CORE SOLIDIFICATION AND DYNAMO EVOLUTION IN A MANTLE-STRIPPED PLANETESIMAL.

A. Scheinberg[1], L.T. Elkins-Tanton[2], G. Schubert[3], D. Bercovici[4], [2]School of Earth and Space Exploration, Arizona State University, 781 Terrace Rd., Tempe AZ 85287, ltelkins@asu.edu, [1]MIT, [3]UCLA, [4]Yale.

Introduction to the problem and approach: The physical processes active during the crystallization of a low-pressure, low-gravity planetesimal core are poorly understood, but have implications for asteroidal magnetic fields and large-scale asteroidal structure. We consider a core with only a thin silicate shell, which could be analogous to the IVA parent body and to some M-type asteroids including (16) Psyche, and use a parameterized thermal model to predict a solidification timeline and the resulting chemical profile upon complete solidification. We then explore the potential strength and longevity of a dynamo in the planetesimal's early history.

We consider two scenarios in which solidification occurs near the core-mantle boundary (CMB). In the first scenario, newly solidified material is attached to the overlying silicate shell and a solidification front proceeds downward concentrically or dendritically (Fig. 1, bottom left and right). In the second scenario, crystals form near but unattached to the CMB, settle out of the convecting liquid, and compact into a cumulate inner core (Fig. 1, top right).

We use scaling analysis and a finite difference thermochemical core model with parameterized convection to 1) evaluate the dominant physical processes during planetesimal core solidification; 2) determine the magnitude and longevity of a planetesimal dynamo during solidification; and 3) determine the physical structure, mineral assemblage, and magnetization we could expect to find in asteroidal cores. As a reference scenario, we examine a hypothetical planetesimal with an initially liquid core of radius 100 km whose mantle was stripped off in a grazing collision, leaving a 1 km silicate shell.

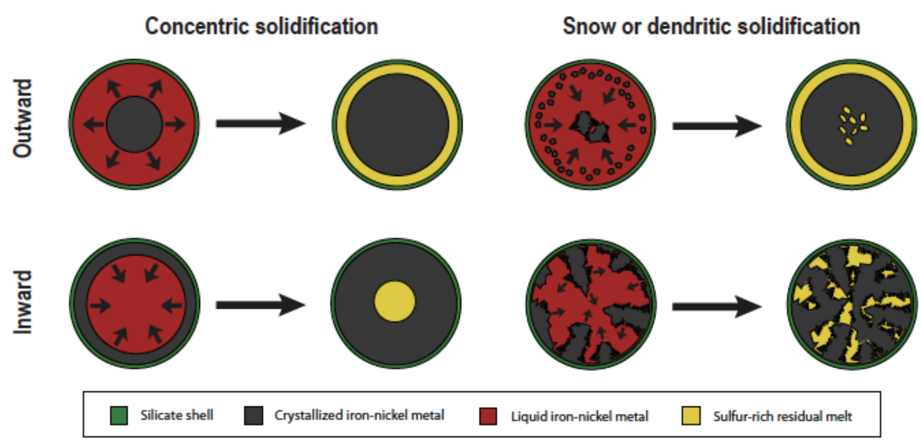

Fig. 1. *Four possible core solidification scenarios and their resulting end-states.* ***Top left****: Concentric outward (Earth-like) solidification.* ***Top right****: Solid inner core growth from accumulated iron "snow" and/or destabilized dendrites.* ***Bottom left****: Concentric inward solidification.* ***Bottom right****: Dendritic inward solidification.*

Methods: In each of the physical scenarios, we simultaneously calculate the composition of the solidifying metal, the evolution of the remaining liquid, its dynamics, and whether the resulting heat flux can produce a magnetic dynamo.

The vigor of convection in the liquid core is critical to the system's evolution. If convection is sufficiently energetic, then the liquid will be chemically well-mixed and adiabatic, allowing solidification to occur primarily at the upper boundary layer of the liquid where its liquidus and thermal profile intersect, and thus allowing fractionation. Following [1], we use a heat flux formulation to estimate the Rayleigh number, which describes convective vigor by comparing buoyancy forces to viscous forces: $Ra = \frac{g(R_0)\alpha q_0 R_0^4}{\mu_l \kappa_c^2 c_P}$, where $g(R_o)$, α, μ_l, κ_c, and c_P are gravity at Ro, thermal expansivity, dynamic viscosity, thermal diffusivity, and specific heat capacity, respectively.

Heat flux out of the liquid, q_o, is limited by the ability of the overlying solid (or immobile liquid) material to conduct heat. Prior to the onset of solidification, $q_o \cong 6$ W m^{-2}. The resulting Rayleigh number of order Ra $\sim 10^{25}$ indicates vigorous convection in spherical geometry (where critical Ra $\sim 10^4$ [2]). However, convection could be stalled by crystal formation within the liquid: a high crystal fraction within the liquid would increase effective viscosity, resulting in a lower Rayleigh number and less efficient mixing.

To calculate the likelihood of a magnetic dynamo, we use a buoyancy-flux based formulation [3, 4]. Full equations and process are described in Scheinberg et al., [5].

Crystallization rates: The maximum crystallization rate will occur at the onset of solidification since at that time the temperature contrast is highest and the conductive shell is thinnest. We find an upper limit on crystallization rate of 10 km^3 yr^{-1}. If solidification occurs from the outside with a spherically symmetric growth front and no trapped liquid, the front would progress inward at a rate of 80 mm yr^{-1}.

Even in the presence of vigorous convection, a concentric inward growth front can proceed only as quickly as sulfur can be removed from the diffusive boundary layer near the growth front. The removal of sulfur is especially crucial because of its effect on the solidification temperature, with a decrease of some 20 K for every percent increase in sulfur. Latent heat must thus also be conducted away.

If sulfur were not remixed, the liquidus temperature within the inner core would not decrease. In this case, thermal convection would not occur and solidification would proceed at all depths simultaneously (bulk solidification). It is possible that when dendritic inward solidification is reduced, convection would resume.

Further, dendrites growing downward from the lid will detach and sink into the interior. Along with dendrites, crystals entrained in the convecting liquid will sink toward the planetesimal's interior. We treat compaction in the center, as well as the timescales of crystal and dendrite settling.

Conclusions: Fractional solidification is unlikely to proceed concentrically inward from the core-mantle boundary for two reasons. First, chemical diffusion is not efficient enough to remove sulfur from the crystallization front. Second, the energy required to re-entrain buoyant, sulfur-rich liquid by convection is not likely to be available. If dendrites did form, then their size would likely have been limited by their gravitational instability.

With these considerations, it is difficult to explain how a 100-km core could have solidified fractionally inward as suggested by the negative correlation of cooling rate to nickel fraction in the IVA meteorites. Overturn of a core that solidified outward could potentially explain such a negative correlation without inward solidification. Alternatively, buoyant, sulfur-rich fluid could potentially be expelled through fractures formed in the solid outer shell, easing the limitations on inward solidification.

We examined two scenarios: inward solidification (both concentric and dendritic) and cumulate inner core growth (Fig. 1). These are two end-member possibilities of planetesimal core solidification. However, these processes could have been operating in tandem, with nonlinear results. In both scenarios examined here, dynamo action during solidification is possible if the body is sufficiently large and the assumed critical magnetic Reynolds number is sufficiently small. In an inwardly solidifying body, such a field could have been captured by the overlying solid iron shell (Fig. 2).

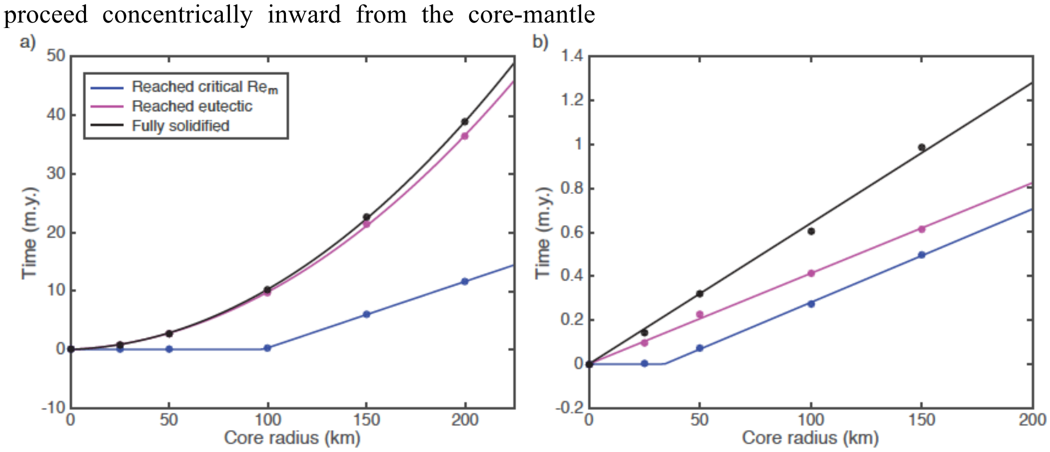

Fig. 2. *Dependence of timescales on core radius. The magnetic field shut-off times are plotted for a critical Re_m of 50 (e.g., [6]). a) Inward solidification. The time required from the onset of solidification to reach the eutectic liquid composition and fully solidify is proportional to radius squared. A dynamo is able to continue operating during inward solidification in bodies larger than ~100 km. Its duration is directly proportional to radius. b) Cumulate inner core solidification. All timescales scale directly with radius.*

[1] Haack & Scott (1992) *JGR*, 97, 14727. [2] Zebib et al. (1983) *Geophys. Astrophys. Fl. Dyn.*, 23, 1. [3] Buffett (2002) *GRL*, 29, 1566. [4] Buffett et al. (1996) *JGR*, 101, 7989. [5] Scheinberg, et al. (2015) *JGR*. [6] Christensen, et al. (1999) *GJI*, 138, 393.