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Evidence of Magnetic Fields During the Formation of Calcium-aluminum-rich Inclusions

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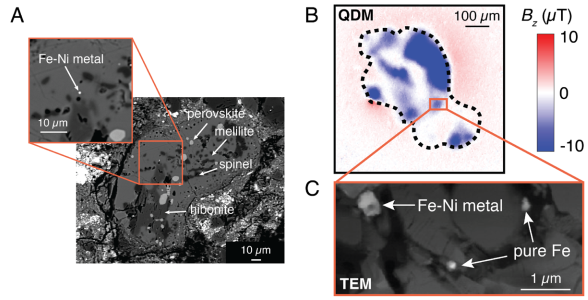
Magnetic fields have been proposed to play a central role in the evolution of protoplanetary disks by transporting mass and angular momentum [1]. Paleomagnetic studies of meteorites have shown that a solar nebula magnetic field of ~50-100 µT existed within ~7 AU of the Sun in the solar nebula ~2-3 million years (Myr) after the formation of calcium-aluminum-rich inclusions (CAIs) and then dispersed by ~4 Myr after CAI formation [1-3]. Nonetheless, the existence of magnetic fields and their role prior to 2 Myr after CAI formation remains undetermined. Understanding this is important because CAIs likely formed when the proto-Sun was a young stellar object (YSO) during the infall and embed phases (i.e., Class 0-I), when gravitational instabilities have been proposed to dominate the dynamics of the disk [1, 4]. To address this, we conducted the first detailed paleomagnetism study of CAIs. We analyzed mutually-oriented CAIs extracted from the CO3.00 chondrite Dominion Range (DOM) 08006. Our previous studies of bulk samples and chondrules from this meteorite indicate that it has avoided total remagnetization since its accretion [2, 3]. Alternating field demagnetization of three CAIs reveals a stable component with coercivities up to 145 mT. Paleointensities obtained from three CAIs indicate that they formed in a mean ancient field of 147.7 ± 22.7 µT. Transmission electron microscopy images show that the primary magnetic carriers are likely to be small (<0.5 µm) nearly pure Fe kamacite, but we also observe the presence of magnetite grains indicating that our paleointensities are likely minimum estimates. Nonetheless, this field strength is compatible with the estimated accretion rates of 10^{-8} to 10^{-4} solar masses per year for Class 0-I YSOs indicating that magnetic fields likely play a central role since the earliest stage of disk formation and evolution.

[1] Weiss B. P. et al. (2021), *Sci. Adv.*, 7, eaba5967

[2] Borlina C. S. et al. (2021), *Sci. Adv.*, 7, eabj6928

[3] Borlina C. S. et al. (2022), *JGR Planets*, 7, e2021JE007139;

[4] Krot A. N. (2019), *MAPS*, 54 (8), 1647-1691



(A) Backscattered electron image of the hibonite-rich CAI used in this study with phases identified through electron microprobe analysis. The presence of fine (<1 µm) Fe-Ni metal, including kamacite, suggests high fidelity recording properties in CAIs. **(B)** Quantum diamond microscope map of the same CAI, showing the out-of-the page component of an anhysteretic remanent magnetization field measured ~5 µm above the sample. Orange box shows one of the magnetic regions targeted with transmission electron microscopy (TEM). **(C)** TEM image of one of the magnetic regions of the CAI from (B) indicates the presence of pure Fe and Fe-Ni metal identified with energy-dispersive x-ray spectroscopy suggesting that CAIs are robust paleomagnetic targets.