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SCIENCE ADVANCES | RESEARCH ARTICLE

SPACE SCIENCES

Paleomagnetic evidence for a disk substructure in the early solar system

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Paleomagnetism: overview

- Inference of ancient magnetic fields recorded by planetary materials.
- In the form of natural remnant magnetization (NRM), several sub-categories.

Basic principle: record ambient field when they cool, crystalize, or accrete, with a certain proportionality:

$$M_{\mathrm{NRM}} = \chi B_{\mathrm{paleo}}$$

Proportionality coefficient obtained/calibrated by subsequent experiments.

See *Weiss, Bai & Fu (2021, Sci. Adv.)* for a review on its application to solar nebula.

Meteorite paleomagnetism: pros & cons

Advantages:

- Directly meausrement of total field strength
- Have age information
- Instantaneous to time-averaged field strength (depending on how magnetization is acquired)

Disadvantages:

- Field orientation is unknown
- Location is unknown (expected to be near midplane, distance based on educated guesses)
- Small number statistics (can be improved over time)

Theoretical model of B field strength

Angular momentum flux carried by accretion flow: $\dot{M}_{\rm acc} j(R)$

Radial transport of A.M.: $2\pi R^2 \int_{z_{\rm bot}}^{z_{\rm top}} dz \left(\overline{\rho \delta v_R \delta v_\phi} - \frac{\overline{B_R B_\phi}}{4\pi} \right)$

Vertical transport of A.M.: $2\pi R^2 \left(\overline{\rho v_z v_\phi} - \frac{\overline{B_z B_\phi}}{4\pi} \right) \Bigg|_{z_{\rm bot}}^{z_{\rm top}}$

Balancing with radial transport: $\dot{M}_{\rm acc} j = 2\pi R^2 L_z (\overline{B_R B_\phi}/4\pi)$

Balancing with vertical transport: $\dot{M}_{\rm acc} j = 8\pi R^3 |\overline{B_z B_\phi}/4\pi|_{\rm base}$

Wardle 2007, Bai & Goodman 2009

Theoretical model of B field strength

Assuming steady state accretion, and depending on the driving mechanism:

$$B_{\rm mid} \approx 0.72\mathrm{G}\left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{\dot{M}_{\rm acc}}{10^{-8}M_\odot \mathrm{y}^{-1}}\right)^{1/2}\left(\frac{fH}{L_z}\right)^{1/2}\left(\frac{R}{\mathrm{AU}}\right)^{-11/8}$$

(For radial transport, with $f = (B_\phi/B_R)_{\rm mid}$)

$$B_{\rm mid} \approx (0.065m)\mathrm{G}\left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{\dot{M}_{\rm acc}}{10^{-8}M_\odot \mathrm{y}^{-1}}\right)^{1/2} f'^{1/2}\left(\frac{R}{\mathrm{AU}}\right)^{-5/4}$$

(For vertical transport, with $m = B_{\phi,\rm base}/B_{\phi,\rm mid}$, $f' = (B_\phi/B_z)_{\rm base}$)

[Weiss, Bai & Fu (2021), generalized version]

Wind-transport is more efficient by (R/H), but geometric factors also matter!

Calibrate the geometric factors

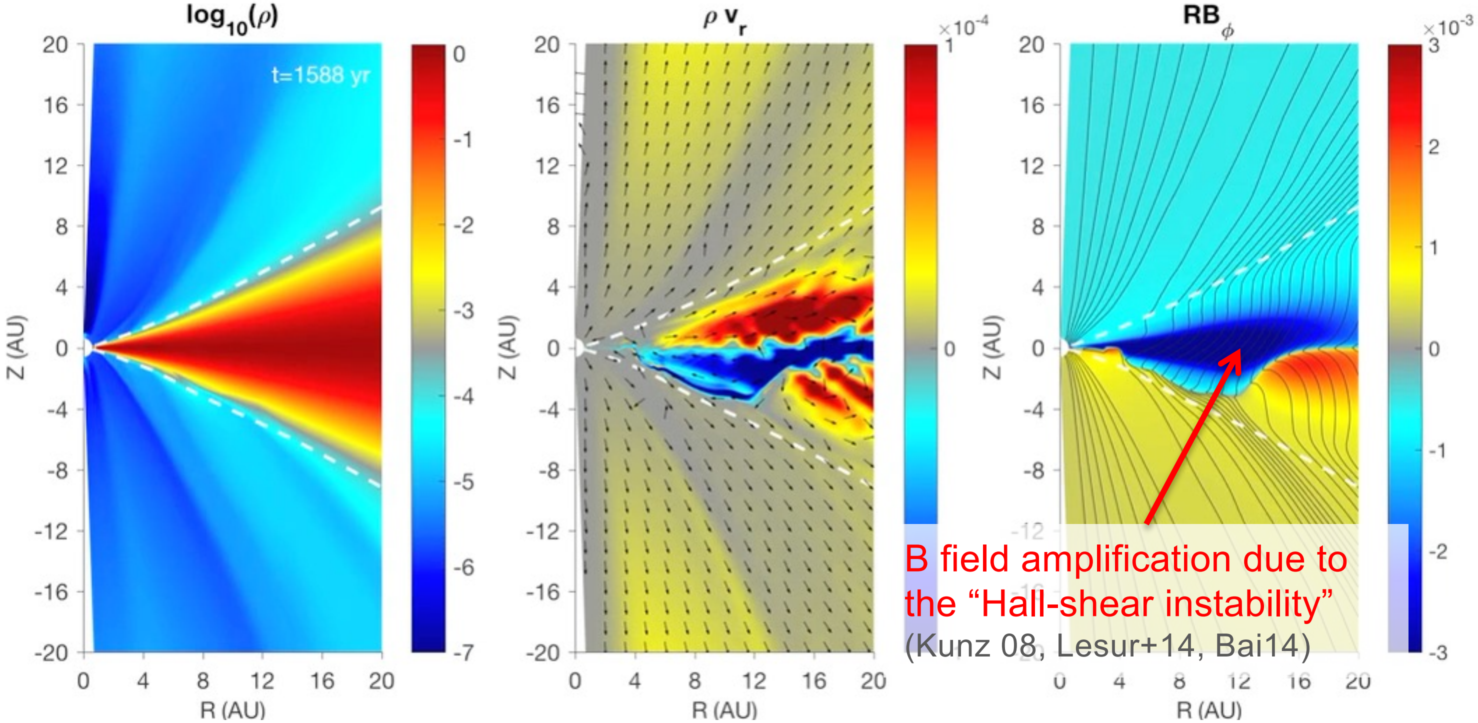
Current understanding:

Disk is threaded by net B_z.

Accretion is primarily wind-driven.

Polarity of B_z matters due to the Hall effect.

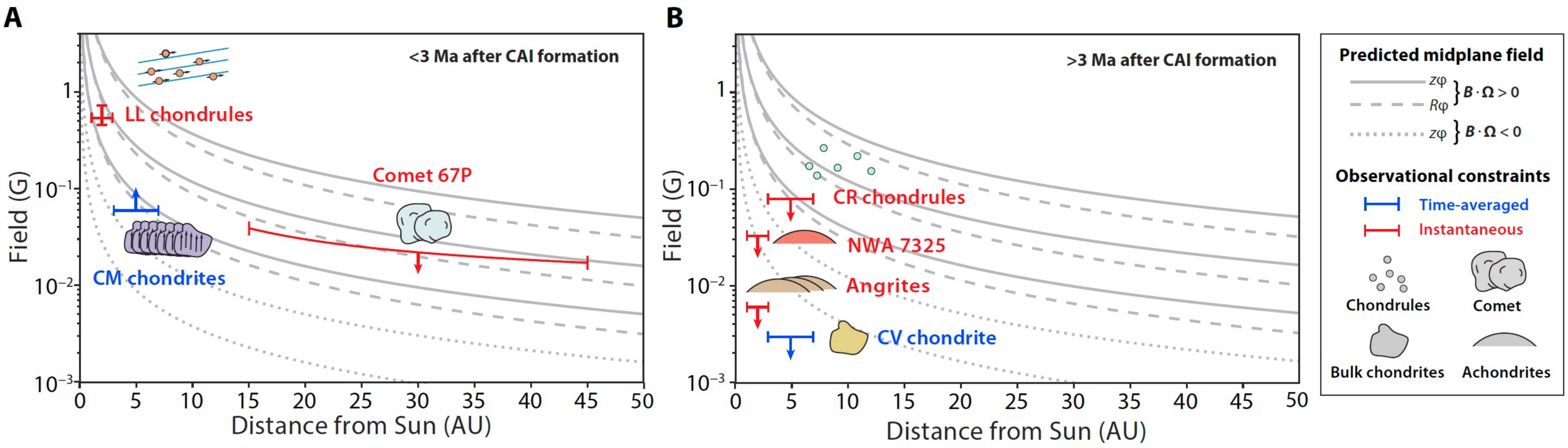
Aligned case:



We have f'~10, and for aligned/anti-aligned cases, m~10 or 1.

(Bai 2017)

Constrains from paleomagnetism (as of 2021.1)

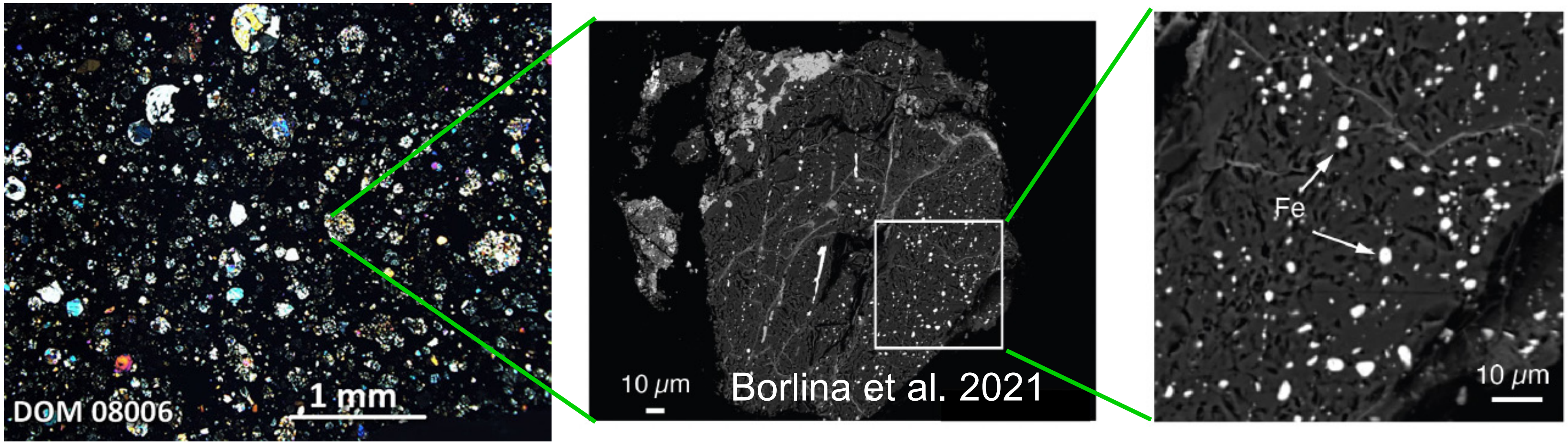


Distance is assumed (2-3 AU for LL chondrite, 3-7AU for carbonacious chondrites).

Sparse data points, many upper/lower limits, but results so far consistent with standard accretion rate in an aligned field geometry.

New samples: CO chondrules

Two CO chondrites, both among the least altered meteorites (i.e., pristine).



Extracted 6 chondrules from the two samples.

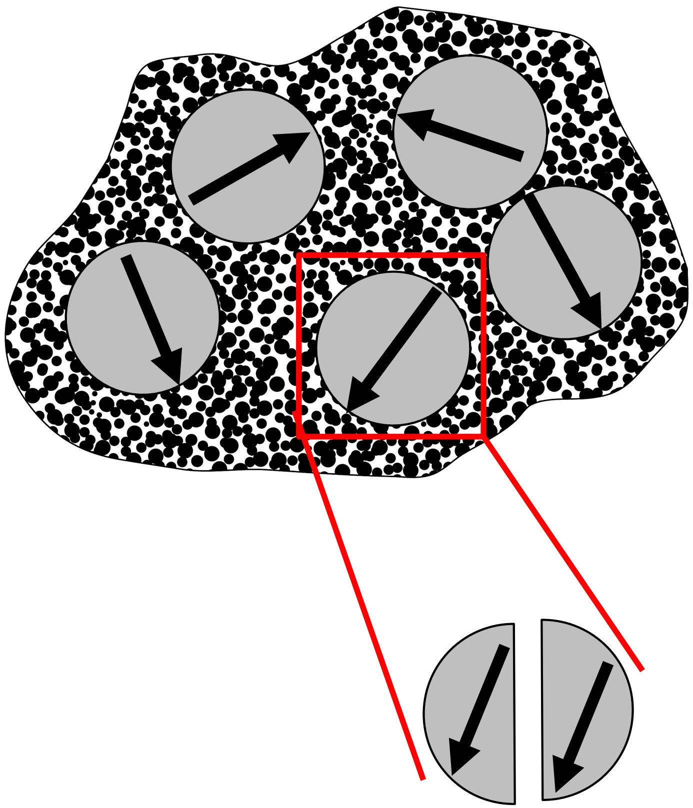
Age: 2.2+/-0.8 Ma after CAI formation.

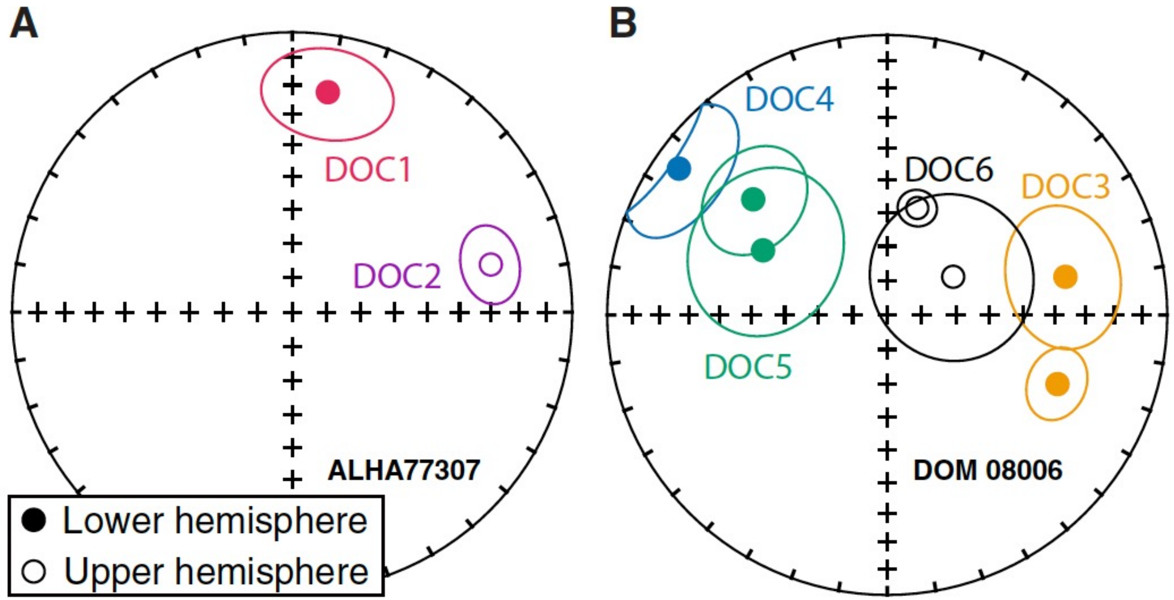
Dusty olivine chondrules contain fine-grained iron as magnetic carriers.

Measurements

Borlina et al. 2021

Conglomerate and unidirection tests:

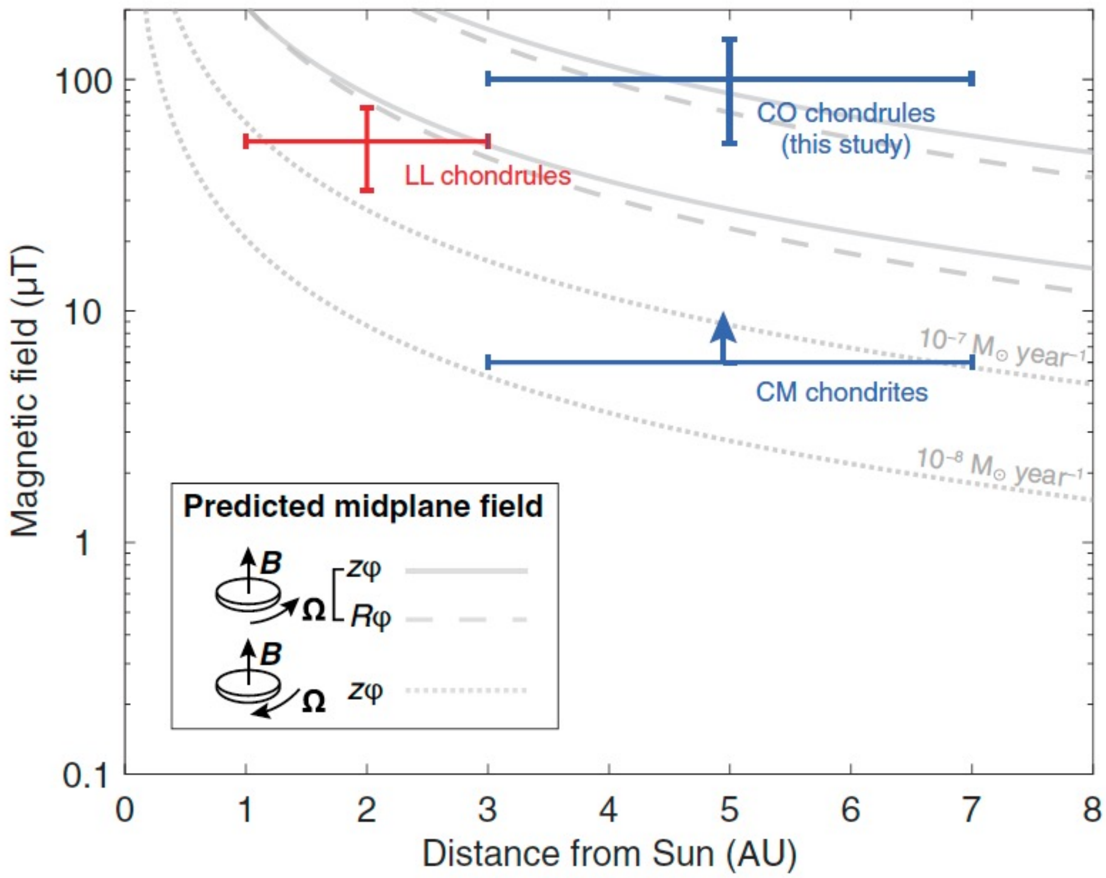




Magnetization is pre-accretional.

Inferred nebula field strength (calibrated and averaging over samples): 1.01+/-0.48 G

Results from CO chondrules



Borlina et al. 2021

In brief, we have:

0.5G at ~2 AU

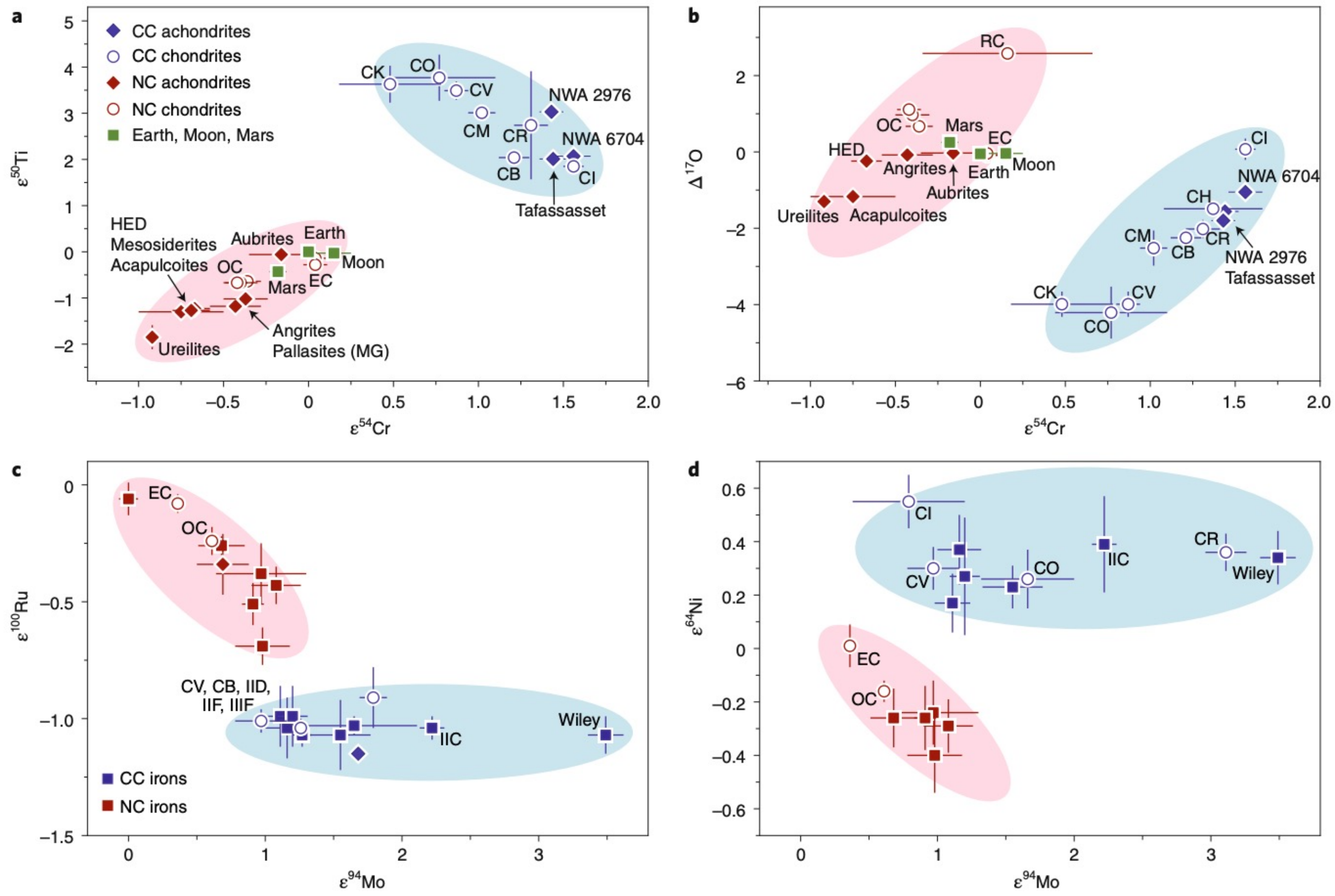
1G at ~5 AU

Given that we expect:

$$\dot{M}_{\rm acc} \sim B^2 R^{5/2}$$

A mismatch in accretion rate by a factor of ~40!

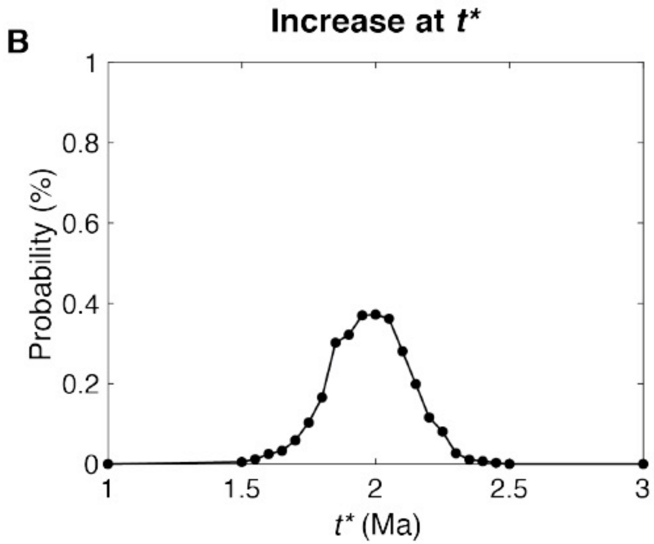
In the context of the isotopic dichotomy



Kuiper et al. 2020

Time-variable accretion?

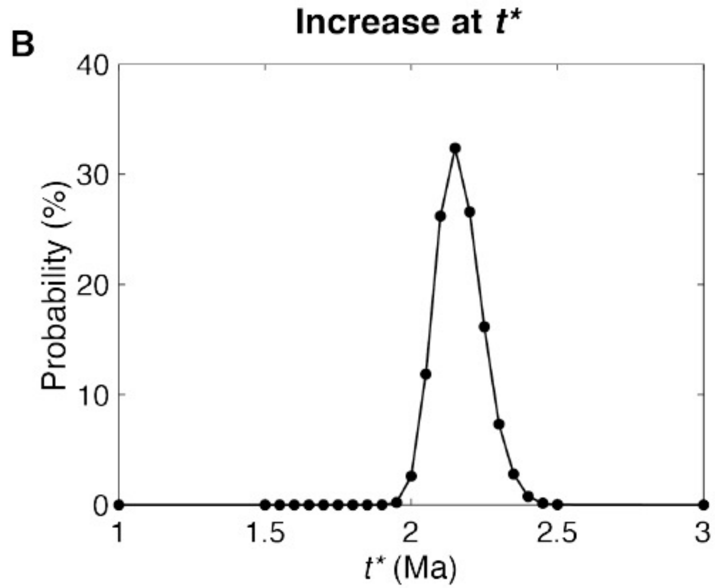
Borlina et al. 2021



CO chondrules: ~2.2+/-0.4 Ma after CAI
LL chondrules: ~2.0+/-0.4 Ma after CAI.

Ages based on Kita & Ushikubo (2011)

Age overlap is against the time-variability scenario.

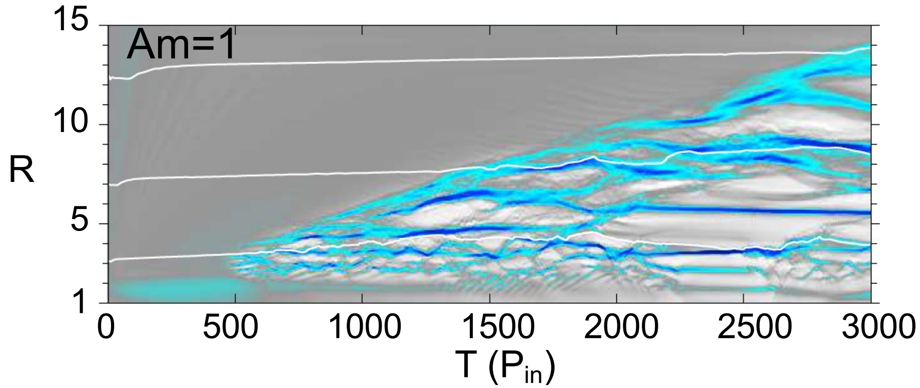


More recently, there are indications that the NC and CC chondrule ages are more non-comtemporous.

Hertwig+2019, Siron+2021

Magnetic substructure in a normal disk?

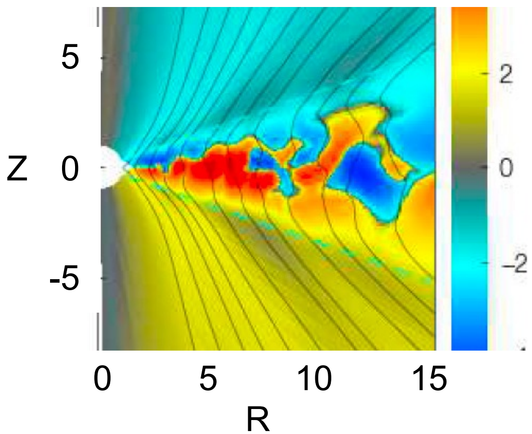
We have seen that evolution of poloidal B flux is highly inhomogeneous.

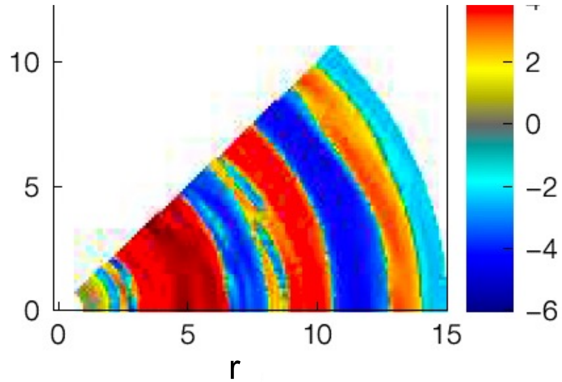


Cui & Bai 2021

See also G. Lesur's talk

However, B field is dominated by B_ϕ: strength is smooth other than sign change.



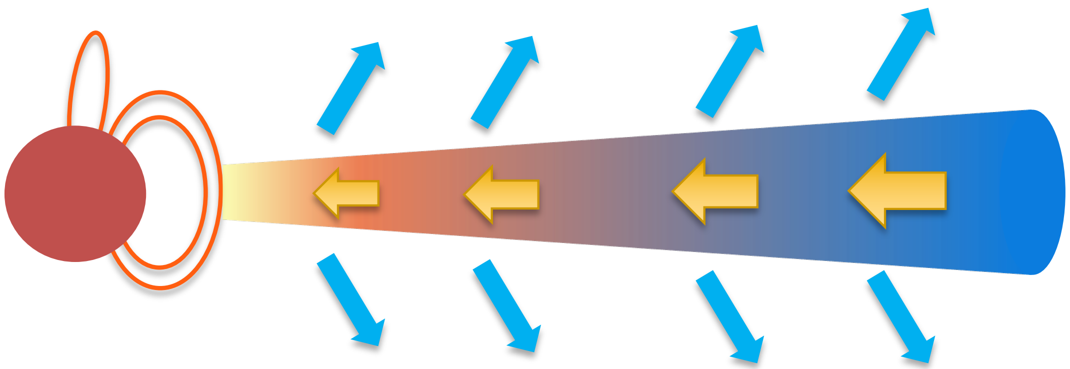


We don't know for sure but seems unlikely.

Spatially-varying accretion?

MHD winds in PPDs are magneto-thermal in nature, with significant mass loss (Bai+2016, Bai 2017, Bethune+2017, Wang+2019, Lesur 2021, but see Gressel+2020).

Significant mass loss would imply increasing accretion rate with radius in steady state.



If the mismatch in accretion rates is indeed so large, something should happen in between.

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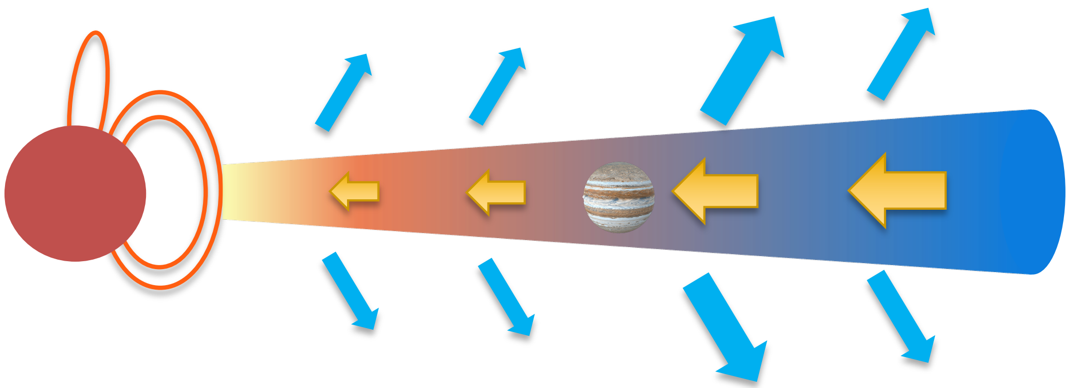

If the mismatch in accretion rates is indeed so large, something should happen in between. The presence of Jupiter?

Summary

- Meteorite paleomagnetism provides alternative means to constrain the strength and evolution of magnetic field in disks.
- Existing paleomagnetic record consistent with wind-driven accretion with aligned B_z for typical nebular accretion rate of 10^{-8} Msun/yr.
- New measurements from the CO chondrules yield nebular field strength even stronger than earlier record from LL chondrules.
- Despite caveats, the results imply a mismatch in nebular accretion rates between the NC and CC reservoir.
- This mismatch might be related to excessive disk mass loss, due to MHD disk winds and/or presence of Jupiter.