MEASUREMENTS OF SOLAR NEBULA MAGNETIC FIELDS FROM CO CHONDRITES.

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Introduction: Magnetic fields have long been theoretically expected to play an important role in the evolution of protoplanetary disks by driving angular momentum and accretion [1, 2]. Recently, paleomagnetic measurements of meteoritic materials have provided evidence for this by demonstrating that magnetic fields of up to tens of µT existed in our solar system during the first few million years (My) after the formation of calcium-aluminum-rich inclusions (CAIs) [3, 4] (Fig. 1). These intensities are consistent with those required to drive mass transport onto the Sun at typical astronomically observed accretion rates of 10^{-8} $M_\odot y^{-1}$ (Fig. 1).

However, the spatial and temporal variation of magnetic fields in the early solar system are poorly constrained. In particular, robust records of the nebular field (a) in the outer solar system and (b) during the first <0.1 My of the solar system are still unknown. To address these gaps, here we report new paleomagnetic measurements from two pristine CO chondrites: Allan Hills 77307 (ALHA 77307) and Dominion Range 08006 (DOM 08006). We use these data to constrain the evolution of the solar system magnetic field at three different times and locations. First, CO matrix materials recorded the time-averaged field at ~5 My after CAI-formation likely between 3-7 AU [5-7]. Second, CO chondrules recorded the instantaneous field ~2.5 My after CAI-formation >3 AU [8, 9]. Third, CAIs may record the field at the very beginning of the solar system: this can help us constrain where and how they formed, and has implications for what processes drove accretion at this time.

Samples and methods:

Meteorite selection: We selected ALHA 77307 and DOM 08006 based on their likelihood to have preserved a record of the solar nebula field. ALHA 77307 is type 3.03 [10], while DOM 08006 is type 3.00, making them some of the most pristine known meteorites [11]. They did not experience significant shock (i.e., < 5 GPa [12]) nor significant terrestrial weathering (they have weathering indices of Ae and A/B, respectively).

Sampling: We acquired bulk subsamples of a few mg using a diamond wire saw. Dusty olivine chondrules (known to be excellent paleomagnetic recorders, [3, 13, 15]) were extracted from polished slices with non-magnetic tools. CAIs were identified by compositional maps of thin sections. All subsamples were mutually oriented.

Results: The samples were demagnetized using stepwise alternating fields (AFs). We measured the natural remanent magnetizations (NRMs) of the matrix using a 2G Enterprises Superconducting Rock Magnetometer 755 in the MIT Paleomagnetism Laboratory. Chondrule NRMs were measured using superconducting quantum interference device (SQUID) microscopy at MIT [16]. ARM paleointensity experiments were used to determine paleointensities from matrix and chondrules [3]. Fidelity tests were used to constrain the weakest field we can retrieve from the samples in the laboratory.

Matrix: We observed that during AF demagnetization, the matrix NRM intensity did not decay and had unstable directions widely scattered amongst the subsamples. This indicates that the matrix samples are essentially unmagnetized. Based on the fidelity tests, we conclude that the magnetic field in the CO chondrite-forming region was <1.5 µT.

Chondrules: We analyzed two chondrules from ALH 77307 and two subsamples of one chondrule from

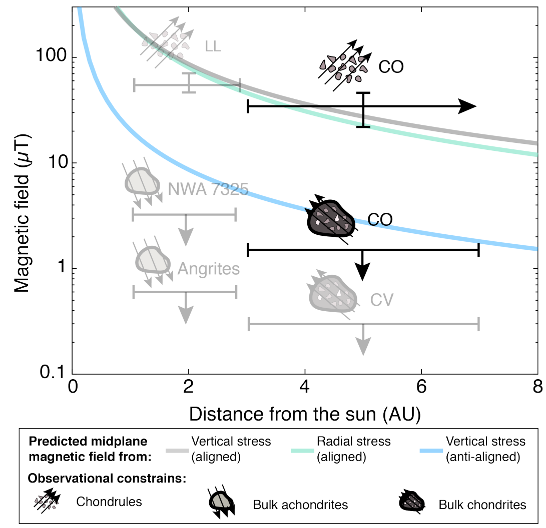

Fig. 1. Paleomagnetic constraints on the solar nebula magnetic field as a function of distance from the young Sun. Grey data points: LL chondrules [3], bulk NWA 7325 achondrites [21], bulk angrites [19] and bulk CV chondrites [22]. Black data points: data from this study, showing measurements of the magnetic field from bulk CO chondrites and CO chondrules. Solid lines show predicted midplane magnetic field: grey and green lines show fields due to radial (eq. 16 of [23]) and vertical (eq. 7 of [23]) stresses assuming the nebular magnetic field and sense of disk rotation are aligned; blue line shows the field due to vertical stress (eq. 7 of [23]) assuming nebular magnetic field and sense of disk rotation are anti-aligned (radial component cancels out for this case). All curves were calculated assuming accretion rates of 10^{-8} $M_\odot y^{-1}$.

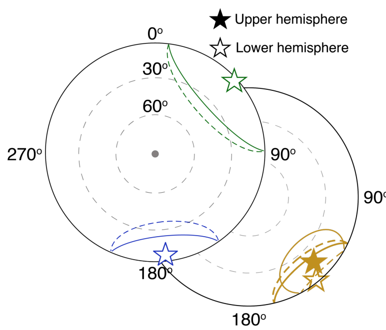

Fig. 2. Equal area stereographic projections showing the direction of the high coercivity components of chondrules, calculated from principal component analysis [24], with appropriate maximum angle deviation. Green and blue stars are two chondrules from ALH 77307: the scattered directions indicate that the meteorite was not remagnetized since the chondrules accreted. Yellow stars are two subsamples of a single chondrule from DOM 08006: their uniform directions consistent with that expected for a thermoremanent magnetization acquired during primary cooling in the solar nebula.

DOM 08006. We observed that the samples have overall a low coercivity component between 0-30 mT, and an origin-trending high coercivity (HC) component blocked between ~30-80 mT. The mean paleointensity for the HC components of the 4 samples is 34.3 ± 12.9 μT (2σ). The two ALH 77307 chondrules have nonunidirectional HC magnetizations (Fig. 2, green and blue), which indicate that they were not remagnetized since accretion onto the CO parent body. The subsamples of the DOM 08006 chondrule have indistinguishable HC directions, indicating that they contain a stable paleomagnetic record consistent with that acquired in the solar nebula as a thermoremanent magnetization.

CAIs: The paleomagnetism of CAIs has essentially never been previously studied. Our backscattered electron microscopy (BSEM) imaging (Fig. 3a) indicates they contain pure Fe inclusions <~0.5 μm, which are known to be excellent paleomagnetic recorders [17]. Our quantum diamond (QDM) magnetometry [18] measurements of the NRM of a CAI demonstrate that they contain magnetization carriers that have detectable magnetization (Fig. 3b).

Conclusions: Our measurements of CO matrices indicate that the outer solar system nebula dissipated by ~5 My after CAI-formation. Because this age is within error of the dissipation of the solar nebula in the inner solar system as constrained by angrite paleomagnetism [19], it suggests near-simultaneous, global dissipation of the nebula, consistent with the proposed mechanism of photoevaporation [20].

The measurements of CO chondrules provide the first identified robust record of the outer solar system magnetic field. The strong paleointensities support the proposal that magnetic fields are acting globally as mediators of accretion in the protoplanetary disk.

Finally, our preliminary measurements of CAIs suggest they contain robust paleomagnetic recorders that might have recorded the magnetic field at the time of the solar system formation.

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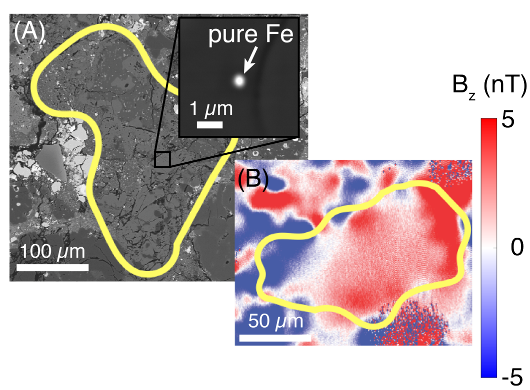

Fig. 3. (A) BSEM image of a CAI (yellow line) from ALH 77307 showing small, pure Fe inclusions that are likely robust paleomagnetic recorders. (B) QDM map of a CAI (yellow outline) from ALH 77307 showing the out-of-the-page component of the magnetic field (B_z) of its NRM. Even though the matrix that surrounds the CAI has a strong magnetic signal, the center of the CAI appears to be magnetized and detectable with our instruments.