**IMPLICATIONS FOR CHONDRULE FORMATION REGIONS AND SOLAR NEBULA MAGNETIC FIELDS FROM STATISTICAL REANALYSIS OF CHONDRULE PALEOMAGNETISM.**

Roger R. Fu[1], Sarah C. Steele[1], Jacob B. Simon[2], Richard Teague[3], Joan Najita[4], David Rea[2]. [1]Department of Earth and Planetary Science, Harvard University, Cambridge, MA, USA (rogerfu@fas.harvard.edu). [2]Department of Physics and Astronomy, Iowa State University of Science and Technology, Ames, IA, USA. [3]Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA, USA. [4]NOIRLab, Tucson, AZ, USA.

**Introduction:** Recent submillimeter observations have revealed that AU-scale dust concentrations, cavities, and gaps, collectively known as sub-structures, occur pervasively in protoplanetary disks [1]. These features may be critical for the concentration of solids and resulting planet formation.

One proposed mechanism for the formation of substructures is magnetohydrodynamic (MHD) self-organization [2]. Paleomagnetic measurements of chondritic meteorites is one of the few available tools for quantifying disk magnetic fields, potentially testing for the role of magnetism in disk structure. Taken together, recent paleomagnetic studies of single chondrules and bulk chondrites provide evidence for a wide range of magnetic field strengths in the solar nebula (Fig. 1). These differences cannot be easily explained by analytical uncertainty or differences in the timescale of magnetization acquisition [3]. Previous authors have therefore interpreted these contrasting paleointensities as evidence for spatial and/or temporal fluctuations in magnetic field strength, potentially linked to sub-structures in the solar nebula.

This conclusion is based on direct comparison of mean paleointensities recovered from distinct meteorite groups. Such a simple statistical comparison may be insufficient for several reasons. First, the assumption that chondrules continuously spun during cooling introduces a factor of 2 uncertainty in chondrule-derived paleointensities. Although some theoretical and observational evidence has been presented in favor of spinning chondrules [4], the core of these arguments rests on uncertain assumptions about nebular gas density.

Second, the distribution of individual chondrule paleointensities may be highly non-Gaussian, especially if local field strengths were time-dependent. Combined with the small number of individual chondrules reported in published studies (≤8), these datasets do not meet the criterion of the central limit theorem; therefore, direct comparison of means and standard errors as described in recent studies are statistically inappropriate [3,5].

Finally, simple comparison of paleointensity means underutilizes the available information because different scenarios and conditions for magnetization acquisition make distinct predictions for the shape of the paleointensity distribution. Analyzing the relative frequencies of observed paleointensity can provide additional insights into the solar nebula environment.

In this work we use a Bayesian framework to reanalyze paleointensities from LL and CO group chondrules. By deriving expected paleointensity distributions corresponding to distinct chondrule and disk conditions, we directly test for whether chondrules spun during magnetization, the time-variability of nebular fields, and the distinctness of magnetic field environments for each chondrite group.

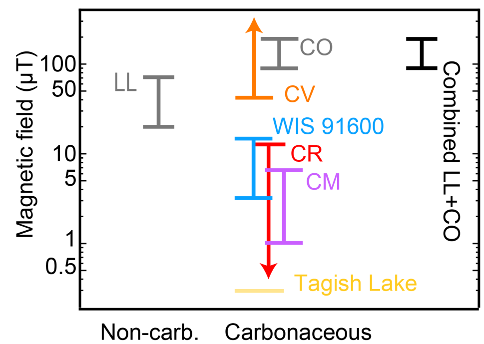


***Figure 1.*** *Compilation of chondrule and bulk chondrite-derived nebular magnetic field paleointensities. See [3 and 5] for references. LL and CO values were recomputed in this work.*

**Statistical methodology:** Groups of eight and five single chondrule paleointensities are available for LL and CO chondrules, respectively (Fig. 2; [4,5]). Bayesian hypothesis testing allows us to compute the relative likelihood of distinct models that may have produced these observations [6]. Specifically, the likelihood ratio between models $M_1$ and $M_2$ assuming no prior bias is:

$$\frac{p(M_1|D)}{p(M_2|D)} = \frac{p(D|M_1)}{p(D|M_2)} \quad (1)$$

where $D$ is a chondrule paleointensity dataset. The individual model likelihoods $p(D|M_x)$ are then found via direct integration across all model parameters.

This integration requires a function describing the probability of each observed paleointensity assuming a given model. We derived these functions for four cases corresponding to stationary and spinning chondrules cooling in a constant or sinusoidally time-varying magnetic field. The field variability timescale is assumed to be much longer than that of chondrule cooling such that each paleointensity is a single, time-weighted sampling of the fluctuating field.

**Implications for chondrule formation:** We first compare the likelihood of spinning versus static chondrule models. In a constant magnetic field, chondrule spin results in a uniform probability of recording any paleointensity between zero and the ambient field value (Fig. 2; [4]). All data are much more consistent with a spinning chondrule model, with probabilities of $p = 0.91$ and $p > 0.999$ for this model in the case of LL and CO chondrules, respectively.

For magnetic fields varying sinusoidally in time, chondrule spinning results in a similar but less decisive shift of paleointensities towards lower values. As a result, we find support for the spinning chondrule model with $p = 0.79$ and $p = 0.91$ assuming distinct and identical peak sinusoidal field strengths in the LL and CO chondrule formation regions (see below).

In summary, we find that the observed paleointensities imply at least 0.79 probability that chondrules spun during cooling with much higher probabilities corresponding to other assumptions. This supports the factor $2\times$ correction in previous and future chondrule paleomagnetism studies [4,5].

Further, the persistence of chondrule spinning over the timescale of remanence acquisition sets an upper bound on the density of ambient gas to order $10^{-8}$ and $10^{-9}$ kg m$^{-3}$ for LL and CO chondrules, respectively. Assuming no compression of the ambient gas due to the chondrule formation mechanism during late stage cooling, these values imply chondrule formation at or beyond 4 and 8 AU for LL and CO chondrules, respectively. Such large orbital radii indicate that CO chondrules likely formed in situ outside the orbit of Jupiter, consistent with isotopic evidence [7].

**Implications for solar nebula magnetism:** Under the assumption of a constant magnetic environment, LL and CO chondrules formed in distinguishable magnetic fields of $34^{+36}_{-14}$ μT and $106^{+88}_{-18}$ μT, respectively. If magnetic fields drove inward mass transport, the $3\times$ stronger fields in the CO formation region correspond to $40-100\times$ faster inner gas accretion, depending on the assumed mechanism of angular momentum transport [8]. No known mechanism for removing mass from intermediate radii between the CO and LL regions can sustain such a large gradient in inward gas accretion [8]. We therefore find that LL and CO chondrule formation in constant magnetic fields is unlikely if these fields were responsible for mass and angular momentum transport.

Alternatively, the available data are consistent with formation of LL and CO chondrules in a sinusoidally varying magnetic field with a peak amplitude $112^{+81}_{-20}$ μT. In this case, fluctuations in the ambient field strength may be due to, for example, "bursty" MHD behavior observed in some simulations of disk mid-planes in the Hall effect regime with anti-aligned net vertical field and angular momentum vectors [9].

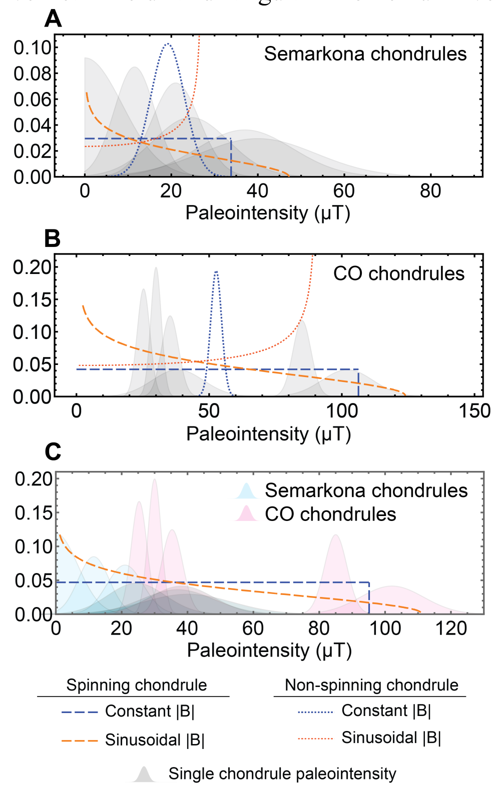


***Figure 2.*** *Probability density functions (PDFs) for the recorded paleointensity assuming spinning and non-spinning chondrules cooling in a constant or slowly varying magnetic field. Dashed and dotted PDFs correspond to the best-fit models for each set of assumed field and chondrule spinning conditions.*

**Conclusion:** Available chondrule paleointensities suggest that chondrules spun continuously during late-stage cooling, requiring a low-density environment. This supports in-situ formation of chondrules and the origin of CO chondrules in the outer disk. Large differences in the paleointensities of LL and CO chondrules are more consistent with a sinusoidally varying magnetic field than locally constant magnetic fields, which would require very large, likely unrealistic gradients in gas accretion rate.

**References:** [1] Andrews, S.M. (2020) *Annu. Rev. Astron. Astrophys.* 58, 483. [2] Suriano S. et al. (2018) *MNRAS* 477, 1239. [3] Fu, R.R. et al. (2021) *AGU Adv.* 2, e2021AV000486. [4] Fu, R.R. et al. (2014) *Science* 346, 1089. [5] Borlina et al. (2021) *Sci. Adv.* 7, eabj6928. [6] Raftery, A.E. (1995) *Sociol. Methodol.* 25, 111. [7] Kleine T. et al. (2020) *Space Sci. Rev.* 216, 55. [8] Lesur, G.R.J. (2021) *Astron. Astrophys.* 650, A35. [9] J.B. Simon et al. (2015) *MNRAS* 454, 1117.