CHONDRITIC MODELS OF 4 VESTA: COMPARISON OF PREDICTED INTERNAL STRUCTURE AND SURFACE COMPOSITION/MINERALOGY WITH DATA FROM THE DAWN MISSION.

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Introduction: Understanding the physical and chemical processes which led to the formation of the terrestrial planets remains one of the principal challenges of the Earth and planetary science communities. However, direct traces of the earliest stages of planet building have generally been wiped out on larger bodies such as the Earth or Mars, obscuring our view of how that process occurred. On the other hand, the planet building process would appear to have been arrested prematurely in the region between Mars and Jupiter, now populated by several hundred thousand compositionally diverse objects that escaped accretion into larger planets. Of these, the asteroid 4 Vesta is of particular interest as it is large (520 km diameter), and known to have a basaltic surface dominated by pyroxenes [1, 2]. Furthermore, visible-IR spectra of Vesta obtained by ground and space-based telescopes are remarkably similar to laboratory spectra measured on meteorites of the Howardite-Eucrite-Diogenite clan (HED), leading to the paradigm that the HEDs came from Vesta [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 10Ma of solar system history [3]. Vesta is therefore a prime target for studies that aim to constrain the earliest stages of planet building, and for that reason it is currently the subject of the Dawn mission [4].

The Dawn spacecraft has been in orbit around Vesta since July 2011 and will remain there through much of 2012. During this time the instruments onboard have already provided unprecedented insight into the physical and gravitational characteristics of the asteroid [5], and will continue to provide increasingly detailed information concerning surface morphology, mineralogy and chemistry.

The importance of bulk composition. While the HEDs provide an extremely useful basis for interpreting data from the Dawn mission, there is no guarantee that they provide a complete vision of all possible crustal (and possibly mantle) lithologies that are exposed at the surface of Vesta [6]. With this in mind, an alternative approach is to identify plausible bulk compositions and use mass-balance and geochemical modelling to predict possible internal structures and crust/mantle compositions and mineralogies. While such models must be consistent with known HED samples, this approach has the potential to extend predictions to thermodynamically plausible rock types that are not necessarily present in the HED collection.

Possible bulk compositions. The meteorite collection in general suggests that the primitive building blocks of the solar system were "chondritic" in composition. However, diverse classes of chondrite exist, from the volatile-rich Ivuna-class (CI), to metal-poor varieties such as the LL ordinary chondrites [7]. For illustrative purposes 9 chondritic groups will be considered here (CI, CV, CO, CM, H, L, LL, EH, EL). It is of note that none of these groups provide a perfect match to the O-isotope composition of the HED parent body. Bulk Vesta could either represent an unknown type of chondrite (a possibility suggested by extreme depletion in volatiles such as Na) or it could be a mixture of two or more known groups. For example, a mixture of ~2/3 H, 1/3 CM has been shown to be capable of reproducing both the oxygen isotopic composition and the Fe-Mn-Mg systematics of the HEDs [8].

Implications for internal structure. Each class of chondrite is different in composition, in terms of sulphur and iron content, in terms of volatile depletion, and in terms of the concentration of incompatible lithophiles such as the REE [7]. As such, for fully differentiated bodies (consisting of core-mantle-crust) the relative proportions and densities of each of these three reservoirs will be different. In general terms, the core will consist of a mixture of Fe-sulphide and Fe-Ni metal while the mantle will be dominated by olivine+pyroxene. The "crust" is assumed here to have the composition of the primitive basaltic eucrite, Juvinas (generated either by partial melting of the bulk silicate fraction, or as a residual liquid of magma-ocean crystallization).

Quantification of the relative proportions and densities of the three principal reservoirs is complicated by the fact that iron may occur in metallic form (in the core) and/or in oxidized form (in the mantle and crust). However, making the assumption that the crust has the composition of Juvinas makes it possible to calculate a single solution to this problem for a given bulk composition. This is because the thermodynamics of Fe-Mg partitioning between basaltic liquid (crust) and olivine (mantle) are well constrained [9], the FeO/MgO of Juvinas thus fixing the FeO/MgO of the mantle. Furthermore, assuming that the REE are perfectly incompatible (i.e. only in the crust), the REE content of Juvinas relative to the assumed bulk composition can be used to calculate the relative proportion of crust and mantle. Given that Mg does not enter the core, mass balance considerations demonstrate that the only way to satisfy the FeO/MgO of the silicate reservoirs is to sequester a fraction of the available iron in the core. Of this iron, some is associated with sulphur (in the form of FeS, controlled by the S-content of the bulk), the remainder occurring in metallic form. In this way, nine different solutions were found.

Of these, solutions corresponding to CI and LL groups predicted a negative metal fraction and were not considered further. Solutions for enstatite chondrites imply significant oxidation relative to the starting materials and these solutions too are considered unlikely. The relative proportion of crust to bulk silicate is typically in the range 15 to 20% corresponding to crustal thicknesses of 15 to 20 km for a porosity-free Vesta-sized body. The mantle is predicted to be largely dominated by olivine (>85%) for carbonaceous chondrites, but to be a roughly equal mixture of olivine and pyroxene for ordinary chondrite precursors. All bulk compositions have a significant core, but the relative proportions of metal and sulphide can be widely different, from the metal dominated case of H-chondrites to the sulphide rich case of CM-chondrites. Using these data, total core size (metal+ sulphide) and average core densities can be calculated (Fig. 1), providing a useful reference frame within which to consider geophysical/gravity data of the Dawn mission.

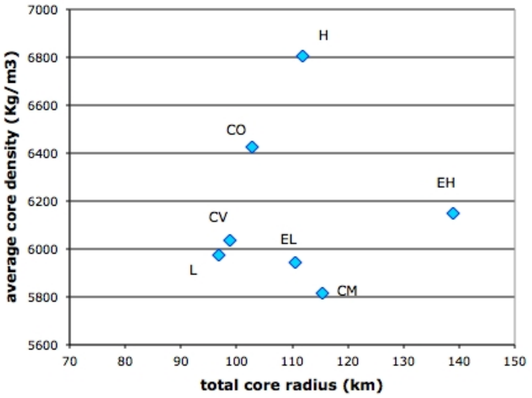

Figure 1. Calculated core size and core density for a Vesta-sized body of different chondritic bulk composition.

Near surface composition and mineralogy. Although the mass-balance approach just described provides useful insight into plausible internal structure, it has no predictive power concerning the composition and/or mineralogy of the crust. For these aspects the MELTS thermodynamic calculator [10] has been used to assess to what extent chondritic bulk compositions can produce Juvinas-like liquids at relevant degrees of partial melting/crystallization. In agreement with experimental studies, [e.g. 11] it is found that certain chondritic compositions (e.g. H) cannot lead to eucrite-like liquids, calculated silica contents being well above those observed. However, further simulations show that if Na content in the bulk is reduced, then a good match to Juvinas is found for all major oxides at a degree of partial melting consistent with the REE data (Fig. 2). This raises the question of whether the HED parent body was assembled from Na-depleted building blocks, or whether Na was lost during differentiation. Further work is in progress to refine acceptable bulk compositions and to predict the mineralogy and composition of the associated solid and liquid products over wide ranges of partial melting and crystallization. This analysis will provide a useful and self-consistent reference frame for interpretation of the Dawn data.

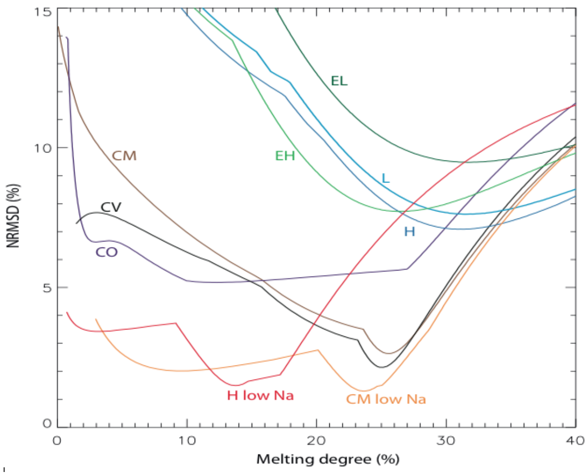

Figure 2. Normalized Root Mean Squared Deviation (NRMSD) of the composition of Juvinas compared to liquids calculated for various degrees of partial melting and bulk composition using MELTS [10]. « low Na » signifies that the sodium content of the bulk composition has been divided by ten. Lower values of NRMSD correspond to closer agreement with the composition of Juvinas.

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