Earth and Planetary Science Letters 404 (2014) 54–66

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

No nebular magnetization in the Allende CV carbonaceous chondrite

R.R. Fu *, E.A. Lima, B.P. Weiss

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form 10 July 2014
Accepted 12 July 2014
Available online 12 August 2014
Editor: C. Sotin

Keywords:
paleomagnetism
meteoritics
planetary accretion
chondrules
planetary dynamos
CV chondrites

ABSTRACT

Magnetic fields in the solar nebula may have played a central role in mass and angular momentum transport in the protosolar disk and facilitated the accretion of the first planetesimals. Thought to be key evidence for this hypothesis is the high unblocking-temperature, randomly oriented magnetization in chondrules in the Allende CV carbonaceous chondrite. However, it has recently been realized that most of the ferromagnetic minerals in Allende are products of secondary processes on the parent planetesimal. Here we reevaluate the pre-accretional magnetism hypothesis for Allende using new paleomagnetic analyses of chondrules including the first measurements of mutually oriented subsamples from within individual chondrules. We confirm that Allende chondrules carry a high-temperature component of magnetization that is randomly oriented among chondrules. However, we find that *subsamples* of individual chondrules are also non-unidirectionally magnetized. Therefore, the high-temperature magnetization in Allende chondrules is not a record of nebular magnetic fields and is instead best explained by remagnetization during metasomatism in a <8 μT magnetic field. This low field intensity suggests that any core dynamo on the CV parent body decayed before the end of metasomatism, likely <40 My after the formation of calcium aluminum-rich inclusions (CAIs). Despite widespread practice, the magnetization in Allende should not be used to constrain magnetic fields in the protosolar nebula.

1. Introduction

During the first several million years of planet formation, dust in the solar nebula accreted to form 100 to 1000 km-scale planetesimals (Chambers, 2004). Theoretical models strongly suggest that magnetic fields played a critical role in the dynamics of the nebular gas and the evolution of solid particles. In particular, large-scale mass and angular momentum transfer in the nebula may have relied on magnetocentrifugal winds and/or turbulence generated by the magnetorotational instability (MRI) (Bai and Stone, 2013; Balbus, 2003). Magnetically-induced turbulence may have also facilitated mutual collisions and local concentration of solid matter, thereby allowing for the accretion of solid bodies (e.g., Cuzzi and Hogan, 2003; Johansen et al., 2007).

The first known macroscopic solids to form in the solar nebula were chondrules and CAIs, millimeter-sized inclusions now found in chondritic meteorites. Chondrules are igneous spherules that melted and cooled quickly in the solar nebula, while CAIs are nebular condensation products often subjected to subsequent reheating (MacPherson, 2007). Because they were heated and cooled in the solar nebula, these objects may have recorded the nebular magnetic field. Therefore, paleomagnetic studies of chondrules and CAIs can potentially provide direct constraints on the strength of nebular magnetic fields and their role in solar system formation. Fields in the midplanes of the terrestrial planet-forming region in protoplanetary disks are currently inaccessible to astronomical measurements (Crutcher, 2012).

Paleomagnetism of chondrite inclusions such as chondrules and CAIs may also have important implications for the setting and mechanism of chondrule formation (Desch et al., 2012). Chondrule formation hypotheses often predict very different magnetic field environments (Desch and Connolly, 2002; McNally et al., 2013). Knowledge of the magnetic field intensity in the chondrule-forming environment would therefore provide new constraints on this enigmatic process.

However, paleomagnetic studies of primitive inclusions face the challenge that chondrules and CAIs in all meteorites have been subject to a combination of secondary alteration and metamorphic reheating after their accretion onto their parent body. These processes may have compromised any pre-accretional natural remanent magnetization (NRM). Furthermore, many meteorite samples experienced remagnetization in strong artificial magnetic fields on Earth following their collection. Such strong fields, if not properly identified and removed, can lead to misinterpretation and severe

* Corresponding author. Tel.: +1 510 304 9435.
E-mail address: rogerfu@mit.edu (R.R. Fu).

http://dx.doi.org/10.1016/j.epsl.2014.07.014

overestimates of ancient magnetic field strengths (Weiss et al., 2010).

Paleomagnetic tests can aid in distinguishing between pre-accretional and post-accretional NRM in chondrites. In the *conglomerate test*, mutually random magnetization directions in chondrules and other inclusions provide evidence for magnetization predating the final assembly of the rock. This is because if the chondrules were completely remagnetized in a spatially uniform field following accretion, they should be magnetized in the same direction within a given meteorite. A second, *unidirectionality test* examines the direction of magnetization in subsamples of individual chondrules and CAIs. A pre-accretional thermoremanent magnetization (TRM) is expected to be unidirectional across subsamples. Both paleomagnetic tests require analysis of mutually oriented samples.

The Allende CV carbonaceous chondrite is probably the most extensively analyzed chondrite using paleomagnetic methods. Measurements of individual, unoriented chondrules (Acton et al., 2007; Emmerton et al., 2011; Lanoix et al., 1978) have inferred magnetic field paleointensities of between 10 and 1600 μT. However, these studies could not establish a pre-accretional origin for the magnetization or rule out artificial isothermal remanent magnetization (IRM) contamination. The latter almost certainly accounts for the paleointensity values >200 μT (Cisowski, 1987; Wasilewski, 1981). Neglecting those affected by IRM, bulk Allende samples and some isolated chondrules carry a strong unidirectional overprint that unblocked below ∼300 °C acquired on the CV parent body (Carporzen et al., 2011; Nagata, 1979a; Sugiura and Strangway, 1985). Carporzen et al. (2011) interpreted this post-accretional magnetization, which they called the middle temperature (MT) component, as evidence for a past magnetic core dynamo on the CV parent body, implying that this body underwent igneous differentiation while preserving a relatively unheated chondritic crust.

Nevertheless, paleomagnetic studies by Sugiura et al. (1979) and Sugiura and Strangway (1985) showed that, after removal of the low temperature overprint at ∼300 °C, individual, mutually-oriented chondrules in Allende had widely scattered magnetization directions that pass the paleomagnetic conglomerate test at the 95% significance level (Watson, 1956). Sugiura and Strangway (1985) concluded that this non-unidirectional component is a pre-accretional TRM acquired in a nebular magnetic field.

However, a major source of subsequent confusion has been that no paleointensities were reported for this non-unidirectional HT component. As a result, many later studies have mistakenly cited paleointensities derived for the other magnetization components in Allende as constraints on nebular fields. In particular, many theoretical studies (e.g., Levy and Araki, 1989; Stepinski, 1992; Rozyczka et al., 1996; Shu et al., 1996; Nübold and Glassmeier, 2000; Desch and Connolly, 2002; Johansen, 2009) have cited the ∼100 μT paleointensity values derived from unoriented chondrules or bulk samples (which should be dominated by the post-accretional MT overprint) or even the high paleointensities of 100–1600 μT from a set of unoriented chondrules likely contaminated by IRMs on Earth (Wasilewski, 1981).

Adding to the uncertainty, the paleomagnetic conglomerate test alone, as performed by Sugiura and Strangway (1985), is in fact insufficient for establishing the pre-accretional origin of the HT chondrule magnetization. Post-accretional recrystallization of magnetic phases in a near-zero magnetic field can also produce randomized magnetization directions (Uehara et al., 2011), potentially leading to a false-positive conglomerate test. In fact, the weak intensity of the HT magnetization and its non-origin trending behavior during higher temperature thermal demagnetization are all characteristics of such null field remanence (see Section 4.1).

Here we report new paleomagnetic analyses on mutually-oriented Allende chondrules and subsamples of individual chondrules with the goal of determining whether the HT component in Allende chondrules is in fact pre-accretional. We find that, although the HT magnetizations of individual chondrules pass the conglomerate test, *subsamples* of individual chondrules also have statistically random magnetization directions, thereby failing the unidirectionality test. Coupled with petrographic observations and modeling of TRM acquisition in the solar nebula, we argue that all observed magnetization components in Allende chondrules are post-accretional. Finally, we discuss the implications of these results for the CV parent body core dynamo hypothesis and the lifetime of such a dynamo.

2. Samples and methods

We performed two kinds of paleomagnetic measurements. The bulk of our analyses employed classic moment magnetometry using a 2G Enterprises Superconducting Rock Magnetometer (2G SRM) 755 at the MIT Paleomagnetism Laboratory. These were supplemented with magnetic field maps acquired with the MIT SQUID Microscope (Weiss et al., 2007).

Samples analyzed using the 2G SRM were extracted from a slab of Allende provided by the American Museum of Natural History called AMNH5056, which is a ∼10 × 10 × 0.8 cm piece previously studied by Carporzen et al. (2011). All samples taken from AMNH5056 are mutually oriented with respect to samples in Carporzen et al. (2011).

Carporzen et al. (2011) conducted a fusion crust baked contact test (Nagata, 1979b; Weiss et al., 2010) on AMNH5056 and showed that the fusion crust, which was melted during atmospheric entry, carries magnetization distinct from that in samples taken ≥1 mm in the interior. This systematic change in magnetization direction and intensity indicates that AMNH5056 escaped significant remagnetization after its arrival on Earth and that the interior magnetization is extraterrestrial in origin. Because AMNH5056 had been stored in the magnetically shielded room at the MIT Paleomagnetism Laboratory (DC field <150 nT) since the experiments in Carporzen et al. (2011), their demonstration of extraterrestrial magnetization in AMNH5056 applies to our samples extracted from this parent piece.

We used nonmagnetic dental tools to extract twenty-one chondrules and six matrix-rich samples from thin (0.5–1.0 mm) slices of Allende cut using a diamond wire saw. Because the Allende matrix is on average 2–4 times more magnetic per unit mass than typical chondrules and CAIs (Table S1; Emmerton et al., 2011; Nagata and Funaki, 1983), we carefully removed all visible traces of matrix material adhered to chondrules. When possible, we subsampled individual chondrules using either a diamond wire saw or dental tools. Seven of the twenty-one chondrules were partitioned into at least two mutually oriented pieces. All chondrule and matrix samples were mutually oriented to better than 5° accuracy. Samples were numbered before extraction, resulting in unused numbers among the successfully extracted and measured samples. We mounted all samples on GE 124 quartz disks with cyanoacrylate or non-magnetic silver paste (SPI Silver Paste Plus). All sample mounts and adhesive had moments less than $\sim 5 \times 10^{-12}$ Am^2, which is the effective noise level of our 2G SRM measurements.

Twelve chondrule samples from six distinct chondrules and four matrix-rich samples were subjected to stepwise thermal demagnetization in air up to the point when the magnetization direction became incoherent or the sample moment spontaneously increased due to alteration of magnetic phases, which occurred at ≤420 °C. Additionally, two matrix-rich samples and thirteen chondrule subsamples from eleven distinct chondrules were subjected to three-axis alternating field (AF) demagnetization up to 85 mT.