CORE FORMATION AND EVOLUTION OF ASTEROID 4 VESTA

Walter S. Kiefer[1] and David W. Mittlefehldt[2], [1]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, kiefer@lpi.usra.edu, [2]Astromaterials Research Office, NASA/Johnson Space Center, Houston TX 77058, david.w.mittlefehldt@nasa.gov.

Introduction

The howardites, eucrites, and diogenites (HEDs) are a suite of related meteorite types that formed by igneous and impact processes on the same parent body [1]. Multiple lines of evidence, including infrared spectroscopy of the asteroid belt and the petrology and geochemistry of the HEDs, suggest that the asteroid 4 Vesta is the parent body for the HEDs [e.g., 2, 3]. Observations by NASA's *Dawn* spacecraft mission strongly support the conclusion that the HEDs are from Vesta [e.g., 4, 5].

The abundances of the moderately siderophile elements Ni, Co, Mo, W, and P in eucrites require that most or all of the metallic phase in Vesta segregated to form a core prior to eucrite solidification [6-8]. These observations place important constraints on the mode and timescale of core formation on Vesta. Possible core formation mechanisms include porous flow, which potentially could occur prior to initiation of silicate melting, and metallic rain in a largely molten silicate magma ocean. Once the core forms, convection within the core could possible sustain a magnetic dynamo for a period of time. We consider each process in turn.

Core Formation: Porous Flow

Melting in the Fe-FeS system begins at the eutectic temperature of 988 °C at 30 weight % S. Inclusion of a small amount of Ni will lower the eutectic temperature slightly and shift it towards lower S [9]. Existing models of the thermal evolution of Vesta all assume an Fe-Ni-S solidus of 940 °C and a near-eutectic liquidus of 960 °C [10-12] and thus require a relatively large amount of S in Vesta's core.

Assuming Vesta has sufficient S to have near-eutectic melting of the metal phase, the metal would be completely molten prior to the onset of silicate melting. At low melt fractions, liquid iron in solid silicates has a high dihedral angle and forms isolated pockets of melt [13]. The dihedral angle is a function of oxygen fugacity, with high values of fO_2 permitting connected sheets of liquid Fe [14], but Vesta likely formed under low oxygen fugacity conditions (at or below the iron-wustite buffer, [e.g., 7]). Even with a high dihedral angle, once the melt fraction of metal exceeds a few percent, connected melt channels are possible [15, 16]. Because of the low viscosity of liquid iron metal and its high density relative to silicates, Darcy flow in such connected melt channels will be efficient, allowing geologically rapid separation of the liquid metal from the solid silicate. However, this separation is likely to be imperfect: once most of the metal has drained from the silicate and the melt fraction drops below the critical level for maintaining connected channels, the channels may pinch off, trapping the last few percent of metal in the solid.

Core Formation: Magma Ocean Metallic Rain

A significant problem with the near-eutectic melting porous flow model outlined above is that the eutectic composition requires a large amount of sulfur (~30 weight %, [9]). In contrast, a recent study synthesized a broad range of constraints on Vesta's composition and favored a model composed of 75% H chondrite and 25% CM chondrite [17]. This corresponds to a core of 16 % S, 73.7 % Fe, and 10.3 % Ni, which is far removed from the Fe-FeS eutectic composition. For this low S abundance, melting of metal still begins at the eutectic temperature but does not conclude until about 1350 °C [9]. Because the HEDs are relatively depleted in volatile elements, it is possible that the S abundance will be even lower than this, which would shift the Fe-FeS liquidus to an even higher temperature. The solidus for the primitive silicate H+CM mantle is likely in the range 1100-1150 °C [18, 19]. Thus, metal and silicate melting are likely to overlap in time during the formation and differentiation of Vesta. It is worth noting that all published Vesta-specific thermal models assume that metallic melting is complete well before the onset of silicate melting [10-12]. Although the overall picture derived in those models is probably generally correct, some of the details of the inferred thermal evolution and differentiation history in those models must be incorrect. For example, in order to use Hf-W radiometric ages for metal-silicate separation [20] as a constraint on the thermal models, the metal liquidus used in the thermal model must be correct.

The viscosity of a suspension of silicate crystals in a silicate melt decreases by many orders of magnitude when the liquid fraction increases from 40% to 60% [21]. When full melting of the Fe-Ni-S metal phase is achieved at 1350-1400 °C, the silicates will be near 50% melt fraction. Assuming that Vesta formed in the first 2-3 half-lives of ^{26}Al after formation of CAIs in the solar nebula and incorporating the insulating effects of a low conductivity megaregolith layer [22], radioactive decay of ^{26}Al can easily heat Vesta to > 1400 °C, including the effects of latent heat for both the silicate and metal phases. At this stage of evolution, Vesta would effectively be a magma ocean.

Given the low viscosity of the silicate melt and the high density contrast between the metal and the silicate, metal blobs will fall to the center of Vesta by Stokes flow in a sort of metallic rain [23, 24]. Based on the various chemical and physical constraints outlined here, we favor a magma ocean and iron metal rain as the most likely method of forming a core on Vesta. Solidification of a magma ocean can also explain the compositional characteristics of the eucrites and diogenites [25].

Core Convection and a Magnetic Dynamo

Definitive observations of an intrinsic magnetic field on Vesta would constrain the structure and rate of cooling of the core and thus would provide important constraints on Vesta's thermal evolution. Unfortunately, *Dawn* did not include a magnetometer as part of its science payload. However, a remnanent magnetic field of at least 2 microtesla has been measured in the eucrite Allan Hills 81001 [26], which in turn implies that Vesta at some point in its history had a convecting liquid metal core.

The short-lived radioactive isotope ^{26}Al is a potent source of radioactive heating in the first few million years of Vesta's history and is concentrated in the silicate portion of Vesta. Thermal evolution models show that ^{26}Al heating of Vesta's mantle initially acts as a thermal blanket and strongly suppresses heat flux out of the core. Cooling of Vesta after ^{26}Al becomes extinct eventually allows the core to briefly convect, but in that model core convection ends before the crust cools below the Curie temperature, such that evidence for a magnetic dynamo would not be preserved [27].

However, several factors may modify this conclusion. First, melt migration in the silicate magma ocean transfers latent heat of melting from the interior to the near surface. Second, magmatism also transports aluminum in plagioclase from the mantle to the crust [28]. Both effects act to cool the mantle relative to models that do not include magmatism and thus reduce the thermal blanketing of the core. Third, ^{60}Fe is a possible radioactive heat source with a half-life that is several times longer than ^{26}Al. The abundance of ^{60}Fe in the solar nebula is controversial and was possibly spatially heterogeneous [29, 30], but ^{60}Ni anomalies in the eucrites Bouvante and Juvinas [31] point to the presence of ^{60}Fe in Vesta. Prior thermal evolution studies have often either neglected ^{60}Fe altogether [27] or assumed that it is 100% partitioned into the core [10, 11, 32]. It is likely that roughly equal amounts of Fe will be in the metal and the silicate portions of Vesta [17], but the much greater concentration of Fe in the core will contribute to driving core convection. We are currently assessing the effects of these factors using a modification of our model for the thermal evolution and dynamo activity on Mars [33]. This model accounts for the thermal evolution of both the core and mantle, including magmatic heat transport, and calculates transport of heat producing elements from the mantle to the crust using appropriate partition coefficients. Compositional convection in the core may also play a role in driving a geodynamo [34], although top-down solidification of the core could create a stably stratified core without a dynamo [35].

References [1] McSween et al., *Space Sci. Rev.* 163, 141-174, 2011. [2] Drake, *Meteoritics Planet. Sci.* 36, 501-513, 2000. [3] Keil, pp. 573-584 in *Asteroids III*, eds. Bottke et al., Univ. Arizona Press, 2002. [4] Russell et al., *Meteoritics Planet. Sci.*, in press, 2013. [5] McSween et al., *J. Geophys. Res.: Planets* 118, 335-346, jgre.20057, 2013. [6] Hewins and Newsom, pp. 73-101 in *Meteorites in the Early Solar System*, eds. Kerridge and Matthews, Univ. Arizona Press, 1988. [7] Righter and Drake, *Meteoritics Planet. Sci.* 32, 929-944, 1997. [8] Holzheid and Palme, *Meteoritics Planet. Sci.* 42, 1817-1829, 2007. [9] Fleet, *Rev. Mineral. Geochem.* 61, 365-419, 2006. [10] Ghosh and McSween, *Icarus* 134, 187-206, 1998. [11] Gupta and Sahijpal, *J. Geophys. Res.* 115, 2009JE003525, 2010. [12] Formisano et al., *Meteoritics Planet. Sci.*, in press, 2013. [13] Shannon and Agee, *Geophys. Res. Lett.* 23, 2717-2720, 1996. [14] Terasaki et al., *Earth Planet. Sci. Lett.* 232, 379-392, 2005. [15] Yoshino et al., Earth Planet. Sci. Lett. 222, 625-643, 2004. [16] Roberts et al., *Geophys. Res. Lett.* 34, 2007GL030497, 2007. [17] Toplis et al., *Meteoritics Planet. Sci.*, in press, 2013. [18] Jurewicz et al., *Geochim. Cosmochim. Acta* 57, 2123-2139, 1993. [19] Jurewicz et al., *Geochim. Cosmochim. Acta* 59, 391-408, 1995. [20] Kleine et al., Geochim. Cosmochim. Acta 68, 2935-2946, 2004. [21] Cashman and Sparks, *Geol. Soc. Am. Bull.* 125, 664-690, 2013. [22] Haack et al., *J. Geophys. Res.* 95, 5111-5124, 1990. [23] Höink et al., *Geochem. Geophys. Geosys*. 7, 2006GC001268, 2006. [24] Ichikawa et al., *J. Geophys. Res.* 115, 2009JB006427, 2010. [25] Mandler and Elkins-Tanton, *Meteoritics Planet Sci*., in press, 2013. [26] Fu et al., *Science* 338, 238-241, 2012. [27] Roberts et al., *Workshop on Planetesimal Formation and Differentiation*, abstract 8033, 2013. [28] Moskovitz and Gaidos, *Meteoritics Planet. Sci.* 46, 903-918, 2011. [29] Quitté et al., *Astrophys. J.* 720, 1215-1224, 2010. [30] Moynier et al., *Astrophys. J.* 741, 71, 2011. [31] Quitté et al., *Geochim. Cosmochim. Acta* 75, 7698-7706, 2011. [32] Neumann et al., *Astron. Astrophys*. 543, A141, 2012. [33] Sandu and Kiefer, *Geophys. Res. Lett*. 39, 2011GL050225, 2012. [34] Nimmo, *Geophys. Res. Lett.* 36, 2009GL037997, 2009. [35] Williams, *Earth Planet. Sci. Lett.* 284, 564-569, 2009.