ONSET OF A PLANETESIMAL DYNAMO AND THE LIFETIME OF THE SOLAR NEBULAR MAGNETIC FIELD. H. Wang[1], B. P. Weiss[1], B. G. Downey[1], J. Wang[2], Y. K. Chen-Wiegart[2], J. Wang[2], C. R. Suavet[1], R. R. Fu[1], E. A. Lima[1], and M. E. Zucolotto[3], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA (huapei@mit.edu), [2]Photon Sciences Directorate, Brookhaven National Laboratory, Upton, NY, USA, [3]Museu Nacional, Rio de Janeiro, Brazil

Introduction: The paleomagnetism of achondritic meteorites provide evidence for advecting metallic core dynamos and large-scale differentiation on their parent planetesimals. Their small sizes (~10^2 km) relative to planets enable new opportunities to understand the physics of dynamo generation in size regimes with distinct thermal evolution parameters. Furthermore, their extremely old ages, up to just several million years (My) younger than the age of the solar system, offer the possibility of constraining the nebular magnetic field environment and its lifetime.

One key unknown about planetesimal dynamos is their onset time. Some theoretical studies have suggested that it might occur instantaneously after large-scale melting [1, 2] while others have argued that a dynamo could be delayed by several to tens of My or longer [3, 4]. Here we present the first paleomagnetic constraint on the onset time of a planetesimal dynamo, with implications for the physics of core formation, planetary thermal evolution, and dynamo generation mechanisms.

Another key unknown is the temporal evolution of the solar nebula and its magnetic fields. Nebular fields have been proposed to play a key role in the mass and momentum evolution of protoplanetary disks [5, 6] and may have been associated with the formation of chondrules [7]. Because the oldest basaltic achondrites are thought to have formed during and soon after the observed ~3-5 My lifetime of protoplanetary nebulae around Sun-like stars, they offer the possibility of constraining the late evolution and lifetime of nebular magnetic fields and the nebula itself.

Samples and Experiments: Our study focused on angrites, a group of ancient basaltic achondrites from an early differentiated planetesimal. With unshocked, unbrecciated textures, they are among the oldest known and pristine planetary igneous rocks.

We selected two of the oldest angrites (D'Orbigny and Sahara 99555; ~4563.4 million years old (Ma) [8, 9]) and a younger angrite (Angra dos Reis; ~4556.6 Ma [8]), which are least likely to have been contaminated by strong magnets. The two older angrites are just ~4 My younger than the oldest known calcium-aluminium inclusions (CAI, 4567.2-4567.9 Ma [10]).

Rock magnetic measurements, including hysteresis loops, back-field demagnetization, first-order reversal curves and thermomagnetic Curie temperature measurements, along with synchrotron transmission X-ray microscopy [11], show that the major magnetization carriers for all three angrites are fine-grained pseudo-single domain magnetite particles, which are among the most reliable paleomagnetic field recorders.

We used alternating field (AF) demagnetization method for anhysteretic remanent magnetization (ARM) paleointensities [1] as well as a new CO_2+H_2 gas mixture system [12] for controlled oxygen fugacity thermal paleointensities. We found that the natural remanent magnetizations (NRM) in D'Orbigny and Sahara 99555 demagnetize at much lower coercivities (~30 to ~50 mT, Fig. 1A) and temperatures (~300ºC) than laboratory-applied total thermoremanent magnetization (TRM) (which persists to > 145 mT and ~500ºC). This indicates that their NRMs are not acquired during primary cooling in a paleomagnetic field, but instead are later overprints from collectors' hand magnets (low coercivity component, LC, < ~10 mT), viscous remanence acquired in Earth's field and possible partial TRMs from metamorphic events on the angrite parent body (APB) (middle coercivity component, MC, ~10-50 mT). Unlike the MC components, the high coercivity (HC, > 75 mT) magnetization in both meteorites are internally non-unidirectional (Fig. 1B, C), indicating no detectable magnetic field during initial cooling from the 580°C Curie temperature.

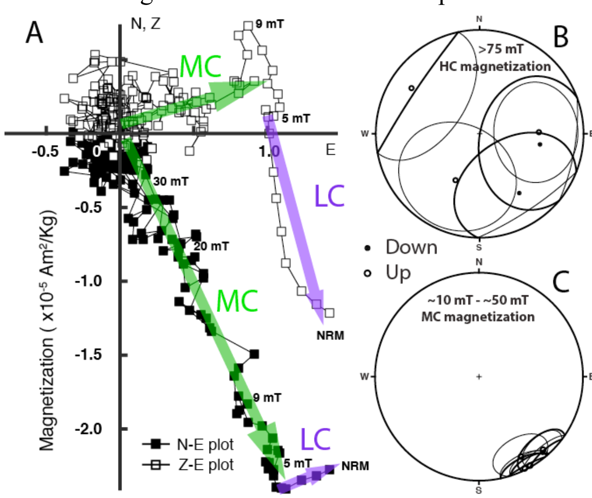

Fig. 1. (A) Two-dimensional projection of the end-points of the NRM vector during progressive AF demagnetization for D'Orbigny subsample F7a. Open (closed) symbols represent projections on the up-east (Z-E) and north-east (N-E) planes. The LC and MC components are labeled with purple and green arrows, respectively. (B) Equal area projection showing paleomagnetic directions of HC magnetization in mutually oriented D'Orbigny subsamples. (C) Directions of MC magnetization for the same subsamples.

The AF demagnetization spectra of NRMs in D'Orbigny and Sahara 99555 closely resemble ~200ºC partial TRMs acquired in a laboratory-applied field of ~10 µT, suggesting an origin from low-temperature metamorphic reheating events during active APB dynamo period. ARM acquisition tests [13] show that their magnetic carriers are stable below ~300ºC. We estimate the initial cooling magnetic field paleointensities from the HC magnetization for D'Orbigny and Sahara 99555 to be less than ~1 µT (Fig. 2A)

In contrast, the NRM of Angra dos Reis behaves similarly to total TRM (also see [1]) and has a unidirectional HC magnetization, confirming its initial thermal origin. It has a ~15 µT magnetic paleointensity (Fig. 2B).

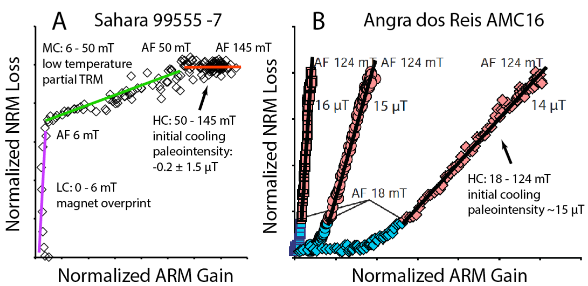

Fig. 2. ARM paleointensities estimated from NRM loss by AF demagnetization versus ARM acquisition using HC components for Sahara 99555 and Angra dos Reis. (A) Sahara 99555 subsample 7 for laboratory direct current (DC) bias field of 50 µT. (B) Angra dos Reis subsample AMC16 for laboratory DC bias fields of 50 µT (squares), 200 µT (circles), and 600 µT (diamonds) (after [1]).

Implications: Our paleointensity results showed that D'Orbigny and Sahara 99555 initially cooled in no detectable magnetic field (paleointensities < ~1 µT) on the APB ~4 My after CAI formation. On the other hand, Angra dos Reis cooled in a ~15 µT APB core dynamo paleomagnetic field ~11 My after CAI formation. This indicates that the APB dynamo initiated between ~4 and ~11 My after solar system formation (Fig. 3). This is consistent with planetesimal evolution models calling for dynamos delayed by at least several million years after core formation. In particular, thermal blanketing effects from ^{26}Al decay in the mantle could initially suppress core convection [3, 4].

The D'Orbigny and Sahara 99555 paleointensities also suggest that external solar nebula magnetic fields in the vicinity of the APB declined from ~50 µT (as recorded by Semarkona chondrules) [7] at ~1.2-3 My after CAI formation [14] to < ~1 µT at ~3.8-4.5 My after CAI formation. These age and magnetic field constraints suggest that the solar nebula dispersed between ~1.2-3 My and ~3.8-4.5 My after solar system formation (Fig. 3), consistent with observed lifetimes of infrared excesses around Sun-like stars [15, 16].

It is estimated that if magnetocentrifugal winds and/or the magnetorotational instability play a central role in driving stellar accretion and momentum transfer, then the observed accretion rates of Sun-like stars would require fields of ~10-100 µT [5, 6, 7]. Because the inferred paleointensity limits from the two older angrites are at least an order of magnitude below these values, magnetic fields may have ceased to play a major role in the Sun's accretion by ~4 My after the formation of CAIs (Fig. 3). In addition, chondrules that formed after this time in the vicinity of the APB would have required nonmagnetic formation mechanisms like nebular shocks [17] and planetesimal collisions [18] rather than x-winds [19], magnetic reconnection flares and current sheets [20].

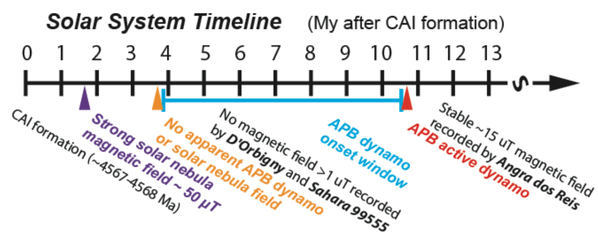

Fig. 3. Constraints on solar nebular field evolution and the onset of the APB dynamo from our paleomagnetic measurements of angrites ([1] and this study) and Semarkona chondrules [7].

References: [1] Weiss, B. P. et al. (2008) *Science, 322*, 713-716. [2] Elkins-Tanton, L. T. (2011) *EPSL, 305*, 1-10. [3] Sterenborg, M. G. and Crowley, J. W. (2013) *PEPI, 214*, 53-73. [4] Roberts, J. H. et al. (2013) *LPI Conf. Abs.*, #8033. [5] Wardle, M. (2007) *Astrophys. Space Sci. 311*, 35–45. [6] Bai, X.-N. and Goodman, J. (2009) *Astrophys. J. 701*, 737–755. [7] Fu, R. R. et al. (2014) *Science, 346*, 1089-1092. [8] Brennecka, G. A. and Wadhwa, M. (2011) *PNAS, 109*, 9299-9303. [9] Spivak-Birndorf, L. et al. (2009) *GCA, 73*, 5202-5211. [10] Wadhwa, M. et al. (2013) *Met. Soc. Abs., 76*, 5253. [11] Wang, J. et al. (2012) *APL, 100*, 143107. [12] Suavet, C. et al. (2014) *GGG, 15*, 2722-2743. [13] de Groot, L. et al. (2012) *PEPI, 194-195*, 71-84. [14] Ushikubo, T. et al. (2013) *GCA, 109*, 280-295. [15] Haisch Jr., K. E. et al. (2001) *Astrophys. J. 553*, L153–L156. [16] Mamajek, E. E. (2009) *AIP Conf. Proc., 1158*, 3-10. [17] Desch, S. J. and Connolly Jr., H. C. (2002) *Meteorit. Planet. Sci., 37,* 183–207. [18] Desch, S. J. and Mouschovias, T. C. (2001) *Astrophys. J., 550*, 314–333. [19] Shu, F. H. et al. (1996) *Science, 271*, 1545–1552. [20] Levy, E. H. and Araki S. (1989) *Icarus, 81*, 74–91.