Magnetic microscopy of meteorites: probing the magnetic state of the early solar system

Richard J. Harrison
University of Cambridge
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With massive thanks to…

Josh Einsle, James Bryson, Claire Nichols, Roberts Blukis
Department of Earth Sciences, Cambridge

Sean M Collins, Zineb Saghi, Alex Eggeman, Ben Martineau, Paul A Midgley
Department of Materials Science, Cambridge

Julia Herrero-Albillos
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Florian Kronast
Helmholtz Zentrum Berlin, BESSY II

Bastian Pfau, Christian Günther, Stefan Eisebitt
Technische Universität Berlin

Paul Bagot
Department of Materials Science, University of Oxford
In the first few million years after formation of the solar system, when high concentrations of now extinct radioactive elements (e.g. Al\textsuperscript{26}) were capable of producing sufficient radiogenic heat, some asteroid bodies became hot enough to melt and separate out into an iron-nickel core and silicate mantle. Magnetic studies of meteorites suggest that before the core cooled and solidified, it generated a dynamo field like that of the Earth.
Paleomagnetic analysis of individual olivine crystals containing metallic inclusions demonstrates fields of ~70-100 μT were present on the parent body. Combining observed blocking temperatures with cooling rate estimates, the results imply that pallasites formed when liquid FeNi from the core of an impactor was injected as dikes into the shallow mantle of a ~200-km-radius protoplanet.

Low unblocking temperature magnetizations (<360°C) observed from Esquel olivine likely have a viscous origin. However, the Esquel pallasite olivine shows a large decrease in natural remanent magnetization (NRM) and a stable direction between ~360° and 500°C (Fig. 2, Aa and dB). Only very small NRM changes are seen at higher demagnetization temperatures, between 500° and 750°C. The dominant drop...
Nucleation and growth of kamacite creates stranded diffusion profile in taenite

Diffusion length $\sim 10$ µm
Nucleation and growth of kamacite creates stranded diffusion profile in taenite
Diffusion length \( \sim 10 \, \mu m \)

48-50% Ni
Tetrataenite rim
Nucleation and growth of kamacite creates stranded diffusion profile in taenite
Diffusion length $\sim 10 \, \mu m$

25-48% Ni
Cloudy zone

48-50% Ni
Tetrataenite rim
Nucleation and growth of kamacite creates stranded diffusion profile in taenite

Diffusion length ~10 µm

- <25% Ni: Plessite
- 25-48% Ni: Cloudy zone
- 48-50% Ni: Tetrataenite rim
Nucleation and growth of kamacite creates stranded diffusion profile in taenite
Diffusion length ~10 µm

Spinodal decomposition within stranded diffusion profile yields cloudy zone
Diffusion length ~ 10-100 nm
STEM EDS Tomography
Atom Probe Tomography

Needle-shaped specimen
Tip radius 20-100nm
Cooled to 20-100K

E-field
~10-50V/nm

HV dc
(2-20kV)

HV pulse

Local-electrode

Field evaporated ion

Laser or voltage pulsing to initiate field evaporation from the tip surface

Position-sensitive detector

$X_D, Y_D$

N

Time-of-flight and position data

50 nm
Atom Probe Tomography
Atom Probe Tomography
Soft ferromagnet

Kamacite

bcc

Soft ferromagnet
during reheating from low temperatures does the Earley, 1950

ture of the paramagnetic fcc phase,

region of the diagram into the two-phase which a meteorite cools from the one-phase taenite (equilibrium phase diagram (Earley, 1950)). No composition change takes place. Only the martensite starting temperature.

Experimental evidence shows that for Fe–Ni alloys, the Widmanstätten pattern does not form by this process.

Therefore, there is strong experimental evidence that the reaction sequence

(kamacite+taenite), with equilibrium compositions given by the

tie line at the reheating temperature.

Narayan and Goldstein (1984a) found kamacite formed along the fields and found that kamacite formed along the

original taenite grain boundaries and at taenite triple

regions of iron meteorites.

and also found an absence of intragranular kamacite.

analyzed a number of binary Fe–Ni experimental alloys from taenite into the two-phase

and also found an absence of intragranular kamacite.

plates, were observed.

kamacite precipitates, such as Widmanstätten pattern does not form by this process.

ordered Ni FeNi–tetrataenite, and

is ordered FeNi–tetrataenite, and

the ordering temperature of FeNi, Narayan and Goldstein (1984a)

(> 25 wt% Ni)

Ph is schreibersite, (Fe–Ni) Ni (wt.%)

Ni CONTENT (wt. %)

Taenite

fcc Soft ferromagnet (> 25 wt% Ni)

γ

γ

γ

γ

M

M

Ms

α

kam

γ

γ

γ

γ

Tc

γ

γ

γ

γ

TT

TT

Tetraenite

Ordered FeNi (L10)

Hard ferromagnet

Easy axis // <001>
Modelling

With thanks to the MERRILL team: Wyn Williams, Karl Fabian, Pádraig Ó Conbhuí, Les Nagi
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Uniaxial anisotropy increased in magnitude from zero to tetrataenite values. Easy chosen along either major, intermediate or minor axes of particle. Exchange parameter kept fixed at taenite value.
Taenite-tetrataenite transition interacting

Uniaxial anisotropy increased in magnitude from zero to tetrataenite values. Easy chosen along either major, intermediate or minor axes of particle. Exchange parameter kept fixed at taenite value.
Hysteresis cycle ± 1 Tesla Out of Plane Field

Collaboration with Bastian Fau, Christian Günther, Stefan Eisebitt, BESSY II
Hysteresis cycle ± 1 Tesla Out of Plane Field

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Hysteresis cycle ± 1 Tesla Out of Plane Field

- Measured hysteresis
- Fitted hysteresis

The same legend applies for all 4 loops shown.
Scanning Precession Electron Diffraction + Fuzzy Cluster Analysis

Three crystallographic orientations of tetrataenite islands

t6 data - coarse
t7 data - medium
t5 data - fine
Field-dependent thermodynamic probability of TT magnetisation states

\[
\frac{\langle n_{+z} \rangle}{N} = \frac{e^{-MB_z/k_BT}}{e^{-MB_x/k_BT} + e^{MB_x/k_BT} + e^{-MB_y/k_BT} + e^{MB_y/k_BT} + e^{-MB_z/k_BT} + e^{MB_z/k_BT}}
\]

\[
\frac{\langle n_{-z} \rangle}{N} = \frac{MB_x e^{k_BT}}{e^{-MB_x/k_BT} + e^{MB_x/k_BT} + e^{-MB_y/k_BT} + e^{MB_y/k_BT} + e^{-MB_z/k_BT} + e^{MB_z/k_BT}}
\]

![Graph showing field-dependent thermodynamic probability of TT magnetisation states](image_url)
X-ray Photoemission Electron Microscopy

1. Images M not B by spatially resolving X-ray magnetic circular dichroism (XMCD) signal.

2. Resolves chemical and magnetic variations with the necessary spatial resolution and over an appropriate field of view (30-100 nm over 5 μm).

3. Can be performed on a polished surface. Sputtering under UHV removes oxide layer and polishing-induced damage layer. High coercivity of tetrataenite ensures that the natural remanent state is preserved, even at the surface.

4. Highly surface sensitive (~ 5 nm), avoiding volume averaging.

5. XMCD signal proportional to projection of M along X-ray direction - easily quantifiable.

XMCD = XASμ_ - XASμ_
Brenham pallasite (6 K/Myr)
Brenham pallasite (6 K/Myr)
Brenham pallasite (6 K/Myr)
IAB Irons - The product of partial differentiation and impacts?

Ruzicka et al. Chemie der Erde (2014)
XPEEM magnetic image 5 µm f.o.v. Imilac Pallasite

Blue = Parallel to X-ray beam
Red = antiparallel to X-ray beam
White = perpendicular to X-ray beam (or zero magnetisation)
Meteorites from the main group pallasite parent body cooled at different rates and reach the tetrataenite ordering temperature at different times.

Each provides a snapshot of the dynamo activity at a given time, capturing the critical period of core solidification.
Extracting intensity and direction of remanence from the images

Figure 4.4: Open circles represent corrected histogram averages for the cloudy zone using Equation 4.2 for each averaged XMCD image of the cloudy zone. Red, purple and green represent rotations 1, 2 and 3 respectively. The average and two standard deviations in peak position is displayed for each rotation. All averages are very close to zero, however rotation 1 shows a slight negative offset and rotation 3 a slight positive offset, as predicted by the fact the relative change in magnetisation direction as the sample is rotated relative to the X-ray beam. The dotted lines show the position of the XMCD averages before correction, which are all negative.

Applying the correction (Equation 4.2) by adding it to each XMCD intensity, the histogram distributions are all approximately centred around zero. The shapes of the histograms notably change between rotations; the first rotation shows the most significant amount of variation from region to region. The second rotation has the narrowest histogram distribution, and the highest degree of symmetry about zero. The third rotation has a slightly wider distribution than the second. This again highlights the importance of carrying out multiple rotations, to take into account these biases.

Relative Paleointensity Estimates for Main Group Pallasites

The magnetic field experienced by the cloudy zone is proportional to the average XMCD intensity in the cloudy zone, and inversely proportional to the size of the tetrataenite islands in the cloudy zone.

\[ \frac{B}{r^3} = \frac{A}{r} \]

where \( B \) is the magnetic field, \( A \) is the average XMCD intensity and \( r \) is the radius of a tetrataenite island. A full derivation is given in Appendix A. The average XMCD intensity was calculated from the histograms of pixel intensity for strips of cloudy zone running parallel to the tetrataenite rim. An estimate of the magnetisation distribution predicted for zero
Testing for statistically significant shift

Figure 4.6: The top panel shows the random assignment of the six calculated tetrataenite rim intensities to an array containing the same number of islands as the region of interest in the cloudy zone. This region of interest contains 100 islands. The average of this random array is the first point in the second graph, shown in light blue. Ten averages of random arrays are shown in this plot, to reflect the 10 X-PEEM images of the cloudy zone acquired. The average of this second plot is then represented by the dark blue point in the bottom graph. The entire process is repeated 10,000 times to determine the range of XMCD intensity averages expected for a random distribution. The yellow box represents zero to 95% confidence ($\mu \pm 2\sigma$).

Figure 4.7: The relative intensities from cloudy zone XMCD intensity for five pallasites, normalised to the highest intensity for Imilac. Results for Brenham and Marjalahti are taken from Nichols et al. (2016). Results for Imilac and Esquel are taken from Bryson et al. (2015). The results for Springwater are from this study, and are shown for all three rotations (rotation 1 is dark blue, rotation 2 is royal blue, rotation 3 is light blue). The grey boxes represent zero to 95% confidence. Brenham, Marjalahti and Springwater all show weaker intensities than Imilac and Esquel, suggesting they are from the quiescent period when no core dynamo was active (Nichols et al., 2016).

Figure 4.8: (a) Relative paleointensities for each of the five pallasites: Marjalahti, Brenham, Springwater, Imilac and Esquel, calculated from the averages of the results in Figure 4.7. The time of CTRM acquisition for each is estimated from the thermal model for the pallasite parent body (Bryson et al., 2015). The grey line represents zero magnetic field to within 95% confidence. Intensities lying below this line cannot be distinguished from zero. (b) Each relative paleointensity value is subtracted from zero to 95% confidence. Any values which become negative are set to zero. (c) Each relative paleointensity corrected for the different depth of each pallasite within the parent body.
Testing for statistically significant shift

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- Marjalahti
- Brenham
- Springwater
- Imilac
- Esquel

±1 S.D. Zero (95% Confidence)
Powering the dynamo

Figure 4.10: Schematics of core solidification mechanisms and surface magnetic field evolution over time. Surface field intensity is not scaled and therefore cannot be compared between figures.

(a) Inward core solidification, initiated at the core mantle boundary. After the solid outer core reaches 10 km in thickness, it begins to delaminate. A dynamo is driven by diapir dripping (Bryson et al., 2017; Neufeld et al., 2017).

(b) Inward core solidification by concentric and dendritic growth can sustain a weak, long-lived compositional dynamo (Scheinberg et al., 2016).

(c) Inner core nucleation and outward solidification. A decrease in field strength is observed as the volume of liquid metal decreases (Aubert et al., 2009; Laneuville et al., 2014).

(d) ‘Iron snow’ mechanism, by which solidification occurs at the core mantle boundary, but crystals then sink to the core centre. Crystals are large enough to settle quickly and not undergo significant remelting. This generates an intense magnetic field which rapidly decays due to the high heat flux out of the core and rapid solidification (Scheinberg et al., 2016).

(e) If iron snow melts whilst it sinks, a sustainable compositionally-driven dynamo can be initiated (Rückriemen et al., 2015).
Conclusions

Meteoritic metal provides:

1. a widespread paleomagnetic target that is present in many different types of meteorite,

2. paleomagnetic signals with remarkably high magnetic stability,

3. a paleomagnetic remanence linked to primary nanostructures formed during cooling on the parent body,

4. new opportunities to study magnetic fields generated by differentiated bodies in the early solar system.
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