METEORITE AND THEORETICAL CONSTRAINTS ON THE CRYSTALLIZATION OF ASTEROIDAL CORES: INSIDE-OUT OR OUTSIDE-IN? J. Yang[1], J. I. Goldstein[1], and E. R. D. Scott[2], [1]Dept of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA. E-mail: jiyang@ecs.umass.edu. [2]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA.

Introduction: Asteroid cores which fractionally crystallized are believed to be the source of the magmatic groups of iron meteorites (those lacking significant silicate inclusions, e.g. IIAB, IIIAB, IVA, etc.) [1], but the manner in which these cores crystallized has been debated. Conventionally, well-mantled metallic cores are thought to have crystallized from the outside-in [2,3], but there is little direct evidence to support this assumption. Metallographic cooling rates and fractional crystallization models for iron groups IIIAB and IVA provide evidence of outside-in crystallization, but the metallic cores of their parent bodies were probably covered by less than a few km thickness of mantle materials during crystallization [4,5]. On the other hand, the cores of the asteroids or protoplanets that generated the IVB iron meteorite and main group pallasite bodies crystallized inside-out prior to impacts that exposed the solid cores [6-8]. Fractional crystallization of a core, like a dynamo-generated magnetic field, requires vigorous convection to ensure chemical homogeneity. Here we discuss why some asteroidal cores crystallized inside-out rather than outside-in and attempt to reconcile meteorite, experimental, and theoretical constraints.

Meteorite Evidence: Major evidence for either inside-out or outside-in crystallization of metallic cores in asteroidal bodies comes from iron meteorites and pallasites. Chemical analysis of several large iron groups, experimental determinations of elemental distribution coefficients between solid and liquid metal, and theoretical models indicate which iron meteorite groups are from cores that fractionally crystallized and the sequence of crystallization in each group [1]. For the main group pallasites, the chemistry of the metal indicates a metal source very similar to IIIAB irons. If the core cooled inside a well insulating silicate mantle, the cooling rates of the iron meteorites would be indistinguishable because the core cooled almost isothermally. Metallographic cooling rates at ~900 K decrease with increasing bulk Ni in both the IIIAB irons (300-60 K/Myr) and IVA irons (6,600-100 K/Myr) whereas cooling rates *increase* with bulk Ni in the IVB irons (475-5000 K/Myr) [4-8]. The discovery of nonconstant cooling rates in iron groups provide important constraints on the thermal, crystallization, and collisional history of each parent asteroidal body. The lowest Ni irons in those three groups were the earliest solids to form. Therefore, the lowest Ni irons in the IIIAB and IVA iron groups were located close to the surface of the cores of their parent bodies, and the lowest Ni irons in the IVB iron group were located close to the center of their core. Therefore fractional crystallization in IIIAB and IVA irons occurred from outside-in whereas in IVB irons fractional crystallization occurred from inside-out.

Factors Controlling Core Crystallization: It is of interest to understand why some cores crystallized outside-in whereas others crystallized inside-out and to understand the processes by which the asteroids formed. The direction of core solidification in a differentiated body is determined mainly by the relative magnitudes of the melting point and adiabatic temperature gradients, which are both controlled by internal pressure. The pressure variation inside an asteroid can be treated in a similar way as that of the Earth using the hydrostatic equation. However, the adiabatic temperature gradients, $\frac{dT}{dP} = \frac{\alpha T}{\rho C_p}$ (where α is the coefficient of volume thermal expansion, T is the temperature, P is pressure, ρ is the density, and C_p is the specific heat at constant pressure), has a big uncertainty because of the uncertainty in the value of the thermal expansion coefficient of liquid metal. The best fit value for the parameters were suggested [9]; T=1811 K, ρ=7,019 kg/m^3, and C_p=835 J/kg-K. However, the value of α is less certain. A value of $\alpha=9.2\times10^{-5}$ K^{-1} has been widely adopted [9] although a new value of $\alpha=13.2\times10^{-5}$ K^{-1} based on the preferred fit of density has been derived recently [3]. If the smaller α value is used, $\frac{dT}{dP} = 28.4$ K/GPa at the melting point. If the larger α value is used, $\frac{dT}{dP} = 40.8$ K/GPa at melting point.

It has been shown that if a large thermal expansion coefficient was chosen, outside-in crystallization would be expected, but if a small thermal expansion coefficient was chosen, inside-out crystallization would be expected [3].

Outside-in crystallization. If a well-mantled core crystallizes inwards, convection is minimized because the latent heat is released slowly due to slow cooling and it is released close to surface. Although two iron meteorite groups IIIAB and IVA showed outside-in crystallization, we believe the parent bodies of those

two groups were broken up during a major collisional period by glancing "hit-and-run" impacts [10] before their cores started to solidify. During inwards solidification of the two cores with little or no mantle, the cooling rate would have been rapid with strong stirring due to the large thermal gradient. The fractional solidification model for element redistribution for these two iron groups is consistent with strong convection. To date, there is no meteorite evidence that a well insulated asteroidal core crystallized inwards.

Inside-out crystallization. Inside-out crystallization could happen when the core is well covered by mantle material if the adiabatic gradient is higher than the melting point gradient. Solidification of liquid iron should start homogeneously when the adiabatic temperature first intersects the melting point temperature at the center of the core, as known for the Earth. However, this is not always the case. Normally undercooling of about $0.2T_m$ degrees (T_m is the melting point in K) is required for homogenous nucleation. For liquid iron, an under-cooling of ~300 K is needed to nucleate solid iron homogeneously [11]. Therefore, even when the adiabatic temperature is below the melting point, solidification by homogeneous nucleation may not start until the liquid temperature is ~300 K below the melting point. On the other hand, if heterogeneous nucleation sites are available, such as refractory inclusions within liquid iron or the mantle, only about 1 K of undercooling is required. Under these conditions, solid iron could start to nucleate heterogeneously either near the center of the core or at the core-mantle boundary.

For the case of heterogeneous nucleation near the core center, refractory inclusions such as SiO_2 could provide nucleation sites allowing the solid to grow from the inside-out. On the other hand, if there are no refractory inclusions in the liquid core, the nucleation will start heterogeneously at the core-mantle boundary (CMB). The newly formed solid iron at the CMB may be detached from the mantle and sink towards the center of the core [12]. In any case, the core center becomes a more favorable site than the core-mantle boundary for further nucleation and growth because of the following two reasons. First, the undercooling is higher at the center of the core than at the CMB. For a 150 km radius body the under-cooling is about 1 K at the core center when there is no undercooling at the CMB. Assuming other conditions are the same, the large amount of undercooling makes the core center much more favorable for new nucleation and growth than the CMB. Second, the activation energy barrier for heterogeneous nucleation ($\Delta G^*_{het} = S(\theta)\Delta G^*_{\text{hom}}$) is much lower at the core center than at the CMB because of the difference in wetting angle which determines the shape factor $S(\theta) = (2+\cos\theta)(1-\cos\theta)^2/4$. The wetting angle θ between liquid iron and olivine at CMB is about 94^o [10] so the shape factor $S(\theta) = 0.55$. The wetting angle between liquid iron and solid iron at the core center is unknown but it is expected to be close to 0^o for liquid metal on its own solid metal [13]. Assuming θ=5^o, then the shape factor $S(\theta) = 1.2\times10^{-5}$. Therefore, the activation energy barrier for heterogeneous nucleation at the core center is 5 orders of magnitude less than that at CMB. Once the solid iron sinks to the core center, the nucleation and the growth of solid iron will be faster at the center. It appears that inside-out growth will be dominant even if the newly crystallized iron at the core-mantle boundary continues to sink towards the center during cooling.

Our results for IVB irons indicate that, at least for low S or S-free iron cores, inside-out growth of the solid core is favored [6,7]. After about 80 vol% original liquid core solidified, an impact broke up the IVB protoplanet and the inner solid core became a metallic asteroid, which was the source of IVB irons.

The crystallization of the metallic core of the parent protoplanet of main group pallasites was similar to that of the IVB irons. After about 80 vol% of the original liquid core solidified from inside-out, a glancing impact broke up the body. The outside 20 vol% residual liquid metal mixed with olivine in the mantle to form a rubble-pile like asteroid, which was the source of the main group pallasites.

Future spacecraft studies of metallic asteroids and impact modeling will be very helpful to test these models.

References: [1] Goldstein J. et al. (2009) *Chemie de Erde*, 69, 293-325. [2-] Haack H. and Scott E. R. D. (1992) *JGR, 97*, 14727-14734. [3] Williams Q. (2009) *EPSL, 284*, 564-569. [4] . Yang J. and Goldstein J. I. (2006) *GCA, 70*, 3197-3215. [5] Yang et al. (2007) *Nature, 446*, 888-891. [6] Yang J. et al. (2009) GCA submitted. [7] Goldstein J. I. et al. (2010) *LPS XLI*, submitted. [8] Yang J. et al. (2009) *Meteorit. Planet. Sci., 44*, A224. [9] Anderson W. W. and Ahrens T. J. (1994) *JGR*, 99, 4273–4284. [10] Asphaug E. et al. (2006) *Nature 439*, 155-160. [11] Turnbull D. and Cech R. E. (1950) *J. Appl. Phys. 21*, 804-810. [12] Wasson J. T. (1993) *Meteoritics, 28*, 455-456. [13] Eckhardt M. M. (1995) *LPS XXVI, 26*, 349-350.