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 (~10⁷ 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 of 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.

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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 aequously 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 ³⁹Xe 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 45673 ± 0.16 My ago; Connelly et al., 2012). Unidirectional NRM formed after ~4 My has also been identified in the CV chondrites ALH 84002 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-accretationally, 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
3. Predicting the solar wind field at the time of Allende magnetization

The solar wind is the extension of the Sun's corona into interplanetary space. This highly conducting plasma flows radially outward, stretching the solar magnetic field and creating the interplanetary magnetic field (IMF). A key factor in testing whether the wind can be responsible for chondrite magnetization is estimating the strength of the IMF at the inferred region of formation of the CV parent body (~2.5 AU or perhaps further; see, for example, Budde et al., 2016) at the time of magnetization (~10 Ma). Direct observations of the speed, density, and magnetic field of stellar winds from other stars at these distances are not available, because stellar winds' low densities do not result in sufficiently strong emission (Wood et al., 2015). On the other hand, the Sun's present-day wind is readily available for direct and continuous observations. Such observations have led to the development of robust theoretical models that can be adapted to the young Sun.

3.1. Our Sun at 10 My

At 10 My after solar system formation, the Sun is expected to be a pre-main sequence T Tauri star, moving along the Hayashi track in the Hertzsprung–Russell diagram toward the main sequence (Kippenhahn et al., 2012). At the start of the Hayashi track, stars are classified as classical T Tauri stars (CTTS), meaning they are surrounded by an accretion disk and/or infalling cloud. Because the meteoritic record shows that the Sun's disk was cleared by ~4 My after CAI formation (Section 2), the Sun had likely passed the CTTS stage by the time Allende acquired its NRM (~10 My). On the other hand, the Sun is expected to become a main sequence star only at ~120 My (Kippenhahn et al., 2012). We can therefore conclude that at the time Allende acquired its NRM, the Sun was likely a weak-line T Tauri star (wTTS) (i.e., a T Tauri star without a disk) and had not yet commenced hydrogen burning.

The identification of the Sun at 10 My as a wTTS has important implications for the type of wind it would have generated. In the CTTS stage, the wind is composed of polar jets, disk winds, and inflow of accreted matter onto the star (Wood et al., 2015). In the absence of the disk, a wTTS will generate a wind similar to the present-day solar wind (i.e., an omnidirectional flow initiated by the thermal pressure gradient between the corona and interplanetary space). The observed properties of solar-like wTTSs at 10 My are listed in Table S3. Of special interest is the average (over the stellar surface) magnetic field of 10–20 mT, which is about ~100 times larger than the Sun's mean surface field today.

3.2. Analytic description of the IMF

The simplest analytical description of the solar wind is due to Parker (1958), describing a radial transonic flow from a hot corona into interplanetary space. The interplanetary magnetic field, \( \mathbf{B}_{IMF} \), at a heliocentric distance, \( r \), has a spiral geometry given by:

\[
\mathbf{B}_{IMF} = B_{r} \left( \frac{R_{s}}{r} \right)^{2/3} \mathbf{r} - B_{s} \left( \frac{R_{s}}{r} \right)^{2} \left( r - R_{s} \right) \hat{\phi} \sin \theta \frac{u_{SW}}{u_{r}} \mathbf{u}_{s} \cos \phi
\]

(1)

where \( \mathbf{r} \) and \( \hat{\phi} \) are unit vectors in the radial and azimuthal directions, respectively, \( \theta \) is the polar angle (measured from the polar rotation axis), \( \Omega_{c} \) is the radial rotation speed of the Sun, \( u_{r} \) is the terminal wind speed (the asymptotic speed at large distances from the Sun), and \( B_{r} \) and \( B_{s} \) are the reference field magnitude and distance, respectively. The distance \( R_{s} \) is defined as the innermost boundary of the Parker solution (also called the source surface), where the field lines are purely radial by construction. Beyond that distance, all field lines are open and become part of the solar wind. See Table 1 for the symbols used in this manuscript.

The assumptions underlying the Parker derivation should hold for a wTTS of age ~10 My because the thermal pressure in T Tauri coronae is sufficient for accelerating the wind to supersonic speeds within distances of a few stellar radii (Kiguchi et al., 1998).

3.3. Uncertainties in analytically estimating the IMF of the young Sun

Although the Parker solution is widely used to approximate the present-day IMF, it is not immediately clear how to adjust the parameters \( u_{r}, R_{s}, \) and \( B_{s} \) to represent the IMF at 10 My: they cannot be directly observed, they are interdependent, and they also depend on the rotation rate, \( \Omega_{c} \), which is much faster for the young Sun (see Table S3). In particular, \( R_{s} \) indirectly controls how much of the coronal magnetic field is open and contributes to the IMF (see Section S4 in the Supplementary Material). To overcome these difficulties, we use an MHD model of the corona of a young star (Cohen et al., 2010) that calculates the velocity and magnetic field self-consistently in a rotating frame. As described below, the
model is driven by the observed surface magnetic field of a young solar analog and produces a realistic three-dimensional magnetic field topology.

3.4. An MHD model of a young stellar analog AB Doradus

Recent years have seen the development of Zeeman–Doppler Imaging (ZDI) of stellar surfaces (Donati et al., 2006) that provide global maps of surface magnetic fields. These can be combined with the large body of observational and theoretical knowledge about our own solar wind to make predictions about the Sun’s early wind. Specifically, several MHD models have been developed that reproduce the large-scale three-dimensional structure of the wind and IMF at 1 AU using surface magnetic field maps as input (most recently in Oran et al., 2013; Meng et al., 2015; Merkin et al., 2016). We use an MHD model of the corona of AB Doradus A (referred to as AB Dor hereafter), a K0 dwarf evolving onto the main sequence (Cohen et al., 2010). The observed stellar properties and those used for the simulation are summarized in Table S3. The model is driven by a ZDI map of AB Dor obtained in December 2007 (see Cohen et al., 2010 for details) (Figs. 2A, B). Although not a G star like the Sun, AB Dor’s simulated wind should reasonably approximate that of the Sun at 10 My for the following reasons:

- Both K and G dwarfs are not expected to generate radiatively-driven winds (Abbott, 1982). Instead, their winds, like that of the Sun, will be driven by thermal pressure and Alfvén waves (Belcher and Olbert, 1975).
- Given AB Dor’s mass and radius (Table S3), the gravitational acceleration at its surface would by similar to that of the Sun (∼1.1 \( g_\odot \)).
- Taking the average of the unsigned flux over the ZDI map of AB Dor yields < \( B > = 22.6 \) mT. This is consistent with the typical 10–20 mT observed surface magnetic fields of 10 My old wTTSs (Table S3).

The model of AB Dor is implemented within BATS-R-US (Tóth et al., 2012), a three-dimensional highly-parallelized MHD code. Cohen et al. (2010) include three different simulations, named Cases A, B, and C. We use the results from Case A (Fig. 2C) because it is most consistent with a 10 My solar-like star as discussed in Section S5.1 in the Supplementary Material. The model solves the ideal MHD equations and the contribution of Alfvén waves to the wind acceleration is approximated by a variable polytropic index. Although a more consistent treatment of Alfvén waves was incorporated in BATS-R-US in later wind models that were validated at 1 AU and beyond (Oran et al., 2013; Meng et al., 2015; Jin et al., 2011), the polytropic model is also adapted to stellar coronae and was shown to well reproduce the IMF structure of the present-day wind over the entire solar cycle (Cohen et al., 2010).

3.5. Deriving the IMF of AB Dor at 2.5 AU

The AB Dor simulation domain extends up to 45 \( R_\odot \) (∼0.2 AU). Fig. 3 shows the radial velocity and magnetic field in the \( x-y \) (equatorial) and the \( x-z \) planes. The rotation axis of the star is along the \( z \)-axis. The equatorial plots (Figs. 3A, C) reveal a spiral structure created by solar rotation like that described by equation (1). To estimate the IMF magnitude at 2.5 AU, we need to extrapolate the solution from the edge of the computational domain to 2.5 AU using equation (1). If we consider the equatorial plane (\( \theta = 0^\circ \)), then the radial component scales as \( 1/r^2 \) while the azimuthal scales as \( 1/r \). Using \( B(r = 45 R_\odot) = 1.2 \) \( \mu T \), and assuming the azimuthal field dominates, the field at 2.5 AU is estimated to be \( \sim 90 \) \( nT \). For simplicity, we take the IMF to be 100 \( nT \) as input to the MHD simulations of Section 5, which should be considered an upper limit (see Section S5.1 in the Supplementary Material).
4. Theory of solar wind interaction with a chondrite parent body

4.1. Governing equations

The large-scale dynamics of the solar wind can be described by the MHD equations. Here we focus on the magnetic induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{\eta}{\mu_0} \nabla^2 \mathbf{B},$$

(2)

where \( \mathbf{B} \) is the magnetic field vector, \( t \) is time, \( \mathbf{u} \) is the velocity, \( \eta \) is the electric resistivity of the body, and \( \mu_0 \) is the permeability of free space. The first term on the right hand side represents magnetic field convection with the plasma and the second term on the right hand side describes magnetic diffusion.

4.2. Analytical criteria for magnetic field pile-up

We consider a resistive body is embedded in the solar wind where the magnetic field is perpendicular to the flow direction. Far from the body, \( \eta \sim 0 \) and the diffusion term in equation (2) can be neglected. Inside the solid body, there is no flow (\( \mathbf{u} = 0 \)) and the convective term vanishes, leaving the field to diffuse inside the body. From dimensional analysis of equation (1), the convection time scale at which the field would flow past a body of size \( L \) with speed \( u \) is given by:

$$\tau_{\text{conv}} = \frac{L}{u},$$

(3)

while the diffusion time through the body is given by:

$$\tau_{\text{diff}} = \frac{\mu_0}{\eta} L^2.$$

(4)

When \( \tau_{\text{conv}} \ll \tau_{\text{diff}} \) (or when \( \eta \to 0 \)), the field around the body would lag behind the free flow, causing field lines to drape and pile-up. This regime describes a flow past an ideal conductor or a body with an ionosphere. A pile-up region was observed around Venus (Kallio et al., 1998), where the magnetic field is enhanced by a factor of 2.5–6.0 (depending on solar wind conditions), and around several comets (e.g., comet 1P/Halley; Israelevich and Ershkovich, 1994) where the magnetic field is enhanced by a factor 2–5.

When \( \tau_{\text{conv}} \gg \tau_{\text{diff}} \) (or when \( \eta \to \infty \)), the magnetic flux diffuses freely through the body. An example of such a body is the Moon, which acts as an ideal insulator. The diffusion time through the lunar crust is \( <0.05 \) s due to its high resistivity \( \sim 10^8 \Omega \text{m} \); Dyal et al. (1977)). This is much shorter than the \( \sim 5 \) s it takes the wind to flow past the Moon, and no pile-up is created.

It is important to note that a resistive crust can efficiently mask a conducting interior. For example, the lunar mantle is up to 7 orders of magnitude more conducting than the crust (Dyal et al., 1977), implying correspondingly higher diffusion times. Nevertheless, extensive in-situ observations (Zhang et al., 2014) show no detectable pile-up around the Moon. This is an important consequence of diffusion in three dimensions: the crust allows the magnetic field to diffuse around the conducting interior. This effect cannot be captured by two-dimensional simulations: in the absence of a third dimension, the body takes the form of an infinite cylinder such that incoming magnetic flux would continuously pile up in front of conducting layers. In three dimensions, on the other hand, the body constitutes a sphere and the field can slip around it to reach a steady state configuration. Whether or not inner conducting layers would impact the bulk flow of the wind depends on the specific resistivity profile. For the Moon, the upper layers are sufficiently resistive and the highly conducting core...
is sufficiently deep such that the conductive interior does not impact the bulk flow of the wind. Regardless of the specific details, all such simulations must be three dimensional unless the body is a perfect insulator and perfect absorber, in which case it does not constitute an obstacle to the flow.

4.3. Estimating the size and resistivity of a chondrite parent body

Although the exact sizes of chondrite parent bodies are not known, meteorite barometry measurements have observed that peak pressures did not exceed 1 kbar (Huss et al., 2006). Assuming hydrostatic equilibrium and a spherical body of uniform density, ρ₀, the central pressure, P₀, is related to the body’s radius, R, by:

\[ P_0 = \frac{2\pi}{3} G \rho_0^2 R^2, \]

where G is the gravitational constant. The minimal density for C-type asteroids larger than 200 km is 1800 kg m⁻³ (Carr, 2012). For a central pressure of P₀ = 1 kbar, this would give a maximal radius of R ~ 470 km. This is comparable to Ceres, the largest known asteroid, which has a mean radius of ∼476 km (Park et al., 2016).

The resistivity of the CV parent body should have varied with temperature. Assuming a crust at <300°C (the peak metamorphic temperatures for many CV chondrites; Cody et al., 2008) and an interior at 600°C (maximum peak metamorphic temperature estimated for CV chondrites; Nagashima et al., 2016) we obtain a resistivity profile that varies between 10⁶ and 10⁷ Ω m with radial distance based on temperature-dependent resistivity measurements of Allende presented in Duba and Boland (1984) [note that we selected the measurements done on Duba and Boland (1984)'s Allende sample while it was cooling]. We assume that the thickness of the outer layer of unheated crust is at 0.1–0.05 R, although smaller values are also possible (Sahijpal and Gupta, 2011).

4.4. Will there be a pile-up at a chondrite parent body?

The one-dimensional diffusion timescale through a slab of length 2 × 470 km with the Allende crustal resistivity is ∼10 s. However, diffusion in three dimensions may be up to 3 times faster (Crank, 1979), giving an expected diffusion time of 3–4 s. This is a factor ~2 higher than the convective timescale (∼1.3 s) for an estimated wind speed of 700 km s⁻¹ taken from the AB Dor simulation (Fig. 3). We conclude that the interaction of a chondrite parent body in the young solar wind constitutes an intermediate case between a Venus-like interaction and a Moon-like interaction, such that only a moderate level of pile-up is expected.

5. Allende in the solar wind: MHD model

5.1. Numerical model

We adapt the BATS-R-US code to solve the ideal MHD equations in regions occupied by the solar wind coupled to the magnetic diffusion equation inside the body. We show that the MHD approximation is justified when considering the IMF at 10 My in Section S1 of the Supplementary Material. The implementation is similar to the Jia et al. (2015) model of the interaction of Mercury’s magnetosphere with the solar wind, except that here we model a non-magnetized body that is directly exposed to the wind and lacks a highly conducting core (full details of the numerical implementation are given in Section S2.1 in the Supplementary Material). The body is modeled as a sphere of radius R = 470 km (Section 4.3) with a radially varying resistivity: η = 10⁷ Ω m extending from the center to the base of an outer layer starting at r = r_magnet. For r > r_magnet, η falls logarithmically to 10⁵ Ω m at r = R (see Fig. S2). The body is centered at position (0, 0, 0) and the solar wind flows in the −x direction. The grid is extended in that direction to contain the wake with dimensions: x = [−9, 3] R, y = [−4.2, 4.2] R, z = [−4.2, 4.2] R. We design a non-uniform spherical grid containing >600,000 cells, with higher resolution in the crust and in the center of the wake where reconnection is expected to occur (see Fig. S2 and Section S2.2 in the Supplementary Material).

The initial condition is that the wind and IMF are both uniform across the body and the magnetic field inside the body is equal to the IMF. Each simulation is run until the pile-up region becomes quasi-static, ensuring the simulation time is longer than the diffusion through the crust (∼4 s) and that the solar wind had sufficient time to pass through the domain several times. The typical simulation time ranged between 19 to 24 s, requiring 6–10 hrs on 1200 processors on NASA’s Pleiades supercomputer. We note that simulating a true steady state would be too costly (the diffusion time through the conducting layers is 300–1000 s and the time step is ∼0.001 s). However, we confirmed that the enhanced field is near-steady by integrating the magnetic field over the entire domain and verifying that the total field magnitude changes by less than <0.2% over time. In any case, the IMF would most likely reverse direction on a scale comparable to an hour or less (Section 7.1) such that the induction process would restart with a different IMF vector, meaning that fully modeling diffusion into the center is unnecessary.

We explore the parameter space with the aim of identifying the solar wind and field configurations that are most favorable for the solar wind magnetization hypothesis. We vary the solar wind conditions (speed, density, and magnetic field direction), as well as the body’s internal resistivity profile. The parameter ranges and their justification are summarized in Table S4 and Section S5 of the Supplementary Material.

6. Results

6.1. IMF perpendicular to the wind flow (Cases I and II)

Case I: Mean ecliptic wind (baseline case)

The most likely wind parameters at 2.5 AU in the ecliptic plane for the Sun at 10 My were calculated in Section S5 of the Supplementary Material, using the AB Dor simulations as input. These give a speed of ∼700 km s⁻¹, a density of 35 particles cm⁻³, and a temperature of 50,000 K (see Table S4). We consider the case where the IMF is perpendicular to the wind flow, pointing in the +z direction, and the wind flows in the −x direction. The body’s crust is assumed to be 0.1 R thick. The radial resistivity profile is shown in Fig. S2B. The results are shown in Fig. 4A, which depicts the magnetic field and field lines in a plane containing the wind flow and the IMF (the x−z plane) and the plasma density in the x−y plane. In this case, the magnetic field is enhanced in the upwind side of the body with a maximum field of ∼360 nT.

Fig. 5 shows the magnetic field both inside and around the asteroid for the Case I simulation. Selected field lines are also shown. It can be seen that the enhanced magnetic field in the pile-up region is diffusing inside the body around the more conducting interior and emerging in the wake.

Case II: Fast stream, thin crust (most favorable case)

Some wind streams found in the AB Dor simulations are much faster than the typical wind in the ecliptic plane. One such stream can be seen in Fig. 3B, located in the northern hemisphere. Although it does not reach the ecliptic plane (and hence planetary bodies) in this specific magnetic topology, such a stream may well be present in the ecliptic plane at another part of the stellar activity cycle. To model such an event, we set the speed to 1100 km s⁻¹ while reducing the initial density to 14 particles cm⁻³. The lower density is due to the fact that far from the Sun, the wind momentum flux is almost uniform and independent of wind speed.
Fig. 4. Simulated magnetic field and density around the asteroid. (A, B, C) Results from Cases I, II, and III, respectively. The wind is flowing from left to right along the −x direction. The red–blue color contours on the meridional (x-z) plane depict magnetic field magnitude. The grayscale contour on the equatorial (x-y) plane depicts the number density. The curves show magnetic field lines and are colored by the velocity in the x direction, demonstrating how the plasma slows down in front of the body and is accelerated down-wind from the reconnection x-point. Note the magnetic field color scale in (C) is narrower than for the other panels because in this configuration (Case III), there is only negligible distortion to the background field due to the body. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

Fig. 5. Magnetic field diffusion in three dimensions, taken from the simulation of Case I at 26 s. The semi-transparent spherical surface marks the surface of the body. Color contours of the magnetic field magnitude are displayed on two perpendicular planes (x−y and x−z). Gray circles mark body-centric radial distances projected on the two planes. The spacings between circles is 1 R. Number labels mark the distance in units of R. The solar wind flows from left to right along the −x axis. Amplification above the initial background field (100 nT) is seen in the upwind side and in the outer shells inside the body, with a maximal field of ∼360 nT. A decrease in field magnitude appears near the center of the body (white and blue regions). The region in blue along the wake axis is a region of field lines disconnected from the wind. The solid curves show selected magnetic field lines. The three lines from the left are solar wind field lines that become increasingly distorted by the body. The four field lines to the right all are passing through the body, demonstrating how the field diffuses around the more conducting interior, and magnetic flux is transported toward the wake region. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

(see Supplementary Material Section S5.4). To maximize the level of pile-up the temperature is set to 500,000 K (maximum thermal pressure in Table S4) and the resistivity profile is changed such that the most resistive crust is now only 5% of the entire body. The modified radial resistivity profile is shown in Fig. S2C. In this case, the maximum magnetic field is again ∼360 nT (Fig. 4B). The pile-ups in Cases I and II are similar, demonstrating that the field enhancement is determined by the conversion of kinetic energy into magnetic energy as the wind decelerates. This demonstrates that for a given resistivity profile, the wind speed determines whether a body would be an obstacle, but the wind speed does not uniquely control the level of pile-up due to coupled changes in wind density.

6.2. The role of magnetic diffusion through the body and reconnection at the wake

The transfer of magnetic flux through the body into the wake is important because plasmas with anti-parallel fields arrive at the wake axis and create a reconnection region. To examine this, we extracted snapshots at 4 times from the Case II simulation, shown in Fig. 6. The dashed field line in each snapshot marks the field line that passes through the body and reaches the x-point but does not reconnect. More field lines become disconnected from the wind (red curves) as time progresses. The field inside the body diffuses along the outer shell fast, but takes longer to diffuse inwards into the more conducting center. The distance (along the x axis) of the reconnection x-point (marked by the blue vertical line) moves down the wake with time, but eventually settles into an almost fixed position. The diffusion through the body and removal of flux in the wake x-point allows the system to reach a quasi steady state. Although the solar wind brings in more flux, the total magnetic field (integrated over the domain) remains close to constant (less than 0.2% change with time).
6.3. IMF parallel to the wind velocity (Case III)

We repeat the same parameters as in Case I, except changing the magnetic field to lie in the $x$ direction. The results (Fig. 4C) show that there is no detectable field enhancement in the upper side of the body. This behavior is explained by equation (2): the amount of magnetic flux brought in by the wind is proportional to $u \times B$ and thus in this configuration there is no new flux to be piled-up.

Fig. 6. Magnetic field magnitude and magnetic field lines around the asteroid, extracted at four times during the Case II simulation. The simulation time is marked on the top left corner of each panel. Color contours show the magnetic field in the $x$–$z$ plane (the plane containing the IMF and the incoming wind flow direction). The green circle outlines the circumference of the body. Solid black curves show the magnetic field lines that are connected to the wind far from the body. The first two field lines from the left in each panel are incoming with the solar wind and show the gradual distortion due to the presence of the body. Other field lines diffuse into the resistive body, and their free edges are dragged by the flow in the $-x$ direction, with each field line reaching closer to the wake axis and the reconnection $x$-point. The dashed black curve marks the dragged field line that reaches close to the $x$-point, but does not reconnect. The location of the $x$-point, where opposite field polarities converge (blue region) changes with time. The vertical blue line marks its location down the wake axis. Downwind from the $x$-point, reconnected field lines are accelerated outward and rejoin the wind. The field lines within the dashed field lines (solid red) are completely disconnected from wind and are partially inside the body and partially in the wake. In the first few snapshots, they have a significant $z$ component, inherited from the initial background field inside the body. As time progresses, the field diffuses in the outer layers and the magnetic field lines become rounded. The pace at which diffusion progresses around and into the center is demonstrated by the shaded color region inside the body, which is the 100 nT contour (i.e., the initial field level). This region slowly engulfs the center and becomes more rounded and enters deeper into the body. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

6.4. Summary

In contrast to the present-day Moon, a warm chondritic body is capable of distorting the upward field because its resistivity is 3 orders of magnitude smaller than that of the lunar crust. However, even the case of strongest possible interaction produces a field enhancement of only a factor of 3–6. By comparison, Venus generates a factor of ~6 enhancement under the much lower ram pressure of the present-day wind (Kallio et al., 1998) due to its highly conducting ionosphere. We tested the robustness of the above conclusion by varying the radius of the body (250 km and 340 km). The results were qualitatively the same, but with lower compression factors, as expected from our discussion of parameter space (Supplementary Material and Table S4). For the present-day wind conditions (speed of 400 km s$^{-1}$ and IMF of 5 nT), the asteroid only caused a factor of 1.5 enhancement.

Another analogous body is Ceres, which is of similar size to the CV parent body assumed here. Hybrid simulations of Ceres in the present-day wind estimate the field enhancement at this body to be a factor 2 (Lindkvist et al., 2017). Ceres is thought to be more resistive than the CV parent body assumed here and it is therefore expected that the enhancement would be lower. Although there are some important differences between Ceres and the CV body, namely that Ceres emits vapor and its interaction is somewhat analogous to a comet, the simulations of Lindkvist et al. (2017) show that the field values obtained here are broadly consistent with those of other bodies.

7. Mean pile-up field over the magnetization timescales

7.1. Systematic periodicities in the IMF

A critical quantity relevant to parent body magnetization by the solar wind is the mean field experienced by the body over the NRM acquisition timescale. The present-day IMF is highly directionally variable and turbulent (Fig. S3). In particular, there are two important large-scale periodicities that will affect the magnetization of a planetary body:

- IMF sectors: The field lines making up the IMF have alternating polarities depending on where the lines originate on the Sun’s surface. A current sheet separates regions of opposite polarity and rotates with the Sun (presently with a period of
The upper limit for the solar wind ram pressure at 2.5 AU (Section 3.4 and Supplementary Material).

- Largest body and thinnest crust (Section 4.3).
- Most favorable configuration of the IMF angle with respect to the flow (Section 6).
- Considering temporal averaging due to observed IMF reversals, that were more frequent at 10 My (Section 7.1).

Under the well-established and systematic periodicities on the IMF, the average IMF component over the solar cycle is a factor of 100 less than the instantaneous field. Thus, the mean field recorded by parent bodies (given the 1–1 My acquisition times of meteorite NRM; Section 2) should be at least a factor of 100 lower, or just <3.5 nT. The mean enhanced field is therefore at least $10^3$ and $10^4$ too small to explain the magnetization of Kaba and Allende, respectively (Table S2). Even if Allende’s paleointensity was only several $\sim 6 \mu T$ instead of $\sim 60 \mu T$ (as recently suggested by Muxworthy et al., 2017), the instantaneous and mean solar wind fields would still be $\sim 20$ and $\sim 2000$ times too weak to account for Allende’s NRM.

8. Conclusions

- We presented the first numerical simulations of the interaction of the solar wind with a resistive, non-magnetized, and airless asteroid for which the field evolution is controlled by magnetic diffusion in the interior. We showed that when such a body has the electrical resistivity of a hot undifferentiated chondrite, it does not constitute a significant obstacle to the wind flow.
- The field is compressed only up to a factor of $\sim 3.6$ at the body under the most favorable instantaneous conditions, leading to an instantaneous field of only $\lesssim 360$ nT, which is 10 and 100 times below most paleointensity estimates for Kaba and Allende, respectively.
- Our analysis of IMF temporal variations shows that even the optimal configuration would be short-lived (persisting for a timescale of an hour) and may be rapidly followed by an IMF in the opposite direction. We argued from analytical timescale analysis that changes in the IMF would wash over the entire body over these timescales.
- Statistical analysis of the present-day solar wind shows the IMF averaged over timescales of years is a 100 times weaker than instantaneous values. Because the existence of IMF sectors and solar activity are well established for T Tauri stars, it is reasonable to assume similar periodicities existed in the young solar wind. This implies the mean amplified field induced in the body would be at least $10^3–10^4$ times below the paleointensities typically estimated for Kaba and Allende, respectively.
- Eliminating the solar wind as a source of magnetization supports the alternative hypothesis that the paleomagnetic record is a record of a core dynamo. Despite being primitive materials, chondrites may be samples of a partially differentiated body (Weiss and Elkins-Tanton, 2013).

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~25 days). This structure is shown in Fig. 7 for the AB Dor simulation.
- The solar cycle: Solar activity and the solar magnetic field vary on a 22-y solar cycle. At solar minimum the magnetic field is largely dipolar and the dipole axis flips between two consecutive minima (i.e., every 11 y).

The effects of these periodicities can be examined quantitatively using in-situ solar wind measurements taken near Earth’s orbit. Fig. 8 shows the distribution of hourly averages of IMF components over 22 y (1995–2007). The components in the x, y, and z directions are measured in the Geostationary-Ecliptic (GSE) system (see Section S3 in the Supplementary Material). The distribution of each component is almost perfectly symmetric, with the mean of the x, y, and z components being $−0.02$, $0.08$, and $−0.01$ nT, respectively (about a factor of 100 less than the instantaneous magnitude of 2–10 nT). Detailed analysis (Supplementary Material and Fig. S4) shows that this effect is already present when averaging over a solar rotation (~25 days), since the Earth spends similar amounts of time in opposite-polarity regions due to the rotating IMF sectors.

Furthermore, Case III demonstrated that there is little to no enhancement when the field is parallel to the velocity. Since the IMF may take many different directions, the ideal configuration will only occur for part of the time (Fig. S5).

We expect the long-term behavior of the IMF at 10 My to be similar except that the Sun at 10 My would have a shorter rotation period of 0.5–2 days (Table S3), meaning field reversals due to IMF sectors are expected to occur several times a day. The faster rotation also implies a shorter solar cycle of 2–5 y or less (Metcalfe et al., 2016).

7.2. An upper limit of the mean pile-up field

The field experienced by the chondrite parent body would be at the most 360 nT for short periods of time (~hours). This should be considered as an extreme upper limit, since it was obtained by setting all free parameters to values associated with the most favorable case:
- The highest estimate of the young Sun’s surface field from astronomical observations of similarly aged stars (Section 3.1).
- The upper limit for the IMF at 2.5 AU, based on self-consistent modeling of the wind driven by an observed ZDI map of a pre-main sequence star (Section 3.4 and Supplementary Material).

![Fig. 8. Temporal variation of the solar wind. Shown is a histogram of hourly averages of IMF vector components measured in the solar wind at 1 AU, over a 22 y period from February 1995 to February 2017, equivalent to a full solar cycle. The blue, orange and yellow data denote the x, y, and z field components, respectively, in the GSE system (Supplementary Material). Data taken from OMNI, a cross-spacecraft calibrated dataset of in-situ solar wind measurements at 1 AU (King and Patashnik, 2006), available through NASA’s CDAWeb. The magnetic field in each hour interval was averaged and averages were binned in 0.5 nT intervals. (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)](image-url)
Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2018.02.013.

References


