



New constraints on the magnetic history of the CV parent body and the solar nebula from the Kaba meteorite



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ABSTRACT

Recent paleomagnetic studies of Allende CV chondrite as well as thermal modeling suggest the existence of partially differentiated asteroids with outer unmelted and variably metamorphosed crusts overlying differentiated interiors. To further constrain the magnetic history of the CV parent body, we report here paleomagnetic results on Kaba CV chondrite. This meteorite contains 11 wt% pseudo-single domain magnetite, making it a rock with an excellent paleomagnetic recording capacity. Kaba appears to carry a stable natural remanent magnetization acquired on its parent body upon cooling in an internally generated magnetic field of about 3 μT from temperatures below 150 °C during thermal metamorphism about 10 to several tens of Myr after solar system formation. This strengthens the case for the existence of a molten advecting core in the CV parent body. Furthermore, we show that no significant magnetic field (i.e. lower than $\sim 0.3 \mu\text{T}$) was present when aqueous alteration took place on the Kaba parent body around 4 to 6 Myr after solar system formation, suggesting a delay in the onset of the dynamo in the CV parent body and confirming that nebular fields had already decayed at that time.

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1. Introduction

Chondritic meteorites have long been regarded as samples from undifferentiated asteroids. However, recent paleomagnetic studies of the CV chondrite Allende have shown that its natural remanent magnetization (NRM) was acquired after accretion and after the likely lifetime of the solar nebula, suggesting that its parent body had generated a dynamo magnetic field and formed an advecting molten core (Carpözen et al., 2011). This implies that partially differentiated asteroids formed with outer unmelted and variably metamorphosed crusts overlying differentiated interiors (Carpözen et al., 2011; Elkins-Tanton et al., 2011; Weiss and Elkins-Tanton, 2013). This idea has important implications for our understanding of asteroid accretion, differentiation, and the links between spectroscopic properties of asteroid surfaces and their deep interior structures (Weiss and Elkins-Tanton, 2013). However, this paleomagnetic evidence was obtained from a single meteorite. To further test this hypothesis, we present a detailed paleomagnetic study of another CV chondrite: the Kaba meteorite.

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Kaba is a fall and is classified as a CV3.0 in the Bali-type oxidized sub-group CV3_{oxB} (Krot et al., 1995, 1998; Huss et al., 2006). Raman spectroscopy of its organic matter (Bonal et al., 2006) and the coexistence of almost pure forsterite and fayalite (Hua and Buseck, 1995) indicate that Kaba is the least metamorphosed and pristine sample available from the CV parent body. Peak metamorphism temperatures have been estimated to be in the <300–370 °C range based on X-ray absorption near edge structure and Raman spectroscopy of insoluble organic matter (Cody et al., 2008). Moreover, Kaba contains abundant magnetite (Watson et al., 1975) and shows no petrographic evidence for shock (Scott et al., 1992), making it prime material for recording the paleomagnetism of the CV parent body. The partial differentiation hypothesis predicts that like Allende, other CV chondrites including Kaba may also contain remanent magnetization acquired during thermal metamorphism and/or aqueous alteration on the parent body. Evidence for a core dynamo origin would be provided by substantial magnetization acquired after the dissipation of the solar nebula [~ 3 –5 Myr after the formation of calcium aluminum-rich inclusions (CAIs) (Wang et al., 2015)].

NRM in Allende attributed to a dynamo unblocks up to 290 °C. Estimates of Allende's peak metamorphic temperatures are uncertain, ranging from 250–600 °C (see refs. Carpözen et al., 2011). Therefore, the NRM in Allende could have been acquired either

during continuous cooling in a field from a peak metamorphic temperature of 290 °C or alternatively during cooling from a higher temperature with the dynamo initiating only when temperatures reached 290 °C. Given Kaba's generally lower peak metamorphic temperature compared to Allende, the partial differentiation hypothesis predicts that Kaba may have an overprint blocked to a lower peak temperature than that of Allende (whose NRM unblocks up to 290 °C).

2. Material and methods

The Kaba meteorite fell in 1857 in Hungary and a single oriented stone of about 3 kg was recovered (Sztrokay et al., 1961). We obtained samples of Kaba from the Natural History Museum in London (two samples from BM.35794), Muséum National d'Histoire Naturelle in Paris (MNHN sample #88), the National History Museum in Vienna (sample #3352), and Arizona State University (ASU). For rock magnetism analyses, one sample from NHM was embedded in epoxy and cut into small pieces with masses of a few mg each using a wire saw cooled with ethanol, with some of these subsamples consisting exclusively of matrix material or chondrule material. The other samples were used for paleomagnetism.

A variety of magnetic properties were measured: NRM and artificial remanence and their behavior upon thermal pressure and alternating field demagnetization, hysteresis parameters, anisotropy of magnetic susceptibility, and magnetic susceptibility as a function of temperature. All magnetic measurements were performed at CEREGE (Aix-en-Provence, France) and in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory (Cambridge, USA). Hysteresis measurements were performed with a Princeton® Micromag Vibrating Sample Magnetometer (VSM) with a maximum applied field of 1 T and a sensitivity of 5×10^{-9} Am². The analysis of hysteresis loops provided saturation remanent magnetization (M_{RS}), saturation magnetization (M_S) and the coercive force (B_C). High field susceptibility (χ_{HF}) was determined by a linear fit for applied fields > 0.9 T of the hysteresis loops. The remanent coercive force (B_{CR}) was determined by DC back field experiments performed with the VSM. The low field specific susceptibility (χ in m³/kg), its variation at low and high temperatures, and its anisotropy were measured using Agico MFK1 apparatus with a sensitivity of 5×10^{-13} m³ and operating at 200 A/m and a frequency of 976 Hz. The anisotropy of magnetic susceptibility (AMS) was characterized by the shape parameter T (Jelinek, 1981), and the anisotropy degree P (ratio of maximum to minimum susceptibility). All remanence measurements were performed with a SQUID cryogenic magnetometer (2G Enterprises, model 755R, with noise level of 5×10^{-12} Am²), with an attached automatic alternating field (AF) 3-axis degausser system (maximum peak field 250 mT) placed in a magnetically shielded room with a residual field of ~ 500 nT. Thermal demagnetization was performed using a MMTD furnace using argon atmosphere above 250 °C (at CEREGE) or an ASC furnace (at MIT). Isothermal remanent magnetization (IRM) was imparted using a pulse magnetizer from Magnetic Measurements. We used this to determine the $S_{-300\text{ mT}}$ ratio, defined as the IRM obtained after applying a 3 T field and then a back-field of 300 mT normalized to the IRM acquired in 3 T. Remagnetization under pressure was studied using a nonmagnetic pressure cell and experimental settings described in Gattacceca et al. (2010). We also experimentally estimated the viscous remanent magnetization (VRM) acquisition and decay rates. Acquisition was monitored over a period of one month by periodic measurements of the VRM gained in the terrestrial field. The decay rate was then measured by periodic measurements with the sample kept in a sub-null (~ 50 nT) ambient field. VRM acquisition and decay were best fitted using a linear fit with log time to compute the acquisition and decay rates noted rates (denoted S_a and S_d).

Table 1
Magnetic properties.

	Unit	Average \pm s.d.	N
Hysteresis properties			
M_{RS}	Am ² /kg	1.69 ± 0.25	8
M_S	Am ² /kg	10.41 ± 2.60	5
B_{CR}	mT	34.6 ± 2.9	21
B_C	mT	14.5 ± 1.8	21
B_{CR}/B_C		2.41 ± 0.24	21
M_{RS}/M_S		0.15 ± 0.0	21
Magnetic susceptibility and its anisotropy			
χ	m ³ /kg	$6.64 \pm 1.1 \times 10^{-5}$	7
P_{AMS}^a		1.065	3
T_{AMS}^a		0.13	3
Remanence			
S_a	Am ² /kg μ T logs	$1.63 \pm 0.61 \times 10^{-6}$	6
S_d	Am ² /kg μ T logs	$4.91 \pm 2.08 \times 10^{-7}$	5
TRM 590 °C	Am ² /kg μ T	3.40×10^{-4}	
pTRM 250 °C	Am ² /kg μ T	5.48×10^{-6}	
ARM 100 mT	Am ² /kg μ T	1.18×10^{-4}	
PRM 2 GPa	Am ² /kg μ T	1.52×10^{-5}	

All abbreviations are defined in the text. TRM, ARM, and PRM intensities are normalized to the ambient field.

^a Tensorial average value.

3. Intrinsic magnetic properties

The magnetic properties of Kaba are summarized in Table 1. Its intrinsic magnetic properties are remarkably homogeneous down to very small scales: χ , M_{RS} , and M_S do not depart by more than 10% away from their mean values for masses ranging from 40 mg (for hysteresis properties) and several grams (for susceptibility) down to ~ 1 mg. The susceptibility measured for an 8 g sample by Rochette et al. (2008) is remarkably similar to the values measured here on \sim mg samples. This indicates that ferromagnetic minerals are homogeneously dispersed throughout the meteorite at fine scales. Only one large porphyritic chondrule (1.5 mm in diameter), which showed abundant opaque grains (100–200 μ m in size) in reflected light microscopy, was found to have χ and M_S significantly higher than the mean (by a factor of two).

Kaba's hysteresis properties are typical of magnetite (Fig. 1a). The ratios $B_{CR}/B_C = 2.39$ and $M_{RS}/M_S = 0.17$ indicate a pseudo-single domain behavior (Fig. 1b). Matrix samples and chondrule samples are subtly different, with the latter being slightly closer to multidomain behavior (Fig. 1b). This indicates a larger ferromagnetic grain size or a different magnetic mineralogy in the chondrules compared to the matrix.

The evolution of magnetic susceptibility at low temperature exhibits a clear Verwey transition at 120 K, indicating the presence of stoichiometric magnetite (Fig. 2). Thermal demagnetization of saturation isothermal remanent magnetization (SIRM) and thermoremanent magnetization (TRM) show major inflexions at 580 °C, indicating that magnetite is the dominant remanence carrier (Fig. 3). This is consistent with measurements of the temperature-dependence of M_S (Watson et al., 1975). The dominance of magnetite is confirmed by an $S_{-300\text{ mT}}$ ratio of 1.00 that exclude the significant presence of high coercivity minerals like pyrrhotite. Petrographic observations also indicate that metal and pyrrhotite, common in other CV chondrites (Rochette et al., 2008) are insignificant in Kaba (Sztrokay et al., 1961). The sulfides described in Kaba (Sztrokay et al., 1961; Rubin and Grossman, 1985; Keller and Buseck, 1990) are mostly pentlandite (paramagnetic) and minor troilite (antiferromagnetic at room temperature). Although troilite may be able to carry a remanent magnetization at room temperature, its low modal abundance (a minor fraction of the total sulfide abundance of about 2 vol%) and weak saturation magnetization (tentatively estimated at about 3.7×10^{-3} Am²/kg

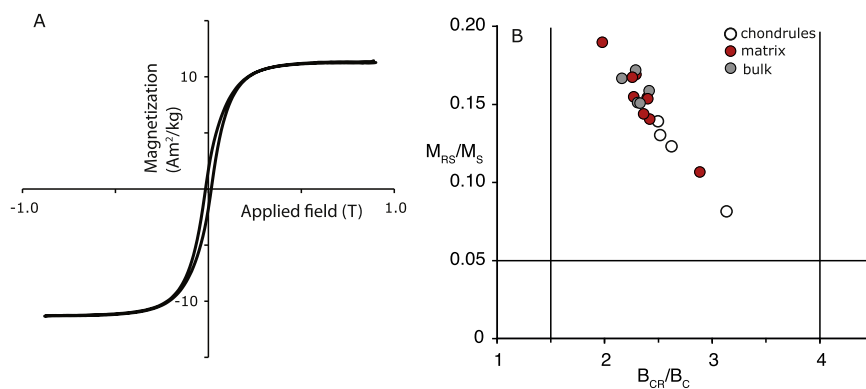


Fig. 1. A) Typical hysteresis cycle for the Kaba meteorite measured on a 7.7 mg matrix sample. B) Hysteresis parameters for twenty samples of the Kaba meteorite. Results are identified for bulk samples, matrix samples and separated chondrule samples.

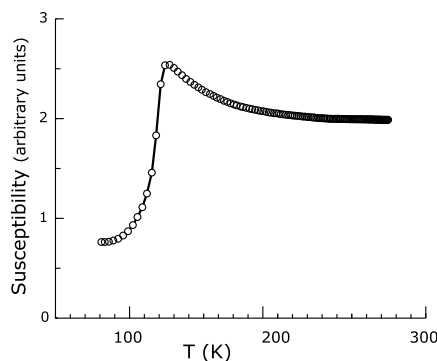


Fig. 2. Evolution of low-field magnetic susceptibility with temperature for a 6 mg sample of Kaba.

in Cuda et al., 2011) preclude any significant contribution of this mineral to Kaba magnetism.

Our measurements of M_S on twenty samples totaling 172 mg indicate a magnetite content of 11.4 wt%, in very good agreement with the 11.3 wt% estimate obtained by Watson et al. (1975) on a 10 mg sample. This confirms the fine scale magnetic homogeneity of Kaba's magnetite content. The magnetic minerals are stable upon heating, as indicated by an increase of SIRM of only 5 to 10% after heating up to 600 °C and the identical thermal demagnetization of SIRM acquired after heating. The thermochemical stability of the ferromagnetic mineralogy is also evident from earlier measurements showing the reversible behavior of M_S during heating and cooling (Watson et al., 1975).

The susceptibility and anhysteretic remanent magnetization (ARM) have modest anisotropy parameters, with degree of anisotropy $P = 1.065$ and shape factor $T = 0.13$ (measured on a larger sample with mass 1.86 g) and $P_{REM} = 1.16$ and $T_{REM} = 0.07$ (defined as degree of anisotropy and shape factor measured on a single 30 mg sample after applying AF demagnetization at 100 mT to the ARM), respectively.

In summary, the magnetic mineralogy of Kaba is simple and highly favorable for paleomagnetic study. In particular, the presence of a single, abundant, and thermally stable ferromagnetic phase (magnetite) is more favorable for paleomagnetic analyses than the mixture of mixture of metal, pyrrhotite and magnetite in Allende (Carpenter et al., 2011).

4. Paleomagnetism

4.1. Demagnetization behavior

The only previous paleomagnetic study of Kaba of which we are aware was that of Larson et al. (1973), who conducted a

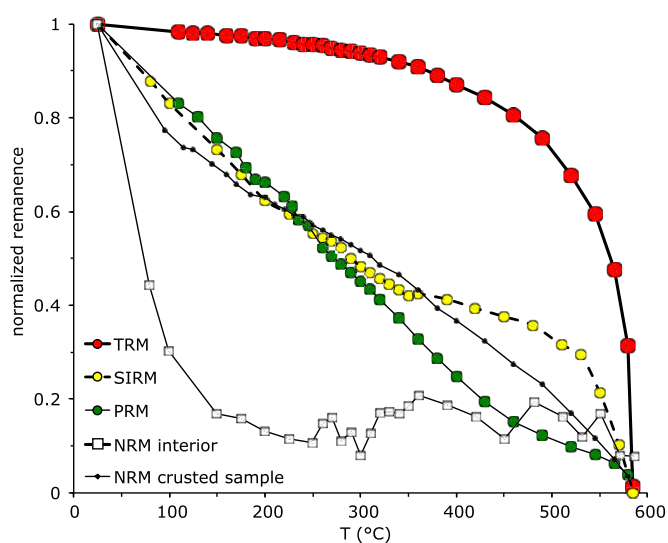


Fig. 3. Thermal demagnetization of various forms of remanence for Kaba: NRM (interior sample P1, and fusion-crust sample V1), laboratory TRM acquired by cooling from 590 °C in a 20 μ T field, SIRM acquired in 3 T, PRM acquired during decompression from 2 GPa in a 500 μ T field and followed by AF demagnetization at 1 mT.

two-step AF demagnetization up to 20 mT of a single fragment of unknown mass. Few conclusions can be derived from these measurements, except that the initial intensity of the NRM was $\sim 1.5 \times 10^{-4}$ Am²/kg. We demagnetized 12 samples with masses ranging from a few mg to ~ 220 mg, using AF demagnetization, thermal demagnetization, or a combination thereof. Five samples were interior bulk samples located more than 5 mm away from the fusion crust. Two samples were bulk samples with fusion crust. Five samples were smaller interior fragments composed mostly of chondrules. In view of the small initial sample size and stringent curation constraints, we were not able to study mutually oriented samples and were only permitted to conduct thermal demagnetization on 4 subsamples (including one with fusion crust). Typical demagnetization data are presented in Fig. 4 and the results summarized in Table 2.

The five bulk samples without fusion crust display a low coercivity (below 10 mT) low-temperature (below 180 °C) component of magnetization. This component cannot be a low-field IRM contamination during curation, handling or sample preparation because of its low REM' value of about 10^{-3} (Gattacceca and Rochette, 2004). It is therefore interpreted as a VRM acquired during the residence of the meteorite in the Earth field since its fall in 1857. It is noteworthy that unlike what is classically ob-

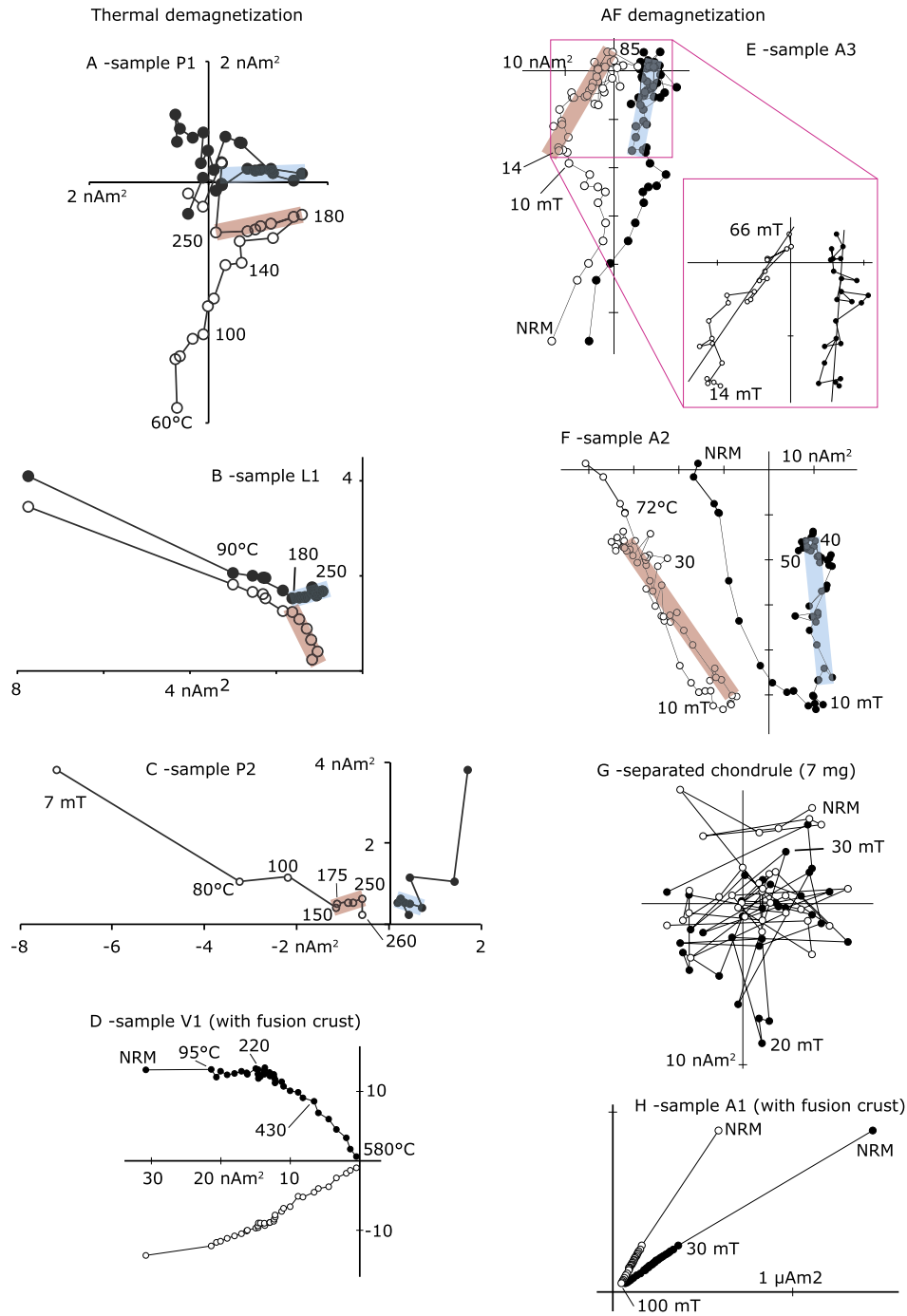


Fig. 4. Orthogonal demagnetization plots for Kaba samples. Open and closed symbols are projections on two perpendicular planes. Selected demagnetization steps are indicated. The MC/MT components defined in the text are highlighted.

served (Enkin and Dunlop, 1988), the VRM acquisition and decay rates that we determined for Kaba differ by a factor of about 3.3 (Table 1, Fig. 5) over the time interval of our measurements, suggesting that the complete decay of a VRM in Kaba will be extremely longer than its acquisition. Because of this, the duration of storage in the low field environment in the laboratory before the NRM measurements, which varied between 10 days and 4 years, may have had only a modest demagnetization effect on the VRM acquired during prior terrestrial residence. In particular, the maximum terrestrial VRM acquired since 1857 (data of Kaba fall, and assuming that the samples have been kept in a fixed position relative to the Earth's magnetic field during storage), that should remain after 10 d and 4 yr of storage in a magnetically

shielded room is $3.9 \times 10^{-4} \text{ Am}^2/\text{kg}$ and $4.1 \times 10^{-4} \text{ Am}^2/\text{kg}$, respectively. Therefore, a VRM of about $4 \times 10^{-4} \text{ Am}^2/\text{kg}$ may be expected in every measured sample. For the three samples without fusion crust that were thermally demagnetized, the VRM components, isolated between 25°C and 150°C, have intensities of 2.35×10^{-4} , 3.00×10^{-4} and $3.25 \times 10^{-4} \text{ Am}^2/\text{kg}$, in close agreement with the estimated theoretical maximum value of $4 \times 10^{-4} \text{ Am}^2/\text{kg}$. In terms of VRM stability, AF levels of 14 mT were required to fully erase a 10-d laboratory VRM, and thermal demagnetization at 130°C was required to fully erase a 14-d laboratory VRM.

Although this low temperature component makes up most of the NRM, a relatively well-defined (average maximum angular de-

Table 2
Paleomagnetic results.

Name	Mass (mg)	Collection	Treatment (AF or thermal)	NRM (10^{-5} Am ² /kg)	MC/MT (10^{-5} Am ² /kg)	MC/MT AF/thermal range	MAD (°)	B (μT)	T_{\min} (°C)	T_{\max} (°C)	N	f	g	q
P1	28	Paris	Th 585 °C	37.1	2.11	150–250 °C	13.3	1.1 ± 0.2	175	250	4	0.47	0.66	2.11
P2	41	Paris	Th 585 °C	22.5	3.66	180–250 °C	14.3	2.7 ± 0.1	180	280	4	0.60	0.58	11.8
L1	27	London	Th 585 °C	39.7	6.41	180–250 °C	11.3	4.7 ± 0.7	180	250	7	0.50	0.77	3.07
A2	193	ASU	AF 100 mT	22.6	17.2	14–42 mT	11.4	9.0						
A3	219	ASU	AF 100 mT	26.3	10.7	14–66 mT	20.9	5.9						
V1 ^a	18	Vienna	Th 585 °C	207	121	220–580 °C	6.3	N/A						
A1 ^a	115	ASU	AF 100 mT	1030	412	30–100 mT	1.3	N/A						

^a Indicates that the sample has visible fusion crust (paleointensity not computed because the fusion crust makes up only a fraction of the sample making estimates meaningless). MAD: maximum angular deviation, B: paleointensity. For Thellier–Thellier experiments paleointensities are given with their standard deviations from the regression line. N number of data used for paleointensity estimate; T_{\min} and T_{\max} give the range of temperature over which the paleointensity was computed; f, g and q are the fraction, gap and quality factors for the paleointensity estimates (Leonhardt et al., 2004). Paleointensities and associated parameters were computed using ThellierTool4.0 software (Leonhardt et al., 2004).

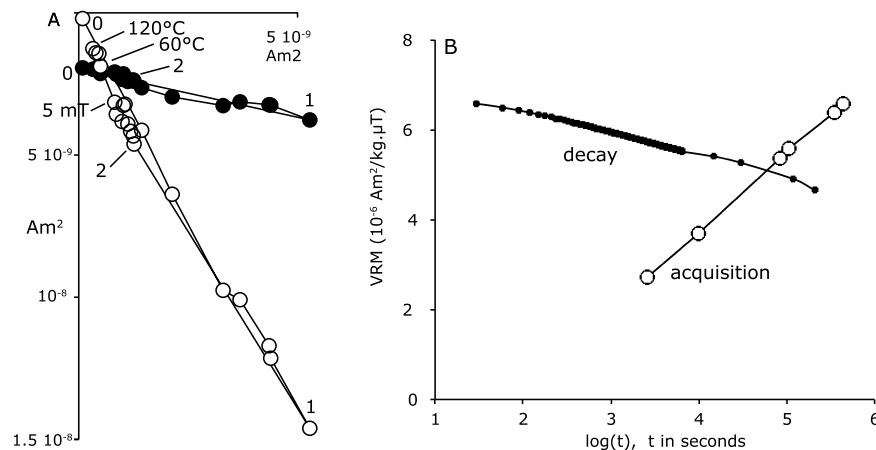


Fig. 5. VRM acquisition and decay experiments for sample Kaba3-1-2b. A) Orthogonal projection of VRM: 0 = initial demagnetized state, 1 = after 11 days of VRM acquisition in the Earth field (53 μT), 2 = after 35 days of VRM decay. Following decay the VRM was AF demagnetized to 5 mT and thermally demagnetized to 120 °C. B) VRM intensity during acquisition (open symbols) and subsequent decay (solid symbols).

viation $13.0 \pm 1.2^\circ$) medium temperature (MT) component unblocks between about 150–180 and 250 °C (Fig. 4). Above 250 °C, the thermal demagnetization behavior is chaotic. Because VRM is best removed by thermal demagnetization, some samples demagnetized by AF were gently thermally demagnetized before AF was applied. Because of curation constraints, maximum temperatures were only in the 70–90 °C range, probably leading to incomplete removal of the VRM. AF demagnetization of bulk samples shows a medium coercivity (MC) component that unblocked between about 10–15 mT up to about 40 mT. Although we could not work on mutually-oriented samples, we note that the intensity of this MT/MC component does not decrease with increasing mass (over the mass range 27–219 mg, see Table 2), which would be the case if it was not directionally homogeneous at this scale. Nevertheless, this MT/MC component does not trend perfectly toward the origin for some subsamples, suggesting the possible existence of a higher coercivity/higher temperature component of magnetization that could not be properly isolated.

Five chondrule-dominated samples, with masses in the range 0.5–7.0 mg, were subjected to AF demagnetization. They show erratic demagnetization from which no component of magnetization can be isolated. An example is the large porphyritic, opaque-rich separated chondrule mentioned above that contains about double the ferromagnetic mineral abundance of the other samples (Fig. 4). This was previously observed in Allende meteorite, where 80% of chondrules do not contain the medium temperature component of magnetization that is otherwise observed in the matrix, bulk samples, and 20% of the remaining chondrules (Fu et al., 2014b; compare our Fig. 4G and their Fig. 3C).

Samples containing fusion crust have a markedly different behavior upon demagnetization, with a well-defined origin-trending component of magnetization that is isolated with thermal demagnetization up to 580 °C or AF demagnetization up to 100 mT (Fig. 4D and 4H). This is a strong indication that the interior samples have not been remagnetized during atmospheric entry and another indication that the components of magnetization isolated above 180 °C in interior samples are pre-terrestrial magnetizations.

4.2. Nature of the MC/MT magnetization

Several magnetization mechanisms may account for the acquisition of the observed MC/MT component: thermoremanent magnetization (TRM), partial TRM (pTRM), shock remanent magnetization (SRM), isothermal remanent magnetization (IRM), chemical remanent magnetization (CRM), or inverse thermoremanent magnetization (ITRM). An IRM is ruled out by REM' value $< 10^{-2}$ (Gattacceca and Rochette, 2004) in the AF range of the MC component. A total TRM is ruled out by the low maximum unblocking temperature of about 250 °C for the MT component, which is well below the 580 °C Curie point of magnetite (Fig. 3). A SRM is ruled out for the same reason since PRM in Kaba has unblocking temperature up to 580 °C (Fig. 3; see also discussion in Tikoo et al., 2015). Moreover, if the NRM is a SRM, a minimum magnetizing field of several hundreds μT is required, which may be larger than some estimates of impact-generated transient magnetic fields on airless bodies (Crawford and Schultz, 1993). Although the unblocking temperature spectrum of a CRM is unknown, it would very likely extend to temperatures well above 250 °C and closer to the Curie

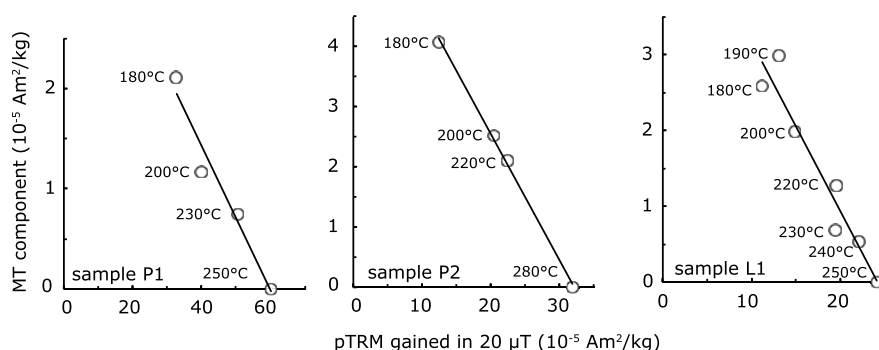


Fig. 6. Thellier–Thellier paleointensity data: intensity of the MT component of the NRM versus pTRM gained in a 20 μT field. Heating temperatures and a linear fit are shown.

temperature of magnetite, which argues against a CRM origin for the MC/MT component. ITRM is acquired when a magnetite bearing rock warms from below the Verwey transition temperature of magnetite (~ 120 K) in the presence of a magnetic field (Dunlop, 2006). However, in view of the long ($> \text{Myr}$) and gradual transfer of meteoroids from the asteroid belt to the Earth, even the center of a several meter-diameter meteoroid coming from the outer asteroid belt would have warmed above 120 K long before it reaches the Earth's orbit (Weiss et al., 2010a). As a consequence, this transition can only take place in the interplanetary magnetic field (< 10 nT), precluding any ITRM acquisition by Kaba. However a small fraction of ITRM can be acquired by magnetite at temperature above 120 K, up to about 250 K, although it will be magnetically soft (Dunlop, 2006). Therefore we tested experimentally the ITRM potential of Kaba by cycling a sample through the Verwey transition in the presence of a 50 μT field. The weak remanent magnetization acquired during the process (most of which was likely a VRM) was completely demagnetized by 10 mT AF, confirming that ITRM cannot account for the MC/MT component. Therefore, the most plausible hypothesis is that the observed MC/MT component is a pTRM acquired by cooling below 250 $^{\circ}\text{C}$.

As we discuss below, the MC/MT component in Kaba appears to have been acquired about 4.5 Gyr ago. It can be estimated from the time-temperature stability diagram for magnetite (Pullaiah et al., 1975) that if the rock was kept in the asteroid belt at an average temperature of about -110°C (e.g., Spencer et al., 1989), such old magnetization will be viscously erased up to only 60 $^{\circ}\text{C}$ (for a laboratory thermal demagnetization timescale of one hour), well below the 150 $^{\circ}\text{C}$ lower bound for the unblocking of the MT component.

4.3. Paleointensity of the magnetizing field

Thellier–Thellier-type experiments were performed on three samples that were alternately heated in a zero field and in-field (20 μT) environment. Acquisition of pTRM was not conducted for each demagnetization step. Over the temperature interval in which the MC/MT component is demagnetized, we observe a good linearity between the MC/MT component lost and pTRM gained over the same temperature interval (Fig. 6). These three experiments provide paleointensity intensities of 1.1, 2.7 and 4.6 μT , with an average 2.8 ± 1.5 μT (Table 2). Taking into account a cooling rate correction (Halgedahl et al., 1980) for the different heating duration between the laboratory experiments (one hour) and thermal metamorphism (Myr scale) reduces these values by a factor of about 1.85, down to an average paleofield of 1.5 ± 0.8 μT .

For the two samples demagnetized with AF, because the MC/MT component is not a TRM, the paleointensity techniques involving normalization by SIRM (e.g., REM' technique, Gattacceca and Rochette, 2004) or ARM (e.g., Stephenson and Collinson, 1974) cannot be strictly applied because they are calibrated only for total TRM.

However, a crude estimate of paleointensity can be obtained by normalizing the MC/MT component intensity by the intensity of a laboratory pTRM acquired by cooling from 250 $^{\circ}\text{C}$ that is demagnetized by AF over the stability interval of the MC/MT component. This gives crude paleointensity estimates of 9.0 and 5.9 μT for these two samples, similar to the paleointensities obtained through thermal demagnetization. Since the REM' method is calibrated with laboratory TRM, these values must also be corrected by a factor of about 1.85 to take into account the low cooling (Myr scale) on the parent body, which gives estimates of 4.9 and 3.2 μT .

For Allende, Fu et al. (2014b) showed that the medium temperature component, interpreted as a pTRM acquired on the CV parent body, is absent in 80% of chondrules. This was interpreted as being caused by a metasomatic event that took place in a null magnetic field tens of millions of years after accretion. Even though our dataset on Kaba is much smaller compared to the extensive work performed on Allende, the three studied chondrules similarly do not show any stable component of magnetization. We propose that late, low-temperature metasomatism also took place in Kaba and erased the original pTRM in the chondrules. This implies that the bulk-sample paleointensities reported above are in fact lower limits since only part of the original rock carries the pTRM whereas the laboratory pTRM was acquired by the entire rock. The same correction is valid for paleointensities based on AF demagnetization data. The matrix:chondrule relative abundances are 68:32 in Kaba (Sztrokay et al., 1961), implying that the above paleointensities have to be corrected by a maximum factor of 1.5 if all chondrules are unmagnetized. This gives maximum paleointensities of 2.3 ± 1.2 μT ($N = 3$) for the thermal demagnetization data, and 3.8 ± 2.2 μT ($N = 5$) including the two paleointensities derived from AF demagnetization data (including the correction for the low cooling rate on the parent body). We note that a similar correction for unmagnetized chondrules should be applied to the Allende bulk-rock paleointensities of Carporzen et al. (2011). The 50:50 matrix:chondrule ratio in Allende (Simon et al., 1995) gives a maximum correction factor of 2 if all Allende chondrules are unmagnetized, indicating maximum paleointensities of order 60 μT when including the factor of 1.85 cooling rate correction discussed above.

4.4. Nature and age of the magnetizing event

Our paleomagnetic measurements suggest that the interior of the Kaba meteorite was magnetized in a magnetic field in the 3 μT range while cooling below 250 $^{\circ}\text{C}$. Several phenomena may account for such a thermal event in Kaba meteorite: thermal metamorphism on the parent body, impact heating on the parent body, and heating during atmospheric entry. Thermoluminescence studies have shown that temperature excursions of 250 $^{\circ}\text{C}$ from atmospheric passage are typically limited to the outer first mm of a meteorite (e.g., Sears, 1975). This has been confirmed by paleo-

magnetic studies that show no detectable thermal remagnetization during atmospheric entry for samples located more than several mm inside meteorites (e.g., [Carporzen et al., 2011](#) on Allende). In the Kaba meteorite, the dichotomy between samples with fusion crust and interior samples and the low paleointensities for the interior samples ($\sim 10\%$ of that of the Earth) provide strong evidence that the interior samples have indeed escaped significant atmospheric heating. Therefore, we rule out atmospheric heating as the thermal event that magnetized the meteorite interior.

Kaba has a shock stage of S1, indicating it has not been exposed to peak pressure above 5 GPa and has therefore experience negligible shock-induced heating ([Scott et al., 1992](#)). It is noteworthy that the shock waves generated in the meteoroid during atmospheric entry and landing on Earth must have been lower than the compressive and tensile strengths of Kaba since the meteorite is a coherent rock. Typical compression and tensile strengths of chondrites are in the range 20–400 MPa and 2–62 MPa, respectively (e.g., [Svetsov et al., 1995](#)). These are at least one order of magnitude smaller than the 5 GPa upper limit considered above and will have no or negligible effect on the paleomagnetic record of the meteorite. It has been recently advocated that even low velocity impacts on porous chondritic targets could result in extremely spatially heterogeneous temperature excursions with the matrix being heated to >1000 K, no significant heating of chondrules, and little bulk heating ([Bland et al., 2014](#)). In this scenario, Kaba could be magnetized during such a low velocity impact event, which would be in agreement with the apparent absence of a MC/MT component in the chondrules. However, there is a major problem with this scenario: the impact compaction scenario predicts that the matrix is heated to a wide range of temperatures at the microscale. For impact scenarios that produce typical matrix temperatures in the range of the peak unblocking of the temperature MT components in Kaba and Allende (i.e., 1 km/s; Fig. 1 of [Bland et al., 2014](#)), the matrix peak temperatures exceed 600°C in many locations. This means that the mm–cm samples studied by [Carporzen et al. \(2011\)](#) for Allende and by us for Kaba would be predicted to have magnetization blocked up to the Curie temperature of their constituent ferromagnetic minerals (pyrrhotite and magnetite, 320 and 580°C , respectively) rather than the observed sharply defined 290°C temperature for Allende and the $<250^\circ\text{C}$ temperature for Kaba.

The third possibility is parent body thermal metamorphism. The maximum unblocking temperature of 250°C observed for the MC/MT component of Kaba is lower than the peak metamorphic temperature of <300 – 370°C inferred from organic thermometry ([Cody et al., 2008](#)). This may imply that the magnetizing field was not present during the whole cooling process, or that it was initially unstable (for instance with a high reversal rate). However, absolute calibration of organic thermometry estimates is apparently uncertain by up to $\sim 200^\circ\text{C}$ (see scatter in Fig. 3. of [Cody et al., 2008](#)). Therefore, metamorphic heating is the only plausible mechanism to account for a pTRM in the Kaba meteorite.

In view of the time-temperature stability of TRM for magnetite, the actual maximum blocking temperature on the parent body depends on the duration of metamorphism on the parent body and the laboratory heating time (one hour). However, exact quantification is difficult in view of the observed discrepancies between the theory and experimental data ([Pullaiah et al., 1975](#)). For a thermal metamorphism scenario, heating times of 1 Myr, 0.1 Myr and 1 kyr would correspond to maximum blocking temperatures of 110, 120, and 150°C on parent body.

The magnetite in Kaba was formed by aqueous alteration on the parent body ([Krot et al., 1998](#)), implying that the MC/MT component cannot be acquired before accretion of the parent body. Magnetite in Kaba has been directly dated to have formed $\sim 3.9 \pm 0.6$ Myr after CAIs ([Pravdivtseva et al., 2013](#)). Using a U/Pb

age of 4567.30 ± 0.16 million yr ago (Ma) for CAIs ([Connelly, 2012](#)), this yields a magnetite-formation age for Kaba of 4563.4 ± 0.7 Ma. Magnetite is often associated with fayalite, suggesting that these minerals were formed almost contemporaneously. Using the Mn–Cr measurements of [Hua et al. \(2005\)](#) and the $^{53}\text{Mn}/^{55}\text{Mn}$ initial value of [Davis et al. \(2015\)](#), we compute a Mn–Cr age of fayalite in Kaba of 6.3 Myr after the formation of CAIs, corresponding to an absolute age of 4561.0 Ma for Kaba fayalite. The magnetite and fayalite ages for Kaba indicate collectively that aqueous alteration and the associated formation of magnetite took place about 4–6 Myr after the formation of the solar system, likely after the protoplanetary disk is dissipated (e.g., [Haisch et al., 2001](#); [Wang et al., 2015](#)). This is an absolute older limit for the age of the MC/MT component. Although it is not constrained, the age of thermal metamorphism and associated acquisition of MC/MT component is likely younger. For instance, in Allende, the major chemical resetting associated with thermal metamorphism took place around 10–15 Myr after CAIs ([Swindle et al., 1988](#); [Carporzen et al., 2011](#)), with possible minor disturbances up to 40 Myr after CAIs ([Carporzen et al., 2011](#)).

4.5. Nature of the magnetizing field

Thermal metamorphism in CV chondrites is apparently too young (10–15 Myr after solar system formation, see above) to record early external fields that may have been present in the protoplanetary disk in the first few Myr after the formation of solar system (e.g., [Bai and Stone, 2013](#); [Crutcher, 2012](#); [Fu et al., 2014a](#); [Wang et al., 2015](#)).

The long, million-year scale, metamorphic cooling ([Huss et al., 2006](#)), places strong constraints on the nature of the magnetizing field. Indeed, the 5–10 μT magnetizing field (or at least some of its components) would have to be stable with respect to the asteroid for time periods longer than the cooling time of the meteorite on its parent body below 250°C (laboratory unblocking temperature of the MC/MT component; see above discussion for the actual temperature on the parent body). This duration cannot be assessed precisely, but is certainly well beyond the duration of impact generated-fields ([Crawford and Schultz, 1999](#)). Anyway, magnetization produced by impact-generated plasma fields has never been unambiguously identified in natural samples despite numerous searches [e.g., [Louzada et al., 2008](#); [Weiss et al., 2010b](#); [Carporzen et al., 2012](#)]. A remanent crustal field, has been invoked to account for the magnetization of some eucrites ([Vernazza et al., 2006](#); [Fu et al., 2012](#)) or Martian meteorites (e.g., [Gattacceca et al., 2013](#)). In the case of Kaba, the inferred paleointensities (about 3 μT) would require a crustal remanent magnetization of the underlying rocks of about $8 \times 10^{-4} \text{ Am}^2/\text{kg}$, computed as $B/\mu_0 \cdot \rho$ where B is 3 μT , μ_0 is the permeability of free space and ρ the bulk density of the underlying rocks taken as 2950 kg/m^3 ([Britt and Consolmagno, 2003](#)). This is about 20 times the MC/MT component measured for the three Kaba samples that were thermally demagnetized, and about 10 times the NRM of Allende meteorite ([Carporzen et al., 2011](#)). Therefore, a crustal remanent field on the CV parent bodies likely cannot generate surface field of the required intensity to magnetize Kaba. Therefore, the only possibility left to account for a stable (relative to the parent body) magnetic field with an intensity of 3 μT is an internally generated magnetic field. This implies that the parent body of Kaba had an advecting molten core.

4.6. Lack of high-blocking temperature magnetization

The absence of stable magnetization unblocked at temperature above 250°C in Kaba is another interesting feature. Indeed, it indicates that either there was no significant magnetic field when

the magnetite crystallized during aqueous alteration. Otherwise, the meteorite would have acquired a CRM with unblocking temperatures extending to close to the Curie temperature of magnetite (580 °C), as has been observed for CM chondrites (Cournède et al., 2015). A comparison of the intensities of NRM after demagnetization at 250 °C and laboratory TRM after demagnetization at 250 °C gives a very upper limit of $0.15 \pm 0.08 \mu\text{T}$ ($N = 3$) for the magnetic field present during crystallization of magnetite, assuming a similar efficiency for CRM and TRM (McClelland, 1996). The duration of aqueous alteration is estimated to be $1\text{--}10^4$ years (e.g., Grimm and McSween, 1989; Wilson et al., 1999). Because the parent body is spinning much faster than this timescale, the nebular field that would be recorded is actually the projection of the field on the asteroid rotation axis. On average this will reduce the recorded field by a factor 2 (Fu et al., 2014a), providing an upper limit of $0.30 \mu\text{T}$ for the ambient field during magnetite crystallization. Another more speculative possibility to account for the absence of CRM in Kaba is that the magnetic field was unstable (for instance, had a high reversal rate) during magnetite crystallization, a process whose duration is estimated between a few hundred years to 1 Myr (Hua et al., 2005).

In this discussion about the lack of high-blocking temperature magnetization in Kaba, it is necessary to evaluate the possibility of low temperature demagnetization (LTD), a process by which multidomain magnetite is partially demagnetized when cycled through its Verwey transition (~ 120 K) in a null magnetic field (e.g., Merrill, 1970; Dunlop and Argyle, 1991). Indeed, although the equilibrium temperature of most objects even in the outer asteroid belt is well above 120 K (e.g., Spencer et al., 1989) in some specific conditions (origin on a slowly rotating parent body, origin from high latitude on the parent body or origin from a permanently shadowed area on the parent body), the Kaba meteorite may have been cycled through the Verwey transition in a null field and demagnetized. We tested this possibility by cycling a matrix sample of Kaba carrying a laboratory ARM (acquired in an alternating field of 100 mT and a DC field of $50 \mu\text{T}$) in a weak field (< 50 nT). This resulted in only LTD of just 1.6% of the original ARM. The absence of significant LTD is explained by the pseudo-single domain nature of the magnetite in Kaba, whereas the LTD dominantly affects the remanence of multidomain grains (e.g., Dunlop, 2006). It is noteworthy that LTD remove preferentially the low unblocking temperature magnetization (Dunlop and Argyle, 1991), which is exactly the opposite of what is measured in Kaba with a pTRM unblocked below 280 °C but no magnetization unblocked above 280 °C.

5. Conclusion

The Kaba CV chondrite contains 11 wt% pseudo-single domain magnetite, making it a rock with an excellent paleomagnetic recording capacity. The NRM is dominated by a terrestrial VRM. But Kaba also appears to carry a stable NRM acquired on its parent body upon cooling in a magnetic field of about $3 \mu\text{T}$ from temperatures below 150 °C during thermal metamorphism. This field was likely generated by a dynamo process within the Kaba parent body, sometime following aqueous alteration that led to crystallization of the magnetite (dated around 4–6 Myr after the formation of solar system). The lower peak unblocking temperature of Kaba's MT component relative to that in Allende is broadly consistent with Kaba's lower peak metamorphic temperature. These results therefore strengthen the case that the CV parent body had a molten advecting core with an outer chondritic shell overlying a differentiated interior. Given that Allende paleointensities are an order of magnitude stronger than those observed for Kaba, the CV parent body paleofield apparently experienced significant temporal variation, which is expected for dynamos [for ex-

ample, order of magnitude variations in the Earth's paleointensity are observed over even just the last few Myr (Selkin and Tauxe, 2000)].

Furthermore, our data also show that no significant stable magnetic field (i.e. lower than $\sim 0.3 \mu\text{T}$) was present when aqueous alteration took place on the Kaba parent body around 4 to 6 Myr after solar system formation, suggesting a delay in the onset of the dynamo in the CV parent body. A similar delay in dynamo onset was observed for the angrite parent body from the lack of stable magnetization (paleointensity $< 0.3 \mu\text{T}$) in three rapidly-cooled ($10\text{--}50^\circ\text{C/h}$) volcanic angrites (Wang et al., 2015). A delay of this duration is broadly consistent with thermal evolution models, which proposed that the initiation of planetesimal core dynamos should be inhibited for at least several Myr after accretion due to thermal blanketing of the core by the ^{26}Al -enriched mantle (Roberts, 2010; Sterenborg and Crowley, 2013). If Allende never reached metamorphic temperatures exceeding the 580 °C Curie point of magnetite (which is supported by most but not all peak-temperature indicators; see references in Carporzen et al., 2011), the lack of NRM blocked above 290 °C in Allende similarly indicates the lack of an early, temporally stable field during formation of its magnetite as well (also estimated to have occurred at several My after CAI formation). Alternatively, if Allende had been metamorphosed to $> 580^\circ\text{C}$, the lack of NRM blocked above 290 °C would indicate near zero-field conditions at 9–10 My after CAI formation, with a dynamo initiating at this time as the meteorite cooled below $\sim 300^\circ\text{C}$.

The absence of an earlier, stable field ($< 0.3 \mu\text{T}$) at the CV parent body is very important because it indicates that the net nebular field (i.e., component of the field that is steady on the timescale of magnetite formation) had decayed away, from intensities of about $50 \mu\text{T}$ at 2–3 Myr after CAI formation (Fu et al., 2014a) to less than $0.3 \mu\text{T}$ at 4–6 Myr after CAI formation, before the later-formed NRM was acquired. This also demonstrates that the mean solar wind field at the CV parent body at this time was also $< 0.3 \mu\text{T}$ [consistent with observations of young (< 0.7 Gy old) stars (Wood et al., 2015; Tarduno et al., 2014)] and therefore cannot account for the unidirectional NRM in CV chondrites [compare with the proposal of Tarduno et al., 2016]. A solar wind origin for the NRM in CV chondrites is anyway highly unlikely given that the solar wind field's sectoral structure (e.g., Gombosi, 1998) means that, as viewed from an asteroid, it reverses direction at least twice during each solar rotation (currently ~ 25 days), which is short compared to duration of aqueous alteration and thermal metamorphism for CV chondrites.

This constraint supports the recent conclusion of Wang et al. (2015) from paleomagnetic measurements of angrites that the nebular field had decayed to $< 0.3 \mu\text{T}$ by 4563.46 ± 0.09 Ma. The null-field constraints from the CV chondrites and angrites are complementary in that the former indicate the absence of a net field at 4–6 Myr after CAI formation averaged over a period lasting 1 y to several Myr, while the latter indicate the instantaneous lack of a total field at three separate locations along the angrite parent body orbit at 3.8 Myr after CAI formation. Our identification of early, zero-field conditions on the CV parent body in turn further supports the hypothesis that the later field was from a parent body dynamo rather than a nebular field.

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