CALCIUM-ALUMINUM-RICH INCLUSION PALEOMAGNETISM: A THEORETICAL PERSPECTIVE.

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Introduction: Magnetic fields are well known to play a crucial role governing angular momentum transport and evolution of protoplanetary disks and the solar nebula, and the resulting gas dynamics is the key to understanding a variety of processes in planet formation [1]. While direct detection of disk magnetic fields is lacking from astronomical observations, meteorite paleomagnetism provides a powerful and complimentary approach for probing the physical processes in the solar nebula [2,3].

Existing paleomagnetic studies of meteorites have so far targeted samples whose ages are typically more than 2 million years (Ma) after the formation of calcium-aluminum-rich inclusions (CAIs). By analogy with the evolutionary stages of protoplanetary disks [e.g., 4], they correspond to the so-called Class II stage, representing the bulk disk lifetime of a few Ma. The inferred nebular magnetic field strengths from these studies are consistent with the theoretical expectations where magnetic fields dominate angular momentum transport, thus reinforcing the theoretical framework for understanding disk evolution and planet formation.

CAIs are among the first solids to have formed in the solar nebula. Although where and how CAIs are formed have long been elusive, there is extensive evidence that they formed close to the Sun (<1 AU) and were then transported to the outer solar system (several AU) [5]. In this conference, Borlina et al. [6] report the first paleomagnetic measurements of CAIs from the CO chondrite Dominion Range (DOM) 08006. The mean paleointensity from three CAIs was found to be 147.7 ± 22.7 μT (2σ), together with upper limits of 20-100 μT from two others. Such field strengths are well below the expected value if the magnetization was acquired during CAI formation close to the Sun (>10^3 μT). It was concluded that CAIs must have acquired their magnetic records at relatively large radial distances.

Chronologically, CAIs are likely formed in the so-called Class 0/I stage, when the disks are embedded in an infalling envelope. This stage is relatively short-lived, with a lifetime of ≲0.5Mys. It is characterized by rapid accretion onto the protostar, accompanied by irregular accretion outbursts [7]. Such a dynamical environment is very different from that of Class II disks. Here, we propose a physical scenario for how the CAIs acquired paleomagnetic records, showing that the predicted nebular field strengths are in excellent agreement with the reported paleointensities [6].

Physical scenario: Here we do not consider how CAIs are formed and assume that CAIs are already transported to the disk outer region beyond a few AU. We anticipate that the paleomagnetic records in the CAIs were obtained following the last time they were heated above the Curie temperature of their constituent ferromagnetic minerals (1053 K for kamacite and martensite) [8].

The inner region of protoplanetary disks is expected to be fully turbulent due to the magneto-rotational instability (MRI) [9], where at temperatures above ~1000 K, thermal ionization of alkali species leads to magnetic fields being well-coupled to the gas [10]. As thermal ionization is extremely temperature sensitive, disk ionization drops dramatically toward outer radii, forming a "dead zone" [11] (Fig. 1). It is anticipated that angular momentum transport is dominated by magnetized disk winds in the cooler outer region [12], while in the inner disk, the MRI plays a dominant role [13], or at least comparable to that of disk winds [14] or gravitational instability [15]. Intriguingly, the threshold temperature for thermal ionization is close to the Curie temperature of metal irons. Therefore, we anticipate that the CAIs can be magnetized in the MRI-active region just inside the dead zone inner boundary.

The radial location of this boundary is determined by how the disk is heated. The entire disk is heated by stellar irradiation, but in the fully MRI-active inner region, heating is dominated by turbulent dissipation (i.e. viscous heating) [16,17]. In general, higher accretion rates leads to stronger viscous heating. Class 0/I disks often experience FU Orionis (FUor) like accretion outbursts in which accretion rates increase by a large factor and reaching 10^{-6} to a few 10^{-4} $M_\odot$ yr^{-1} [7]. Such outbursts substantially heat up the inner disk, pushing the water snow line to tens of AU [18]. Likewise, the dead zone inner boundary must also migrate outward by a large amount.

There is strong evidence that CAIs have undergone multiple flash/intermittent heating events [e.g., 19-21], speculated to be associated with FUor-like outbursts [22]. They are likely due to the temperature fluctuations

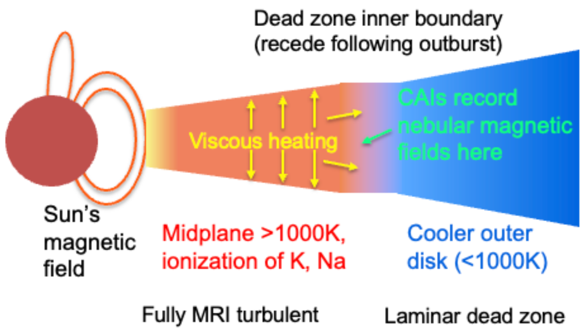

Fig. 1. Sketch of protoplanetary disk structure at the Class 0/I phase. The disk inner region is hot and fully MRI turbulent due to thermal ionization, with disk temperature (>1000K) sustained by viscous heating. A cooler outer region is MRI inactive known as the dead zone. We propose that CAIs acquire magnetic record in the active inner disk near the dead zone inner boundary, as this location recede following FUor-like accretion outbursts.

in the MRI-active region, which can reach order unity in localized current sheets [23,24]. We anticipate that CAIs also acquired their magnetization in such events, and they retain the magnetic record from the last of such events as the outburst fades.

Results: Under this physical scenario, we construct a standard α-disk model [25] in steady state to account for the structure of the hot ($\geqslant$1000 K) disk inner region dominated by the MRI turbulence. For a solar-mass star we find the disk midplane temperature:

$$T_c \approx (1650\ \mathrm{K})\alpha_{0.03}^{-1/5}\dot{M}_{-6}^{2/5}\kappa_5^{1/5}R_{\mathrm{AU}}^{-9/10}, \quad (1)$$

where $\alpha_{0.03}$ is the normalized viscosity normalized by 0.03, $\dot{M}_{-6}$ is the accretion rate normalized by 10^{-6} $M_\odot$ yr^{-1}, κ_5 is the opacity (assumed to be constant) normalized by 0.5 m^{2}kg^{-1}, and R_{AU} is radial distance normalized by AU.

A useful relation in the MRI turbulence that allows us to directly connect the disk model result to the mean field strength is that $\alpha\beta \approx 1/2$, where β is the ratio of gas to magnetic pressure of the turbulent field [26]. Using this relation, we derive disk field strength to be

$$B \approx 468\mu\mathrm{T}\ \alpha_{0.03}^{1/20}\dot{M}_{-6}^{2/5}\kappa_5^{-1/20}R_{\mathrm{AU}}^{-51/40}. \quad (2)$$

Note that this expression differs from equation (2) of Weiss et al. [2] because here the disk model takes into account viscous heating, whereas the derivations in [2] assume passively heated disk by stellar irradiation, applicable to the bulk part of disks in the Class II phase.

We assume the CAIs experience their final heating/ magnetization event in regions with mean temperature ~1000 K. Equation (1) thus gives the relation between accretion rate and radial distance. Substituting this relation into (2) to cancel out $\dot{M}_{-6}$, we then expect CAIs to record a paleomagnetic field strength of

$$B_{\mathrm{paleo}} \approx 283\mu\mathrm{T}\ \alpha_{0.03}^{1/4}\kappa_5^{-1/4}R_{\mathrm{AU}}^{-3/8}. \quad (3)$$

This result is very insensitive to the choice of α and κ, which are expected to vary between 0.01-0.1 and about 0.3-1 m^{2}kg^{-1}, respectively.

For a maximum accretion rate during FUor-like outbursts of several 10^{-4} $M_\odot$ yr^{-1} [6], we find from equation (1) the maximum distance of $R \approx 30$ AU to reach 1000K. Furthermore, we estimate a minimum distance of formation if we assume CAIs are magnetized beyond ~3 AU as inferred from the formation region of their parent body (carbonaceous chondrites). This 30-3 AU radial range leads to a paleointensity between 52-188 μT (large radii for weak field). Further accounting for the uncertainties in α and κ, this range is enlarged to 34-288 μT. The obtained range of field strengths is in remarkable agreement with the values obtained in [6].

Conclusions: We have proposed a physical scenario where the CAIs acquired paleomagnetic records near the dead zone inner boundary following FUor-like accretion outbursts at early phases of the solar nebula. Employing the standard α-disk model that takes into account viscous heating, we show that the expected field strength falls in a narrow range. Together with the paleomagnetic measurements of the CAIs [6], this represents a major step forward in understanding the physical processes behind the formation, transport and accretion of the CAIs.

References: [1] Armitage P. J. (2019), *SAAS*, 45, 1; [2] Weiss B. P. et al. (2021), *Sci. Adv.*, 7, eaba5967; [3] Borlina C. S. et al. (2021), *Sci. Adv.*, 7, eabj6928; [4] Shu F. H. et al. (1987), *ARA&A*, 25, 23-81; [5] Krot A. N. (2019), *MAPS.*, 54, 1647-1691; [6]. Borlina C. S. et al. (2022), *LPSC*, submitted; [7] Audard M. et al. (2014), *Protostars and Planets VI*, 387-410; [8] Tikoo S. M. et al. (2014), *EPSL*, 404, 89–97; [9] Balbus S. A. and Hawley J. F. (1991), *ApJ*, 376, 214-222; [10] Desch S. J. and Turner N. J. (2015), *ApJ*, 811, 156; [11] Gammie C. F. (1996), *ApJ*, 457, 355-362; [12] Bai X.-N. and Stone J. M. (2013), *ApJ*, 769, 76; [13] Zhu Z. et al. (2020), *MNRAS*, 495, 3494-3514; [14] Cui C. and Bai X.-N. (2021), *MNRAS*, 507, 1106-1126; [15] Deng H. et al. (2020), *ApJ*, 891, 154; [16] Hirose S. and Turner N. J. (2011), *ApJL*, 732, L30; [17] Mori S. et al. (2019), *ApJ*, 872, 98; [18] Cieza L. A. et al. (2016), *Nature,* 535, 258–261; [19] Wark D. and Boynton W.V. (2001), *M&PS*, 36, 1135-1166; [20] Simon J. I. et al. (2017), *EPSL*, 472, 277-288; [21] Hu J. Y. et al. (2021), *Sci. Adv.*, 7, abc2962; [22] Boss A. P.et al. (2020), *ApJ*, 901, 81; [23] McNally C. P.,et al. (2013), *ApJL*, 767, L2; [24] McNally C. P. et al. (2014), *ApJ*, 791, 62; [25] Shakura N. I. and Sunyaev R. A., 1973, *A&A*, 500, 33-51; [26] Bai X.-N. and Stone J. M. (2011), *ApJ*, 736, 144