The primordial history of Vesta and the Jovian Early Bombardment. D. Turrini[1], A. Coradini[1], C. Federico[2], M. Formisano[1,3], G. Magni[1], [1] Institute for Space Astrophysics and Planetology INAF-IAPS, via Fosso del Cavaliere 100, 00133 Rome, Italy (e-mail: diego.turrini@ifsi-roma.inaf.it); [2] Department of Earth Science, University of Perugia, Perugia, Italy; [3] Department of Physics, University of Rome "La Sapienza", Rome, Italy.

Introduction: The first phase in the lifetime of the Solar System is that of the Solar Nebula, when the Solar System was constituted by a circumsolar disk of gas and dust particles where planetesimals and planetary embryos were forming. This phase is assumed to start about 4569 Ma ago [1] with the condensation of the Ca-Al-rich inclusions and to end in less than 10 Ma [2] with the dispersal of the nebular gas.

Across this $\Delta T < 10$ Ma timespan planetary accretion was acting in the Solar Nebula to form the planetesimals, the planetary embryos and the giant planets. According to meteoritic evidences, some of the accreting planetesimals differentiated extremely early in the history of the Solar System, i.e. about 1-2 Ma after the formation of CAIs (see [3] and references therein). Such primordial differentiation was due to the presence of short-lived radionuclides, mainly ^{26}Al and ^{60}Fe in bodies larger than 20 - 30 km in radius (ibid). The spectral connection between Vesta and the Howardite-Eucrite-Diogenite (HED) suite of achondritic meteorites indicated that Vesta was among the planetary bodies which formed and differentiated very early in the history of the Solar System (see e.g. [3,4] and references therein). Moreover, recent results [5] suggest that the differentiation of Vesta completed and the interior of the asteroid was largely solidified only a few Ma after CAIs, i.e. about an order of magnitude earlier than previously estimated basing on the size of Vesta.

In the following we report the first results of our crossed investigation of the thermal history of Vesta [6] and of the effects on Vesta of the primordial bombardment triggered by the formation of Jupiter in the Solar Nebula [7]. The goal of this project is to assess if the Dawn mission could allow us to probe a previously unexplored phase in the life of the Solar System.

The thermal evolution of Vesta: The preliminary results of our thermal model [6] allow us to assess the heating history of Vesta and to constrain the accretion and differentiation timescales of the asteroid. When compared with the HED meteorites, our results suggest that Vesta should have completed its accretion in less than 1 Ma (see Fig. 1 and [6]) after the condensation of CAIs and/or the injection of ^{26}Al in the Solar Nebula.

For accretion times of about 2 Ma, Vesta would never reach the melting temperature of silicates [6], in contrast with the achondritic nature of the HED meteorites. For accretion times of about 1.5 Ma, moreover, Vesta would reach the melting temperature of silicates only after 6 Ma [6], in contrast with the crystallization ages of the oldest Diogenites [5].

We refer the interested reader to the abstract by Formisano et al. for more details on our thermal model of Vesta and the constrains on its formation and thermal histories.

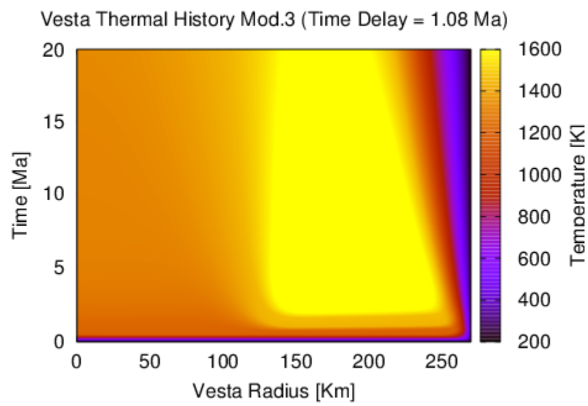

Figure 1: thermal evolution of Vesta over 20 Ma due to the decay of short-lived radionuclides assuming an accretion time of Vesta of 1.08 Ma [6].

The Jovian Early Bombardment: Our results [7] indicates that the formation of Jupiter caused a phase of primordial bombardment we labeled the Jovian Early Bombardment (JEB in the following). While the migration of Jupiter enhances the intensity of the JEB due to the sweeping of the resonances across the asteroid belt, the formation of the giant planet is necessary and sufficient condition for triggering the JEB [7]. Planetesimals from both the inner and the outer Solar System participate to the JEB, but the leading role in determining the effects of the JEB is played by the planetesimals affected by the 3:1 and the 2:1 resonances with Jupiter [7]. The survival of the considered target bodies to the JEB depends on the size distribution of the planetesimals populating the Solar Nebula, the abundance of large planetesimals (i.e. D > 100 km) in the disk being a critical factor to this regard [7,8]. Another critical factor is the location of the target bodies respect to the two previously mentioned resonances [7,8]. If the disk of planetesimals was dominated by large bodies, like in the case of planetesimals formed in turbulent circumstellar disks, the JEB would cause the ablation of bodies of 500 km or smaller [8]. Conversely, disks dominated by small planetesimals (i.e. D < 20 km), like those formed in quiescent circumstellar disks or produced by collisional evolution, represent more favorable environments for the survival of bodies of 200 km or bigger [8]. Planetesimals of 200 km, however, would survive only in the scenario where Jupiter's migration was limited [8]. In all other scenarios, they are generally disrupted if Jupiter migrated by 05 AU or more [8].

	Collisionally evolved planetesimals (Morbidelli et al. 2009)			
Migration Scenario	N_{coll}	Crustal Erosion (km)	$Q_D/Q^*_D \geq 0.01$	$Q_D/Q^*_D \geq 1$
No Migration	15158.5	0.17	0.00	0.00
0.25 AU	20976.3	0.21	0.00	0.00
0.50 AU	36132.1	1.61	0.66	0.00
1.00 AU	66419.1	11.57	5.09	0.01

Table 1: the JEB on Vesta [9] due to collisionally evolved planetesimals following the size-frequency distribution of the best-fit case from [10].

Vesta and the JEB: Vesta and Ceres [7] would undergo an intense cratering that would saturate their surfaces with craters as big as 150 km, with a tail of few bigger craters (200-300 km). Due to its lower gravity, Vesta would undergo a higher degree of surface erosion than Ceres due to the JEB [7,8,9]. Under the simplifying assumption of a uniform distribution of the craters, on Vesta the JEB could excavate up to a depth of about 10 km (see Table 1 and [9]). A more realistic estimate, where about 70% of the impacts would concentrated between +45° and -45° of latitude, yields excavation depths twice as high in such an equatorial belt. Moreover, assuming a conservative depth-to-diameter ratio of 1:7, the JEB could excavate the crust of Vesta either locally or regionally [7,9].

The role of Vesta in unveiling the history of the Solar System: The geophysical history of Vesta. as inferred by HED meteorites, suggests that its differentiation ended in a few Ma: as such, Vesta could be the only body we know of whose solid crust was already formed and whose interior was mostly solidified at the time of the formation of Jupiter. This hypothesis is supported also by the preliminary results of our theoretical studies of the thermal history of Vesta (see Fig. 1 and [6]), even if they presently do not yet allow us to estimate the cooling history of Vesta. Depending on the relative timing between the formation of Jupiter and the differentiation of Vesta, the local or regional excavation of the primordial crust of the asteroid could have caused large-scale effusive phenomena similar to the Lunar maria [7,9]. In all scenarios, moreover, the JEB would have saturated the surface of Vesta and likely covered the asteroid with a regolith layer [7,9]. This could have affected the mechanical properties of the Vestan surface and thus the later cratering events due to the collisional evolution of the asteroid belt. The data that the Dawn mission is presently collecting on Vesta will allow us to test the Jovian Early Bombardment hypothesis and to investigate the early evolution of the Solar System [11].

References: [1] Bizzarro M. et al. (2005). ApJL, 632, L41-L44; [2] Meyer M. R.(2008). Proc. of Intern. Astron. Union, 4, 111; [3] Scott E. R. D. (2007), An. Rev. of Earth and Planet. Sci., 35, 577; [4] Keil K. (2002), in Asteroids III, Eds. W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, University of Arizona Press; [5] Schiller M. et al. (2011). ApJL, 740, L22; [6] Formisano M., Federico C., Coradini A., Turrini D. (2011), abstract presented at the EPSC-DPS 2011; [7] Turrini D., Magni G., Coradini A. (2011), MNRAS, 413, 2439; [8] Turrini D., Coradini A., Magni G. (2011). ApJ, under revision. [9] Turrini D., Coradini A., Magni G., Formisano M., Federico C. (2011), abstract presented at the EPSC-DPS 2011; [10] Morbidelli A., Bottke W. F., Nesvorny D., Levison H. F. (2009), Icarus, 204, 558; [11] Coradini A., Turrini D., Federico C., Magni G. (2011). SSR, DOI 10.1007/s11214-011-9792-x.

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