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Paleomagnetism of Rumuruti chondrites suggests a partially differentiated parent body

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Abstract: Different types of magnetic fields were at work in the early solar system: nebular fields generated within the protoplanetary nebula, solar fields, and dynamo fields generated within the solar system solid bodies. Paleomagnetic studies of extraterrestrial materials can help unravel both the history of these magnetic fields, and the evolution of solar system solid bodies. In this study we studied the paleomagnetism of two Rumuruti chondrites (PCA 91002 and LAP 03639). These chondrites could potentially bear the record of the different fields (solar, nebular, dynamo fields) present during the early solar system. The magnetic mineralogy consists of pseudo-single domain pyrrhotite in LAP 03639 and pyrrhotite plus magnetite in PCA 91002. Paleomagnetic analyses using thermal and alternating field demagnetization reveal a stable origin trending component of magnetization. Fields of 12 µT or higher are required to account for the magnetization in PCA 91002, but the timing and exact mechanism of the magnetization are unconstrained. In LAP 03639, considering various chronological constraints on the parent body evolution and on the evolution of the different sources of magnetic field in the early solar system, an internally-generated (dynamo) field of ~5 µT recorded during retrograde metamorphism is the most likely explanation to account for the measured magnetization. This result indicates the existence of an advecting liquid core within the Rumuruti chondrite parent body, and implies that, as proposed for CV and H chondrites, this chondritic parent body is partially differentiated.

1. Introduction

The study of the natural remanent magnetization (NRM) of extraterrestrial materials gives clues as to the history of the primitive solar system and its evolution (Weiss et al., 2010). Indeed, paleomagnetic studies of meteorites provide a unique window into understanding early solar magnetic fields generated in the proto-planetary nebula (Cournède et al., 2015; Fu et al., 2014), as well as magnetic fields generated within the planetesimals through advection in a conducting liquid core by the dynamo effect (e.g., Weiss et al., 2008; Carporzen et al., 2011; Gattacceca et al., 2016).

Rumuruti (R) chondrites could potentially bear the record of different fields present during the early solar system. They could have recorded a nebular field which would constrain the intensity and lifetime of the solar nebula field (Weiss et al., 2017). On the other hand, because the R chondrites have suffered thermal metamorphism, it is possible to test if, like CV chondrites and H chondrites (Carporzen et al., 2011; Bryson et al., 2019a), R chondrites recorded a magnetic field generated within the parent body by a dynamo powered by advection in a liquid conducting core. Such a result would put strong constraint on the parent body history and inner structure because it implies protracted accretion and partial differentiation (Elkins-Tanton et al., 2011), and on its size (Bryson et al., 2019b).

In this study we test whether the paleomagnetic signals of R chondrites bear the record of nebular or parent body magnetic fields. We performed a detailed paleomagnetic study of two R chondrites collected in Antarctica: Pecora Escarpment (PCA) 91002 and LaPaz (LAP) 03639.

1.1 Rumuruti Chondrites

The Rumuruti chondrites are named after the Rumuruti meteorite that fell in Kenya in 1934, and have been recognized as a new chondrite group in 1994 (Schulze et al., 1994). They are described in details in a review paper by Bischoff et al., (2011). Most R chondrites are breccias of unequilibrated, petrologic type 3 fragments (Bischoff, 2000), and clasts metamorphosed to various degrees (e.g., Bischoff et al., 1994; Schulze et al., 1994; Kallemeyn et al., 1996). They contain chondrules, with average apparent diameter ~350 µm, set in an abundant matrix, with a chondrule/matrix ratio of about 1. They are highly oxidized meteorites, as reflected by the elevated fayalite content of olivine ($Fa_{36\text{-}40}$ for equilibrated lithologies) and by the rarity or absence of Fe,Ni metals (e.g., Rubin and Kallemeyn, 1994). Iron is either oxidized or found in the form of iron sulfides (~6 vol% on average, mainly pyrrhotite and pentlandite). Mineralogical features reflect variations in local conditions on the R chondrite parent body such as inhomogeneous distribution of water (Isa et al., 2011).

The high oxidation state, high matrix/chondrules modal abundance ratio, relatively low abundance of droplet chondrules, high $\Delta^{17}O$ (Rubin and Kallemeyn, 1994 and Bischoff et al., 1994) suggest that the R chondrites parent body formed at heliocentric distance greater than that of ordinary chondrites and lower than that of carbonaceous chondrites (Kallemeyn et al., 1996; Khan et al., 2013). Accretion models (Desch et al., 2018) suggest that the parent body of R chondrites accreted at 2.6 AU from the Sun. The accreting material, including pyrrhotite, was likely oxidized before accretion (Bischoff, 2000; Gainsforth et al., 2017), although a parent body origin for pyrrhotite has also been proposed (Schrader et al., 2016). The R chondrite parent body has suffered thermal metamorphism and hypervelocity impacts. Thermal metamorphism led to an onion shell structure, as indicated by Ar-Ar and I-Xe dating

(Dixon et al., 2003; Claydon et al., 2013). The presence of type 5 and type 6 material suggests metamorphic temperatures of up to at least 700 to 800°C (Dodd, 1981). The peak metamorphic temperature in R5 chondrite LAP 04840 has been estimated to 670±60°C from amphibole-plagioclase thermometry (Mc Canta et al., 2008). These temperature estimates are coherent with olivine-chromite geothermometry on ordinary chondrites indicating temperatures of 550-690°C for type 4/5 material and 880°C for type 6 material (Wlotzka, 2005).

Evidence arises that R chondrite breccias were produced by impacts following metamorphism (Scott et al., 1985). The mixing of fragments of equilibrated lithologies (type 5 and 6) from greater depth with clasts from near-surface lithologies (e.g., type 3 material) may have occurred at ~4.47 Ga (Dixon et al., 2003). Impact heating is evidenced by the occurrence of impact melt rocks (Bischoff et al., 2006), sulfide-rich shock veins and plagioclase-rich melt pockets (Rubin and Kallemeyn, 1994). These impact-related lithologies cooled rapidly and were incorporated into the surface breccias. In a later evolutionary phase, further impact activity led to lithification of the loose regolith without significant reheating (Bischoff et al., 2011). Consolidated breccias can be produced even under shock pressures of 5-10 GPa (e.g. Bischoff et al., 1983). Indeed, most R chondrites are have shock stages S2 or S3, indicating peak pressure of ~5 to 10-15 GPa (Stöffler et al., 1991).

Rumuruti is the only fall of the R chondrite group. Other R chondrites were found in hot and cold deserts and show various degrees of terrestrial weathering. With increasing weathering, S and Ni become increasingly depleted because of sulfide alteration. PCA 91002 has a weathering index wi=1 indicating no or minor alteration (Rubin and Huber, 2005). LAP 03639 has a weathering category A/B indicating only moderate weathering. Both meteorites have been little affected by terrestrial weathering. This is confirmed by our petrographic observations of polished sections that show no significant alteration of sulfides in both meteorites.

1.2 Rumuruti Chondrite magnetic properties and paleomagnetism: state of the art

The major magnetic mineral in R chondrites is pyrrhotite, with an average abundance of ~6 wt% (Schulze et al., 1994; Kallemeyn et al., 1996). The pyrrhotite analyses point toward hexagonal pyrrhotite ($Fe_{0.93-0.96}S$). Hexagonal pyrrhotite is normally antiferromagnetic (in contrast with the ferromagnetic monoclinic pyrrhotite $Fe_{0.87}S$), but in R chondrites it seems to be in a metastable ferromagnetic state (Rochette et al., 2008). Magnetite abundance averages 0.35 wt% (Kallemeyn et al., 1996; Rubin and Kallemeyn, 1994), and a minority of R chondrites have magnetite as their main magnetic carrier (Rochette et al., 2008). Fe,Ni-metals are extremely rare (below 0.1 wt%, Schulze et al., 1994). Other non-ferromagnetic opaque minerals encountered in R chondrites are chromite and ilmenite with abundances of 0.45 wt% and below 0.1 wt%, respectively. The paleomagnetism of five bulk samples of Rumuruti chondrites (all Antarctic finds including PCA 91002) was studied by Gattacceca and Rochette (2004). A stable remanent magnetization was evidence in all five meteorites, mostly carried by pyrrhotite with the exception of the magnetite bearing Asuka 881988 meteorite (Rochette et al., 2008). Natural Remanent Magnetization (NRM) normalization techniques indicated similar paleointensities around ~5 µT for all five meteorites. In view of the pressure-induced magnetic phase transition of pyrrhotite at 2.8 GPa (e.g., Rochette et al., 2003) and the typical peak shock pressures of Rumuruti chondrites (shock stage S2, with peak pressures >5 GPa), the NRM of these meteorites was interpreted as likely postdating the last major impact they had suffered. The NRM was regarded either as a shock remanent magnetization (SRM) or, for highly-shocked samples a thermoremanence acquired during post-impact cooling. In either case, the paleointensity estimates suggested the existence of a magnetic field of several µT (possibly transient in the SRM hypothesis) at the surface of the Rumuruti parent body at the time of the impact event.

2. Samples and methods

The two R chondrites studied here, PCA 91002 and LAP 03639, were collected during the ANSMET Antarctic meteorite search expeditions in 1991 and 2003, respectively. PCA 91002 contains about 10-20 vol% of light colored type 5 and 6 clasts within a type 3.8/3.9 ground mass, and is accordingly classified as R3.8-6 (Rubin and Kallemeyn, 1994). It has fragments that experienced different shock stages, the majority displaying shock stages S3 and S4 (Rubin and Kallemeyn, 1994), but the overall shock stage of the breccia is S2 (Kallemeyn et al., 1996). LAP 03639 was originally classified as R4, but has been reclassified as R5 (Schrader et al., 2016). It is unbrecciated and we observed sharp optical extinction in the 20 large (>50 µm) olivine single crystals that we checked, indicating a shock stage S1 using the criteria of Stöffler et al., (1991). We were allocated in 2013 samples PCA 91002,57 (1.3 g) and LAP 03639,24 (1.2 g), both sampled > 5 mm away from fusion crust. Samples were stored in a magnetically shielded room (field < 400 nT) during several months to allow partial decay of the viscous remanent magnetization potentially acquired during exposure of the meteorites to the geomagnetic field since their fall. As the original orientation of samples on the parent body is unknown, sample orientation was chosen arbitrarily. Samples were cut in mutually-oriented sub-samples with a wire saw. All subsample mass averages 160 mg for a typical size of 4x4x3 mm.

Cooling of room temperature saturation isothermal remanent magnetization (RT-SIRM), warming of low temperature SIRM (LT-SIRM), and hysteresis loops versus temperature were investigated with a Princeton Micromag Vibrating Sample Magnetometer (VSM), with a maximum applied field of 1 T and a moment sensitivity of 10^{-9} Am^2. The hysteresis loops provided saturation remanent magnetization (M_{RS}), saturation magnetization (M_S) and the coercive force (B_C). The remanent coercive force (B_{CR}) was determined by back-field experiments performed with the VSM. Low temperature (10 to 300 K) experiments were also carried out using a Quantum Design Magnetic Properties Measurements System (MPMS).

The low field specific susceptibility (noted χ in $m^3\ kg^{-1}$) and its anisotropy were measured using the Agico MFK1 bridge (with sensitivity of $5 \times 10^{-13}\ m^3$). The MFK1 was operated at 200 $A.m^{-1}$ peak field and at a frequency of 976 Hz. Anisotropy of magnetic susceptibility (AMS) was characterized by the shape parameter T, varying from −1 (prolate) to +1 (oblate), and the anisotropy degree P (ratio of maximum to minimum susceptibility). High field susceptibility (χ_{hf}) was determined by linear fitting of the 0.9-1 T field interval of the hysteresis loops.

The remanence measurements were performed with a SQUID cryogenic magnetometer (2G Enterprises, model 755R, with noise level of $10^{-11}\ Am^2$) with an attached automatic alternating field (AF) 3-axis demagnetization system (maximum peak field 170 mT) placed in a magnetically shielded room. Thermal demagnetization was performed using an MMTD furnace, under argon atmosphere above 250 °C. For most samples, we measured the S_{-300} ratio that is the IRM obtained after applying a 3 T field and then a back field of − 0.3 T normalized to the IRM acquired in 3 T. The NRM of all samples and its stability against stepwise alternating field (AF) demagnetization up to 120 mT were measured. At each AF step the sample was demagnetized and measured at least three times in order to reduce spurious anhysteretic effects and measurement noise. The directions of the components were computed using principal component analysis, without anchoring to the origin. After the study of NRM all samples were given an anhysteretic remanent magnetization (ARM, peak AF field of 100 or 300 mT, and a 100 μT bias field) that was subsequently stepwise AF demagnetized. Piezo-remanent magnetization (PRM) acquisition through hydrostatic loading was realized on bulk rock samples using a non-magnetic pressure cell (Gattacceca et al., 2010). A “Thellier-Thellier” type paleointensity experiment following the II method (Konigsberger, 1938) was conducted using the MMTD furnace equipped with a coil connected to a stabilized DC power supply (applied field 10 μT). Thellier-Thellier paleointensity experiments were processed using Thellier Tool software (Leonhardt et al., 2004). SIRM, acquired in 3 T field with a pulse magnetizer, was also investigated on three subsamples of each meteorite. The rate of acquisition of viscous remanent magnetization (VRM) of the samples was studied through measurement of the VRM decay rate, since both rates are similar (Enkin and Dunlop, 1988). VRM was acquired in a field of 100 µT for 12 days and its decay was then measured versus time. All magnetic measurements were performed at CEREGE (Aix-en-Provence, France), with the exception of remanent measurements for one subsample of each meteorite at the paleomagnetic laboratory of the University of California Santa Cruz (USA) followed by the MPMS analysis at the Institute for Rock Magnetism at the University of Minnesota (USA).

^{40}Ar/^{39}Ar stepwise degassing was conducted at Berkeley Geochronology Center following the analytical procedures described in Shuster et al., 2010 on a whole-rock aliquot of LAP 03639. The sample was first irradiated within an aluminum disc alongside the Hb3gr fluence monitor [age = 1081 Ma (Renne et al., 2011)] for 50 hours at the Oregon State University TRIGA reactor in the Cadmium-Lined In-Core Irradiation Tube (CLICIT) facility. Following irradiation, a small (~mg) aliquot of the sample was placed into high-purity Pt-Ir tubes and incrementally degassed under ultra-high vacuum using a 30W diode laser (810 nm wavelength), controlled to setpoint temperatures in feedback with a coaxially aligned optical pyrometer. The extracted gas was then purified with one hot and one cold SAES® GP-50 getter pump, each fitted with a C-50 cartridge. The isotopic composition of Ar was then measured at each degassing step using a Mass Analyzer Products 215c mass spectrometer. Apparent ^{40}Ar/^{39}Ar ages for each degassing step were calculated relative to the Hb3gr fluence monitor using the decay constants and standard calibration of Renne et al., (2011) and isotope abundances of Steiger and Jäger (1977). Due to uncertainty in the non-radiogenic ^{40}Ar component, we report ages assuming a trapped (i.e., non-radiogenic) ^{40}Ar/^{36}Ar = 0 and assuming the terrestrial atmospheric ^{40}Ar/^{36}Ar = 298 (Supplemental Table 1), which likely spans the complete range of plausibility for any trapped, non-radiogenic Ar.

3. Rock magnetism results

3.1. Magnetic mineralogy

Hysteresis properties of these two meteorites have been previously published in Tikoo et al., 2015. S_{-300} are -0.79 and -0.61, and B_{CR} average 68 mT and 118 mT in PCA 91002 and LAP 03639, respectively (Table 1), indicating that the remanence is dominated by a high coercivity mineral (pyrrhotite). M_{RS}/M_S and B_{CR}/B_C ratios are characteristic of pseudo-single domain carriers (Supplemental Table 2 and Supplemental Fig. 1).

Low temperature remanence measurements are shown in Fig. 1. In PCA91002 a possible Verwey transition (characteristic of magnetite) near 125 K can be seen in the LT-SIRM measurement, but not in the RT-SIRM curve, suggesting this may rather be a ferromagnetic to paramagnetic transition, such as the Curie point of chromite (Gattacceca et al., 2011). MPMS measurements (Supplemental Fig. 2) indicate the presence of magnetite in PCA 91002 and show a transition at ~ 15-20 K in both meteorites possibly interpreted as a spinel. The absence of Besnus transition suggests the presence of hexagonal (Rochette et al., 2008; Horng and Roberts, 2018) rather than monoclinic pyrrhotite.

The variation of M_S with temperature allowed us to estimate the proportion of pyrrhotite (M_S=24 $Am^2.kg^{-1}$) and magnetite (M_S=92 $Am^2.kg^{-1}$) for the two meteorites (Supplemental Fig. 3). LAP 03639 and PCA 91002 contain 0.11 wt% and 0.16 wt% of pyrrhotite, and 0.02 wt% and 0.10 wt% of magnetite, respectively.

Magnetic susceptibility was measured on at least three sub-samples of each meteorite, giving an average log χ of 3.04±0.07 and 2.94±0.05 for PCA 91002 and LAP 03639, respectively, with χ in 10^{-9} m^3/kg. (Table 1). The relatively small scatter in the susceptibility measurements, suggest that magnetic grains are homogeneously distributed at the scale of our samples (~ 0.14 g). Our results are also in agreement with values obtained previously on much larger samples (log χ = 3.11±0.05 on 13 g and 45 g samples of PCA 91002 in Rochette et al., 2008), again indicating homogeneous dispersion of magnetic minerals at the scale of the meteorite. It is noteworthy that silicate paramagnetism (estimated from the hysteresis loops shown in Supplemental Fig. 1) accounts for a significant part (50% in both studied samples) of the total susceptibility.

3.2. Remanent magnetizations

We have investigated the properties of the ARM and SIRM of both meteorites. Their intensities are reported in Table 2. Median destructive field (MDF) is used to describe the stability of SIRM and ARM against AF demagnetization. The two studied meteorites exhibit high MDF values both for ARM and SIRM. The ARM acquired in an alternating field of 100 mT exhibits similar range of stability with MDFs averaging ~48 mT in both meteorites. The ARM acquired in an alternating field of 300 mT shows MDF of 65 mT for PCA 91002 and 95 mT for LAP 03639. It is noteworthy that in view of the dominance of a high coercivity mineral, these ARM do not affect all ferromagnetic grains and this must be kept in mind when interpreting its properties. The average saturation magnetization for PCA 91002, with a mean log M_{RS} of 1.47 (with M_{RS} in 10^{-3} $Am^2.kg^{-1}$), is in agreement with the value of 1.61 reported by Rochette et al., 2008. MDF of SIRM averages 60 mT and 110 mT in PCA 91002 and LAP 03639, respectively.

Because both studied meteorites remained in the geomagnetic field in Antarctica for typical times of ~50 kyr (average terrestrial age of Antarctic meteorites, Welten et al., 2006), VRM must be considered as a possible significant contribution to their NRM. In the worst case and unlikely scenario where the meteorite remained in a fixed position with respect to the geomagnetic magnetic during 50 kyr in Antarctica and during the 10-20 years of curation, followed by 6 months of VRM decay in our magnetically shielded room, we use the measured VRM decay rate (equal to the acquisition rate, Supplemental Fig. 4) to estimate the maximum VRM that may be present in our samples. The results indicate that VRM may account for ~12% and ~30% at most of the measured NRM in PCA 91002 and LAP 03639, respectively

(Supplemental Table 3). Thermal demagnetization of the SIRM (Fig. 2) shows that both studied R chondrites are demagnetized at relatively low temperature with less than 10% and 30% of the magnetization remaining at 250 °C in LAP 03639 and PCA 91002, respectively. Together with the high coercivity and the low unblocking temperatures, this indicates that pyrrhotite dominates the remanence signal. It is noteworthy that PCA 91002 shows a second inflexion at ~580°C characteristic of magnetite.

3.3 Magnetic anisotropy

The degrees of anisotropy of magnetic susceptibility (AMS) degrees are weak (1.02 to 1.04, Table 1) and fall in the range (1.016-1.065) previously estimated on larger samples (Gattacceca et al., 2005). The anisotropy of ARM (AARM) has the same principal axes as the AMS axes. AARM is moderate, and cannot account for deviations the paleomagnetic directions of more than a few degrees. It is noteworthy that mutually oriented samples have similar orientation of AMS and AARM axes (Supplemental Fig. 5), indicating a homogeneous fabric at the scale of about 1 cm (initial size of the largest studied samples). The observed homogeneity of the fabric in our samples indicates that for the brecciated sample (PCA 91002) the magnetic fabric, and hence the preferential orientation of pyrrhotite grains, was acquired after brecciation. The most likely scenario is that the fabric was imparted by an impact event (as already observed in ordinary chondrite breccias (e.g., Gattacceca et al., 2005)), possibly the impact that lithified the breccia.

4. Paleomagnetism

4.1 Demagnetization behavior

For each meteorite, AF and thermal demagnetizations were performed; four subsamples were AF demagnetized, one thermally demagnetized after the removal of the low coercivity (LC) component with AF, and one was demagnetized following the Thellier-Thellier II method (Koenigsberger, 1938). The results are listed in Table 3, and displayed in Fig. 3 and 4.

For LAP 03639, NRM intensities are homogeneous and average 3.22±0.8 x 10^{-5}Am².kg^{-1}. All subsamples display a very similar demagnetization pattern during AF demagnetization with a low coercivity (LC) component isolated below ~15 mT, and a high coercivity (HC) component isolated between 19 and 145 mT on average. Above 145 mT, the demagnetization path becomes erratic, as is often the case when demagnetizing pyrrhotite with AF. Thermal demagnetization (after removal of the LC component with AF treatment), shows a HT component isolated between 55 and 250°C (Fig 3) with the same direction as the HC component (Fig 4a). HC/HT directions are well clustered among the different mutually-oriented subsamples with a Fisher precision parameters k= 163.7(Fig 4a).

For PCA 91002, NRM intensity ranges from 1.64 to 9.84×10^{-5}Am².kg^{-1}, in agreement with previously reported values (2.98×10^{-5} Am².kg^{-1} for a 437 mg sample in Gattacceca and Rochette, 2004). AF demagnetization reveals a LC component isolated below 17 mT, and a well-defined origin-trending high-coercivity (HC) component isolated between 20 and 138 mT on average. Above 138 mT, as observed in LAP 03639, the demagnetization path becomes erratic. After removal of the LC component by AF, thermal demagnetization reveals a high-temperature (HT) component isolated between 160° and 520°C (Fig. 3). The directions of the HT and HC component are relatively clustered with a Fisher precision parameter k=9.2 (Fig. 4b).

In order to check that the HC components are origin-trending, we compared the Maximum Angular Deviation (MAD) of these components with the angle (called α in the following, and given in Table 3) formed by the direction of the component and the direction of the first (i.e., lowest coercivity) NRM vector of the component (as described in e.g., Garrick-Bethell et al., 2009). Unlike the commonly used deviation angle (dANG), α has the advantage of using data further from the origin and therefore less noisy. Then, like the dANG, if α is smaller than the MAD, the component is considered origin-trending. In all samples but one α is lower or very close (within 2°) to the MAD suggesting that HC and HT directions trend toward the origin in both meteorites, and can be considered as Characteristic Remanent Magnetizations (ChRM). Only one subsample of PCA 91002 has α=14.2° compared to a MAD of 5.8°.

4.2 Paleointensities and origin of the magnetizing field

We first normalized the NRM by the SIRM (REM' method of Gattacceca and Rochette, 2004) to estimate paleointensities with a non-destructive technique. For LAP 03639, the carrier of the magnetization is pyrrhotite and we used the calibration constant a=3000 µT proposed by Gattacceca and Rochette (2004) for the REM' method, very close to the average computed from the experimental calibration results for pyrrhotite compiled in Weiss and Tikoo (2014) in their Table S4 (a=3089±1322 µT, N=15). For PCA 91002, the magnetization is carried by both pyrrhotite and magnetite, and we used the average a=3000 µT proposed by Gattacceca and Rochette (2004). The ARM normalization method (e.g., Stephenson and Collinson, 1974), is not readily applicable to pyrrhotite-bearing rocks in view of the high coercivity of pyrrhotite and the absence of specific calibration. The destructive Thellier-Thellier method was used for one sample of each meteorite. It must be kept in mind that all these methods are designed and calibrated for the case where the NRM is a TRM.

REM' values are fairly constant over the HC component interval for both meteorites (Fig 5) averaging $(1.79\pm0.15)\times10^{-3}$ in LAP 03639 and $(9.87\pm3.07)\times10^{-4}$ in PCA 91002, corresponding to paleointensity of 2.96±0.75 µT in PCA 91002 and 5.38±0.36 µT in LAP 03639, with an uncertainty of a factor 2 (Table 3). We also used an alternative processing (as described in Garrick-Bethell et al., 2009) where we fit the NRM lost and SIRM lost over the HC interval with a linear regression, using the first vector of the HC component as the reference vector (Fig 5), using the same calibration constant a=3000 µT. The paleointensities associated with the ChRM are consistent between both methods and average 2.3 ± 0.4 µT and 5.1 ± 0.9 µT for PCA 91002 and LAP 03639, respectively (Table 3). All the values mentioned above are in agreement with the previous estimate of 5.3 ± 3.3 µT obtained for five R chondrites using the REM' normalization method (including PCA 91002, Gattacceca and Rochette, 2004). It is noteworthy that for PCA 91002 these estimates must be regarded as lower limits if the ChRM is interpreted as a SRM because this mechanism is less efficient than TRM (e.g., Gattacceca et al., 2008; Tikoo et al., 2015).

The results of the Thellier-Thellier experiments are presented in Figure 6. For LAP 03639, although the Arai plot shows good linearity (Sb/B=0.13), and satisfactory f and g factors (see Leonhardt et al., 2004 for a definition of these parameters), the partial TRM (pTRM) checks are unsatisfactory with a ∂(CK) parameter of 41.1%, indicating alteration and destruction of the pyrrhotite starting at temperatures as low as 150°C. As a consequence, the paleointensity of 42.0±5.4 µT that can be computed over the temperature interval 125-225°C strongly overestimates the real paleointensity and in any case cannot be regarded as reliable. For PCA 91002, although the demagnetization plot shows a single component of magnetization over the whole 125-550°C interval, the Arai plot shows a peculiar strong slope break at ~350°C. The presence of this kink exactly at the Curie temperature of pyrrhotite, combined with the relatively poor pTRM checks on the lower temperature segment (50-350°C, with ∂(CK)=17.1%), and the alteration of pyrrhotite at such low temperatures in the LAP 03639, suggest alteration of pyrrhotite (rather than magnetite) at low temperatures in PCA 91002 and preclude robust interpretation of the lower temperature segment of the Arai plot in terms of paleointensity. In the higher temperature interval (350-550°C), the pTRM checks are satisfactory with ∂(CK)<3% (class A criteria of Calvo-Rathert et al., 2016) suggesting that the magnetite in PCA 91002 is stable upon heating. Several other parameters (f, g and MAD) are also satisfactory (class A) over this latter temperature interval. The paleointensity computed over the 350-550°C interval 12.1±2.2 µT can therefore be considered as a reliable result.

5. Discussion

After removal of a LC component, the origin-trending magnetization directions isolated by AF and thermal demagnetization in mutually-oriented samples can be considered as the ChRM. The LC components of the NRM are likely terrestrial, either of viscous origin or the result of magnetic overprints during sample curation, handling, and/or preparation. These terrestrial components are not discussed in further detail.

The clustering of ChRM directions between mutually oriented sub-samples indicates a post-accretion magnetization for both meteorites and even post-brecciation and lithification for PCA 91002 at least at the original scale of the studied sample (1.2 g).

In view of the terrestrial residence time of the studied meteorites (50 kyr), the terrestrial VRM is expected to be stable up to 80-120°C upon laboratory thermal demagnetization whether it is carried by pyrrhotite (Pullaiha et al., 1975) or magnetite (Dunlop et al., 2000). The ChRM in both meteorites is unblocked up to significantly higher temperature (220°C for LAP 03639, 550° for PCA 91002), so that a VRM origin of the ChRM is ruled out.

In order to further constrain the nature of the ChRM, we compared the AF demagnetization behavior of ChRM, with that of SIRM, and PRM used as an analog for shock remanent magnetization (e.g., Tikoo et al., 2015) over the interval used to define the HC component for both meteorites (Fig 5, Supplemental Fig. 6). Similarly, we compared the ChRM and SIRM behaviors upon thermal demagnetization (Fig 2). It is noteworthy that in view of the high coercivity of pyrrhotite (only 40% of the SIRM is demagnetized at 100 mT AF) and the field used for ARM acquisition (100 mT AF), ARM cannot be considered as an analog for TRM as classically used for extraterrestrial rocks containing minerals with lower coercivity such as magnetite or kamacite (Stephenson and Collinson, 1974).

In LAP 03639, the main magnetic carrier, pyrrhotite is very sensitive to pressure remagnetization and can be entirely reset by static stress of 2.8GPa, (Rochette et al., 2003). In our hydrostatic pressure based experiments, we observe that the behavior of the PRM (acquired at 2GPa) is different from that of the ChRM (Supplemental Fig. 6), indicating that the ChRM is unlikely a SRM. Moreover, the low shock state (S1) and the unbrecciated nature of LAP 03639 suggests that it is unlikely that this meteorite underwent an impact-induced short thermal excursion that would have allowed the record of a transient shock-generated field. Furthermore, a SRM nature of the ChRM would require a minimum ambient field of 360 µT at the time of impact (Supplemental Table 4). This field was calculated by extrapolating our experimental data at 2 GPa to 2.8 GPa using a linear fit. Above this 2.8 GPa threshold additional PRM cannot be acquired, at least for monoclinic pyrrhotite that shows a phase transition at this pressure. We acknowledge that this linear extrapolation and 2.8 GPa threshold are debatable, especially when applied to the pyrrhotite in Rumuruti chondrites that may be in a more complex metastable hexagonal phase. Therefore, the required paleofield value of 360 µT for a SRM remains a rough indication. However, such high values are unreasonably high compared to magnetic fields intensities estimated to be present in the early solar system history, likely disk-generated fields (maximum 100 µT in the midplane of the disk, e.g., Turner and Sano, 2008), solar wind fields (Oran et al., 2018), or shock-generated fields (Crawford and Schultz, 1999) although the scaling laws for these shock-generated fields are uncertain. A chemical remanent magnetization (CRM) origin for the ChRM would mean that pyrrhotite was formed on the parent body by aqueous alteration following thermal metamorphism, a sequence of events that is not expected on asteroidal bodies (Krot et al., 2006; Greshake, 2014). The low weathering grade of both studied meteorites, and the absence of primary metal that under terrestrial conditions weather into magnetite, preclude the possibility that the NRM can be a CRM acquired through crystallization of ferromagnetic minerals during the Antarctic stay of the meteorites. Eventually, the most plausible possibility is that the ChRM is a TRM, with the meteorite being magnetized over its full blocking temperature spectrum (Fig 2) during cooling following peak thermal metamorphism or during a later thermal event (shock heating). The ^{40}Ar/^{39}Ar age spectrum for LAP 03639 provides no evidence of diffusive loss of ^{40}Ar, as we observed concordant step ages in the initial ~70% of extracted Ar (Fig 7). The error-weighted mean of the first 14 degassing steps, calculated assuming a trapped ^{40}Ar/^{36}Ar = 298, is 4564 ± 17 Ma (Fig 7). As the K-Ar system is sensitive to diffusive loss of radiogenic ^{40}Ar at elevated temperatures, it may be reset due to impact heating (Shuster et al., 2010). On the R parent body, the main impact events were dated to start at 4.47Ga (Dixon et al., 2003). The old ^{40}Ar-^{39}Ar age of LAP 03639 indicates that this meteorite has not been affected by these impact events, although a mild post-shock temperature sufficient to remagnetize the meteorite (≥250°C) may not be high enough or sustained for a long enough period to reset or affect the Ar-Ar chronometer (Shuster et al., 2010). Considering an initial temperature of the asteroid of -150°C, typical temperatures in the asteroid belt, a temperature increase of 400°C would have been necessary to achieve the 250°C needed to magnetize the meteorite. A 400°C temperature increase would have required shock pressures in excess of 35 GPa or multiple low pressure impacts (<5 GPa) (Bland et al., 2014). In the former case, such pressures would correspond to a shock stage S4, generating the presence of melt pockets that are not observed in LAP 03639 for which we have determined a shock stage S1. In the latter case, the multiple low pressure necessary to reach ~400°C of bulk heating would have induced large temperature changes (up to localized melting) in the matrix, which is not observed in LAP 03639. Therefore, a post-shock TRM is unlikely for the origin of the ChRM of LAP 03639. The petrographic type (R5) of LAP 03639 suggests peak metamorphism temperatures of about 850°C (Schrader et al., 2016) which is well above the maximum unblocking temperature of ~250 °C observed during thermal demagnetization of NRM (Fig 2). As shown by the complete demagnetization of the SIRM at 250 °C (Figure 2), LAP 06639 has no paleomagnetic recording capacity above this temperature. The high metamorphic grade and the unbrecciated and unshocked (S1) nature of LAP 03639 indicate that most likely scenario is that the ChRM of LAP 06639 was acquired during retrograde thermal metamorphism when the meteorite was cooling below 250°C in a field of ~5 µT.

In PCA 91002, the ChRM is post-accretion as indicated by the similar ChRM directions in mutually-oriented samples. No light-colored equilibrated clasts larger than 1 mm was observed in our sample. In view of the typical size of our sub-samples, and homogeneous ChRM, the magnetization is clearly post-brecciation as any surviving magnetization in type 5 and type 6 clasts would have been randomized. The presence of unequilibrated type 3 material in this meteorite indicates that post-lithification long-term temperatures were below ~500 °C to preserve this unequilibrated mineralogy. Like in LAP 03639, the NRM could be a CRM, a TRM, or a SRM (Fig 2). A CRM is unlikely because it would require post brecciation hydrothermalism, but aqueous alteration usually predates thermal metamorphism on asteroidal bodies (e.g., Krot et al., 2006; Greshake, 2014). The shock level S2 of the meteorite (Kallemeyen et al., 1996), indicates maximum shock pressure between 5 and 10 GPa. This is above the magnetic transition of pyrrhotite at 2.8 GPa, but below that of magnetite at 12-16 GPa (Ding et al., 2008). If the ChRM was a SRM, it would require minimum ambient field in the range 20-175µT at the time of impact (depending on the fit, linear or polynomial, used to extrapolate our PRM experiments) (Supplemental Table 4). Therefore, considering the lower end (20 µT) of this rough estimate, a SRM nature of the ChRM for PCA 91002 remains possible. This may also account for the strong kink of the Arai plot at 350°C that may indicate that the NRM is indeed not a TRM. If the ChRM is a TRM preserved in magnetite, a stable field of about 12 µT (as evaluated by the Thellier-Thellier method) had to be present during cooling below ~550°C, regardless of the process that generated the temperature increase (thermal metamorphism or shock). In the case of thermal metamorphism, this ~550°C estimate is marginally consistent with the peak metamorphism temperature of ~500°C suggested by the 3.8/3.9 metamorphic type of the groundmass of this meteorite. Although the ChRM has to be older than 4.37±0.01 Ga. However, this ^{40}Ar-^{39}Ar age of PCA 91002 is ill-constrained (Dixon et al., 2003), and does not really bring decisive constraints on the nature of the ChRM. Despite a more complex and less constrained scenario, the results for PCA 91002 indicate that a field of at several µT (12 µT if the ChRM is a TRM, >20 µT if it is a SRM) had to be present at some point in the history of this meteorite.

It is noteworthy that for both meteorites, the scenari discussed above hold whether the pyrrhotite is of nebular origin (Gainsforth et al., 2017), or formed during high temperature parent body processes at temperature of about 600°C (Schrader et al., 2016).

Solar field have been shown to be much weaker than the paleointensity of several µT evidenced in both meteorites (Oran et al., 2018). Therefore, they cannot account for the measured magnetization. A recent compilation of several studies on four different meteorite groups provided consistent constraints on the nebular magnetic field lifetime (Weiss et al., 2017). In detail, a nebular field of 5-50 µT was estimated in LL chondrites chondrules, ~1-3 Ma after CAIs (Fu et al., 2014) ; a time-average field of ~2 µT was determined for CM chondrites, 3.20±0.66 Ma after CAIs (Cournede et al., 2015); an instantaneous field < 0.6 µT at 3.8 Ma after CAIs was determined from angrites analysis (Wang et al., 2017); and the Kaba CV chondrite showed that the time averaged field was <0.3 µT at 4.50±1.66 Ma after CAIs (Gattacceca et al., 2016). Therefore, the nebular field likely persisted until sometimes between

4564.3 and 4563.5 Ma using an age of the 4567.30±0.16 Ma for the crystallization of CAI (Connelly et al., 2012). The Ar-Ar age of 4563±17 Ma measured for LAP 03639 in this study cannot discriminate between a nebular and an internal origin of the magnetizing field. However, the accretion age of the Rumuruti parent body is estimated at 2.1±0.1 Myr after solar system formation (Sugiura and Fujiya, 2014), i.e. at 4565.2 Ga. All parent body thermal models show that the peak of thermal metamorphism is reached shortly after accretion but that cooling below the temperatures relevant for paleomagnetism (550°C and below here) occurs several Myr after accretion (e.g., Golabek et al., 2014), so most probably after 4563 Myr. Therefore, a retrograde metamorphic cooling below ~250°C in LAP 03639 would be too young to record time-averaged or instantaneous nebular magnetic fields that should have decayed to at most 0.5 µT by 4563.5 Ma at such heliocentric distances. The most likely hypothesis for a late (at least 4 Myr after solar system formation) stable field of several µT is a dynamo field, generated within the parent body, as proposed for angrites (Weiss et al., 2008), CV chondrites (Carporzen et al., 2011; Gattacceca et al., 2016), and H chondrites (Bryson et al., 2019a). This would imply that like that proposed for the CV chondrites (Carporzen et al., 2011), and H chondrites (Bryson et al., 2019a), the R chondrite parent body may have had a molten advecting liquid core, and that R chondrites originate from an undifferentiated shell overlying a partially differentiated interior.

6. Conclusion

The R chondrites LAP 03639 and PCA 91002 both carry a stable remanent magnetization acquired in a field of several µT. The magnetization scenario for PCA 91002 is not well constrained because of the complex geochronology data and shock effects, but a field of at least 12 µT is necessary to account for the observed magnetization whatever the nature of the ChRM. For LAP 03639, the most plausible scenario is that the remanent magnetization is the result of cooling below 250°C during retrograde metamorphism in the presence of an internally generated (dynamo) magnetic field of ~ 5 µT. This result implies the existence of an advecting conductive liquid core within a partially differentiated Rumuruti chondrite parent body. Together with H and CV chondrite parent bodies, this is the third example of a partially differentiated chondritic parent body.

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Captions

Figures

Fig. 1: Measurements of low temperature (LT) and room temperature (RT) SIRM for samples studied here. In the LT-SIRM measurement of PCA91002, the vertical arrow near 125 K possibly indicates a Verwey transition (characteristic of magnetite).

Fig. 2: Normalized intensities of NRM (black line) and SIRM (gray line) versus thermal demagnetization for the studied R chondrites.

Fig. 3: Orthogonal projections of AF and AF + Thermal demagnetization data for the two studied R chondrites. All the orthogonal projections are represented in the same referential (W, Up). The solid and open circles represent vector end points projected onto horizontal and vertical planes, respectively. The blue and red arrows highlight the interpreted low and high coercivity components, respectively. For sample E1 of both meteorites, AF steps above 130 (in PCA 91002) and 180 mT (in LAP 03639) are not shown because of their erratic behavior.

Fig. 4: Stereographic projection of the stable component of magnetization and their 95% confidence interval (black circles) for LAP 03639 (a) and for PCA 91002 (b). Boxes: LC components, Circles: HC/HT components (ChRM). Star and their 95% confidence interval (grey circles) represent the mean direction of the LC and/or HC component(s). Open and solid symbols are projection in the upper and low hemisphere, respectively.

Fig. 5: Normalized intensities of NRM (black line), ARM (dashed line) and of IRM (gray line) versus demagnetizing field (left) and REM' values versus alternating field demagnetization (middle) for three subsamples of each of the two studied R chondrites. On the REM' plots, the LC (light grey) and HC (black) portions are represented. The horizontal line indicates the integrated REM' value and the range of integration of the HC component. NRM lost vs IRM lost plots (right) over the LC (open circles), HC (black circles) are shown. The equation of the linear regression fit and the associated R^2 are indicated on the graph for each portion.

Fig. 6: Arai plots of the normalized NRM remaining versus the normalized pTRM gained during Thellier–Thellier II method experiment (left) and the corresponding orthogonal projections (right). All the orthogonal projections are represented in the same referential (W,

Up, same as Figure 3). The solid and open circles represent vector end points projected onto horizontal and vertical planes, respectively. The blue and red arrows highlight the interpreted low and high coercivity components, respectively.

Fig. 7: Apparent $^{40}Ar/^{39}Ar$ age (A), Ca/K (B) spectra for LAP 03639. Each spectrum is plotted against the cumulative release fraction of ^{39}Ar. Dimensions of boxes indicate ±1 standard deviation (vertical) and the fraction of ^{39}Ar released (horizontal). Ca/K ratios were calculated from the $^{37}Ar_{Ca}/^{39}Ar_K$ ratio assuming the relative production ratio for Ca to K is 1:1.96. In panel (A), the green boxes were calculated assuming a trapped $^{40}Ar/^{36}Ar = 0$, and red boxes were calculated assuming a trapped $^{40}Ar/^{36}Ar = 298$.

Tables:

Table 1:

Title: Intrinsic magnetic properties of studied Rumuruti chondrites.

Samples studied in this work with their intrinsic magnetic properties. M_{RS}: saturation remanence, S_{-300} (=(IRM-0.3T)/(IRM3T)), χ: magnetic susceptibility, χ_p: paramagnetic susceptibility, χ_f: ferromagnetic susceptibility. All susceptibilities are in 10^{-9} m^3 kg^{-1}, χ_f: susceptibility variation corrected for paramagnetic susceptibility, P, T: anisotropy degree and shape parameter for magnetic susceptibility, P_{rem}, T_{rem}: anisotropy degree and shape parameter of remanence.

Table 2:

Title: Artificial remanent magnetizations of studied Rumuruti chondrites.

Remanent magnetizations with the corresponding median destructive field (MDF) results obtained for the studied samples. M_{RS}: saturation remanence (SIRM, acquired in 3 T or 1 T

(*) field), ARM: anhysteretic remanent magnetization was acquired in an AF of 100 mT, or of 300 mT (∗), and a 100 µT steady field. PRM: piezo-remanent magnetization was acquired in 2GPa in a field of 751.4 µT.

Table 3:

Title: Paleomagnetic results.

NRM components identification and interpretation for the studied samples. REM’: REM’ integrated over the given alternating demagnetization field range with associated paleofield estimate (µT). Directional information of the identified components are reported. LC = low coercivity component, HC=high coercivity component HT= high temperature component. α is also given to check the origin trending tendency of the HC/HT (see text). The paleofield (µT) using linear regression with IRM method is also given (see text).

Supplemental material: Figures

Supplemental Fig. 1: Hysteresis loops for LAP 03639 sample D4 (m=149 mg, dashed line) and PCA 91002 sample D4 (m=178 mg, full line) raw and corrected for the paramagnetic and diamagnetic contribution using the slope over the 0.9-1 T field range.

Supplemental Fig. 2: MPMS data; Zero field cooling (ZFC) curves for the two studied meteorites.

Supplemental Fig. 3: Hysteresis loop versus temperature (not corrected), zoom of the low applied magnetic field region, back field curves versus temperature, B_{CR}, M_S and M_{RS} and B_C versus temperature for the two studied meteorites.

Supplemental Fig. 4: VRM decay curves for both meteorites (see text).

Supplemental Fig. 5: Magnetic anisotropy: maximum (squares) and minimum (circles) axes of magnetic susceptibility and ARM (indicated by the letter R) for the two studied R chondrites (equal area stereographic projection on lower hemisphere).

Supplemental Fig. 6: Left: NRM (plain line) and PRM (dashed line) (acquired at 2GPa) behavior upon AF demagnetization. Right: PRM acquisition curve and extrapolation up to 5GPa using a linear or a logarithmic fit.

Supplemental material: Tables

Supplemental Table 1:

Title: Complete ^{40}Ar/^{39}Ar incremental heating results for LAP 03639.

Isotope abundances given in 10^{-15} mol (spectrometer sensivity is ~1.12 x 10^{-14} mols/nA), and corrected for ^{37}Ar and ^{39}Ar decay, half-lives of 35.2 days and 269 years, respectively, and for spectrometer discrimination per atomic mass unit of 1.004535 ± 0.002968. Isotope sources calculated using the reactor constants in Renne et al. (1998), assuming (^{38}Ar/^{36}Ar)cos = 1.54, (^{38}Ar/^{36}Ar)trap = 0.188, and (^{40}Ar/^{36}Ar)trap = 0. No corrections were made for cosmogenic ^{40}Ar. Ages calculated using the decay constants and standard calibration of Renne et al. (2011) and isotope abundance of Steiger and Jäger (1977) and calculated relative to Hb3gr fluence monitor (1081 Ma). Corrections were made for reactor produced ^{38}Ar and ^{36}Ar in age calculations. J-Value is 0.013048 ± 0.000260. Average analytical blanks are: ^{40}Ar = 0.015; ^{39}Ar = 0.0001; ^{38}Ar = 0.00002; ^{37}Ar = 0.0001; ^{36}Ar = 0.00007 (nanoamps). Temperature was controlled with approximately ± 10 °C precision and ± 10 °C accuracy; each heating duration was 600 seconds. [1]Calculated assuming (^{40}Ar/^{36}Ar)trap = 0. [2]Calculated assuming (^{40}Ar/^{36}Ar)trap = 298. n.d. is not determined.

Supplemental Table 2:

Title: Samples studied in this work with their intrinsic magnetic properties.

M_{RS}: saturation remanence, M_S: saturation magnetization, B_C: coercivity, B_{CR}: coercivity of remanence. Some of the data have already been published in Tikoo et al., 2015.

Supplemental Table 3:

Title: VRM properties for the studied Rumuruti chondrites.

Estimated residential time on Earth, Sd: VRM decay rate obtained using a linear fit (SP Fig. 4), VRM_{max} calculated for the estimated time spend on Earth since their fall (residential time on Earth), and maximum percentage of VRM regarding NRM intensity for the two studied meteorites.

Supplemental Table 4:

Title: PRM properties for the studied Rumuruti chondrites.

PRM intensity value extrapolated at 2.8, 5, 10, 20 and 35GPa using a linear or a logarithmic fit (cf SP Fig. 6), and corresponding minimum paleointensity value required at the time of impact to impart it.