REPORT

SOLAR SYSTEM FORMATION

Lifetime of the solar nebula constrained by meteorite paleomagnetism

Huapei Wang,[1*†] Benjamin P. Weiss,[1] Xue-Ning Bai,[2] Brynna G. Downey,[1] Jun Wang,[3] Jiajun Wang,[3] Clément Suavet,[1] Roger R. Fu,[1] Maria E. Zucolotto[4]

A key stage in planet formation is the evolution of a gaseous and magnetized solar nebula. However, the lifetime of the nebular magnetic field and nebula are poorly constrained. We present paleomagnetic analyses of volcanic angrites demonstrating that they formed in a near-zero magnetic field (<0.6 microtesla) at 4563.5 ± 0.1 million years ago, ~3.8 million years after solar system formation. This indicates that the solar nebula field, and likely the nebular gas, had dispersed by this time. This sets the time scale for formation of the gas giants and planet migration. Furthermore, it supports formation of chondrules after 4563.5 million years ago by non-nebular processes like planetesimal collisions. The core dynamo on the angrite parent body did not initiate until about 4 to 11 million years after solar system formation.

Theoretical studies suggest that magnetic fields mediated the global evolution and structure of protoplanetary disks by transporting angular momentum and driving stellar accretion (*1*). They also directly influence disk dynamics by generating turbulence and launching disk winds (*1*). These processes strongly affect the sequence of planet formation, including the formation of chondrules (*2*) and the accretion of planetesimals (*3*). Recent astronomical observations (*4*) have provided evidence for large-scale magnetic fields in protoplanetary disks, and recent paleomagnetic measurements of chondrules from the Semarkona meteorite (*5*) have found that the midplane solar nebula magnetic field was 5 to 50 μT in the terrestrial-planet region sometime between ~1 and 3 million years (My) after solar system formation [defined here as the crystallization age of calcium- and aluminum-rich inclusions (CAIs) at 4567.30 ± 0.16 million years ago (Ma) (*6*)]. These field intensities are consistent with those predicted for typically observed protostellar accretion rates of ~10^{-8} solar masses ($M_{\odot}$) per year (*7*). Because the presence of ionized nebular gas is necessary to sustain magnetic fields against diffusive decay, these data indicate that the nebula persisted for at least 1 to 3 My after solar system formation.

It remains unknown when the solar nebula magnetic field and the gaseous nebula itself dispersed. The dispersal times of the field and nebula set the time scale for stellar accretion, the formation of the gas giants, and the epoch of large-scale planetary migration and have major implications for dust dynamics and disk structure (*8*), the final sizes eccentricities of the terrestrial planets (*9*), and the viability of hypothesized chondrule and planetesimal formation mechanisms involving nebular gas or magnetic fields. For example, disk gravitational instabilities could in principle have formed the giant planets in <0.1 My, while core accretion is favored by longer (several to perhaps >10 My) time scales (*10*).

There are currently no direct, accurately dated meteoritic constraints on the lifetime of the nebula and nebular magnetic fields in the early solar system (*11*, *12*). Astronomical observations have inferred that half of all protoplanetary disks around Sun-like young stellar objects (YSOs) disperse somewhere between ~2 and 6 My after formation (*13*, *14*), with this large age uncertainty due to difficulties in determining YSO ages (*13*). In addition to this uncertainty in the median disk lifetime, it is also unknown where our own solar system lies in the distribution of disk lifetimes. To characterize late-stage nebular magnetism and constrain the lifetime of the early solar nebula, we studied the paleomagnetism of angrites, a group of ancient basaltic achondritic meteorites (*15*) containing fine grains of ferromagnetic magnetite grains. Paleomagnetism combined with radiometric ages can provide a direct and precisely dated measurement of the nebular field strength in the terrestrial planet–forming region.

Because angrites are samples of a differentiated planetesimal that formed an early metallic core (*15*), their paleomagnetism also offers the opportunity to characterize planetesimal core dynamo activity. The small radii (~10^2 km) of planetesimals allow the study of dynamo generation in bodies smaller than planets that have distinct thermal evolution parameters (*16*). However, a key unknown about planetesimal dynamos has been their onset time. Some theoretical studies have suggested that they might occur instantaneously after large-scale melting (*17*, *18*), whereas others have argued that dynamos should be delayed by several to tens of My or longer (*19*, *20*). Paleomagnetic measurements on angrites of different ages could establish the temporal history of the angrite parent body dynamo and, in particular, its onset time.

Angrites are among the oldest known and most pristine planetary igneous rocks and have very precisely dated formation ages due to their high U/Pb compositions (*15*). We studied three volcanic angrites: D'Orbigny, Sahara 99555, and Asuka 881371, which have pyroxene Pb/Pb ages of 4563.37 ± 0.12 My (*21*), 4563.54 ± 0.14 My (*21*), and 4562.4 ± 1.6 My (*15*), respectively. Because these meteorites cooled rapidly (10° to 50°C/hour) (*22*), they should have acquired thermoremanent magnetization (TRM) just ~3.8 My after solar system formation if an ambient field was present. Angrites are thought to have originated from the inner solar system [<~5 astronomical units (au)] (*23*) and so should provide field records from the midplane of the terrestrial planet–forming region. We also analyzed the younger plutonic angrite Angra dos Reis, which has a pyroxene Pb/Pb age of 4556.51 ± 0.11 My (*21*) and cooled at >1000°C/My (*24*). All of these meteorites are essentially unshocked, unbrecciated, and unmetamorphosed since final cooling (*15*). In particular, at least D'Orbigny and Angra dos Reis have never subsequently been heated above the ~500°C U/Pb phosphate closure temperature (*21*, *24*, *25*), and all three angrites have whole-rock (U-Th)/He ages within the uncertainties of their Pb/Pb pyroxene formation ages (*26*). Rock magnetic measurements and synchrotron transmission x-ray microscopy (*18*, *27*) demonstrate that the major magnetization carriers in angrites are pseudo–single domain magnetite and titanomagnetite grains (and possibly also iron sulfides in Angra dos Reis). Such magnetite has higher coercivity (i.e., resistance to being remagnetized by applied fields) and is more stable during laboratory heating than the multidomain iron-nickel minerals that dominate most basaltic achondrite groups. Recovered the day after it fell to Earth (*15*), Angra dos Reis largely avoided weathering after landing and remagnetization by collectors' hand magnets.

A previous paleomagnetic study of D'Orbigny, Asuka 881371, and Angra dos Reis identified natural remanent magnetization (NRM) interpreted as evidence for dynamo action on their parent planetesimal (*18*). This conclusion rested largely on the high-fidelity record in Angra dos Reis, which was the only large meteorite studied that was not affected by magnet overprints. However, the previous study was unable to employ thermal demagnetization, a key technique for isolating primary magnetization. To address this limitation, we conducted thermal demagnetization and thermal

[1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA. [2]Institute for Theory and Computation, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA. [3]National Synchrotron Light Source-II, Brookhaven National Laboratory, Upton, NY, USA. [4]Museu Nacional, Rio de Janeiro, Brazil.
***Corresponding author. Email: huapei@mit.edu** †Present address: China University of Geosciences, 388 Lumo Road, Wuhan, Hubei 430074, China.

paleointensity analyses in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory using a 2G Enterprises Superconducting Rock Magnetometer (SRM) in combination with a recently developed controlled-atmosphere system optimized for the oxygen fugacity conditions of angrite petrogenesis (*28*). We found that for atmospheres with oxygen fugacities ranging from approximately 0 to 1 dex below the iron-wüstite buffer, magnetic carriers in D'Orbigny and Sahara *99555* are largely thermochemically stable during heating up to ~400° to 500°C, whereas Angra dos Reis is largely stable up to ~200°C (supplementary text). We also conducted new nondestructive alternating field (AF) demagnetization, as well as anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), Shaw (*29*) and Thellier-Thellier (*30*) paleointensity analyses.

Our thermal demagnetization of Angra dos Reis shows that it contains a low-temperature (LT) component that demagnetizes up to ~200°C and a high-temperature (HT) component that unblocks between ~200°C and up to >~300°C. The LT and HT components have similar directions to low-coercivity (LC) (unblocking below ~15 mT) and high-coercivity (HC) (stable to >290 mT) components, respectively, previously identified by AF demagnetization from mutually oriented samples (*18*). A positive fusion-crust baked contact test and the high stability and unidirectionality of the HT/HC component in Angra dos Reis confirm the previous conclusion (*18*) that it is a TRM from primary cooling on the angrite parent body (supplementary materials). Using previously published ARM paleointensity data (*18*), we find that the HT/HC component formed in a field of ~17 μT (with a minimum value of 8.5 μT), consistent with previous results (*18*) (supplementary text).

AF demagnetization revealed that the NRMs of interior samples of D'Orbigny and Sahara *99555* consist of LC components that unblock up to ~4 to 10 mT and ~6 to 10 mT, respectively. Additional AF and thermal demagnetization showed that, after the removal of the LC components, middle-coercivity (MC)/middle-temperature (MT) components unblock up to ~65 mT and ~50 mT and up to ~200°C, respectively (Figs. 1 and 2 and supplementary text) (*31*). High ratios of NRM to IRM (ranging from ~10 to 100%) (tables S2 and S3) over the coercivity range of the LC components and a failed fusion-crust baked contact test for D'Orbigny (*18*) demonstrate that the LC components are likely overprints from hand magnets, as previously suggested (*18*). However, our experiments show that the MC/MT components are also likely overprints because they demagnetize at lower temperatures (Fig. 2, A and B) and AF levels (fig. S8, A and B) than laboratory-applied total ARM with a bias field of 20 μT (an analog for TRM acquired in a ~4-μT field using a TRM/ARM ratio of 5) (supplementary text), which persists to >400°C and >100 mT. Instead, the MT components demagnetize at similar AF levels as a partial thermoremanent magnetization (pTRM) acquired by heating to ~200° to 300°C in a ~10-μT field (Fig. 2, C and D, and table S4).

This indicates that there exists a population of grains with high coercivities (>70 mT) and unblocking temperatures (>200°C) that are essentially unmagnetized. This lack of high-stability NRM is also manifested by the fact that after removal of the MC/MT components, the remaining magnetization directions of mutually oriented samples are collectively scattered (fig. S6) and have weak paleointensities (tables S2 and S3). The low peak 125° to 225°C unblocking temperature of the MT component in D'Orbigny suggests it could be a viscous remanent magnetization (VRM) acquired in Earth's field (supplementary text). On the other hand, the 200° to 425°C peak blocking temperature of the MT component for Sahara *99555* may be too high for it to be a terrestrial VRM, whereas a fusion-crust baked contact indicates that fusion crust–rich samples do not have strong MC components (supplementary text). Instead, the MT component in Sahara *99555* may be a weak thermal overprint from later magmatism on the angrite parent body during the epoch

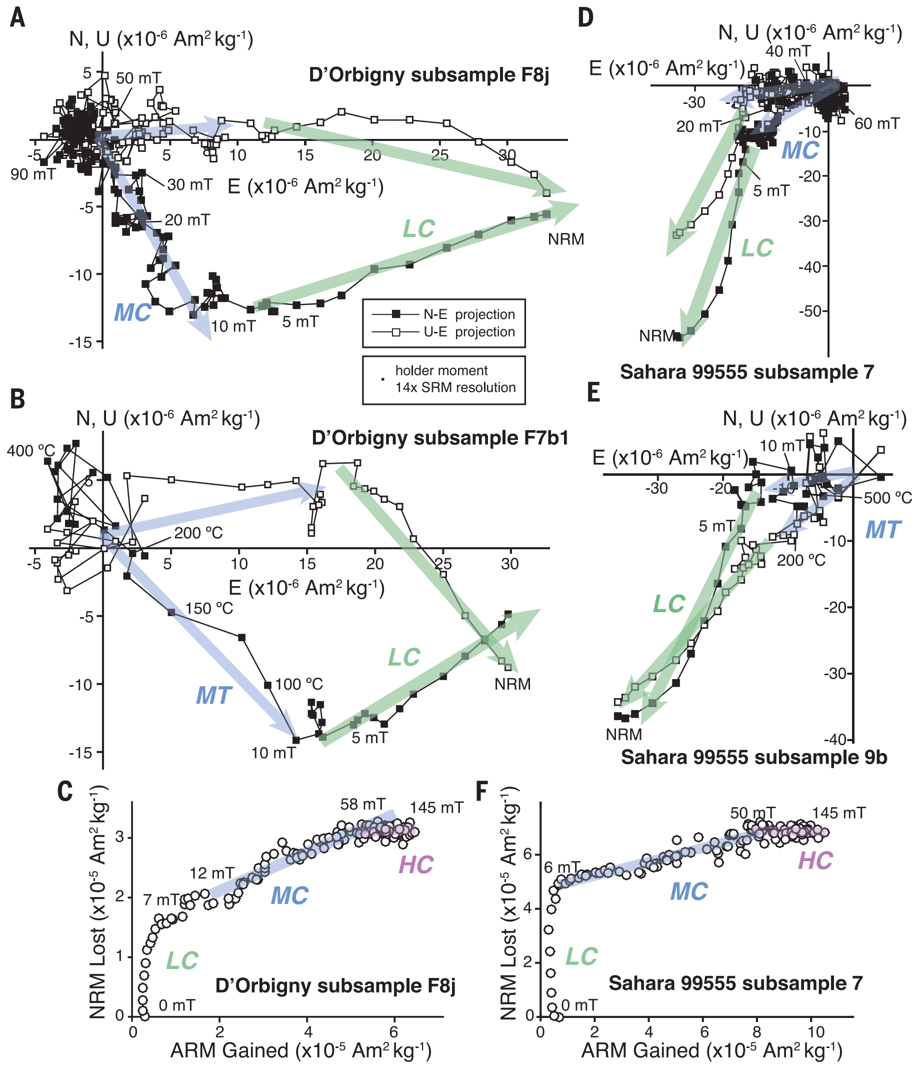

Fig. 1. Demagnetization and paleointensity analyses of volcanic angrites. Two-dimensional projection of the end points of the natural remanent magnetization (NRM) vector during alternating field (AF) demagnetization and thermal demagnetization for D'Orbigny subsamples F8j and F7b1 (**A** and **B**) and Sahara 99555 subsamples 7 and 9b (**D** and **E**). Open (filled) symbols represent projections on the up-east (U-E) and northeast (N-E) planes. Low coercivity (LC) and medium coercivity (MC)/medium temperature (MT) components are labeled with blue and green arrows, respectively. Selected AF and thermal demagnetization steps are labeled. The size of the square in the bottom legend denotes the moment per unit mass of sample (assuming a 100-mg sample) for the sample holder (i.e., GE 124 quartz glass sample mounts and quartz glass sample handling rod) and is ~14 times the intrinsic resolution of the MIT SRM (supplementary text and fig. S5). (**C** and **F**) Anhysteretic remanent magnetization (ARM) paleointensities estimated from NRM lost during AF demagnetization as a function of ARM gained (in a 50-μT bias field) for D'Orbigny subsample F8j (C) and Sahara 99555 subsample 7 (F). Blue and purple lines denote MC and HC magnetization ranges, respectively. The HC paleointensities are 0.4 ± 0.6 μT (C) and −0.1 ± 0.6 μT (D).

of dynamo activity, possibly associated with formation of the plutonic angrites at 11 My after solar system formation (*18*).

After removal of the MC components by AF demagnetization to 45 to 65 mT, D'Orbigny and Sahara 99555 subsamples contain only directionally unstable HC magnetization that is nonunidirectionally oriented across the parent samples. This magnetization is nevertheless at least two orders of magnitude above the sensitivity of the MIT SRM (supplementary text). Our ARM and IRM acquisition and demagnetization experiments yield HC paleointensity values < ~1 μT (Fig. 1, C and F, and figs. S7 and S11). Based on the vector mean of the subsample paleointensities for D'Orbigny and Sahara 99555, we further estimate an upper limit on the paleointensities from the HC range of 0.3 μT (best estimate), or possibly as high as 0.5 μT considering systematic uncertainties in calibration coefficients associated with the ARM and IRM paleointensity methods (supplementary text). Our reanalysis of previous AF demagnetization data for Asuka 881371 (*18*) indicates that the meteorite only contains a weak LC component blocked up to 4.2 mT (likely terrestrial VRM), along with a substantial quantity of unmagnetized grains in an HC range extending up to 81.4 mT with near-zero paleointensity (−0.3 ± 0.5 μT) (supplementary text). The lack of NRM in the most stable grains of the three volcanic angrites indicates that there was no detectable magnetic field during initial cooling below the Curie temperature on the angrite parent body, such that the residual scattered HC magnetization is likely a combination of spurious remanence acquired during demagnetization and spontaneous magnetization. We conclude that, with the advantage now provided by controlled-atmosphere thermal demagnetization, the previous angrite paleomagnetic study (*18*) inappropriately interpreted the MC component of D'Orbigny as a primary TRM acquired on the angrite parent body. Here, we have shown that of the four studied angrites, only the younger (i.e., plutonic) angrite Angra dos Reis records a dynamo field, which was active by 11 My after solar system formation.

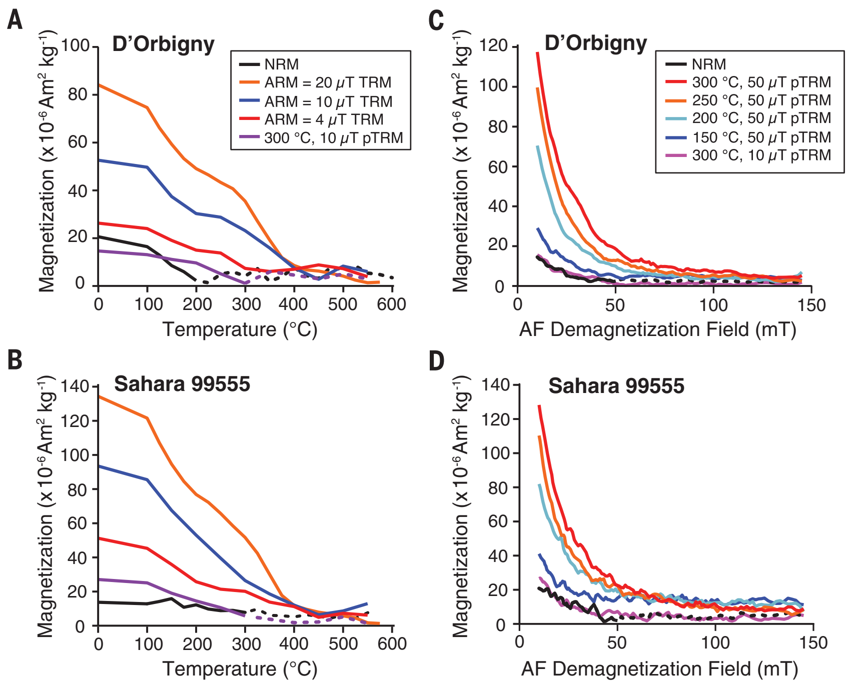

Fig. 2. Demagnetization spectra of volcanic angrites. (**A** and **B**) Thermal demagnetization spectra of NRM (black line) compared with thermal demagnetization of ARM and partial thermoremanent magnetization (pTRM) for D'Orbigny (A) and Sahara 99555 (B). The ARMs were imparted with (i) a 600-μT bias field in a 290-mT alternating field (AF), here divided by a plot scaling factor of 6 to normalize to a 100-μT bias field ARM, which is equivalent to total TRM acquired in a 20-μT bias field (orange line); (ii) a 50-μT bias field in a 260-mT AF, equivalent to total TRM acquired in a 10-μT field (blue line); (iii) a 20-μT bias field in a 260-mT AF, equivalent to total TRM acquired in a 4-μT field (red line). The TRM-equivalent fields for these ARMs were estimated using TRM/ARM = 5. The pTRMs were imparted by cooling from 300°C in a 10-μT bias field (purple line). Demagnetization of NRM was conducted on D'Orbigny and Sahara 99555 subsamples F7b1 and 9b, respectively. Demagnetization of ARM was conducted on (i) F8n and 10a, (ii) F8g1 and 3b1, and (iii) F8g2 and 3b2 for D'Orbigny and Sahara 99555, respectively. Demagnetization of pTRM was conducted on D'Orbigny and Sahara 99555 subsamples F7e and 7, respectively. (**C** and **D**) AF demagnetization spectra of NRM compared to AF demagnetization of pTRM. The pTRMs were acquired in a 50-μT bias field cooling from 300°C (red line), 250°C (orange line), 200°C (light blue line), 150°C (dark blue line), and in a 10-μT bias field cooling from 300°C (purple line). The D'Orbigny subsample is F8e (all curves five-point boxcar-smoothed) and the Sahara 99555 subsample is 7 (all curves three-point boxcar-smoothed). Thermal demagnetization and partial TRM acquisition were conducted in the oxygen fugacity controlled atmosphere. Data for (A) and (B) can be found in data S2.

In contrast, we have found that the volcanic angrites D'Orbigny, Sahara 99555, and Asuka 881371 initially cooled in no detectable magnetic field (<0.3 μT) at ~4 My after solar system formation. This suggests that the angrite parent body dynamo field and any crustal remanent fields were absent at this time. Because the angrites cooled through their magnetization acquisition temperature rapidly (over ~10 to 60 hours) relative to the expected time scale of nebular field variations [tens of years at 2 to 3 au from the Sun (*32*)], they should have been magnetized by any local external fields (*33*). Given that the angrite parent body was likely rotating [which would produce a measured paleointensity that is on average half that of the actual ambient field strength (*5*)], this means that the local nebular field, as well as any other external fields from the young Sun and solar wind, was <0.6 μT at that time. Assuming the angrite parent body originated in the region of the present-day asteroid belt and that three meteorites studied here did not cool simultaneously, our three meteorite paleointensity constraints apply to three separate azimuthally distributed locations distributed along the angrite parent body's orbital ellipse in the midplane at ~2 to 3 au from the Sun.

Magnetic field variations on scales comparable to the disk scale height (~0.1 au at 2 to 3 au from the Sun) should be smoothed out on time scales well below an orbital period (several years at this orbital distance) due to the high resistivities expected for protoplanetary disks (supplementary text). Therefore, these near-zero field conditions likely extended throughout the terrestrial planet–forming region at this time. Combining our results with previous chondrule paleointensities (*5*), this suggests that the nebular field declined from ~5 to 50 μT at ~1 to 3 My to <0.6 μT at ~3.8 My after solar system formation (i.e., at ~4563.46 ± 0.09 Ma given the mean of the pyroxene Pb/Pb ages of D'Orbigny and Sahara 99555) (Fig. 3).

Assuming that magnetic fields played a dominant role in regulating the evolution of the solar nebula, our field constraint indicates that by this time, the Sun's accretion rate dropped to below 10^{-9} $M_\odot$ year^{-1} or possibly even below 10^{-10} $M_\odot$ year^{-1} (with the exact upper limit depending on the nature of the specific magnetic mechanisms that drove accretion earlier in solar system history) (supplementary text). However, in the absence of a nebular magnetic field, purely hydrodynamic processes, such as the vertical shear instability (*34*), may also contribute to the disk angular momentum transport. Although further studies are needed, our current understanding suggests that these hydrodynamic processes are unlikely to operate efficiently in the inner solar nebula (supplementary text).

The above upper limits on the accretion rate are 10 to 100 times below those inferred from chondrule paleointensity measurements at 1 to 3 My after solar system formation (*5*). Both

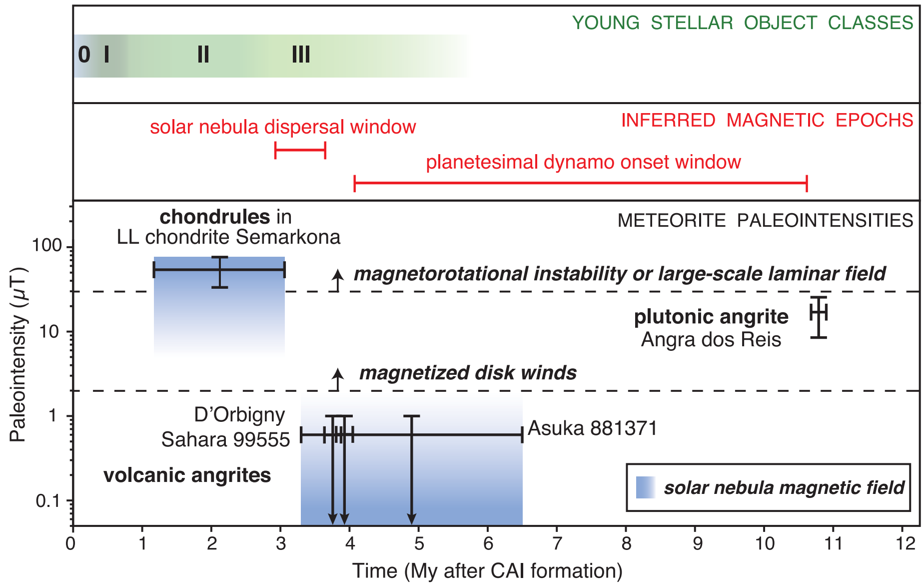

Fig. 3. Timeline for early solar system magnetism and the solar nebula. Black crosses show magnetic field paleointensity constraints from chondrules from the LL3.00 chondrite Semarkona (*5*); the volcanic angrites D'Orbigny, Sahara 99555, and Asuka 881371; and the plutonic angrite Angra dos Reis, along with associated uncertainties in age and intensity (vertical and horizontal error bars). Volcanic angrite paleointensities are upper limits only. Time scale is referenced to formation of CAIs, here assumed to be 4567.30 ± 0.16 Ma (*6*). Blue boxes show inferred constraints on the solar nebula background magnetic field. For Semarkona, the nebular field could be an order of magnitude weaker than the measured chondrule paleointensity measurements (cross) if the local field were enhanced by nebular shocks (*5*). For volcanic angrites, the nebular field upper limit shown is twice the measured paleointensity upper limits (to correct for rotation of the angrite parent body). Red lines show inferred dispersal time of the solar nebula and the onset time of the angrite parent body dynamo. Green shading indicates equivalent evolutionary stages of young stellar objects (*6*, *11*). Dashed lines indicate the lower limits for two nebular field angular momentum transport mechanisms (magnetorotational instability or large-scale laminar field and magnetized disk winds) at 2.5 au distance from the Sun and assuming a solar accretion rate of 10^{-8} $M_\odot$ year^{-1} (supplementary materials).

astronomical observations and theory have found that such a decline in accretion rates is associated with near-total dissipation of the nebula, with disk dispersal occurring in just 10^5 years (*7*). By implication, our near-zero paleointensities therefore suggest that by ~3.8 My after solar system formation, the nebular gas itself in our solar system had similarly dispersed. This is compatible with the observed ~2- to 6-My characteristic lifetimes for extrasolar protoplanetary disks (*13*, *14*).

The timing of the solar nebula dispersal has major implications for the formation of the giant planets. The minimum nebular lifetime of ~1 to 3 My is likely not so short as to require the giant planets to have formed by very rapid mechanisms such as collapse due to gravitational instabilities (*10*). Nevertheless, the giant planets must still have largely finished accreting their gaseous envelopes by ~3.8 My after solar system formation, which strains some variants of the rock–ice core accretion model (particularly for Uranus and Neptune) (*10*). The nebula lifetime constraint sets a 3.8-My time scale for the orbital migration of all planets via gas-disk interactions in the solar system, which strongly influenced their final orbital locations (*35*). Migration of Jupiter and Saturn in turn influenced the overall solar system architecture (*36*). Additionally, chondrules younger than ~3.8 My after solar system formation, such as those in CB chondrites (*37*), would have required non-nebular and nonmagnetic formation mechanisms [e.g., planetesimal collisions (*38*)], rather than nebular shocks (*39*), X-winds (*40*), or current sheets (*2*).

Although the oldest investigated angrites formed in no detectable paleomagnetic field, we have confirmed that Angra dos Reis cooled in a ~17-μT field at ~11 My after solar system formation. This late age [postdating >95% of observed protoplanetary disk lifetimes (*14*)] suggests that the field source was internally generated, possibly by a core dynamo or, conceivably, crustal remanence produced by an earlier dynamo. Therefore, the angrite parent body dynamo did not initiate until sometime between ~4 and ~11 My after solar system formation (Fig. 3). This late timing is consistent with recent planetesimal thermal evolution models invoking shallow magma oceans (*41*), which predict that planetesimal dynamos would not initiate until the core began to crystallize. It is also consistent with thermal evolution models invoking large-scale magma oceans that considered thermal blanketing of the core by ^{26}Al decay in the mantle (*19*, *20*), which would delay thermal convection dynamos until several My after accretion [which occurred <0.25 My after solar system formation for the angrite parent body (*42*)] and differentiation, assuming negligible quantities of ^{60}Fe in the core.

We conclude that our paleomagnetic analyses of three volcanic angrites, in combination with previous analyses of Semarkona chondrules, suggest that the early solar system midplane magnetic field at ~2 to 3 au declined from ~5 to 50 μT at ~1 to 3 My after solar system formation to less than 0.6 μT sometime before ~3.8 My after solar system formation, consistent with the rapid dispersal of the solar nebula by this time. Our constraint on the timing of the nebula dispersal is consistent with theoretical predictions and astronomical observations of the lifetimes of extrasolar protoplanetary disks. It sets a deterministic time scale for many aspects of solar system formation and evolution, including the accretion time scale of the Sun, formation mechanisms for young chondrules, and the formation and orbital migration time scales of the planets.

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SUPPLEMENTARY MATERIALS

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Science

Lifetime of the solar nebula constrained by meteorite paleomagnetism

Huapei Wang, Benjamin P. Weiss, Xue-Ning Bai, Brynna G. Downey, Jun Wang, Jiajun Wang, Clément Suavet, Roger R. Fu and Maria E. Zucolotto

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Meteorite magnetism in the early solar system

The young solar system contained a disc of gas and dust within which planet formation occurred. The disc eventually dissipated after the Sun ignited and the planets formed, but exactly when that happened has been difficult to determine. Wang *et al.* measured tiny magnetic fields preserved in angrites, an ancient type of meteorite. They interpret a drop in magnetic field strength about 4 million years after the solar system formed as a sign that the gas had cleared—along with the magnetic field that it carried. The results will enhance our understanding of planet formation, both in our solar system and around other Sun-like stars.

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