A CORE DYNAMO ON AN IRON METEORITE PARENT BODY AND THE MAGNETISM OF METALLIC ASTEROIDS.
B. P. Weiss[1], J. F. J. Bryson[1], R. J. Harrison[2], J. A. Neufeld[2], L. T. Elkins-Tanton[3], C. T. Russell[3], C. A. Raymond[4], F. Nimmo[5], J. Herrero-Albillos[6], F. Kronast[7], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [3]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [3]Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA, [4]Jet Propulsion Laboratory, Pasadena, CA, USA, [5]Department of Earth and Planetary Sciences, UCSC, Santa Cruz, CA, USA, [6]Centro Universitario de la Defensa, Zaragoza, Spain, [7]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany.

Introduction: The Earth's metallic core solidifies from the inside-outward, powering its dynamo. It has been suggested that the lower pressures in smaller planetary bodies means their cores may have solidified from the outside-inward [1]. However, a lack of observations of magnetism generated by inward solidification make its existence and nature highly uncertain. The IVA iron meteorites have been proposed to originate from a planetesimal whose silicate mantle was stripped away by collisions, leaving a molten ball of metal that cooled rapidly and solidified from the top down [2]. Here, we test the hypothesis that some inwardly-crystallizing planetesimals generated dynamos by acquiring time-resolved paleomagnetic measurements of three IVA iron meteorites. We also discuss future opportunities from magnetometry observations at the metallic asteroid 16 Psyche acquired by the proposed Discovery-class Psyche mission [3].

Experimental methods: We employed two paleomagnetic techniques to study the IVA iron meteorites. Firstly, the remanent magnetization of the cloudy zone in matrix metal from the Steinbach and Chinautla meteorites was imaged using synchrotron X-ray microscopy [4]. Secondly, we analyzed the natural remanent magnetization (NRM) of silicates with kamacite and tetrataenite inclusions from the Steinbach and São João Nepomuceno (SJN) meteorites using alternating field (AF) demagnetization and paleointensity analyses.

Experimental results: Both techniques detected substantial NRM in all three meteorites.

X-ray microscopy. Nonzero x-ray magnetic circular dichroism values in the two meteorites indicate the presence of a substantial magnetic field during the formation of their cloudy zone tetrataenite. We find that both the inferred direction and intensity varied from region to region within each meteorite. Inferred paleointensities range from >0 μT to >100 μT .

Silicate demagnetization. Silicate subsamples from Steinbach did not demagnetize up to a peak AF intensity of 1.1 T; the NRM is therefore carried by non-cloudy zone tetrataenite. The directions of this stable component were randomly scattered among the subsamples; paleointensities ranged from 50-300 μT.

The SJN subsamples exhibited two NRM components carried by kamacite. A directionally scattered low coercivity component unblocked by 20 mT and is likely an IRM from a hand magnet. A weak, unidirectional and origin-trending, high coercivity component that unblocked from 20 mT up to 60-145 mT may be a primary thermoremanence; apparent paleointensities for this component range from 163 ± 65 to 14 ± 1 μT for four subsamples.

Discussion: Our data indicate the existence of substantial ancient magnetic fields on the IVA parent body. The Steinbach and Chinautla meteorites cooled through 800 K at 150 K/My and 110 K/My, respectively, such that the small measured changes in metal formation temperature (~30 K) correspond to long time periods (~300 ky). The >>1 day cooling timescales of these meteorites exclude impact plasma-generated field sources, while Re-Os ages (ranging from 10-100 My after solar system formation [5]) indicate a core dynamo rather than the nebula as the likely field source.

X-ray microscopy. The scattered paleomagnetic field directions provide evidence of a directionally varying core-dynamo field. This scatter is expected because of the 300 ky timescale of NRM acquisition.

Silicate demagnetization. The coercivity spectra of Steinbach silicates demonstrate that the tetrataenite is present as part of plessite. This intergrowth forms via a martensitic transition whose formation temperature depends on the size of the metal grain and its Ni concentration. Because these properties likely vary among subsamples, the observed random directions are also consistent with a directionally-varying field. Furthermore, the NRM intensities of the subsamples are too intense to reflect a spontaneous moment.

The range of observed paleointensities in SJN are similar to those observed using X-ray microscopy and from demagnetization of the Steinbach subsamples. The clustered high coercivity NRM directions imply a single paleofield direction. SJN's fast cooling rate means it could have cooled through the remanence acquisition temperature range (~100 K) faster than the variation in field orientation, providing a ~10 kyr lower bound to the rate of change of the field direction.

Dynamo generation: On Earth, dynamo activity is driven by the rejection of light elements by the gradually solidifying inner core. During inward core solidification, these elements are released into the top of the liquid and therefore provide no driving force for con vection and hence for dynamo generation. The NRM in IVA iron meteorites must therefore reflect a mechanism fundamentally different from that of Earth.

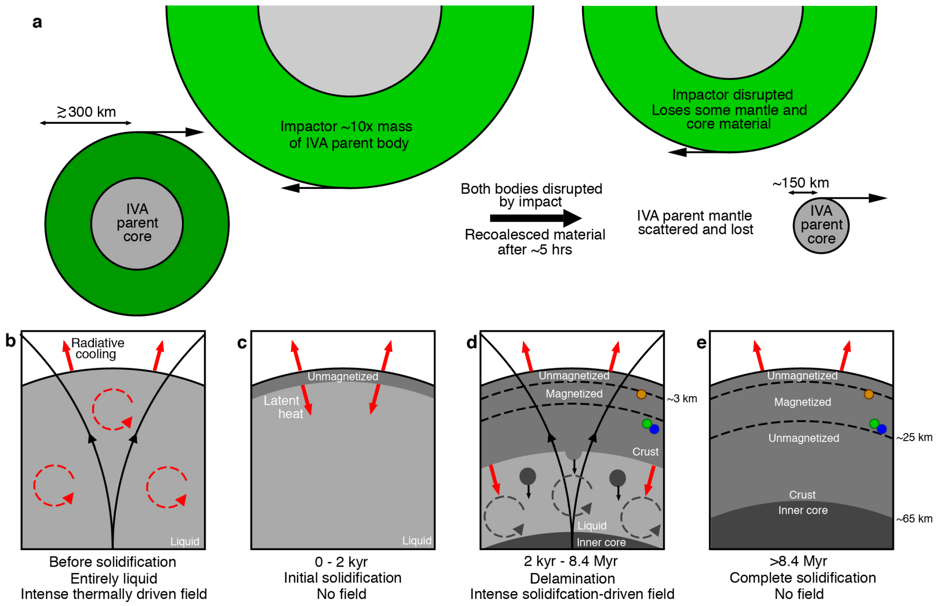

Fig. 1. Formation and solidification of the IVA parent body. a A hit-and-run collision liberated the IVA parent core. Greens: mantle; greys: core. **b** The liberated liquid core (light grey) loses heat rapidly (straight red arrows), driving thermal convection (dashed red arrows) and generating a field (curved black lines). **c** Once the core starts solidifying (darker grey), latent heat release (inward red arrows) prevents thermal convection, inhibiting a dynamo. The shallow crust (≲3 km) cools through 593 K during this period, so is expected to be unmagnetized. **d** Once sufficiently thick, diapirs (dark grey) start delaminating and accumulate to form an inner core. This generates convection (dashed grey arrows) and magnetism. Intermediate depth crustal material (~3-25 km) cools though 593 K during this period, becoming magnetized. Orange, green and blue dots indicate inferred source depths of SJN, Steinbach and Chinautla, respectively. **e** Once entirely solid, the body cannot generate a field. Deep crustal (~25-65 km) and inner core materials cool through 593 K during this period and so are unmagnetized.

To investigate this, we modeled the cooling and solidification of an unmantled core. We found that the molten body initially cooled rapidly, resulting in vigorous convection and a thermally-driven field. Eventually, a solid metallic crust started to form, adding latent heat to the liquid (Fig. 1). This caused the liquid to stagnate and resulted in a period of no magnetic activity. This crust continued to thicken, leading the hot, basal material to drip off as km-sized metallic diapirs. These diapirs sank and accumulated to form an inner core, providing a large buoyancy flux that stirred the liquid and hence generated a dynamo. We calculate that this field should have been intense and multipolar (i.e., directionally varying), consistent with our data.

Conclusion: We find that these meteorites experienced intense and directionally-varying fields consistent with that expected for a dynamo driven by the delamination and sinking of basal material from an inwardly-solidifying metallic crust. Compared to other potential field generation mechanisms [6], delamination is extremely efficient, likely capable of generating magnetic activity at slow cooling rates [7] such as those within the cores of mantled bodies. Delamination may explain the present-day magnetism of Mercury [8] and Ganymede [9] and may have powered widespread magnetic activity among differentiated planetesimals.

Implications for the Psyche mission: This study is the first identification of dynamo activity on an iron meteorite parent body. The only known naked metallic core in the solar system today is the asteroid 16 Psyche. Tetrataenite in Steinbach and Chinautla is highly magnetic but appears to be nonunidirectionally magnetized at sub-mm scales. On the other hand, the minimum 10 ky timescale of field variations inferred from SJN implies that kamacite-bearing silicates in the outer crust may be approximately unidirectionally magnetized at > several km spatial scales. The silicate's high observed NRM intensities (10^{-5} to 10^{-2} Am^2/kg) imply that Psyche's remanent field might be detectable by the Psyche mission, which carries two boom-mounted three axis fluxgate magnetometers [3]. This will enable the mission to further test the hypothesis that some small planetary bodies formed inwardly crystallizing metallic cores and generated dynamos.

References: [1] Williams Q. (2009) *EPSL, 284*, 564-569. [2] Yang J. et al. (2007) *Nature*, *446*, 888-891. [3] Elkins-Tanton, L. T. (2016) *LPS XLVII*, submitted. [4] Bryson J. F. J. et al. (2014) *EPSL*, *396*, 125-133. [5] McCoy et al. (2011) *GCA*, *75*, 6821-6843. [6] Stevenson D. J. (2010) *SSR*, *152*, 341-390. [7] Nimmo, F. (2009) *GRL*, *36*, L102010. [8] Anderson B. J. et al. (2011) *Science*, *333*, 1859-1862. [9] Hauck S. A. et al. *JGR*, *111*, E09008.