OUTER SOLAR SYSTEM MAGNETIC FIELDS RECORDED IN CR CHONDRITES. R.R. Fu[1], P. Kehayias[2], B.P. Weiss[3], D.L. Schrader[4], R.L. Walsworth[5]. [1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA USA. (rogerfu@fas.harvard.edu). [2]Sandia National Laboratories, Albuquerque, NM USA. [3]Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA USA. [4]Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ. USA. [5]Department of Physics, Harvard University, Cambridge, MA USA.

Introduction: Simulations of magnetized gas dynamics in the partially ionized protoplanetary disk suggest that magnetic fields may have led to turbulence within the nebular gas and mediated the radial transport of mass and angular momentum [1, 2].

Paleomagnetic measurements on chondritic materials have the potential to constrain the intensity of magnetic fields in the early solar system. Igneous components in chondrites, such as chondrules, may have acquired a thermoremanent magnetization (TRM) during cooling, preserving a record of nebular magnetic fields.

A previous paleomagnetic study of dusty olivine-rich chondrules in the Semarkona LL3.0 chondrite recovered magnetizations with uniform directions within single chondrules and randomly oriented relative to other chondrule [3]. These results were interpreted to suggest that magnetic fields of ~50 µT existed in the inner solar nebula assuming that the chondrule formation mechanism did not significantly enhance background field levels. Such strong magnetic fields would have been sufficient to mediate the transport of mass and angular momentum.

The recovery of magnetic field records from different chondrite groups may provide constraints on nebular dynamics at other times and disk locations. Specifically, isotopic heterogeneity among meteorite groups suggest that carbonaceous chondrites may have originated from beyond the orbit of Jupiter [4].

However, paleomagnetic studies of nebular magnetic fields based on carbonaceous chondrites have been limited by the rarity of unaltered ferromagnetic minerals of nebular origin. Recent studies of both CV and CM chondrites provide evidence of ancient magnetic fields with 2-60 µT intensity [5, 6]. However, because the ferromagnetic minerals investigated in those studies are of parent body origin, the results could not distinguish between a nebular and parent body dynamo origin for the inferred magnetic fields.

Isolating a nebular paleomagnetic record from CR chondrites: We performed paleomagnetic experiments on oriented chondrule sub-samples from the CR chondrites GRA 95229 and LAP 02342 obtained from the Antarctic Meteorite Collection at Johnson Space Center. In both cases, we isolated the magnetic signals of Fe-bearing mineral phases that originate from the solar nebula and have avoided post-accretional remagnetization processes. Metal grains in both meteorites show a general lack of plessitic Fe-Ni exsolution textures, implying thermal metamorphism to less than ~200°C [7, 8].

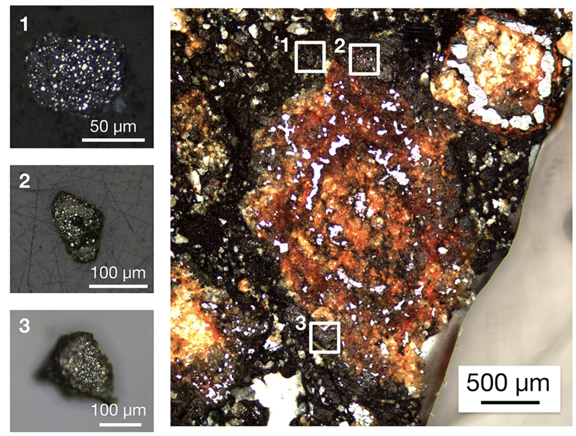

Figure 1: Reflected light optical images of large chondrule in GRA 95229 with sulfide-rich rim. Enlarged images of the extracted rim samples are shown in the panels to the left of the main image. Numbered boxes denote the locations of sample extraction.

Importantly, we limited our measurements to ferromagnetic phases that have not undergone chemical alteration on the CR chondrite parent body. For GRA 95229, we isolated and measured seven mutually oriented samples of the sulfide-rich rim from a single, large (~1.5×2 mm diameter) chondrule (Fig. 1). These sulfides have been shown to have a nebular origin, forming during late stage chondrule cooling [9, 10]. Our optical microscopy of GRA 95229 sulfide rims revealed no evidence of secondary mineral formation, such via reaction with aqueous fluids, on the iron sulfide grains. In the case of LAP 02342, previous electron microscopy suggests that Fe-Ni grains from chondrule interiors are free of secondary Fe-oxides and sulfides that may form during parent body alteration or terrestrial weathering [8].

Results from bulk samples: We measured 5 bulk samples (i.e., mixed chondrule and matrix) from GRA 95229 and 17 bulk samples from LAP 02342 to identify any post-accretional magnetic overprints. All bulk samples were measured using a 2G Superconducting Rock Magnetometer (SRM).

In the case of LAP 02342, bulk samples from within 1 mm of the fusion crust were observed to carry a unidirectional component of magnetization blocked between 0 and >145 mT upon alternating field (AF) demagnetization (Fig. 2). Fusion crust-bearing bulk samples from GRA 95229 also exhibit a coherent direction, although with considerable scatter consistent with a magnetization acquired during atmospheric entry. AF demagnetization of GRA 95229 bulk samples is ongoing. The observed magnetization direction carried by fusion crust-bearing samples is absent from material taken >1 mm from the fusion crust in both meteorites. These data suggest that material within 1 mm of the fusion crust in both meteorites acquired a magnetization during atmospheric entry and that this magnetization has not affected material in the interior.

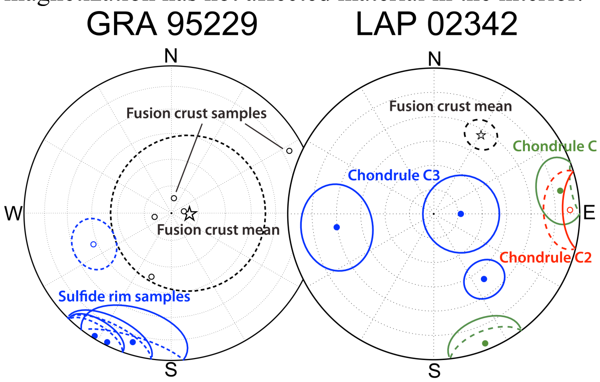

Figure 2: *Equal area stereonet projections of fusion crust-bearing bulk samples and isolated chondrule sample magnetization directions. Note the clustered distribution of chondrule sub-sample directions in GRA 95229 and the scattered directions in LAP 02342.*

Results from isolated chondrule samples: Our paleomagnetic experiments showed that single chondrules from GRA 95229 and LAP 02342 carry distinct patterns of magnetization.

For GRA 95229, we subjected seven mutually oriented sulfide rim samples from a single chondrule to AF demagnetization up to 250 mT or until the loss of stable magnetization in the sample. Due to their weak magnetic moments ($\leq 10^{-12}$ Am^2), we measured the sulfide samples using the Harvard quantum diamond microscope (QDM). We found that five sulfide rim samples carried identifiable components of magnetization blocked between 22.5 and 250 mT. Four of these samples carried origin-trending high coercivity magnetizations that may potentially be primary in origin. These four samples are unidirectional among the sulfide rim samples within the same chondrule and are inconsistent with a random set of directions at the 95% confidence level. Such a uniform distribution of magnetization directions within a single chondrule suggests that the GRA 95229 chondrule formed in an environment with substantial ambient magnetic fields. Anhysteretic remanent magnetization (ARM) experiments to quantify the strength of the ancient magnetic field are ongoing.

For LAP 02342, we recovered paleomagnetic data from eight samples extracted from the interiors of three chondrules (two porphyritic olivine, one cryptocrystalline). We subjected five samples to stepwise AF demagnetization up to 290 mT while the remaining samples underwent stepwise thermal demagnetization to 624°C in an oxygen fugacity-controlled atmosphere to mitigate the effects of sample alteration [11]. Due to their weak magnetic moments, seven out of eight chondrule samples were measured using the MIT SQUID Microscope while one sample was measured on the SRM.

We extracted at least two subsamples from each of three LAP 02342 chondrules. No LAP 02342 chondrule carried a unidirectional component of magnetization (Fig. 2). To provide an upper bound to the magnetic field in which the LAP 02342 chondrules formed, we performed ARM acquisition experiments using a 290 mT AC field on two subsamples of chondrule C1. These samples acquired a unidirectional magnetization for bias field of 7.5 µT, but failed to do so to for a bias field of 5 µT. Accounting for the two-fold probabilistic reduction in magnetic field intensity due to chondrule rotation [3], we conclude that LAP 02342 chondrules formed in a nebular magnetic field weaker than approximately 15 µT.

Discussion: Our paleomagnetic results suggest that chondrules from CR chondrites formed in relatively weak, but still significant magnetic fields. The upper bound of 15 µT derived from LAP 02342 chondrules suggests that their formation environment had weaker magnetic fields than that of Semarkona chondrules, which may be due to formation at a later time near the end of the solar nebula [12], at large orbital radii, or both. However, the record of unidirectional magnetization in the GRA 95229 chondrule suggests that magnetic fields may have still been strong enough to effect the dynamics of nebular gas [1]. Experiments to quantify the paleofield intensity recorded in the GRA 95229 chondrule rims are in progress.

References: [1] Simon, J.B. et al. (2018) *ApJ* 865, 10. [2] Klahr, H. et al. (2018) in Handbook of Exoplanets. [3] Fu, R.R. et al. (2014) *Science* 346, 1089. [4] Kruijer, T.S. et al. (2017) *PNAS* 114, 6712. [5] Fu, R.R. et al. (2014) *EPSL* 404, 54. [6] Cournede, C. et al. (2015) *EPSL* 410, 62. [7] Kimura, M. et al. (2008) *MPS* 43, 1161. [8] Briani, G. et al. (2013) *GCA* 122, 267. [9] Schrader, D.L. et al. (2015) *MPS* 50, 15. [10] Singerling, S.A. and Brearley, A.J. (2018) *MPS* 1-29. [11] Suavet, C. et al. (2014) *GGG* 15, 2013GC005215. [12] Schrader, D.L. et al. (2017) GCA 201, 275.