MODELLING THE THERMAL HISTORY OF ASTEROID 4 VESTA. J. M. Solano[1], W.S.Kiefer[2] and D. W. Mittlefehldt[1], [1] ARES, NASA/Johnson Space Center (james.m.solano@nasa.gov), [2] Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058

Introduction: The asteroid 4 Vesta is widely thought to be the source of the HED (Howardite, Eucrite and Diogenite) meteorites, with this link supported by spectroscopic and dynamical studies [1]. The availability of the HED meteorites for study and the new data being gained from the Dawn mission provides an excellent opportunity to investigate Vesta's history. In this study, modelling of Vesta has been undertaken to investigate its evolution from an unconsolidated chondritic body to a differentiated body with an iron core. In contrast to previous modelling, both heat and mass transfer are considered as coupled processes. This work draws on models of melt segregation in terrestrial environments to inform the evolution of Vesta into the differentiated body observed today.

In order for a core to form in this body, a separation of the metallic iron from the silicates must take place. Temperatures in excess of the solidus temperatures for the Fe-FeS system and the silicates are therefore required. The decay of short lived radio-nuclides, primarily ^{26}Al and ^{60}Fe with half lives of 0.72Myr and 2.6Myr respectively, provides the heat source for this melting early in solar system history. (This recently revised measurement of the ^{60}Fe half life suggest its decay may be less important than previously thought [2].) Evidence from excess ^{26}Mg in eucritic plagioclase, showing crystallization ages within 5Myr of CAI formation, and ^{53}Mn-^{53}Cr dating, showing igneous activity as early as 3Myr, support an early formation of Vesta [3].

Thermal modelling has shown accretion before 2Myr leads to temperatures in excess of the silicate solidus [4]. By removing the metallic component, either at a constant rate or instantaneously, ^{26}Al becomes quantitatively concentrated in the mantle enhancing heat production in the silicates and eventually the formation of a magma ocean, whilst ^{60}Fe becomes concentrated in the core [5]. At low melt fractions, formation of the core requires the segregation of the metallic iron from the silicates and occurred early in Vesta's history. To segregate metal into the core, an interconnected pore space must be present through which melt can move. Recent experiments on olivine-Fe-Ni-S mixtures show an interconnected pore space forms at 1273K and above 2.5GPa [6] though centrifuge experiments suggest significant melt segregation may not occur until the onset of silicate melting [7]. Melting and deformation experiments on H6 chondrites however, show at low melt fractions, ~5%, metallic melt can migrate at strain rates of $10^{-6}s^{-1}$ [8]. Timescales of $<10^4$yrs are expected for the transport of metallic melt in 100km size asteroids via porous flow under these circumstances.

Numerical Methods: A system of governing equations, solving for conservation of energy, mass and momentum, has been developed and applied to the problem of heating and phase change due to radioactive decay in a spherically symmetric body. This coupled system of equations is then solved numerically using finite difference methods.

Heat is supplied to the body via the decay of both ^{26}Al and ^{60}Fe, with their abundances determined from canonical CAI ratios. Heating due to gravitational effects and impacts are ignored, as they generate a much smaller amount of heat than provided via radioactive decay.

Accretion is accounted for by increasing the number of nodes within the model at a pre-determined rate, consistent with both planetary growth models [9] and previous thermal modelling [10]. As growth of Vesta likely occurred before the oligarchic stage, the rate of increase in radius is constant with time [11].

Sintering, the process whereby the accreted dust grains clump together forming larger grains as temperature increases, is also modelled. Sintering begins at a temperature of 670K and is complete at 700K. Over this temperature range, physical properties (e.g. porosity, thermal conductivity, specific heat capacity) change in a sigmoidal fashion from pre- to post-sintered values [10]. Associated with the sintering is volume loss and therefore nodes in the simulation are designed to be constant mass and are able to vary in size. As initial porosity is 50%, sintering reduces the total volume of the body to half the original volume, conserving mass.

Recent gravity surveys undertaken during the Dawn mission have suggested the core is ~110km in radius [12]. A core of this size implies, assuming total separation of the metallic iron from the silicates, an initial metallic content of ~15%. This value is similar to that observed in the H-chondrites and used by previous authors in modelling the bulk composition of Vesta [13]. This initial composition determines the physical properties locally. An increase in core radius to 120km however, requires ~20% initial metallic content and a decrease to 100km requires an iron content of 10%, again assuming completes separation. Other chondritic compositions, e.g. L, LL and CI, may serve as better initial compositions and have been used for the Vestan bulk composition [14]. These compositions are also considered as the starting material.

Significant melt generation and migration takes place after the onset of silicate melting at 1400K. Once a high enough melt fraction is attained, generated locally either through melt transport or phase change, the bulk rheology will change from solid, dominated by compaction, to liquid, dominated first by crystal settling and then convection at higher temperatures. This takes place at melt fractions in the region of 40-60% and represents the transition to the magma ocean. The current model only describes the first process, compaction, with future developments including the transition to crystal settling and parameterised convection.

Results: Accretion and sintering of Vesta, followed by melting and then segregation can lead to complex thermal histories. A range of unknowns, such as accretion rate and accretion time, have been tested yielding a range of cases.

Accretion and Sintering: Very high accretion rates tend to the case of instantaneous accretion as presented by previous authors. In these cases, the body is fully accreted before sintering takes place and a small thermal gradient is present in the bulk of the body. For slower accretion rates, the thermal gradient from centre to surface increases. In these cases, the solidus front of the Fe-S system moves from the centre outward with time as heating takes place leading to regions both with and without melt present. For slower accretion rates, sintering can begin to take place at the centre of the body before accretion is complete leading to two separate regions: the first is consolidated with higher thermal conductivity at the centre and the second is an unconsolidated region at the surface with lower thermal conductivity. Late accretion times lead to temperatures too low to lead to wide-scale melting in agreement with previous authors.

Melt Segregation: Melt segregation speeds are dependent on the acceleration due to gravity, which can be determined locally in the model, varying from the centre where they are lowest, to the surface where they are highest. The maximum gravity at the surface of Vesta is $0.27 ms^{-2}$; ~30 times lower than in the terrestrial environment. The decrease in segregation rates, due to lower gravity, is buffered by the high density contrast of metal-silicate systems, $\Delta\rho$ ~$3500 kgm^{-3}$ compared to ~$500 kgm^{-3}$ in silicate-silicate systems. Lower viscosities for the metallic liquid than silicate liquids also help increase the segregation rate.

Using the time- and length-scales of the McKenzie formulation [15], characteristic segregation rates of 2.38km/yr and characteristic segregation times of 16.7yrs are found over length-scales of 39km, dependent on grain size. Characteristic segregation times are small due to the low viscosity of metallic melt, as low as 0.01Pa.s [6], and the high density contrast present in the system.

After melting begins, melt can migrate rapidly downwards, forming an iron rich region before the onset of wide-scale silicate melting.

Regolith: At the surface of the body, before temperatures exceed the sintering temperature, unconsolidated material remains. The thickness of this layer decreases with time as the body heats and consolidates, eventually leaving a veneer of insulating material with lower thermal conductivity at the surface. The thickness of this layer is typically of the order of 5-10km and varies with time. This layer arises naturally as part of the formation process without the need to externally force a mega-regolith. Removal of this layer via bombardment or eruption of magma at the surface will limit the ability of the body to retain heat due to increased thermal conductivity, increasing the cooling rate.

Conclusions: Accretion and sintering can lead to variations in temperature and lead to the production of an insulating regolith layer at the surface. The underlying material becomes consolidated and begins melting. Using a multiphase formulation of compaction, segregation times can be determined within the model, without the need to introduce external parameters. Iron-rich melt migrating downwards at low melt fractions provides an efficient mechanism for core formation to begin before large scale silicate melting.

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