Magnetic meteorites and the early solar system

James F J Bryson, Francis Nimmo and **Richard J Harrison** describe what meteorite magnetism can tell us about dynamo activity early in the history of the solar system.

1 Ancient and present-day magnetic activity on rocky bodies in the solar system

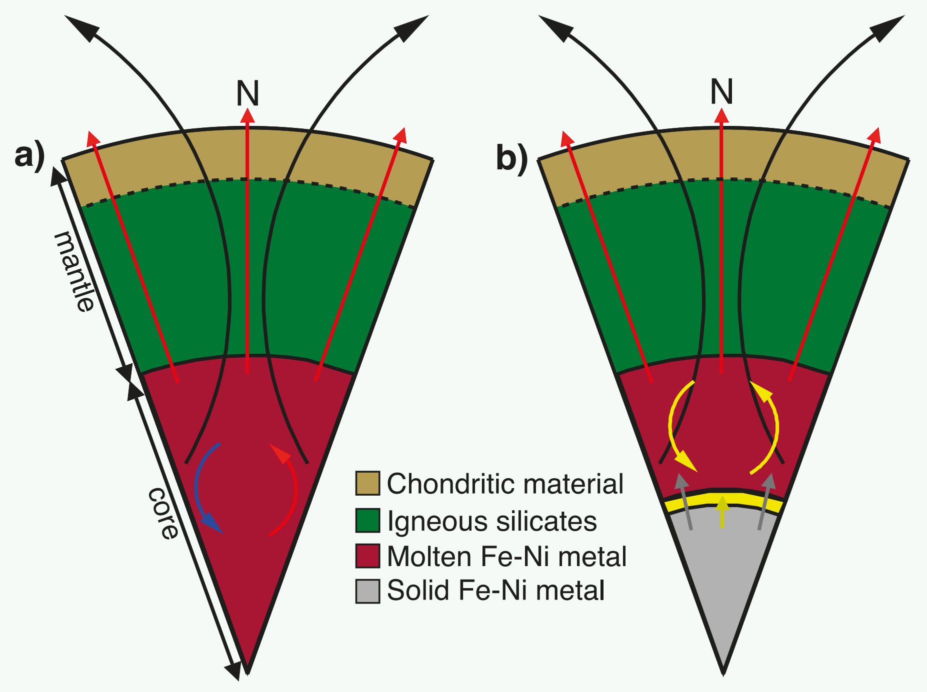
planetary body	radius (km)	time (Myr ago)	approx. field intensity (μT)	comment
Earth	6371	0, 500, 3500	50, 50, 30	evidence of continuous field from ~3500 Myr ago to present day
Venus	6050	0	0	unknown ancient field
Mars	3390	0, 4000	0, 50	field likely to be present prior to 4000 Myr ago
Ganymede	2630	0	>0.7	unknown ancient field
Mercury	2440	0	~0.3	field generated at present day
Moon	1740	0, 3500, 4000	0, 20, 20–100	very early field uncertain, evidence of recent (1000 Myr ago) weak fields
Vesta	263	0, 3690	0, >2	field recorded by meteorites thought to be crustal remanence imparted by earlier dynamo
pallasite parent body	~200	4500	100	field intensity could have been altered by mantle-hosted metal

Today, the Earth generates a magnetic field through convection of the electrically conducting molten iron in its outer core. Core convection is governed by the thermal and chemical processes that operate deep within our planet; thus measurements of the intensity and direction of the magnetic field can provide insights into the thermochemical state of the Earth's interior. Crustal rocks can also record and preserve a memory of the field they experienced as they were forming. Paleomagnetic measurements can therefore provide records of ancient magnetic activity and, by extension, the internal conditions of our planet in the past (Tarduno *et al.* 2014). A combination of paleomagnetic and present-day magnetic measurements therefore allow us to study the long-term and large-scale evolution of our planet over billions of years; this method could also potentially allow us to predict how it may behave in the future.

Beyond the Earth, planetary magnetic fields on other terrestrial bodies (inner solar system planets, moons and asteroids) can also be measured relatively easily from orbital and fly-by satellite observations (table 1). For example, the MESSENGER mission has recently reached the end of its extended mission to measure, among other properties, Mercury's magnetic field and crustal remanence (Anderson *et al.* 2011). These magnetic observations are being used to reconstruct the present day and past behaviour of Mercury's interior and, along with other measurements made by MESSENGER, we are starting to understand the processes driving this curious body.

Another planet of interest is Venus, which, despite similarities in size and composition to the Earth, does not generate a magnetic field at the present day. However, unlike the Earth, Venus's surface is not tectonically active, which may inhibit the heat flux through its mantle. In this scenario, Venus's mantle temperature is expected to be increasing at present, which would inhibit core convection and hence the generation of a planetary magnetic field (Nimmo 2002). This deduction is a good example of how magnetic activity (or the lack of it in this case) can be tied to the large-scale thermal and compositional conditions of a planet; it is this aspect of planetary magnetic fields that make them attractive in planetary sciences.

A different class of planetary bodies of interest from a magnetic perspective are asteroids (rocky bodies with radii <~500 km). Asteroids display a range of sizes, surface compositions and



1 Schematic of dynamo generation within a partially differentiated asteroid. (a) Thermally driven convection (red and blue curved arrows) can generate magnetic fields (curved black lines) for a range of heat flux values out of the core (straight red lines). (b) Compositionally driven convection (curved yellow arrows) can generate magnetic fields via the rejection of light elements from the advancing solid (straight yellow arrow) that migrate upwards under gravity. This process depends on the growth of the solid (straight grey arrows), which in turn is dictated by the heat flux out of the core.

morphologies and, because of their relatively small size, they are cold and inactive at the present day. For example, no asteroid has been observed to be generating a magnetic field. However, this may not have been the case during the early solar system, when these bodies were hot. Most meteorites are samples of asteroids and display widely varying compositions and textures, containing some of the oldest structures in the solar system. Paleomagnetic measurements of meteorites can therefore provide insight into the internal processes that acted within asteroids, and allow us to peer back in time to the conditions present as the solar system was forming (Weiss *et al.* 2010). Crucially, because asteroids cooled much faster than the Earth, meteorites could contain magnetic information from the entire active lifespan of a planetary body, so could be used to study processes that are yet to occur on our own planet (e.g. complete core solidification). Indeed, paleomagnetic measurements of meteorites have been used to study a wide range of phenomena such as planetary collisions, the collapse of the protoplanetary dust cloud, and how asteroids evolved to the inactive bodies we know today.

In this review we focus on paleomagnetic measurements of meteorites, in particular what these experiments can tell us about the thermochemical evolution of their parent asteroids. The results of these measurements have important implications for the structure and formation of these bodies and have been used to study the thermochemical processes that govern planetary evolution. Interestingly, these results all point to similarities between asteroids and the Earth, allowing us to think of asteroids as small, accelerated analogues of our own planet. Here we describe the main mechanisms of planetary magnetic field generation, followed by a summary of paleomagnetic results from each type of meteorite, and finally the implications of these measurements for theories of planetary evolution and formation.

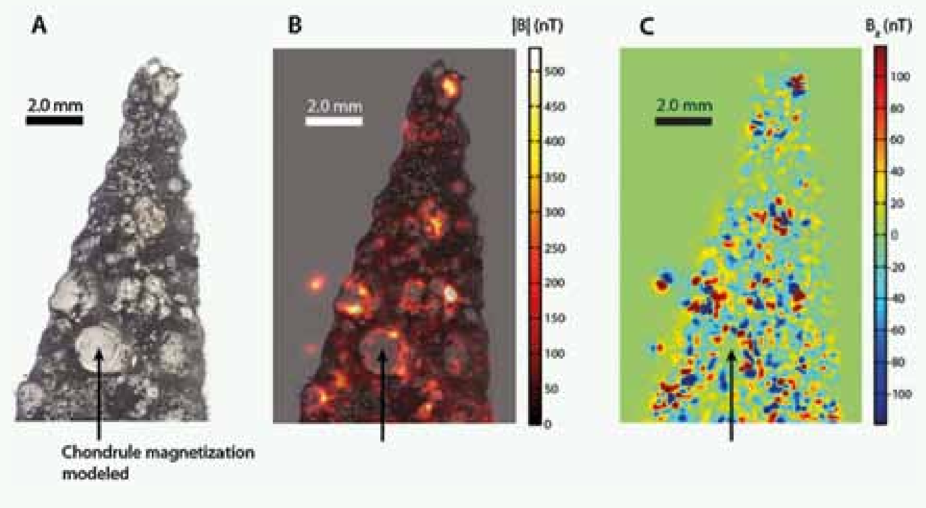
Planetary magnetic fields

Many planetary magnetic fields are dynamic, displaying both spatial and temporal variations in their intensity, direction and polarity (Gubbins 2008). This behaviour implies that such planetary fields are the result of a self-exciting dynamo driven by motion of an electrically conductive fluid in a planetary core, rather than a permanent magnet (Stevenson 2003). The liquid part of a core can move for various reasons. The sources of motion often relate to the large-scale and long-term evolution of a planetary body; one aim of planetary magnetic studies is to deduce the mechanism driving motion in the core and, by extension, the thermal and chemical conditions within a planetary body. Beyond mechanical driving of the core fluid (which has been proposed to have occurred on the ancient Moon (Le Bars *et al.* 2011), the two primary mechanisms of convection relate to thermal and compositional buoyancy of the core liquid. Although the details of this process depend on many physical properties of a planetary body (e.g. size, core composition, mantle composition, etc), ultimately core convection is dictated by the cooling of the body. This is governed by the ability of a body to transfer heat out of the core, and hence depends on the thermal properties of the mantle. So, although the field is generated by the core, it is controlled by the mantle.

“Core convection can result directly from the transfer of heat in a planet as it cools”

Core convection can result directly from the transfer of heat within a planet as it cools (figure 1). If heat is extracted from the core at a greater rate than can be conducted along the adiabat, the result is fluid motion that can create magnetic fields. Calculations of the spatial and temporal release of heat in an asteroid-sized body suggest that this process could have powered convection in them only during the first ~10–50 Myr of the solar system (Elkins-Tanton *et al.* 2011). Thermally driven magnetic fields on asteroids are therefore predicted to have been early and relatively short-lived.

Compositional convection is driven by the solidification of the core. Once a body has cooled to the point where the core temperature is below its freezing temperature, the core will start to solidify. As it does so, light elements (such as S, O, C, Si) are rejected from the advancing solid, and the resulting changes in buoyancy of the liquid part of the core can lead to fluid motion (Nimmo 2009). This is the case at the present day in the Earth, where the solidification of the inner core produces a light-element enriched liquid layer at the boundary between the inner and outer core that moves upwards under gravity, creating convection (Fearn & Loper 1981). Whether this mechanism was capable of generating magnetic activity on asteroid-sized bodies has been a matter of debate, because of uncertainties about the direction of core solidification in these small bodies. The relatively large internal pressure gradient within an Earth-sized body results in bottom-up core solidification (i.e. from the centre, towards the core–mantle boundary).



2 Reproduced from Fu *et al.* (2014a). (A) Light microscope image of a section of the Allende meteorite. (B) Magnitude of total magnetic field 100 μm above the section. (C) Vertical component of the magnetic field 100 μm above the section. The arrow marks an individual chondrule. The magnetic fields were measured using a scanning SQUID microscope.

Due to their smaller size, many asteroids have been predicted to have solidified from the top down, i.e. from the core–mantle boundary, towards the centre. Although this direction of solidification does not preclude compositional convection, it would have to operate through a different mechanism to that acting within the Earth.

Importantly, as the density contrast produced by the rejection of light elements is greater than that caused by liquid cooling, compositional convection is a much more efficient mechanism of field generation than thermal convection (Nimmo 2009). It is therefore expected that thermal convection may have been relatively sparse in the early solar system. Nevertheless, because of the young age of most of the magnetic remanences that have been found in the studies, the majority of paleomagnetic results from meteorites have been linked to thermally driven convection as a result of the uncertainties regarding core solidification (Weiss *et al.* 2010). The ability of an asteroid to generate thermally driven magnetic activity has key implications for its thermochemical structure at the time the field was generated.

Rocky meteorites

Most rocky meteorites are thought to represent the mantles or crusts of asteroids, and are divided into two major categories: chondrites and achondrites (Scott 2011). Chondrites consist of primitive material believed to have formed in the solar nebula and then accreted to form asteroids. The building blocks of chondrites include chondrules (mm-sized spherical inclusions that were once molten) and Ca–Al-rich inclusions (CAIs, the oldest solids in the solar system). Evidence suggests that these phases were heated when they were part of their parent asteroid although, crucially, they did not melt during this time. In contrast, rocky achondrites lack primitive material and show large degrees of thermal alteration. It is believed that achondrites represent chondritic material that did melt while it was part of its parent asteroid.

Chondrites and achondrites are subdivided based on minor element and isotopic compositions, and it has been argued that each subcategory represents a distinct parent asteroid (Weiss & Elkins-Tanton 2013). Current theories of planetary formation suggest that these meteorite classes represent fundamentally different bodies that differ primarily in their timing of accretion relative to the timescale of radioactive decay of ^{26}Al (~3 Myr), which is the primary source of heat in these bodies. From a paleomagnetic perspective, planetary melting is crucial because this process provides a viable method for planetary differentiation (the separation of rocky and metallic components under gravity to form a mantle and core), which is a stringent requirement for a planetary magnetic field. Hence, the remanent magnetization within chondrites and achondrites is expected to differ and could be used to elucidate the details of asteroid structure and differentiation.

Rocky meteorites are notoriously difficult to measure and interpret paleomagnetically. Many contain nanometre-scale, stable magnetic inclusions that are typically reliable paleomagnetic recorders. But the overall remanence of a rocky meteorite can be a complex amalgamation of numerous components, each of which could reflect a range of primary and/or secondary processes. For example, the overall remanence carried by a chondrite is expected to consist of a pre-accretionary component, carried by the chondrules themselves and other primitive phases, as well as a component reflecting any potential magnetic activity on the parent body, induced through thermal and/or chemical alteration. A range of secondary processes can also adversely alter the primary remanence of a meteorite such that it can be difficult to interpret their magnetization: processes on the parent body such as late-stage thermal or aqueous alteration, shock and cold brecciation, and on Earth such as remagnetization on entry, further shock, weathering, and quality of care during collection and curation. The remanence carried by achondrites could also contain primary and secondary components, although they are not expected to have retained any pre-accretionary information. The major technological achievement in paleomagnetism over the past 10–15 years has been the development of sophisticated techniques capable of measuring and decoding the magnetization history within bulk rocky meteorite samples. Indeed, many of the early paleomagnetic measurements made on rocky meteorites are now thought to be inaccurate as a result of the quality of past techniques (specifically those that involve potential sample alteration through heating).

Recently, chondrites have been measured paleomagnetically by means of the physical separation and isolation of pre- and post-accretionary phases. A chondritic meteorite that has been particularly well studied is the Allende CV carbonaceous chondrite (which is rich in organic molecules). The material within this large meteorite experienced both aqueous and thermal alteration while it was part of its parent asteroid. Despite this alteration, this meteorite had previously been thought to contain accurate records of pre-accretionary magnetization. However, a recent paleomagnetic study of individual chondrules extracted from this meteorite suggests this is not likely (figure 2, Fu *et al.* 2014a). Instead, the conditions within the parent body removed this early magnetization, and the remanence in the Allende meteorite is likely to represent purely post-accretionary processes. Paleomagnetic studies of subsamples of the Allende meteorite that acquired a magnetization ~9–10 Myr after solar system formation suggest that it recorded a unidirectional post-accretionary field with an intensity of ~20 μT (the present-day Earth field is ~30–60 μT), consistent with a planetary magnetic field (Carporzen *et* *al.* 2011). Interestingly, subsamples of the Allende meteorite that correspond to a magnetization acquisition age of ~40 Myr show a much weaker field (Fu *et al.* 2014a). Considering the early ages, this trend could be interpreted as the decay of the thermally driven magnetic fields that are predicted to operate shortly after the birth of the solar system. Chondritic parent bodies are not expected to have generated magnetic fields, because they have not differentiated or formed a core. These observations are inconsistent with this hypothesis, and the implications for the structure of chondritic parent bodies are discussed below.

Using advanced scanning magnetic microscopies, the pre-accretionary remanence within individual chondrules extracted from the Semarkona LL ordinary chondrite (ordinary chondrites make up ~85% of meteorites on Earth and contain low levels of organic molecules) have been used to estimate the strength of the pre-accretionary magnetic field (Fu *et al.* 2014b). This field was generated at the same time as chondrules and other early solids formed and the solar nebula collapsed. The Semarkona meteorite displays no thermal or chemical alteration, making it the ideal sample to investigate this ancient process. The inferred field intensity of 54 ± 21 μT has been linked to mechanisms of mass and angular momentum transfer within the protoplanetary disc as well as supporting chondrule formation through nebular shock or planetesimal collisions.

"Neither the Moon nor Mars generate a field, but their crusts hold a magnetic remanence"

Bulk ordinary chondrite samples are particularly difficult to study paleomagnetically because the remanence carriers have low coercivity. Despite these difficulties, there is evidence that the LL chondrites contain a directionally heterogeneous remanence down to the mm-scale (Gattacceca *et al.* 2003). Within thermally altered LL chondrites, this remanence could be interpreted as either remanence acquisition in a weak or null field, cold brecciation or late-stage remagnetization. If this remanence is shown to correspond to magnetization in a null field, this observation could be used to argue that some chondrites do in fact originate from undifferentiated bodies. It is intriguing to note that subsamples of H ordinary chondrites display a directionally homogeneous remanence, suggestive of magnetization by a dynamo field (Weiss & Elkins-Tanton 2013). Because of the difficulties in measuring these samples with conventional paleomagnetic techniques, this observation is yet to be investigated in detail. But this remanence could be the first tantalizing glimpse of dynamo activity on an ordinary chondritic parent body.

Paleomagnetic measurements have also been performed on rocky achondrites originating from a range of parent bodies. One class of achondrites that is of particular interest is the HED (howardite–eucrite–diogenite) meteorites. This diverse and numerous group contains the only achondrites that originate from an asteroid to have their parent body – the asteroid Vesta – confidently identified (Fu *et al.* 2012, Binzel & Xu 1993). This allows the measured properties of these meteorites to be linked to the measured properties of Vesta, with the prospect of linking these data to direct observations of differentiation, core activity and planetary melting. Fu *et al.* (2012) performed paleomagnetic measurements on the ALHA81001 HED meteorite and suggest that it cooled in the presence of planetary magnetic field with an intensity of >2 μT. This meteorite also shows a relatively young remanence acquisition age (3.69 Gyr), inconsistent with thermally driven magnetic activity early in the evolution of the solar system. These authors argue that this meteorite experienced a secondary magnetic field generated by the crustal remanence induced by an extinct thermally driven dynamo. The intensity of this original dynamo field would have to have been between ~10 and 100 μT. The presence of a crustal remanence has also been proposed as the origin of the apparent absence of space weathering from solar winds on Vesta (Fu *et al.* 2012).

Direct evidence of early magnetic activity recorded by an achondritic asteroid has been demonstrated within the Angrite meteorites (Weiss *et al.* 2008a). This group originates from an unknown parent asteroid and displays excellent paleomagnetic recording capabilities. Indeed, paleomagnetic measurements of three of the meteorites in this group suggest they experienced an early magnetic field of intensity ~10–20 μT. This early and relatively intense magnetic field is consistent with the Angrite meteorites directly recording the dynamo field itself. This study was one of the first to demonstrate that asteroids were capable of generating magnetic activity, and paved the way for future studies as well as providing a fundamental insight into the internal conditions of asteroids.

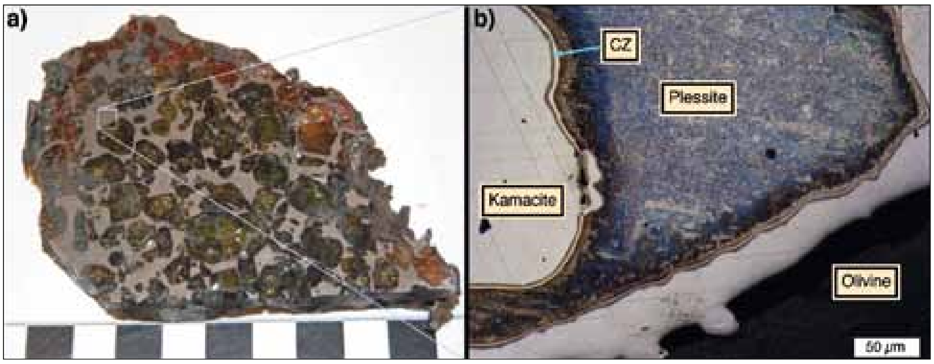
Two other classes of achondrites that warrant particular discussion are lunar and martian meteorites. Neither the Moon nor Mars generate global fields at the present day, but the crusts of both bodies display a magnetic remanence. Although these meteorites (and Apollo samples in the case of the Moon) originate from larger bodies than the others considered here, they are nonetheless extremely informative about dynamo activity. This is particularly true for the Moon, where the remanence acquisition age of lunar samples (both meteorites and Apollo mission samples) spans almost 4 billion years. Paleomagnetic measurements therefore provide a record of lunar magnetic activity, and hence the internal conditions of the Moon, across its entire cooling history (Weiss & Tikoo 2014). These measurements show that the lunar dynamo field intensity was initially strong (40–100 μT), then decreased relatively suddenly (to <10 μT), staying at this weak value for billions of years. Very young samples (<7 Myr old) include tantalizing evidence that the lunar core was still active then.

The Moon has also been studied extensively from a dynamo modelling perspective. By comparing these model results to the measured record, the lunar dynamo has been proposed to have been driven by various mechanisms over its history. The earliest lunar dynamo activity is thought to originate from thermal convection. The longevity of this mechanism is uncertain as a result of the unknown water content of the lunar mantle; this property affects mantle thermal conductivity (Evans *et al.* 2014). Once the Moon had cooled and could no longer generate this field, it has been proposed that some convection was mechanically forced as a result of surface impacts (Le Bars *et al.* 2011). The following period of dynamo activity is thought to result from precessional motion of the Moon that led to flow of the core liquid (Dwyer *et al.* 2011). Finally, recent and long-lived magnetic activity may be the result of compositional convection arising from core solidification (Laneuville *et al.* 2014). These last models predict that the Moon should still be generating a magnetic field; simultaneous top-down core solidification has been proposed as a way of addressing this discrepancy.

Martian meteorites often contain abundant magnetic phases (containing up to 15 wt% magnetic oxides, Gattacceca *et al.* 2014), and paleointensity measurements of these samples suggest Mars experienced a field of ~50 μT (Weiss *et al.* 2008b). This is compatible with the strong crustal remanence in Mars's southern hemisphere, which is probably the result of an earlier dynamo field that shut down ~4 Gyr ago.

Stony-iron meteorites

Stony-iron meteorites consist of roughly equal amounts of rocky and metallic material, and are divided into two main groups: the pallasites and mesosiderites. The metal in these meteorites has a relatively large grain size and so consists of multiple magnetic domains, making it a poor and unreliable paleomagnetic recorder. As a result, accurate paleomagnetic measurements on bulk samples of these meteorites



3 (a) Image of the Imilac pallasite. The scale bar corresponds to cm increments.
(b) Optical microscopy image of the metal next to an olivine crystal. The sample has been etched to highlight the microstructures that are generated in meteoritic metal. The cloudy zone (CZ) is visible as a brown rim around the plessite.

remained elusive for decades. However, recent measurements using novel techniques from a pair of pallasites have been used to investigate both the origin of these meteorites and the processes that governed the evolution of their parent body.

The pallasites consist of centimetre-sized olivine crystals embedded within a continuous Fe–Ni matrix. The presence and proximity of these phases led to the original proposal that these meteorites originate from the core–mantle boundary of an asteroid. Tarduno *et al.* (2012) noted that some of the olivine crystals in the Imilac and Esquel pallasites contain strings of nanometre-scale Fe inclusions. These particles are small enough to be reliable paleomagnetic recorders, and by isolating olivine crystals from their surrounding metal matrix these authors were able to obtain the first reliable measurements of the field generated by the pallasite parent asteroid. Single-crystal paleomagnetic measurements show that these meteorites experienced field intensities of >70 µT, which are consistent with a relatively intense planetary magnetic field. The presence of this remanence raises questions about the origin of the pallasites. The nm-scale Fe particles record the magnetic field as they cooled below the relatively low temperature of 633 K. A core can only generate a planetary magnetic field if it is at least partly liquid, i.e. when it was at temperatures >1200 K. Planetary cooling models show that the core–mantle boundary is expected to have been only slightly cooler than the core; in other words, this region would not have been capable of recording a magnetization while the core was liquid. Therefore, the pallasites could not originate from this depth in their parent asteroid. Tarduno *et al.* (2012) propose instead that the pallasites originate from the upper- to mid-mantle of a 200 km radius asteroid, and the presence of metal is likely to be the result of a planetary impact between a larger body and smaller body (~1/10 of the mass of the larger body). During this event, the core of the smaller body could have been injected into the mantle of the larger body; the pallasites are samples of the resulting metal–silicate mixture.

Cloudy zones

Despite the majority of the metal in the pallasites being a poor paleomagnetic recorder, there are specific regions that could provide reliable paleomagnetic information. The pallasites typically cooled at rates of <10 K/Myr (Yang *et al.* 2010), which permits low-temperature phase transitions that are kinetically hindered on laboratory timescales. For example, slow cooling of the metal in these meteorites allowed lamellae of the bcc Fe-rich phase kamacite to form, resulting in the characteristic Widmanstatten microstructure associated with meteoritic metal. As these lamellae form and advance, Ni is rejected from the bcc crystal structure and accumulates in the surrounding fcc taenite phase. This generates a variation in the Ni content in the taenite adjacent to the lamellae interface. The Ni content decreases from ~50% down to the bulk composition (typically ~10%) over ~1–20 µm, depending on the meteorite (Goldstein *et al.* 2009). On slow cooling, metal with this Ni concentration range can order to form the phase tetrataenite, which consists of alternating atomic layers of Fe and Ni and is intrinsically an extremely magnetically hard material (intrinsic coercivity >2 T). For Ni concentrations between ~45% and 25%, tetrataenite forms via spinodal decomposition as nm-scale islands in an intergrown region known as the cloudy zone (CZ, figure 3). This consists of small islands of a magnetically hard phase, characteristic of a reliable paleomagnetic recorder (Bryson *et al.* 2014). Hence, by studying the magnetic remanence of the CZ in isolation, meteoritic metal could provide reliable paleomagnetic information. Furthermore, the CZ forms locally at later times for lower local Ni contents, i.e. at a further distance from the kamacite lamellae (Bryson *et al.* 2014a). Thus, the spatially resolved magnetization across the CZ corresponds to a time-resolved record of the magnetic activity experienced by this intergrowth.

"A core can only generate a planetary magnetic field if it is at least partly liquid"

However, the CZ forms only a small total volume within a meteorite; it is unfeasible to extract and study this region from bulk samples or isolate its remanent magnetization from that of the entire sample with traditional paleomagnetic techniques. Instead, Bryson *et al.* (2015) used magnetic microscopy to image the magnetization of just the CZ in the Imilac and Esquel pallasites (figure 4). Images of the nm-scale magnetization across the width of the CZ (corresponding to different remanence acquisition ages), showed that the magnetic field experienced by the Imilac meteorite remained at ~120 µT for 4–8 Myr, while the field recorded by the Esquel meteorite decreased from ~80 µT to a plateau at 30 µT, before finally falling to ~0 µT over a period of 5–10 Myr (figure 5). These values are consistent with those found by Tarduno *et al.* (2012), further suggesting that the pallasite parent body produced an intense magnetic field. By relating values of the cooling rates measured from the size of the structures within the CZ to those predicted from planetary cooling models, these authors argue that the Imilac and Esquel meteorites recorded their magnetizations during the early and late stages of core solidification, respectively. Within this time period, the field could have resulted from compositional convection. To test this hypothesis, the field trends were predicted on the basis of calculations of the core–mantle boundary heat flux and inner-core growth rate. These trends were found to agree with the experimental results, with the Imilac meteorite recording a dipolar field, and the Esquel meteorite recording a dipolar–multipolar field transition, the multipolar regime and then the eventual shut down of magnetic activity associated with complete core solidification. The experimental observations are, therefore, all consistent with a field generated by compositional convection.

Despite stony-iron meteorites having been considered as unreliable samples for paleomagnetic studies, it is now clear that they contain a wealth of information. Indeed, this family of meteorites has illuminated some key aspects of planetary collisions and thermochemical evolution.

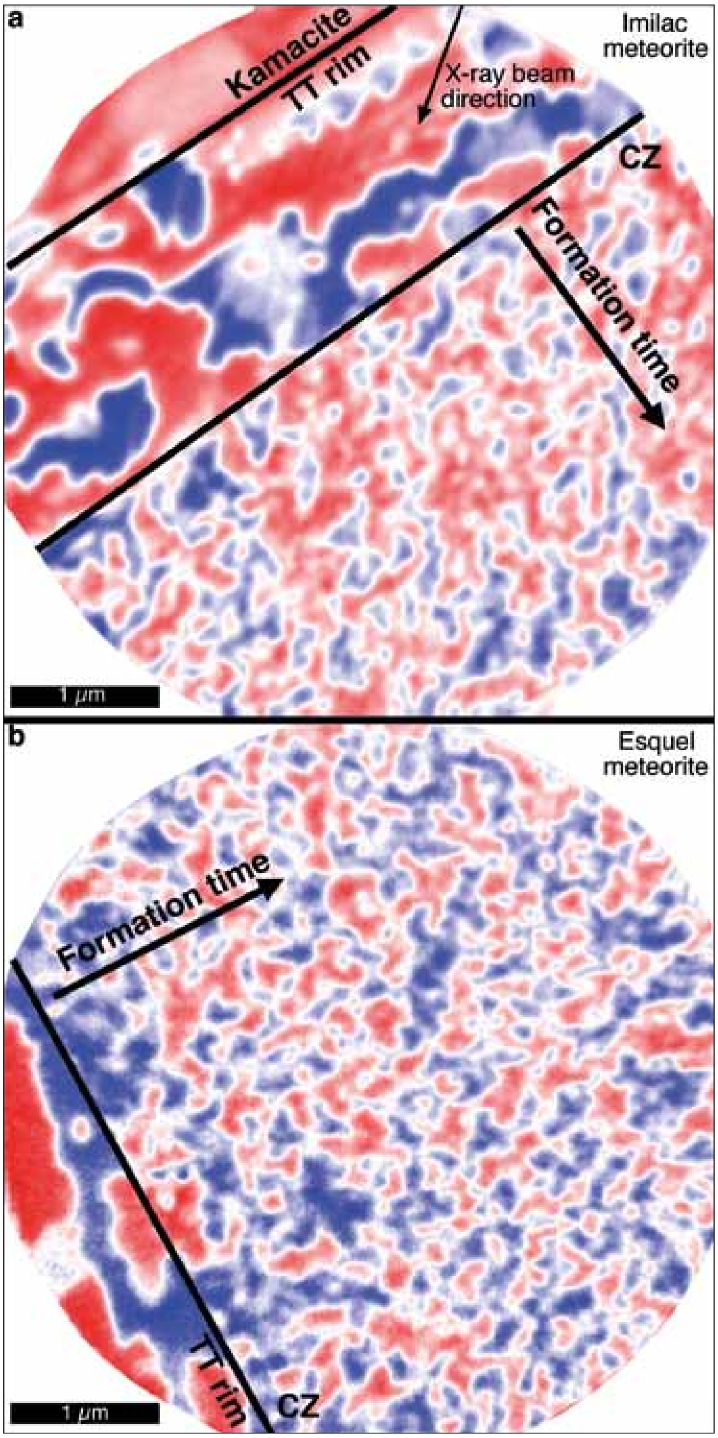
Iron meteorites

Iron meteorites are comprised entirely of meteoritic metal and are thought to represent asteroid cores. These meteorites are therefore the result of destructive planetary collisions during the early solar system. Due both to the unreliable recording nature of meteoritic metal and their proposed origin, these meteorites have not been widely studied paleomagnetically. However, they display the same microstructures as those seen in the metal of the pallasites, so they could potentially contain reliable paleomagnetic information. To date, this approach has only been applied to the Tazewell IIICD iron meteorite (Bryson *et al.* 2014b), which has been studied using the same magnetic microscopy technique as that used to study the metal within the pallasites. Somewhat unsurprisingly, this meteorite does not appear to have recorded a magnetic field. If this meteorite does indeed originate from a core, the CZ does not form and record magnetic activity until temperatures have fallen well below that required for the core to be liquid.

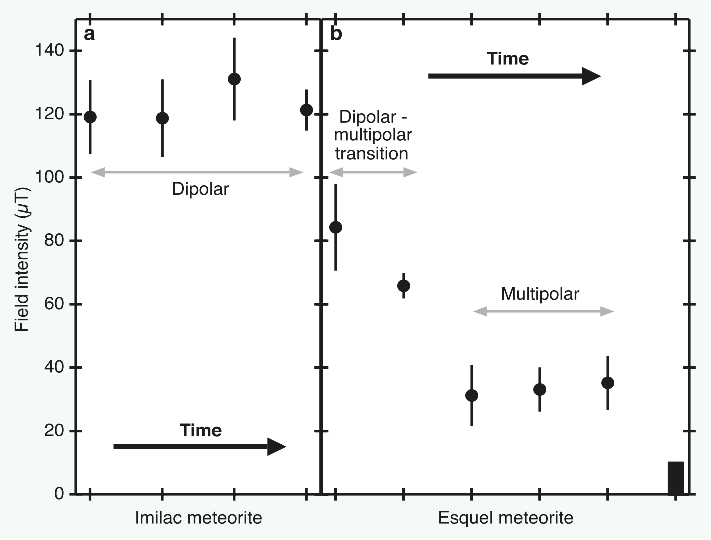
This is not to say that all iron meteorite groups are expected to lack a magnetic remanence. Some iron meteorite groups (e.g. IIE) are thought to originate from surface metal pools (McDermott *et al.* 2014) resulting from a similar collision to that proposed to generate the pallasites. In this case, these meteorites could have recorded the magnetic field generated by their parent body, and paleomagnetic studies of their CZ could provide time-resolved records of magnetic activity. IVA iron meteorites are another group that could be of interest. These meteorites cooled uncharacteristically quickly, which has led to suggestions that they originate from a core that had its mantle stripped from it by planetary collision (Asphaug 2009, Yang *et al.* 2007). The resulting liquid body would have cooled at the high rates observed in the IVA meteorites and, as a result of its direct contact with space, is also expected to have undergone top-down solidification. It is feasible that meteorites from the upper part of the solid metal shell could have recorded the field generated while the deeper liquid was still convecting. The IVA iron meteorites represent a unique opportunity to study the mechanisms of field generation in a top-down solidifying core.

Implications

The majority of measured rocky and stony-iron meteorite groups carry a magnetic remanence consistent with a planetary magnetic field. This suggests that many small planetary bodies generated magnetic activity during the early solar system. This is in stark contrast to ideas from 10–15 years ago when there was little to no accurate paleomagnetic evidence that these bodies could generate magnetic fields.



4 5 µm field-of-view XPEEM images of the CZ in (a) the Imilac and (b) the Esquel pallasite based on a figure from Bryson *et al.* (2015). Blue and red correspond to positive and negative projections of the magnetization of the sample surface onto the X-ray beam direction. The CZ forms over time, with the oldest region adjacent to the tetrataenite (TT) rim. The strength and orientation of the field experienced by each meteorite can be extracted from these images.



5 Field intensity experienced by (a) the Imilac and (b) the Esquel pallasite over time (Bryson *et al.* 2015). Each point corresponds to ~1–2 Myr. The Imilac meteorite is thought to have recorded a dipolar field, while the Esquel meteorite captured a dipolar–multipolar transition, multipolar regime and the end of dynamo activity with complete core solidification.

Generally, both paleomagnetic measurements and geochemical dating of rocky meteorites (both achondrites and carbonaceous chondrites) suggest that many asteroids were capable of generating early magnetic activity. These observations are consistent with thermally driven magnetic activity, which is supported by measurements and models of lunar dynamo activity. This deduction is consistent with ideas about achondritic parent bodies, which are thought to have formed a core, but is in direct disagreement with current theories of the development of chondritic parent bodies. These bodies are not thought to have a core and hence would be incapable of generating a magnetic field. These recent paleomagnetic measurements suggest that partially differentiated parent bodies (Elkins-Tanton *et al.* 2011, Weiss & Elkins-Tanton 2013), consisting of a chondritic lid above differentiated material, could have been present during the early solar system.

"The thermally driven magnetic activity era is predicted to have been short and weak"

The presence of this type of body means that accretion to form planetary bodies would have been a slow and potentially multistage process. In recently proposed models of the formation of these asteroids (Elkins-Tanton *et al.* 2011), differentiation occurs during the earliest stages of the solar system, and the chondritic lid is acquired slowly over millions of years as pre-accretionary material from the solar nebula gradually rains down. A decreasing thermal gradient through the chondritic lid can explain the varying degrees of thermal alteration observed within chondrites.

Currently, there is evidence of post-accretionary magnetic activity in multiple carbonaceous chondrite parent bodies, but no firm evidence for it in ordinary chondrite parent bodies. This trend could be a result of the difficulties in performing accurate paleomagnetic measurements on ordinary chondrites, but it is also interesting to consider the interpretation that planetary lids composed of carbonaceous material may allow for magnetic activity, while ordinary chondritic lids do not. Carbonaceous chondrites show larger degrees of aqueous alteration than ordinary chondrites, implying there was more water within carbonaceous chondrite lids than ordinary chondrite lids. The mantle water content of the Moon has been linked to the heat flux through the lunar mantle and the longevity of the lunar dynamo (Evans *et al.* 2014); extending this idea to chondritic parent bodies, it could be the composition of the carbonaceous chondrites themselves that allowed their parent bodies to generate magnetic activity.

Paleomagnetic measurements of stony-iron meteorites strongly suggest that asteroids were capable of generating compositionally driven dynamo fields. Whether this mechanism of field generation could act on asteroids was uncertain for some time but, now there is experimental evidence of their existence in the past, we can consider how likely they may have been to exist in the early solar system. Compositional convection is much more efficient than thermally driven flow and could generate fields for liquid-core cooling rates as low as 0.001 K/Myr. It is likely to have occurred on the vast majority of differentiated small bodies that solidified from the bottom up, whereas thermally driven dynamos were probably rare. The compositionally driven magnetic activity would have been relatively late, because it could only have generated a field once bodies had cooled enough for their cores to start solidifying, and relatively long-lived, because it appears to have lasted for most of the time it took for the core to solidify. These are opposite traits to thermally driven fields, and suggest that there could have been a widespread epoch of magnetic activity among differentiated small bodies in the early solar system (Bryson *et al.* 2015).

By combining observations from all meteorite groups, we can start to build up a picture of convection through the history of the core of a small body. Initially, the thermal structure of an asteroid allowed for thermally driven magnetic activity; models suggest that this ceased ~10–50 Myr after the formation of the solar system. After this time, dynamo activity could result from impacts. However, this mechanism is only capable of producing stochastic and extremely short-lived core motion. A continuous magnetic field would require a near-constant bombardment, which is unlikely. We therefore predict a period of largely quiescent dynamo activity after the thermally driven activity. Once cooling had reached the point where the core started to solidify, compositional convection could have generated magnetic activity. This is certainly the case for cores solidifying from the bottom up; evidence is still required to show whether the same is true for top-down solidifying cores. The first, thermally driven, epoch of magnetic activity is predicted to have been relatively short-lived and weak, whereas the second, compositionally driven, epoch was widespread, intense and long-lived.

Testable hypotheses

This picture leads to testable hypotheses. First, there should be meteorites within the same group that capture different epochs of activity (thermal, quiescence and compositional). The cooling rate of a meteorite may correlate with its original depth in the parent body, and hence the time it cooled to the remanence acquisition temperature. Therefore, by studying meteorites from the same family with a range of cooling rates, a long time-resolved record of magnetic activity can be obtained from the same parent body, which could be used to argue for either the presence or absence of these different epochs of activity. Secondly, meteorite groups other than the pallasites should have captured compositionally driven magnetic activity. Demonstration of this activity in other meteorites would support its proposed widespread occurrence.

A final piece of future work that would illuminate our understanding of these processes is further study of top-down core solidification (Williams 2009). Modelling work is underway for Ganymede, the Moon and Mercury, in combination with observational data. If this mechanism is found to generate magnetic activity, the coverage of the compositionally driven epoch of magnetic activity could be extended to essentially all differentiated small bodies, implying that magnetic activity was widespread in the early solar system. ●

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