NEBULAR MAGNETISM RECORDED IN THE SEMARKONA METEORITE. R. R. Fu[1], E. A. Lima[1], B. P. Weiss[1], R. J. Harrison[2], D. S. Ebel[3], and S. J. Desch[4]. [1]Dept. of Earth, Atmospheric and Planetary Sciences, Massachusetts Institue of Technology (MIT), Cambridge, MA (rogerfu@mit.edu), [2]Dept. of Earth Sciences, Cambridge University, Cambridge, UK, [3]Dept. of Earth and Planetary Sciences, American Museum of Natural History (AMNH), New York, NY, [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ.

Introduction: The formation of chondrules, ~1 mm igneous inclusions found in primitive meteorites, was a key stage in solar system formation. Chondrules likely make up a significant fraction of the mass of asteroids and terrestrial planet precursors. They may have also participated in turbulent instabilities or enhanced the sticking efficiency of dust particles, thereby facilitating the accretion of emerging planets [1, 2].

The mechanism of chondrule formation remains a fundamental unsolved problem in solar system formation. Hypothesized formation mechanisms predict different magnetic field intensities at the locations of chondrule heating. The x-wind model implies strong solar fields of ~1000 μT [3] while magnetic reconnection and the short circuit instability may generate transient fields of >500 μT [4, 5]. In contrast, shocks are expected to amplify background fields by a factor of ~10 [6] while planetesimal collisions may not cause any amplification of background fields [7]. Assuming minimum background magnetic fields of ~10 μT inherited from the collapsing molecular cloud [8, 9], magnetic fields at the locations of chondrules formed via these mechanisms can be substantially lower than 100 μT. Magnetic field strength is therefore a distinguishing characteristic among chondrule formation models.

A second fundamental open question about solar system formation is the mechanism of mass and angular momentum transfer, which is a requirement for the accretional collapse of the solar nebula. Among proposed mechanisms, the magnetorotational instability (MRI) model predicts turbulent magnetic fields with strengths in excess of ~100 μT at 1 AU in the active layers [10]. Alternatively, the magnetocentrifugal winds (MCW) model predicts large-scale, organized magnetic fields stronger than ~6 μT [9]. Finally, hydrodynamical effects such as the baroclinic instability do not require a minimum magnetic field [11].

Paleomagnetic experiments on individual chondrules could potentially constrain the strength of nebular magnetic fields. Given the wide range of magnetic field strengths predicted in models of both chondrule formation and of mass and angular momentum transport, palemagnetic data would place strong constraints on the nature of both processes.

The choice of Semarkona: Post-accretional processes on meteorite parent bodies may completely overprint pre-accretional magnetization, posing a significant challenge to paleomagnetic studies. Most previous studies of pre-accretional fields have focused on the Allende CV chondrite [e.g. 12]. However, all magnetic phases in Allende formed during aqueous alteration on the CV parent body and cannot carry pre-accretional magnetization [13]. Furthermore, Allende chondrules carry internally non-unidirectional magnetization, which is inconsistent with pre-accretional thermoremanent magnetization (TRM; [14]).

In contrast to Allende, the Semarkona LL3.0 ordinary chondrite exhibits minimal secondary alteration within chondrules [15]. Furthermore, Semarkona contains dusty olivine-bearing chondrules, which are rich in fine metal grains and so permit high-fidelity recording of ancient magnetic fields [16]. These properties point to dusty olivine chondrules from Semarkona as among the most reliable known recorders of pre-accretional magnetic fields.

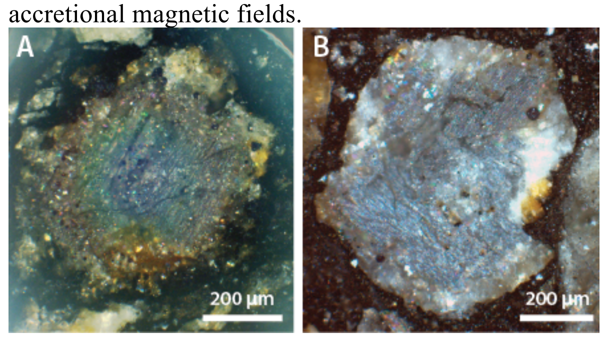

Fig. 1. Crossed-polarized reflected light photomicrographs of two dusty olivine-bearing chondrules measured in this study. Images taken before extraction with non-magnetic micromill. (**A**) Sample DOC1. (**B**) Sample DOC4.

Experimental Methods: We extracted five dusty olivine-bearing chondrules samples (DOCs) from a 0.17 g section of Semarkona from the AMNH (Fig. 1). Two of the five extracted DOCs were further cut into two sub-samples. Furthermore, 30 bulk samples containing a mixture of chondrule, matrix, and sometimes fusion crust material were extracted to characterize any post-accretional overprints present in the sample. All cuts and extraction were performed with a non-magnetic tungsten wire saw at the AMNH or micromill at the MIT Paleomagnetism Laboratory. All samples were mutually oriented to better than 5° accuracy.

Samples with natural remanent magnetizations stronger than $\sim 1\times 10^{-10}$ Am^2 were measured on a 2G Enterprises Superconducting rock magnetometer. For weaker samples, including all isolated chondrules, we mapped the magnetic field ~200 μm above the sample surface using the scanning SQUID Microscope at the

MIT Paleomagnetism Laboratory and inverted for their magnetic moment assuming a dipolar magnetic source.

All samples were subjected to three-axis alternating field (AF) demagnetization up to 290 mT or until the magnetization became unstable. Paleointensities for DOCs were calculated using the anhysteretic remanent magnetization (ARM) normalization method, which produces errors of less than ~30% for dusty olivine-bearing samples [16].

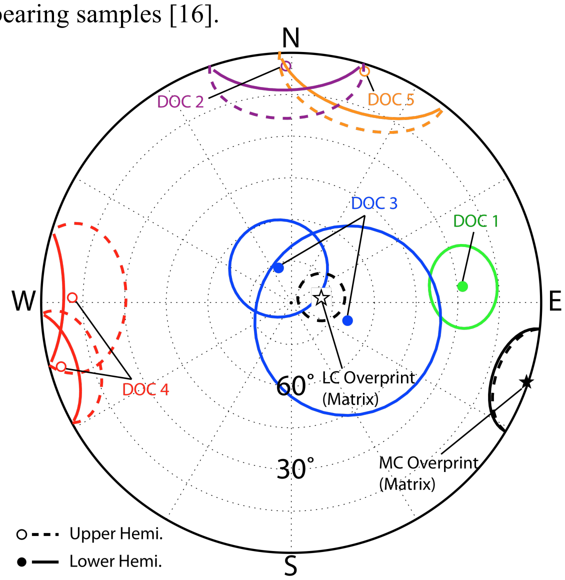

Fig. 2. Equal area projection of HC magnetization component directions in dusty olivine-bearing chondrules with maximum angular deviation (MAD) uncertainties. Subsamples of the same chondrule are plotted with the same color. Black stars and circles represent the mean direction and 95% confidence intervals of post-accretional overprints.

Evidence for pre-accretional magnetization: Chondrules that recorded a TRM in the solar nebula are expected to carry internally unidirectional magnetization while different chondrules should exhibit random (i.e., pass the paleomagnetic conglomerate test) or pseudo-random magnetization directions [17].

Upon AF demagnetization, all DOCs carry a high coercivity (HC) component of magnetization as well as a weaker low coercivity (LCa) overprint. The HC magnetization directions of the five DOCs show a statistically random distribution [Fig. 2; 18]. Furthermore, the direction of the HC component is internally unidirectional in both sub-sampled DOCs.

Matrix-bearing samples carry a weak unidirectional and therefore post-accretional low coercivity (LC) overprint. Bulk samples within 2-5 mm of the fusion crust also carry a medium coercivity (MC) overprint due to atmospheric heating. The HC component in all DOCs differs from the direction of the post-accretional LC and MC overprints. These characteristics indicate that HC magnetization in Semarkona DOCs represents pre-accretional magnetization.

The paleointensity recovered from the HC components of three DOCs is 7±3 μT. Because of the rotation of chondrules during cooling, the recorded paleointensity represents the magnitude of the background magnetic field projected onto the rotation axis, implying that the mean recorded paleointensity is 0.5 times that of the background field. Nebular magnetic fields therefore had intensities of ~14±6 μT.

Implications for chondrule formation and disk dynamics: We have obtained the first unambiguous paleomagnetic constraint on the intensity of solar nebula magnetic fields. The paleointensity of 14±6 μT reflects that of fields present during cooling after the chondrule formation process. These field strengths are most consistent with chondrule formation mechanisms such as planetesimals collisions that permit very weak magnetic fields. This paleointensity may also be consistent with nebular shock models if the baseline magnetic fields in the nebula are much weaker than ~10 μT or if compression of magnetic fields is less than a factor of 10 [8]. In contrast, the strong magnetic fields predicted by magnetic reconnection and the x-wind are inconsistent with these paleointensities [3, 4]. Although the short circuit instability generates peak fields with intensity >500 μT, fields present during the cooling process of chondrules may be lower and further theoretical work is required to assess this [5].

Regardless of the mechanism of chondrule formation, our low inferred paleointensities imply that background magnetic fields in the nebula were likely less than 14 μT. Such low magnetic fields are most consistent with either the MCW model or non-magnetic mechanisms of angular momentum transport but the upper end of this range is also consistent with the MRI if chondrules formed away from the active regions.

References: [1] Beitz E. et al. (2012) *Icarus* 218, 701. [2] Cuzzi J. N. et al. (2008) *ApJ* 687, 1432. [3] Shu F. H. et al., (1997) *Science* 277, 1475. [4] Levy E. H. and Araki S. (1989) *Icarus* 81, 74. [5] McNally C. P. et al. (2013) *ApJL* 767, L2. [6] Desch S. J. and Connolly, H. C. Jr. (2002) *MAPS* 37, 183. [7] Asphaug E. (2011) *EPSL* 308, 369. [8] Desch S. J. and Mouschovia T. C. (2001) *ApJ* 550, 314. [9] Bai X.-N. and Stone J. M. (2013) *ApJ* 769, 76. [10] Wardle M. (2007) *Astrophys. Space Sci.* 311, 35. [11] Klahr H. H. and Bodenheimer P. (2003) *ApJ* 582, 869. [12] Sugiura N and Strangway D. W. (1985) *JGR* 90, C729. [13] Krot A. N. et al. (1998) *MAPS* 33, 1065. [14] Fu R. R. et al. (in prep.). [15] Rubin A. E. et al. (1999) *GCA* 63, 2281. [16] Lappe S.-C. L. L. et al. (2013) *GGG* 14. [17] Fu R. R. and Weiss B. P. (2012) *JGR* 117. [18] Watson G. S. (1956) *Suppl. MNRAS* 7, 160.