**CONSTRAINING NEBULAR MAGNETIC FIELDS IN THE OUTER SOLAR SYSTEM FROM CO CHONDRITES** C. S. Borlina[1], B. P. Weiss[1], J. F. J. Bryson[2], R.R. Fu[3], E. A. Lima[1], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [3]Deparment of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA.

**Introduction:** A fundamental question in planet formation is how mass and angular momentum are transported in protoplanetary disks to enable stellar accretion. This in turn has implications for a variety of other unsolved problems, including how chondrules form [1-2], planets accrete [1] and nebular reservoirs mix [3, 4]. It has long been suggested that turbulence played a central role in driving angular momentum transport throughout much of the disk [1]. However, purely hydrodynamic instabilities are not capable of generating sufficient turbulence to account for the observed accretion rates of sun-like young stellar objects of ~$10^{-8}$ solar masses ($M_{sun}$) per year [5-6]. A way to produce such accretion rates is to invoke magnetic fields generated in the solar nebula [5]. These fields would drive angular momentum and mass transport within the protoplanetary disk via the magnetorotational instability (MRI) and/or magnetocentrifugal winds (MCW) [5].

Assuming magnetic stresses are responsible for accretion, a relation between magnetic field strength and heliocentric distance can be predicted (Fig. 1) [5]. This relationship can be tested by measuring the paleointensity of the solar nebula field from laboratory studies of meteoritic chondrules from proposed formation distances [7]. Such data can also constrain potential chondrule forming processes, which make widely varying predictions for the intensity of the local magnetic field [7, 8]. Alternatively, if this relationship is independently validated, paleointensities can be used to determine the unknown formation region of meteoritic materials [7, 9].

A previous study of chondrules from the LL3.0 ordinary chondrite Semarkona inferred paleointensities of 54 ± 21 μT at a heliocentric distance of ~2-3 AU [7]. Such field intensities are consistent with chondrule formation by nebula shocks or planetesimals collisions (Fig. 1) [7]. Here, we describe new magnetic measurements of chondrules hypothesized to have formed in the outer solar system (beyond Jupiter). In particular, we measured isolated chondrules from CO carbonaceous chondrites, a group of meteorites thought to have formed in the outer solar system based on isotopic measurements [10, 11]. We focused on two CO chondrites, Allan Hills 77307 (ALHA 77307) and Dominion Range 08006 (DOM 08006).

**Samples and Methods:**

*Sample selection criteria:* These two meteorites were selected based on several criteria that favor their ability to have preserved a record of the solar nebula field. Specifically, these samples experienced minimum aqueous alteration and metamorphism (i.e., they are both type 3.0, with a post-accretion event dating 5 million years after the formation of Ca,Al-rich inclusions [12, 13]), they did not experience significant shock (i.e., both < 5 GPa [14]), and experienced minimum terrestrial weathering (ALHA 77307 and DOM 08006 have a weathering index of Ae and A/B, respectively).

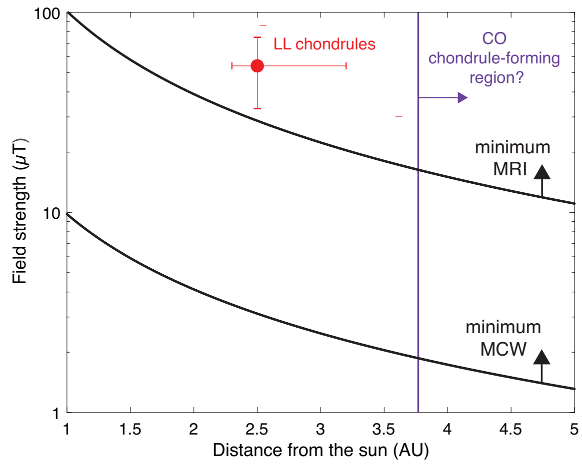


**Fig. 1.** Black lines show the minimum values of the instantaneous field strength for MRI and MCW [5, 7]. Red point shows the field strength retrieved from the Semarkona study [7]. Purple line shows the proposed forming region of CO chondrites according to ref. [19]. Paleomagnetic measurements can help constrain the forming region of chondrules in the CO chondrites.

*Magnetic carriers in chondrules:* Ferromagnetic inclusions in chondrules record the magnetic fields present at the time of their cooling or crystallization. For this study, we have targeted chondrules containing dusty olivines. Dusty olivine contains Fe-metal exsolved from the parent Fe-bearing olivine under reducing conditions in the nebula. Previous studies have shown that dusty olivine is an excellent paleomagnetic recorder [7,15-17].

*Identification of paleomagnetic targets:* We prepared ~100 μm thick sections from the meteorites using a diamond wire saw. Following this, the sections were polished and observed under a petrological microscope to locate dusty olivine in the chondrules. Mutually-oriented chondrules were then extracted manually with non-magnetic tools for paleomagnetic measurements.

**Preliminary Results:** In one thick section of ~25

$mm^2$ from DOM 08006 containing ~100 chondrules, we were able to identify one dusty olivine bearing chondrule (Fig. 2A). This chondrule was demagnetized with stepwise alternating fields (AF). We measured its natural remanent magnetization (NRM) using superconducting quantum interference device (SQUID) microscopy [18]. The measured NRM was $1.54\times10^{-11}$ $Am^2$ (Fig. 2B). Following AF demagnetization of the NRM, the sample was given an anhysteretic remanent magnetization (ARM) in a 50 μT bias field, yielding a magnetic moment of $2.53\times10^{-11}$ $Am^2$.

**Initial Conclusions:** We have determined that the sample was not exposed to a strong magnet since the 50 μT bias field ARM is stronger than the NRM. From our initial AF demagnetization, we can obtain a first-order paleointensity estimate [7]. If in fact the NRM is a primary record of the solar nebula field, we obtained an estimate for the magnetic field in the chondrule-forming region of ~41 μT.

This preliminary conclusion will be tested with alternating field demagnetization of additional dusty olivine chondrules from both samples, which will enable a conglomerate test to establish whether their NRM is pre-accretional in origin (e.g., [7]). We are also conducting quantum diamond magnetometry maps [7] to demonstrate that the magnetic sources are in fact from the fine metal grains in the dusty olivine .

**References:** [1] Turner N. J. et al. (2014) *Protostars and Planets VI*, pp. 411-432. [2] S. J. Desch et al. (2012) *MAPS,* 47, Nr 7, 1139-1156. [3] Scott et al. (2018), *ApJ*, 854. [4] Kruijer et al. (2017), *PNAS,* 114, 26. [5] X. N. Bai and J. Goodman (2009), *ApJ*, 701. [6] A. P. Boss and F. J. Ciesla (2014), *Treatise on Geochemistry,* pp 1-23. [7] R. R. Fu et al. (2014), *Science*, 346. [8] C. Mai et al. (2018), *ApJ,* 857. [9] J. F. J. Bryson et al (2019), *LPS L.* [10] P. H. Warren (2011), *GCA*, 75, 6912-6926. [11] Scott et al. (2018), *ApJ*, 854. [12] D. L. Schrader and J. Davidson (2017), *GCA*, 214, 157-171. [13] P. M. Doyle et al. (2014), *Nat. Comm.*, 6, 7444. [14] J. N. Grossman and A. J. Brearley (2005), *MAPS,* 40, 87-122. [15] S. L. L. Lappe et al. (2011), *G-cubed*, 12. [16] J. Shah et al. (2018), *Nat. Comm.*, 9, 1173. [17] J. F. Einsle et al. (2016), *Am. Mineral.,* 101, 2070-2084. [18] B. P. Weiss et al. (2007), *JGR,* 112, B09105. [19] S. J. Desch et al. (2018), *ApJ Supp. Ser., 238.*

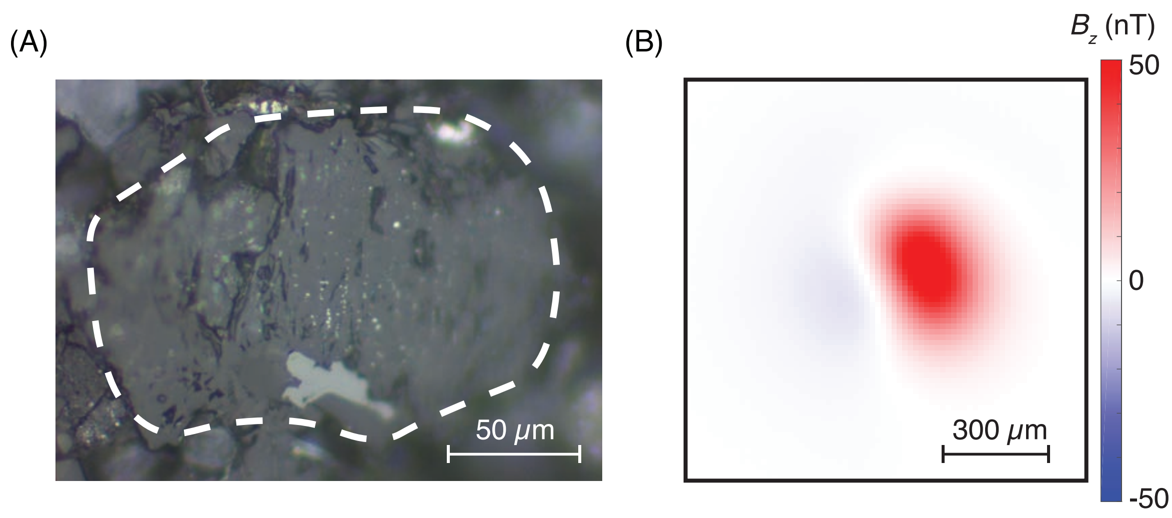


**Fig. 2.** (A) Reflected light microscope image of a dusty olivine chondrule from DOM 08006. Dashed white line shows the chondrule area. Dark grey is olivine and small white dots are fine Fe-metal grains. (B) Out-of-the-page component of the magnetic field ($B_z$) of the NRM of the chondrule from (A) measured with the SQUID microscope. The magnetic moment is $1.54\times10^{-11}$ $Am^2$.