiation is given by the spectral connection between Vesta and HED meteorites ([9,14]) recently confirmed by DAWN. The energy for the differentiation is supplied by the decay of short lived radionuclides, in particular the ^{26}Al (the primary source of energy [8]) and the ^{60}Fe. Recent results [11], however, indicate a faster cooling of the interior of Vesta than previously thought. If confirmed, this would imply that the thermal history of Vesta diverges from the generally accepted picture [1]. In this work we constrain the time scale of accretion and differentiation of Vesta, by developing several thermal and structural scenarios based on radiogenic heating (^{26}Al and ^{60}Fe). The scenarios differ for the delay Δt_d in the injection of ^{26}Al by the Solar Nebula. We take in account also the contribution of long-lived radionuclides, such as ^{40}K, ^{232}Th, ^{235}U and ^{238}U. We observe the differentiation of the asteroid leading to the formation of a metallic core (mainly iron) and a silicatic crust. The model does not include any cooling mechanisms other than heat conduction and thermal irradiation at the surface. To provide a theoretical support to NASA Dawn team for the data analysis and interpretation, we started the project to study the thermal evolution of primordial Vesta.

Thermal Model: We consider primordial Vesta as a sphere of radius of 270 Km [11] and total mass 2.70 $\times 10^{20}$ kg [12]. The initial temperature is fixed to 200 K [6]. The initial composition is a homogeneous mixture of silicatic (77%) and metallic (23%) material. When the melting temperature of Fe-FeS is reached, the percolation of the iron into the silicatic matrix takes place while when the the melting temperature of silicate is reached the differentiation and subsequent core formation occur [4]. During the differentiation, the molten layer is topped by a solid conductive layer whose thickness is a function of the temperature of the molten material and of the efficiency of the conduction. The solid layer thickness is identified by the intersection between the temperature profile and the horizontal line for the melting temperature solidus (cyan) for the silicatic component, as we can see in Fig.1, in which we show the temperature profile as a function of the radial distance, after 20 Ma, for the models with a delay $\Delta t_d > 1$ Ma

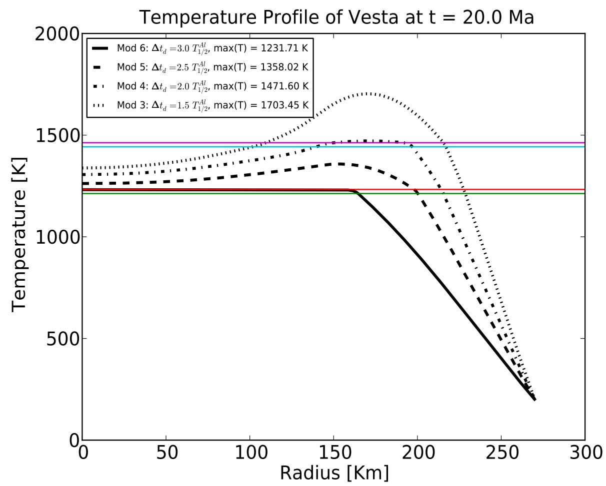

Figure 1: Temperature profile of Vesta a t = 20 Ma. The cyan (red) and magenta (green) lines are the starting and ending temperature for silicatic (metallic) component following [1].

We solve numerically the following coupled set of differential equations [7], by using a finite-difference 1D method direction with a donor-cell scheme:

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_f \vec{v} \cdot \vec{\nabla} T = \vec{\nabla} \cdot (K_m \vec{\nabla} T) + H \quad (1)$$

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = \nabla \cdot (D_m \nabla C). \quad (2)$$

In Eq.1 H represents the source term which is the heat provided by the decay of ^{26}Al expressed as [2]:

$$H_{Al} = \rho C [^{26}Al]_0 H^* e^{-\lambda t}, \quad (3)$$

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. In Eq.1 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 an elemental volume. The terms $(\rho c)_m$ and K_m represent the overall heat capacity and thermal conductivity respectively. Eq.2 is the mass transfer equation in a porous medium [3], in which C represents the concentration of metallic component and D_m is the diffusion coefficient. The heat provided by the decay of

Scenarios	Delay [Ma]	Delay $[T^{26}_{1/2}Al]$
0	0	0
1	0.36	0.5
2	0.72	1.0
3	1.08	1.5
4	1.43	2.0
5	1.79	2.5
6	2.15	3.0

Table 1: Delay time Δt_d expressed in Ma and half-life of ^{26}Al for the different scenarios we considered.

^{60}Fe and long-lived radionuclides is treated similarly. Tab.1 shows the developed scenarios: the intensity of the source of energy depends on parameter Δt_d

The spatial resolution of our grid is 100 m and the time step is adaptive following the stability condition in [5]. In Fig.2 we show an example of thermal evolution of the radial temperature profile of Vesta for the scenario characterized by Δt_d = 1.08 Ma, in which we can distinguish the starting point of the differentiation and the solid layer thickness.

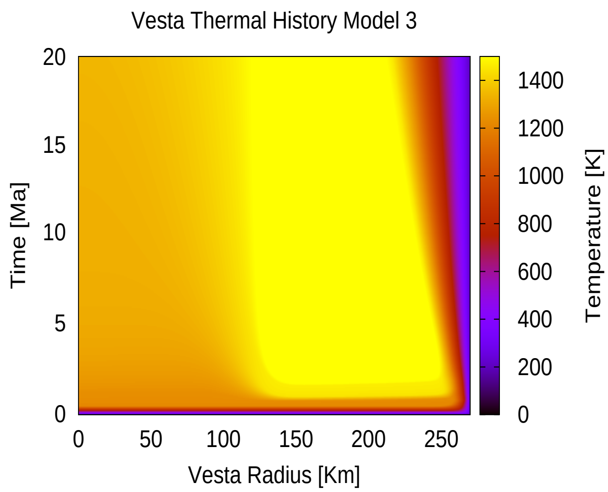

Figure 2: Temporal evolution of the radial temperature profile of Vesta for the scenario with Δt_d = 1.08 Ma after 20 Ma.

Since our model does not take into account heat removal mechanisms other than conduction and irradiation at the surface, our results supply a reliable picture of the thermal history of Vesta up until the onset of the differentiation. As a consequence the scenarios characterized by $\Delta t_d < 1$ Ma reach unrealistic temperatures exceeding 2000K (see Fig.3)

Summary and Conclusions: When compared to the data provided by HED meteorites, our results suggest short accretion and differentiation times of Vesta

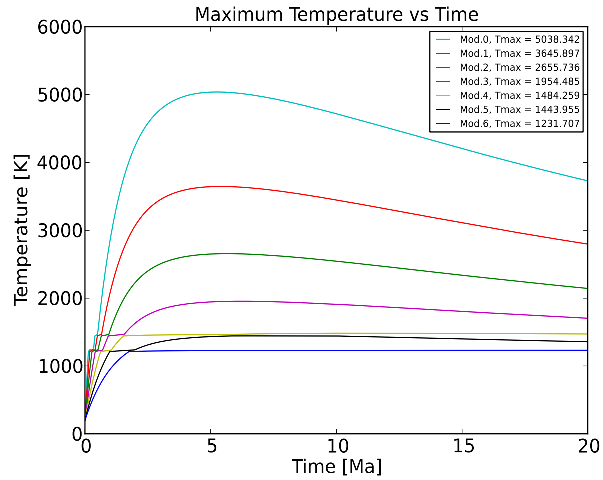

Figure 3: Maximum temperatures inside Vesta as a function of the time.

after CAIs. The scenarios characterized by $\Delta t_d > 2$ Ma show temperature not reaching the melting temperature of silicate and for this reason they are incompatible with the basaltic magmatism suggest by HEDs ([9,10]). In the scenarios with 1.5 Ma $< \Delta t_d < 2$ Ma, silicate melting occurs at about t = 6 Ma: this is incompatible with the crystallization ages of the oldest HEDs ([10,11]). Finally, values of $\Delta t_d < 1$ Ma are the most compatible with the geologic history of Vesta as suggested by HEDs, but we stress the fact that our model does not consider any heat removal mechanisms and the convection. Our present model, however, allows us to delineate the heating history of Vesta, putting important constraints on time scales of accretion and differentiation of the asteroid.

References: [1] Ghosh, A. and McSween, H., 1998, Icarus 134, 187-206. [2] Castillo-Rogez,J. et al., 2007, Icarus 190, 179-202. [3] Nield, D.A. and Bejan, A., 2006, Springer, 402. [4] Yoshino, T. et al, Earth and Planetary Science Letter, 222,652-643. [5] Nafi Toksoz, M. et al., Thermal History and Evolution of the Moon, 1972. [6] Lewis, J.S., 1974 ,Science 186, 440-443. [7] Castillo-Rogez,J. et al., 2009, Icarus 204, 658-662. [8] Urey H. C., 1955, Proc. Natl. Acad. Sci. U.S., 41, 127. [9] Keil, K. et al., 2002, Asteroids III (Tucson:University Arizona Press), p. 573 [10] Bizzarro, M. et al., 2005, ApJL., 632, L41-L44. [11] Schiller, M. et al., 2011, ApJL 740 L22. [12] Thomas, P.C. et al., 1997b, Icarus 128, 88-94 [13] Hertz, H.G., 1968, Science 160, 299-300 [14] Scott, E.R.D., 2007, An.Rev.of Earth and Planet.Sci, 35, 577