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Were chondrites magnetized by the early solar wind?

Rona Oran[a,*], Benjamin P. Weiss[a], Ofer Cohen[b]

[a] Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[b] Lowell Center for Space Science and Technology, University of Massachusetts, Lowell, MA 01854, USA

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A B S T R A C T

Chondritic meteorites have been traditionally thought to be samples of undifferentiated bodies that never experienced large-scale melting. This view has been challenged by the existence of post-accretional, unidirectional natural remanent magnetization (NRM) in CV carbonaceous chondrites. The relatively young inferred NRM age [∼10 million years (My) after solar system formation] and long duration of NRM acquisition (1–10^6 y) have been interpreted as evidence that the magnetizing field was that of a core dynamo within the CV parent body. This would imply that CV chondrites represent the primitive crust of a partially differentiated body. However, an alternative hypothesis is that the NRM was imparted by the early solar wind. Here we demonstrate that the solar wind scenario is unlikely due to three main factors: 1) the magnitude of the early solar wind magnetic field is estimated to be <0.1 μT in the terrestrial planet-forming region, 2) the resistivity of chondritic bodies limits field amplification due to pile-up of the solar wind to less than a factor of 3.5 times that of the instantaneous solar wind field, and 3) the solar wind field likely changed over timescales orders of magnitude shorter than the timescale of NRM acquisition. Using analytical arguments, numerical simulations and astronomical observations of the present-day solar wind and magnetic fields of young stars, we show that the maximum mean field the ancient solar wind could have imparted on an undifferentiated CV parent body is <3.5 nT, which is 3–4 and 3 orders of magnitude weaker than the paleointensities recorded by the CV chondrites Allende and Kaba, respectively. Therefore, the solar wind is highly unlikely to be the source of the NRM in CV chondrites. Nevertheless, future high sensitivity paleomagnetic studies of rapidly-cooled meteorites with high magnetic recording fidelity could potentially trace the evolution of the solar wind field in time.

1. Introduction

The accretional textures of chondritic meteorites indicate they did not undergo planetary melting processes. This has been traditionally interpreted to mean that their parent bodies did not experience endogenic melting in their interiors, and that large-scale differentiation and core formation did not take place (Weiss and Elkins-Tanton, 2013). Nevertheless, it has long been recognized that the Allende meteorite, a CV carbonaceous chondrite, contains intense NRM that is unidirectional across scales of at least ∼10 cm and is a record of an ancient field of ∼30–100 μT. This observation, reproduced by five separate laboratories over nearly five decades (see references in Carporzen et al., 2011, plus a subsequent study by Muxworthy et al., 2017), indicates that the CV parent body was cooled or aqueously altered in an ancient magnetic field after accretion.

Initially, the magnetizing field was assumed to be the field of the solar nebula (Nagata, 1979). However, the inferred formation age of Allende's magnetization apparently postdates the lifetime of the solar nebula: the NRM was dated by I-Xe thermochronometry to 9–11 My after the formation of calcium aluminum-rich inclusions (CAIs), while the nebula dispersed by ∼4 My after CAI formation (Wang et al., 2017; Weiss et al., 2017), indicating that the magnetizing field was unlikely to be nebular in origin (here we take the time of solar system formation just after the collapse of the parent molecular cloud to be the time of CAI formation at 4567.3 ± 0.16 My ago; Connelly et al., 2012). Unidirectional NRM formed after ∼4 My has also been identified in the CV chondrites ALH 84028 and ALH 85006 (Klein et al., 2014) and post-accretional NRM has also been observed in the CV chondrite Kaba (Gattacceca et al., 2016). Muxworthy et al. (2017) proposed that Allende recorded a uniform thermoremanent magnetization nearly instantaneously due to heating by impacts (although see Scheinberg et al., 2015, for an alternative view). They interpreted the NRM to be a record of a ∼6 μT paleofield whose source is either a transient impact-generated field or a nebular field dated prior to ∼4 My after CAI formation.

* Corresponding author.
E-mail address: roran@mit.edu (R. Oran).

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These results have motivated the proposal that the magnetizing field was that of a core dynamo which, unlike the solar nebular field, could have persisted for hundreds of My (Carporzen et al., 2011; Elkins-Tanton et al., 2011; Weiss and Elkins-Tanton, 2013). This picture was recently supported by Shah et al. (2017), who suggested that the CV chondrite Vigarano recorded a uniform field post-accretionally, with a mean strength of ∼4 μT. They proposed that the magnetization could be shock remanent magnetization acquired in the presence of a core dynamo. A core dynamo field implies that the CV parent body was partially differentiated and had a metallic core overlain by a melted silicate mantle and relic chondritic crust. Such a view is at odds with the traditional view that chondrite parent bodies did not experience large-scale melting and were undifferentiated. Nevertheless, unidirectional, postaccretional magnetization has subsequently been identified in CM carbonaceous chondrites (Cournède et al., 2015) and H chondrites (Bryson et al., 2016) (Table S1), hinting at the possibility that partially differentiated chondrite parent bodies may have been common in the early solar system.

1.1. The hypothesis of asteroid magnetization by the solar wind

The core dynamo proposal for chondrite paleomagnetism has been recently challenged by an alternative hypothesis: that chondrites were magnetized by the solar wind (Tarduno et al., 2017). This proposal is surprising because the solar wind today certainly could not produce chondrite magnetization due to the fact that its present-day magnetic field is typically 2–7 nT at Earth's orbit, which is 3 to 4 orders of magnitude lower than the paleointensities for CV chondrites (Table S1). To achieve the required field intensity, two effects were proposed. First, it was suggested that the early solar wind magnetic field was likely more intense than that of today. Second, it was suggested that when the wind encounters the chondrite body, it piles up against it to form a region of amplified field. Tarduno et al. (2017) hypothesized that this amplified field would explain CV paleomagnetism.

1.2. Challenges associated with the solar wind magnetization hypothesis

There are three major difficulties that the solar wind magnetization hypothesis must overcome. First, the solar wind field at ∼10 My after solar system formation is not well known. There are no direct measurements of the early solar wind, and winds of Sun-like young stellar objects (YSOs) are difficult to detect spectroscopically due to their low emission (Wood et al., 2015).

Second, amplification of the solar wind field by the body would occur only if the body causes the wind to slow down and pile up against it. Pile-up regions have been found around two kinds of planetary bodies: magnetized planets, such as Earth, Mercury, Jupiter, and Saturn (whose magnetospheres can deflect the wind) and non-magnetized bodies that have ionospheres, such as Venus and comets (which can exert a gas pressure on the wind and support an induced magnetosphere) (Kivelson and Russell, 1995). In contrast, non-magnetized and airless bodies with largely nonconductive, silicate interiors lack either mechanism for slowing down the wind (e.g., the Moon; Kivelson and Russell, 1995). Given that the solar wind hypothesis for CV chondrite paleomagnetism considers a small, airless, undifferentiated body, a pileup could only occur for an exceptionally high wind speed and exceptionally high electrical conductivity of the body's interior (Section 4).

A third factor is the temporal variability of the wind. The bulk paleointensities of most chondrites (Table S1) are a record of the vector mean field magnitude recorded over periods ranging from years to millions of years (Section 2). On the other hand, the solar wind varies on a wide range of timescales. Apart from turbulent variations, the magnetic field exhibits large-scale semi-periodic reversals in direction over timescales of days to years (Section 7). It is crucial to consider the mean field experienced by an orbiting planetary object and not just the instantaneous values.

1.3. Goals

We test the solar wind magnetization hypothesis in four stages:

I. We estimate the properties of the Sun and its surface magnetic field at the time Allende's NRM was acquired (∼10 My after solar system formation) using observations of solar analogs and constraints from the meteoritic record (Sections 2 and 3).
II. We adopt a coronal model of a young solar-like star (Cohen et al., 2010) as a proxy for the Sun at 10 My and derive a range of solar wind conditions at 2.5 AU from the Sun that could have existed at that time (Section 3).
III. The predicted solar wind properties are used as input to a suite of magnetohydrodynamic (MHD) simulations of the interaction of the wind with a hypothetical undifferentiated chondrite parent body including magnetic field diffusion inside the body. We identify the most favorable case for field amplification by the body. In the Supplementary Material, we show that the MHD approximation is appropriate in this regime due to the large magnetic field of the ancient solar wind. To our knowledge, these are the first simulations of the interaction of the wind with a non-magnetized, airless body having a chondritic resistivity, and thus of an interaction dominated by magnetic diffusion in the interior of the body (Section 6).
IV. We perform a statistical analysis of solar wind variability to estimate the mean field induced on the body over the timescales of magnetization (Section 7).

This paper is organized as follows. In Section 2, we summarize the paleomagnetic observations to be explained. In Section 3, we estimate the solar wind field strength at 10 My after solar system formation. In Section 4, we present an analytic description of the role of resistivity in solar wind pileup. In Section 5, we describe the numerical model of the wind flow around the parent body. In Sections 6 and 7, we present the results of the simulations and discuss the role of solar wind variability. In Section 8, we present our conclusions, showing that moderate field amplification at the body and the variability of the solar wind imply that undifferentiated chondritic bodies cannot have been significantly magnetized by the solar wind and that other magnetic field sources are more plausible.

2. Timeline of meteorite magnetization

A key constraint for identifying the origin of the field that magnetized chondrites is the timing of NRM acquisition (Fig. 1 and Tables S1 and S2). The first large-scale magnetic field in the solar system was likely that of the ionized nebula, which was in turn probably inherited from the parent molecular cloud (Desch and Mouschovias, 2001). Records of a 5–∼50 μT nebular field in our solar system at 1–3 My after CAI formation have been identified using paleomagnetic measurements of chondrules from the LL chondrite Semarkona (Fu et al., 2014). Disk magnetic fields may also have been observed in other systems of similar age (Stephens et al., 2014), although the interpretation of the observations as an evidence of a magnetic field are not conclusive (Kataoka et al., 2015).

Furthermore, recent paleomagnetic analyses of volcanic angrites (Wang et al., 2017) and the ungrouped achondrite NWA 7325 (Weiss et al., 2017) show that the magnetic field was indistinguishable from zero (<0.6 μT and <1.7 μT, respectively) by 3.8 and 4.2 My after CAI formation, respectively. As discussed in