Synchrotron X-ray imaging of nanomagnetism in meteoritic metal

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AGU Fall meeting 2013, Rock Magnetism: Beyond the State-of-the-Art
Introduction

To date, nanopaleomagnetism has been studied mostly using high-resolution magnetic microscopies, for example electron holography:

**Advantages**
- Very-high spatial resolution (1 - 2 nm)
- Provides images of magnetic dipolar interactions

**Disadvantages**
- Excessive off-line processing; inhibits measurements of dynamic phenomena
- Sample experiences large magnetic fields during preparation; restricts study of natural remanences
- Images magnetic induction, not magnetisation

**Poster, Today:** Nanopaleomagnetism of Meteoritic Fe-Ni: the Potential for Time-Resolved Remanence Records within the Cloudy Zone. GP41D: Understanding Planetary and Stellar Magnetic Fields

Bryson et al., EPSL (2014)
Nanomagnetism can be imaged directly by utilising circularly polarised X-rays:
- XMCD intensity is a measure of the projection of the magnetisation onto the X-ray beam direction
- Can study dynamic processes
- Element specific
**X-ray Microscopy**

**Scanning Transmission X-ray Microscopy (STXM)**

**Advantages:**
- High spatial resolution (best 25 nm)
- High energy resolution

**Disadvantages:**
- Cannot study natural remanences
- Long acquisitions
- Studies relatively small areas

Out-of-plane worm-like magnetic domains – Co/Pt bilayer at Co absorption edge

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Stohr et al., Surface review and Letters (1998)

X-ray Microscopy

X-ray Photoemission Electron Microscopy (XPEEM)

**Advantages:**
- Can study natural remanences
- Capable of producing maps of all three spatial components of magnetisation

**Disadvantages:**
- Lower spatial resolution (best 40 nm)
- Surface sensitive (top 5 - 30 nm)
- Sample surface must be conductive (coating)

Kittel structure – Co/Cu/Py/Cu(001) trilayer at Co absorption edge

Wu et al., Journal of Physics: Condensed Matter (2010)

Stohr et al., Surface review and Letters (1998)
Meteoritic Metal

Widmanstatten microstructure

Kamacite
Tetrataenite (TT) rim
Cloudy Zone (CZ)
Plessite

Tazewell IIICD Iron meteorite
The Cloudy Zone

Bryson et al., EPSL (2014)

3D spinodal nanostructure, intergrown islands of tetrahtenite (FeNi) and matrix (ordered Fe₃Ni)
Over time islands and matrix evolve and coarsen
The Cloudy Zone

Bryson et al., EPSL (2014)

Tetrataenite (L1₀ superstructure) is an extremely hard magnetic phase and adopts one of 6 possible magnetisation directions. The proportion of the magnetisation directions depends on external fields.
Scanning transmission X-ray microscopy

Kamacite
Tetrataenite rim
Cloudy zone

Tazewell IIICD Iron meteorite

Magnetisation projected onto X-ray beam
White – zero signal, easy axis 1
Blue – positive signal, easy axis 2
Red – negative signal, easy axes 3

Advanced Light Source, Lawrence Berkeley National Laboratory
Photoemission electron microscopy

Kamacite
Tetrataenite rim
CZ
Plessite

BESSY II, HZB, Berlin

Tazewell IIICD Iron meteorite

Magnetisation projected onto X-ray beam
Blue – positive signal, easy axis 1
Red – negative signal, easy axes 2 and 3
Bryson et al., (in prep)
Quantitative Analysis

Simulated nanostructure

Out-of-plane magnetisation

Magnetisation projection onto X-ray direction

Projected magnetisation at experimental resolution

Realistic PEEM image

Bryson et al., (in prep)
Quantitative nanopaleomagnetism

Coarse CZ

Intermediate CZ

Fine CZ

Magnetic wall

Coarse and intermediate CZ – equal easy axis proportions
Fine CZ – unequal easy axis proportions
Entire CZ – short range order present

Bryson et al., (in prep)
Quantitative natural nanopaleomagnetism

**Imilac pallasite**
- Experimental data
- Simulated data

8% +ve easy axis 1
17% -ve easy axis 1
29% +ve easy axis 2
8% -ve easy axis 2
23% +ve easy axis 3
15% -ve easy axis 3

**Esquel pallasite**
- Experimental data
- Simulated data

14% +ve easy axis 1
0% -ve easy axis 1
32% +ve easy axis 2
24% -ve easy axis 2
17% +ve easy axis 3
14% -ve easy axis 3
Quantitative natural nanopaleomagnetism

**Imilac pallasite**
- 8% +ve easy axis 1
- 17% -ve easy axis 1
- 29% +ve easy axis 2
- 8% -ve easy axis 2
- 23% +ve easy axis 3
- 15% -ve easy axis 3

**Esquel pallasite**
- 14% +ve easy axis 1
- 0% -ve easy axis 1
- 32% +ve easy axis 2
- 24% -ve easy axis 2
- 17% +ve easy axis 3
- 14% -ve easy axis 3

Field intensity
- > 3.5 $\mu$T
- > 1.5 $\mu$T
Conclusions

Demonstrated the capabilities of synchrotron X-ray imaging in geomagnetism by studying novel nanomagnetic structures in meteoritic metal:

- Images magnetisation directly
- High spatial resolution (best 30nm) and large field of view (15 µm)
- Sub-micron-scale paleomagnetism

Coarse CZ in the Tazewell iron meteorite displays equal proportions of the possible easy axes, suggesting an absence of external fields during CZ formation, while in the Imilac and Esquel pallasites there are unequal proportions of the possible magnetisation directions, suggesting there were magnetised in fields of > 3.5 µT and > 1.5 µT respectively.