BULK COMPOSITION OF VESTA AS CONSTRAINED BY THE DAWN MISSION AND THE HED METEORITES. M.J. Toplis[1], H. Mizzon[1], O. Forni[1], M. Monnereau[1], T.H. Prettyman,[2] H.Y. McSween,[3] T.J. McCoy,[4] D.W. Mittlefehldt,[5] M.C. De Sanctis[6], C.A. Raymond,[7] C.T. Russell,[8]. [1]University of Toulouse (mtoplis@irap.omp.eu), [2]Planetary Science Institute, [3]University of Tennessee, [4]Smithsonian Institution, [5]NASA Johnson Space Center, [6]IAPS-INAF, Rome, [7]JPL, Caltech, Pasadena, [8]University of California, Los Angeles.

Introduction: Of the objects in the main asteroid-belt, Vesta is of particular interest as it is large enough to have experienced internal differentiation (520 km diameter), and it is known to have a basaltic surface dominated by FeO-bearing pyroxenes (e.g. [1]). Furthermore, visible-IR spectra of Vesta and associated Vestoids are remarkably similar to laboratory spectra of Howardite-Eucrite-Diogenite (HED) meteorites, leading to the paradigm that the HEDs ultimately came from Vesta (e.g. [2]). Geochemical and petrological studies of the HEDs confirm the differentiated nature of the near-surface region of their parent body, and imply that crust extraction occurred well within the first 10 Ma of solar system history (e.g. [3]).

Vesta is therefore a prime target for studies that aim to constrain the earliest stages of planet building, and it is within this context that the NASA Dawn spacecraft [4] orbited Vesta from July 2011 to September 2012. The results of the Dawn mission so far have significantly reinforced the HED-Vesta connection, confirming a significant degree of internal differentiation [5], a surface mineralogy compatible with that of the HEDs [6], and near-surface ratios of Fe/O and Fe/Si consistent with HED lithologies [7].

The combination of data from the HED meteorites and the Dawn mission thus presents an unprecedented opportunity to use Vesta as a natural laboratory of early differentiation processes in the early solar system. However, the bulk composition of Vesta remains a significant unknown parameter, but one that plays a key role on the physical and chemical properties of the internal and surface reservoirs (core, mantle, crust). Several attempts have been made to constrain the bulk composition of the eucrite parent body, early endeavours relying on petrological or cosmochemical constraints (e.g. [8]). More recently, individual chondrite-class compositions, or mixtures thereof, have been considered, constrained by considerations such as O-isotopes, trace-element ratios and siderophile element concentrations of the eucrites [9-11].

The work presented here builds upon these latter studies, with the primary aims of: i) illustrating the potential diversity of the geochemical and geophysical properties of a fully differentiated Vesta-sized parent body, and ii) assessing which, if any, of the known chondritic bulk compositions are plausible analogues for proto-Vesta.

Methods and general approach: Despite the consensus that the primitive building blocks of the solar system were "chondritic", diverse classes of chondrite exist, from the volatile-rich Ivuna-class (CI), to metal-poor varieties such as the LL ordinary chondrites, to highly reduced types such as enstatite chondrites. While there is no guarantee that Vesta accreted from known chondritic precursors, these compositions provide a convenient reference frame. Twelve chondritic compositions are considered here, comprising 7 carbonaceous groups (CI, CV, CO, CM, CK, CR, CH), the three ordinary chondrite groups (H, L, LL) and the two enstatite chondrite groups (EH, EL). Significant differences in composition exist between these groups, notably in terms of Mg/Si, S and Fe content, volatile content, oxidation state of Fe, and the concentration of incompatible lithophiles such as the REE. The role of these factors on the mineralogy and internal structure of a fully differentiated parent body will be explored.

Because our aim is to quantify the first-order effects of differentiation, we focus on those chemical elements that dominate the mass of the bulk object (Si, Al, Mg, Ca, Ti, Na, Fe, Ni, S, O). Minor and trace elements (e.g. Mn, REE) are considered where they provide complementary constraints. The basis of our analysis consists of distributing each chemical element between one or more of the principal differentiated geochemical reservoirs (core, mantle, crust), assuming a distribution that is consistent with the thermodynamics of element partitioning at magmatic temperature, in particular that for Fe-Mg. An iterative process is applied to find the iron content of the core for a given bulk composition that results in a bulk $Kd^{Mg-Fe}_{mantle-Juvinas}$ that is consistent with relevant olivine-pyroxene mixtures, assuming that the primitive main-group eucrite Juvinas is a first-order proxy of Vesta's crust. Further details of the methods used can be found in [12].

In this way, estimates of the relative masses of the core (Fe-Ni-S), the mantle and the basaltic crust are provided. In detail, the core is divided into a sulphide and a metal component. Relative masses may be converted to absolute masses using the mass of Vesta as determined by the Dawn mission [5]. Masses are converted to volumes using mineral densities (see [12]). The total volume is calculated for each bulk composition and compared with the measured volume of Vesta [5], differences being assigned to porosity.

Constraining bulk composition: *Core size and density.* All bulk compositions tested have a significant core, but the relative proportions of metal and sulphide can be widely different. No satisfactory thermodynamic solution exists for the CI and LL groups. For the other groups, the metal fraction (relative to sulphide) is predicted to be as little as ~20% (in the case of a CM bulk composition), to almost 100% (in the case of a CH bulk composition). Core size (radius) is typically predicted to be in the range 90 to 120 km, although total core size (metal+ sulphide) and average core density nevertheless span significant ranges (Fig. 1).

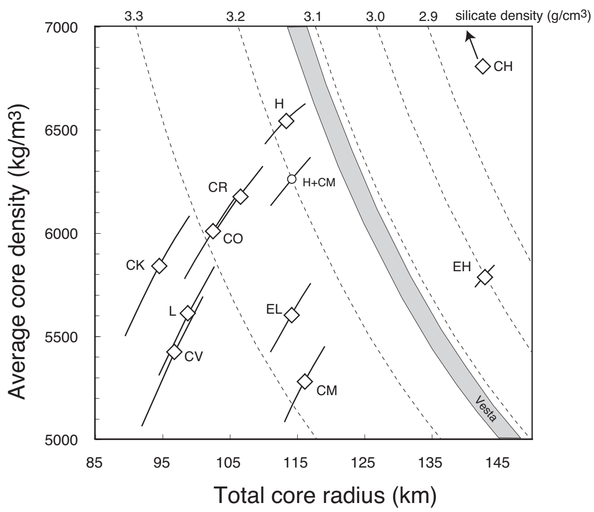

Fig. 1. Optimal values of total core radius and average core density (open symbols), and an indication of the range of possible solutions (solid lines). The range of values constrained by the Dawn mission is shown as a grey band.

The bulk density of Vesta and its J2 gravity coefficient determined by the Dawn mission provide an independent constraint on internal mass concentration. Using simple 2-layer models, it may be shown that for reasonable values of oblateness, the density of the upper silicate layer is in the range 3050- 3140 kg/m^3 [5], constraining core size and density as illustrated in Fig. 1. Interestingly, none of the predicted cores provide a perfect match to the geophysically constrained range of acceptable values, although the closest approach is for H-chondrite composition.

Composition and mineralogy of the crust-mantle system. The geochemistry of HEDs also provides insight into the bulk composition of Vesta. For example, with the estimates of core size and composition above it is possible to calculate the Fe/Mn ratio of the mantle and compare this with geochemical data from the eucrites. This exercise shows that carbonaceous chondrites have predicted Fe/Mn well above observed values, while the H-chondrite and enstatite-chondrite bulk compositions provide satisfactory agreement. We have also considered if it is possible to generate Juvinas-like liquids at appropriate degree of melting/crystallization using the MELTS thermodynamic calculator, considered the calculated mineralogy of the mantle and the likelihood of generating abundant pyroxene lithologies such as diogenites, as well as calculating crustal thickness. For all criteria, a Na-depleted H-chondrite bulk composition provides the best fit, although oxidation state and O-isotopes are not perfectly reproduced, suggesting that bulk Vesta may contain ~25% of a CM-like component [11].

Identification of an acceptable bulk composition is an important step forward, as it opens the possibility to predict the mineralogy and composition of solid and liquid products over wide ranges of partial melting and crystallization (e.g. the phase diagram shown in Fig. 2), providing a useful and self-consistent reference frame for interpretation of the Dawn data. Furthermore, knowledge of the bulk composition (core and bulk silicate) provides essential constraints for thermal and physical models of Vestan evolution at high temperature that may ultimately lead to a better understanding of the differentiation process on protoplanetary bodies such as Vesta (e.g.[13]).

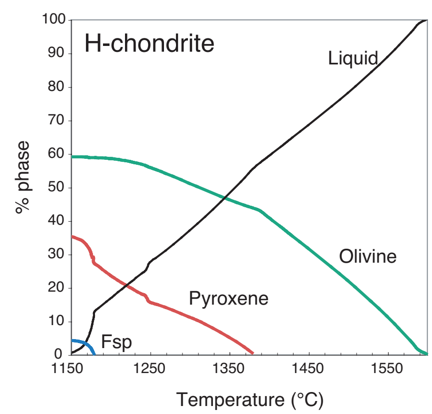

Fig. 2. Preliminary phase diagram for the bulk-silicate fraction of Vesta derived from a Na-depleted H-chondrite source.

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