Using Meteorite Magnetism to Understand the History of Our Solar System: A Decade of Progress and Upcoming Challenges

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Meteorites offer us a glimpse into the early history of our solar system, and the processes that governed the formation of the planets. Throughout their long and complex histories, meteorites form magnetic minerals via primary crystallization and cooling, as well as via later-stage metamorphism and aqueous alteration on their parent bodies. This can result in complex magnetization records with different minerals acquiring magnetic field records at various times and via different mechanisms. Early attempts to recover paleomagnetic field histories from these extraterrestrial materials were thwarted by the fact that the bulk magnetic properties of meteorites are inherently unstable. In order to disentangle these composite paleomagnetic signals, individual sources of magnetization need to be targeted, either by physically isolating grains, or by using experimental methods with a high spatial resolution.

Over the last decade, researchers have developed experimental approaches with exceptionally high spatial and magnetic moment sensitivity to directly measure the stable magnetic sources in meteorites. Superconducting quantum interference device (SQUID) microscopes have allowed the paleomagnetic signals carried by individual sub-mm diameter grains, such as single zircon crystals and chondrules to be recovered (Borliena et al., 2020; Fu et al., 2014). Synchrotron X-ray photoemission electron microscopy has enabled the composition and magnetization of microstructures in iron meteorites (this approach can only be used for conductive materials) to be mapped out with nanoscale resolution, and paleointensities at least partially quantified (Bryson, Church, et al., 2014; Bryson, Herrero-Albillos, et al., 2014). These studies have revolutionized our understanding of planetary processes, from constraining the strength of the nebula magnetic field, to identifying partially differentiated planetesimals, and demonstrating that asteroids can—and often do—generate intrinsic magnetic fields (Bryson et al., 2015; Carporzen et al., 2011; Fu et al., 2014).

The most recent innovation, the quantum diamond microscope (QDM), has even higher spatial and moment sensitivity than the SQUID microscope, and multiple sources of magnetization within a single meteorite sample can now be accurately targeted (Fu et al., 2020; Glenn et al., 2017). Fu et al. (2021) have used the QDM to re-assess the magnetization of the Allende meteorite. Their study has led to the re-interpretation of the magnetization, which has been the subject of numerous paleomagnetic studies. Previous studies interpreted the paleomagnetic signals as a partial thermal remanent magnetization (TRM), acquired during late-stage reheating and subsequent cooling on the meteorite's parent body (Carporzen et al., 2011; Muxworthy et al., 2017). However, QDM analysis has demonstrated Allende's magnetization is carried by pyrrhotite that grew during early aqueous alteration and acquired a chemical remanent magnetization (CRM) (Fu et al., 2021). The authors argue that the absence of a coherent magnetization in awaruite, an FeNi phase which is interpreted to have grown contemporaneously with the pyrrhotite, precludes a TRM. It remains open to debate why awaruite would not acquire a similar CRM to the pyrrhotite. Magnetic phases will acquire a CRM if they grow in the presence of an external magnetic field. The CRM acquisition process is inherently poorly understood, and remains an active area of research. A particular problem is that laboratory approaches mimic TRM acquisition (i.e., remanence acquired by cooling below the magnetic Curie temperature) by reheating samples to “reverse” the magnetization process. There are currently no approaches for reliably recovering paleointensities from CRMs, although there is a general consensus that this is a less efficient process than TRM acquisition and therefore thermal paleointensity experiments will provide a reasonable lower limit on the ancient magnetic field strength.

Accurately constraining the strength and duration of ancient magnetic field signals is critical for interpretation of their origin. Fu et al. (2021) have argued that Allende was magnetized by the solar nebula field. The authors...
report an intense magnetic field (>40 μT), which is significantly stronger than that acquired by other meteorite groups at a similar time. This suggests the nebula magnetic field was very heterogeneous, with significant implications for the role of planet formation and instabilities in controlling the structure of the protoplanetary disk. However, given the uncertainty in CRM acquisition processes, and the discrepancy between the paleomagnetic record carried by awaruite and pyrrhotite, the reported paleointensities and resulting interpretations should be considered with these caveats in mind. Previous studies have suggested the solar wind, a core dynamo, or impact-generated magnetic fields could be responsible for the recovered magnetization in Allende (Carporzen et al., 2011; Muxworthy et al., 2017; O’Brien et al., 2020). The solar wind imparts very weak magnetic fields, which challenge the fidelity limit of many paleomagnetic recorders. Core dynamo fields can vary in strength and longevity, with significant implications for interior planetary dynamics although such interpretations require very well-resolved paleointensities. Finally, impact events are postulated to create intense, short-lived magnetic fields and therefore can only be captured by almost-instantaneous remanence acquisition.

While great leaps forward have been made in the field of extraterrestrial paleomagnetism in the last decade, these advances have also highlighted gaps in our theoretical knowledge. One such gap is the remanence acquisition processes in more unusual magnetic carriers that are not typically encountered in terrestrial samples, including iron sulfides and iron-nickel phases. For example, a recent study using high resolution electron microscopy and micromagnetic simulations has revolutionized our understanding of how tetrataenite, a common FeNi phase in meteorites, acquires a magnetic field record (Einsle et al., 2018). Tetrataenite magnetisation is acquired later in the meteorite’s cooling history than previously thought (Bryson, Church, et al., 2014; Bryson, Herrerro-Albillos, et al., 2014). This is just one example of how our fundamental understanding of remanence acquisition processes has significantly changed our interpretation of extraterrestrial magnetic field records. Similar studies will be of paramount importance for understanding how to extract reliable paleomagnetic signals from other extraterrestrial magnetic phases. This groundwork needs to be carried out before future paleointensity estimates can be used to interpret early solar system and planetary processes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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