EVIDENCE FOR NON-STEADY ACCRETION IN THE SOLAR NEBULA INFERRED FROM PALEOMAGNETISM OF CO CHONDRULES. C. S. Borlina[1], B. P. Weiss[1], J. F. J. Bryson[2], E. A. Lima[1], Xue-Ning Bai[3], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]Department of Earth Sciences, University of Oxford, Oxford, UK, [3]Institute for Advanced Study, Tsinghua University, Beijing, China

Introduction: It has been theorized that magnetic fields play a central role during the evolution of protoplanetary disks, driving accretion and transporting angular momentum [1]. In support of this, paleomagnetic measurements, specifically chondrules from an LL chondrite, have provided evidence for the presence of magnetic fields with an intensity of 54 ± 21 µT in the solar system during ~1-3 million years (Ma) after the formation of calcium-aluminum-rich inclusions (CAIs) [2, 3].

Isotopic measurements indicate that all known meteorites are derived from two main regions: the non-carbonaceous and carbonaceous reservoirs [4]. Here we assess the nature and origin of the gap that separated these reservoirs using paleomagnetic measurements. While the LL chondrule records of the nebular magnetic field were obtained for the non-carbonaceous reservoir [3] (Fig. 1), robust chondrule records of the carbonaceous region have been lacking. To address this, we targeted chondrules from CO carbonaceous chondrites to obtain records of the magnetic field at ~2.5 Ma after CAI formation in the carbonaceous reservoir. We then compared field records from the two reservoirs with theory to assess the spatial dependence of nebular magnetism and its implications for the disk's density distribution.

Samples and Methods: We selected the CO carbonaceous chondrites ALHA 77307 (type 3.03) and the DOM 08006 (type 3.00) because they experienced minimal aqueous alteration and metamorphism on the parent body, such that their chondrules are very likely to have preserved a record of the solar nebula field [5]. In particular, DOM 08006 is one of the most pristine known meteorites [6]. These meteorites also did not experience significant shock (i.e., <5 GPa [7, 8]) or significant terrestrial weathering [5, 6].

We targeted dusty olivine chondrules from these samples since they are known to be robust paleomagnetic recorders containing metal grains that formed prior to accretion of the CO parent body [3, 9-11]. Al-Mg ages indicate that the chondrules formed at 2.5 ± 0.3 Ma after CAI formation in the carbonaceous reservoir [12, 13]. Two mutually-oriented dusty olivine chondrules were obtained from ALHA 77307 and four from DOM 08006. Three of the latter were split into two subsamples, totaling seven mutually-oriented subsamples from DOM 08006.

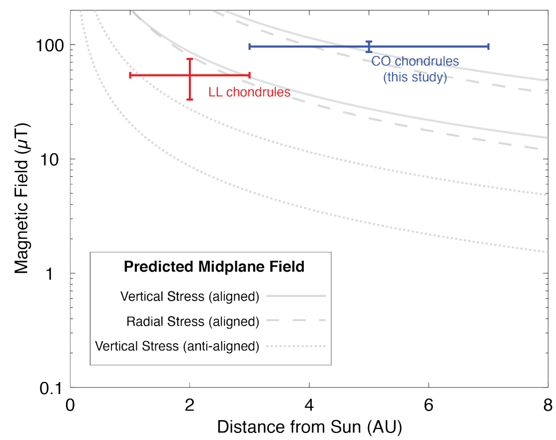

Fig. 1. Paleomagnetic constraints on the solar nebula magnetic field as a function of distance from the young Sun. Data points show measurements from LL [3] and CO chondrules (this study), which support the presence of magnetic fields in the first ~3 Ma after CAI formation. Solid and dashed lines show predicted midplane magnetic field, respectively, due to vertical (eq. 7 of ref. [17]) and radial (eq. 16 of ref. [17]) stresses assuming the nebular magnetic field and sense of disk rotation are aligned; dotted line shows the field due to vertical stress (eq. 7 of ref. [17]) assuming nebular magnetic field and sense of disk rotation are anti-aligned. Top and bottom curves were calculated assuming accretion rates of, respectively, 10^{-7} $M_{\odot}y^{-1}$ and 10^{-8} $M_{\odot}y^{-1}$

The chondrules were demagnetized using stepwise alternating fields and their natural remanent magnetization (NRM) measured using superconducting quantum interference device (SQUID) microscopy at MIT [14]. NRM component directions were calculated using principal component analysis [15]. Paleointensity estimates were acquired using anhysteretic remanent magnetization methods [3] which have been previously calibrated for dusty olivine thermoremanent magnetization (TRM) [9].

Results: We found that the majority of the chondrules have a low coercivity component blocked between 0-30 mT and an origin-trending high coercivity (HC) component blocked between ~30-160 mT. The intra-meteorite non-unidirectionality of the HC components among the chondrules of ALHA 77307 and DOM 08006 (Fig. 2) demonstrates that the samples have not been remagnetized since accretion to their parent body. The unidirectionality among single-chondrule subsamples from DOM 08006 (Fig. 2B) is consistent with the chondrules having acquired a stable TRM in

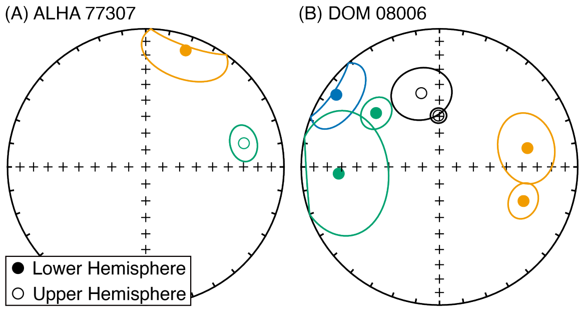

Fig. 2. Equal area stereographic projections showing the direction of the high coercivity components of chondrules, calculated from principal component analysis [15], with appropriate maximum angle deviation. Distinct colors show isolated chondrules from (A) ALHA 77307 and (B) DOM 08006. Directions denoted by the same color in (B) represent subsamples from the same chondrule. The scattered directions between distinct chondrules in (A) and (B) indicate that the meteorites preserve primary magnetic records and were not remagnetized after the chondrules accreted. The uniform directions among chondrules subsamples in (B) are consistent with that expected for a thermoremanent magnetization acquired during primary cooling in the solar nebula.

the solar nebula. Accounting for chondrule spinning during the TRM acquisition [3] we determined a mean paleointensity for the HC components of the seven samples of 96.2 ± 10.1 μT (2σ).

Discussion: Our results support the presence of magnetic fields in the carbonaceous reservoir at ~2.5 Ma after CAI formation in the midplane between 3-7 AU from the Sun [16]. Comparing the CO paleointensities to those from the non-carbonaceous reservoir and theory relating the spatial distribution of magnetic field in protoplanetary disks to magnetically driven accretion rates [17] (Fig. 1), we observe that our measurements do not follow the expected decay of the magnetic strength for a disk with a smoothly decaying mass distribution and constant accretion rate. Rather, our mean paleointensities are almost twice as strong as those reported from the non-carbonaceous reservoir. These results support the presence of non-steady accretion in the early solar system, implying that the accretion rate could have changed spatially or temporally in the solar nebula. This could have resulted from a tenfold increase in the accretion rate over time (Fig. 1) or from spatial inhomogeneities in the magnetic field intensity.

While an increase in the accretion rate could have been associated with accretion bursts [18], the presence of inhomogeneities could have been associated with the existence of density substructures in the disk [19]. In particular, magnetic flux tends to concentrate in the gaps, which may lead to inhomogeneities in the total field strength [20-22]. The presence of a gap in the early solar system disk is consistent with the proposed idea of two spatially isolated reservoirs. However, it is not possible to distinguish between proposed mechanisms for gap formation (e.g., formation of Jupiter, snowlines, or other processes that can produce a local pressure maximum [4, 23]). Nevertheless, the potential presence of magnetic inhomogeneities in the early solar system supports an additional hypothesis for gap formation whereby mechanisms associated with magnetic inhomogeneities could have opened the gap and kept the two reservoirs apart [19].

Finally, the presence of non-steady accretion in the carbonaceous reservoir has also been invoked to explain the lack of detectable magnetization of the CR chondrules. However, given their young age (3.7 Ma after CAI formation) [16], the latter could also be explained by the prior dissipation of the solar nebula (<3.94 Ma after CAI formation in the non-carbonaceous and <4.89 Ma after CAI formation in the carbonaceous reservoir [24]).

Conclusions: The measurements reported here support the presence of magnetic fields in the carbonaceous reservoir at ~2.5 Ma after CAI formation. They also indicate the presence of non-steady state accretion in the early solar system, possibly associated with variations of accretion rate over time or the presence of a gap in the protoplanetary disk. Finally, our measurements support an additional hypothesis for disk substructure formation, where magnetic inhomogeneities could have created the gap that separated the non-carbonaceous and carbonaceous reservoirs.

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