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**HISTORY OF THE SOLAR NEBULA FROM METEORITE PALEOMAGNETISM.** B. P. Weiss<sup>1</sup>, R. R. Fu<sup>2</sup>, H. Wang<sup>3</sup>, X.-N. Bai<sup>4</sup>, J. Gattacceca<sup>5</sup>, R. J. Harrison<sup>6</sup>, D. L. Schrader<sup>7</sup>, <sup>1</sup>Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, <sup>2</sup>Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, <sup>3</sup>Planetary Science Institute, School of Earth Sciences, China University of Geosciences, Wuhan, China, <sup>4</sup>Institute for Theory and Computation, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA, <sup>5</sup>CNRS, Aix-Marseille Université, Institut de Recherche pour le Développement, Collège de France, CEREGE, Aix-en-Provence, France, <sup>6</sup>Department of Earth Sciences, University of Cambridge, Cambridge, UK, <sup>7</sup>Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

**Introduction:** A key stage in the origin of planetary systems is the formation of a gas-rich protoplanetary disk. Theoretical studies suggest that magnetic fields mediated the global evolution and structure of protoplanetary disks by transporting angular momentum and driving disk accretion [1]. However, the nature and history of nebular magnetic fields have been poorly constrained. Here we review recent advances in our understanding of the magnetism of the solar nebula as inferred from meteorites. We discuss their implications for the mechanism and rate of accretion, the dispersal time of the nebula, the formation of chondrules and the gas giants, and planetary migration.

**The solar nebula and nebular magnetism:** Until recently, evidence for magnetic fields in the terrestrial planet-forming regions of disks around young stellar objects (YSOs) and in the early solar system had been absent. Two recent classes of measurements are filling this gap: astronomical and meteoritic studies.

*Astronomical observations:* Although there are presently no techniques available for resolving magnetic fields in the midplane region at stellar distances of  $\sim 0.1$ -50 AU, Zeeman spectroscopy and spectropolarimetry have mapped magnetic field intensities and directions on the surface of T Tauri stars and their innermost disks ( $< 0.05$  AU)[2]. The orientations of magnetic fields at scales of  $> 50$ -100 AU could be mapped via their alignment of the spin axes of aspherical dust grains spun-up by radiation torques, which leads to emission polarized perpendicularly to the field direction [3]. Recent millimeter and mid-infrared observations have observed polarized emission of embedded objects and those with visible disks with masses ranging from  $\sim 0.2$ -2.5 solar masses ( $M_{\odot}$ ) [3]. However, it is unclear whether the observed polarization is a signature of magnetic fields or is due to dust self-scattering [4, 5].

*Meteorite measurements:* Recent paleomagnetic measurements of chondrules from the Semarkona meteorite [6] indicate that the solar nebula magnetic field was 5-50  $\mu\text{T}$  in the midplane at  $\sim 2$ -3 AU at the time of chondrule formation at  $\sim 1$ -3 My after the formation of calcium aluminum-rich inclusions (CAIs) (assumed here to be  $4567.30 \pm 0.16$  My ago [7], just after the collapse of the molecular cloud). Furthermore, paleomagnetic studies of seven CM chondrites indicate they were magnetized by a field of  $> 4 \pm 3$   $\mu\text{T}$  sometime between 2.4-4 My after CAI formation (from I-Xe dating) although it is unclear whether this field was nebular or generated by the CM parent body [8] (note these paleointensities are twice those reported by [8] to take into account rotation of the

CM body). Collectively, these data indicate a minimum duration of between  $\sim 2 \pm 1$  My after CAI formation for the nebular field and a minimum duration of  $\sim 3.7 \pm 0.3$  My after CAI formation for the nebular gas. The CM chondrite data constrain the field averaged over the time-scale of aqueous alteration of the meteorites ( $\sim 1$ - $10^4$  years) while the Semarkona data are near-instantaneous field records.

**Lifetime of the nebula:** There have been few direct, accurately-dated meteoritic constraints on the lifetime of the nebula and nebular magnetic fields [9]. We review recent advances in astronomical and meteoritic studies.

*Astronomical observations:* Measurements of infrared excesses have inferred that 50% of all protoplanetary disks around Sun-like YSOs disperse somewhere between  $\sim 2$ -6 My after collapse of their parent molecular clouds [10, 11], with this large age uncertainty due to the poorly-known ages of YSOs [10]. In addition to this uncertainty in the median disk lifetime, it is also unknown where our solar system lies in the distribution of disk lifetimes.

*Meteorite measurements:* Because the sustenance of magnetic fields requires a conducting medium, the dispersal of the solar nebula can be timed by determining when nebular fields disappeared as inferred from the absence of paleomagnetism in meteorites younger than a certain age (see [13] for details). Our recent studies of four different meteorite groups have provided consistent constraints on the timing of the dispersal of the nebular magnetic field.

First, the absence of stable magnetization with unblocking temperatures above 250°C in the Kaba CV chondrite indicates that the field during magnetite formation was less than  $\sim 0.3$ -3  $\mu\text{T}$  [12] at  $\sim 4$ -6 My after CAI formation as dated by I-Xe and Mn-Cr chronometry [12]. Secondly, it was found that volcanic angrites cooled in a null field environment ( $< 0.6$   $\mu\text{T}$ ), precisely timed by Pb-Pb chronometry to have occurred at  $\sim 3.8$  My after CAI formation [13]. Thirdly, the absence of primary magnetization in the ungrouped achondrite NWA 7325 indicates that it also cooled in the absence of a field ( $< 1.6$   $\mu\text{T}$ ) at  $\sim 4.2 \pm 0.3$  My after CAI formation as indicated by Al-Mg ages [14]. Finally, ongoing analyses of chondrules from the CR chondrite LAP 02342 [15] find that they carry no internally-coherent components of magnetization, suggesting that the magnetic field strength in the CR chondrule formation environment was  $< 15$   $\mu\text{T}$  at  $\sim 3.7 \pm 0.3$  My after CAI formation (from Pb-Pb and Al-Mg chronometry [16]).

Independently from meteorite paleomagnetism, it has been observed that the elemental (Si/Mg and Fe/Mg) [17] and isotopic (for W and Mo) [18] compositions of chon-

drules differ from those of the accompanying matrices in several chondrite groups even though the bulk composition of the chondrites is solar. Assuming this complementarity formed prior to accretion [19], it suggests that both chondrules and matrix formed out of a single reservoir of solar composition. If the reservoir was the nebula, this would imply the nebula persisted until at least the formation of CR chondrules at  $\sim 3.7 \pm 0.3$  My after CAI formation [16]. However, because chondrule-matrix complementarity only requires that the parent reservoir was chondritic in composition and was not necessarily the gaseous nebula itself, it does not strictly constrain the nebula's lifetime.

#### Implications:

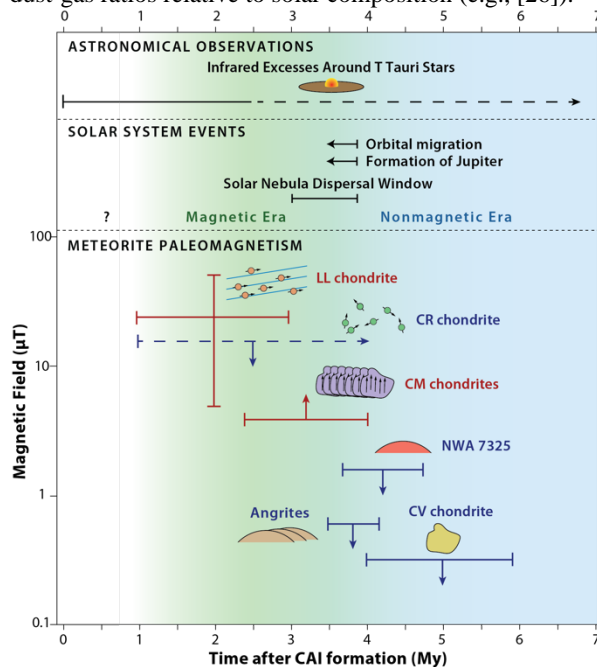
**Accretion and nebular lifetime:** The 5-50  $\mu\text{T}$  paleointensities inferred from Semarkona chondrules are consistent with typically observed protostellar accretion rates of  $\sim 10^{-8}$  solar masses ( $M_{\odot}$ )  $\text{year}^{-1}$  [20]. This supports the hypothesis that nebular magnetism played a central role in mass and momentum transport in the protoplanetary disk.

The most precisely dated zero-field constraint ( $<0.6$   $\mu\text{T}$  inferred from angrites) suggests that accretion rates dropped to  $<10^{-9}$   $M_{\odot}$   $\text{year}^{-1}$  by 3.8 My after CAI formation [21]. Astronomical observations and theory have found that such a decline in accretion rates is associated with near-total dissipation of the nebula in just  $10^5$  years [21]. Therefore, our near-zero paleointensities suggest that by  $\sim 3.8$  My after CAI formation, the nebular gas itself in our solar system had similarly dispersed. This timing is compatible with the observed  $\sim 2$ -6 My half-lifetimes for extrasolar protoplanetary disks [10, 11].

**Giant planet formation and migration:** This nebula lifetime is not so short as to require the giant planets to have formed by very rapid mechanisms such as collapse due to gravitational instabilities (which can occur in  $<0.1$  My) [22]. Combined with recent isotopic evidence that Jupiter reached 50 Earth masses ( $M_{\oplus}$ ) following the formation of CR chondrites [23], it indicates that Jupiter then grew from  $<50 M_{\oplus}$  to its final size of  $318 M_{\oplus}$  within  $\leq 0.5$  My by  $\sim 3.8$  My after CAI formation. This rapid rate strains some variants of the core accretion model, particularly for the ice giants [22]. The nebula lifetime also sets a 3.8-My limit for planetary orbital migration via planet-disk interactions.

**Chondrule formation:** The Semarkona paleointensities also can be used to distinguish between hypothesized chondrule formation mechanisms. The paleointensities are significantly lower than the  $>80$  to  $400$   $\mu\text{T}$  values predicted for chondrules formed by the x-wind model [24]. Furthermore, mechanisms invoking intense currents such as magnetic reconnection flares and current sheets predict fields  $>500$   $\mu\text{T}$  during chondrule heating [25]. Instead, they appear to be more consistent with chondrule formation by nebular shocks [26] (for which fields are expected to be  $<100$   $\mu\text{T}$ ) and/or planetesimal collisions (which are compatible with a wide range of field values) [6].

Additionally, the existence of magnetization in Semarkona chondrules requires that they did not collide during cooling in order to maintain a steady orientation with the background field. For relative chondrule velocities of  $0.001$ - $1$   $\text{m s}^{-1}$ , this constrains chondrule number densities to between  $40$ - $4 \times 10^4$   $\text{m}^{-3}$ , consistent with chondrule forming in regions with in the nebula with enhanced dust-gas ratios relative to solar composition (e.g., [26]).



**Fig. 1.** Meteorite paleomagnetism and astronomical constraints on the intensity and lifetime of the solar nebula field and inferred associated solar system events. Each point in the bottom panel represents the paleointensity of the ambient field from a given meteorite or meteorite group. Downward- (upward-) pointing arrows indicate upper (lower) limits. CV chondrite value is from blocking temperatures  $>250^{\circ}\text{C}$ . See text for references.

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