A 3D nanoscale approach to nebular paleomagnetism in the Semarkona LL3.0 ordinary chondrite

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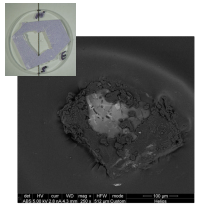
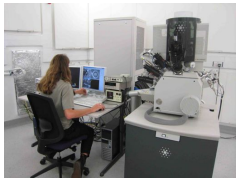
Solar nebula magnetic fields

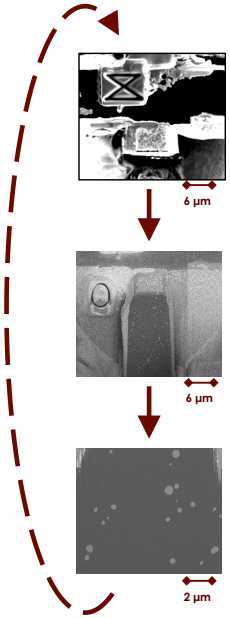
Fu et al.[1] recently measured the magnetic field intensity of the early solar nebular using single grains of dusty olivine in the Semarkona meteorite. Here we employ a variety of electron microscopy and numerical approaches to uncover the underlying rock magnetic properties of the dusty olivine inside one of the individual chondrules studied by Fu et al.





Central to this work, we use an FEI Helios Dual Beam Focused Ion Beam – Scanning Electron Microscope (FIB-SEM) to determine the three dimensional size distribution and orientation of the Fe nanoparticles inside dusty olivine.

Focused Ion Beam NanoTomography

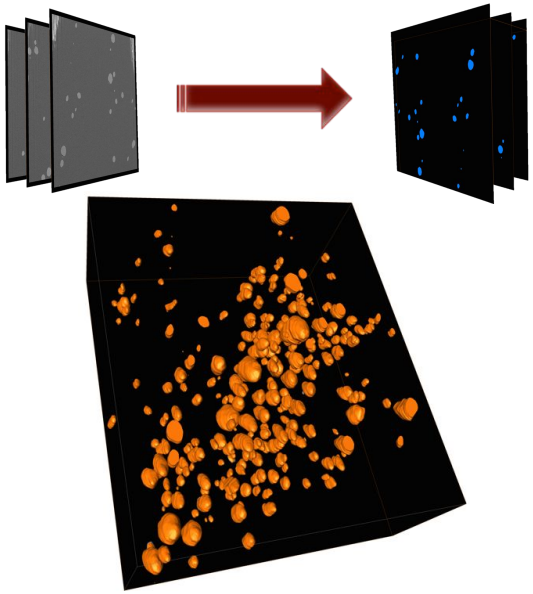


Using the Auto Slice and View G3 automation package, FIB patterning performs sequential and selective removal of 20 nm slices in the dusty olivine grain.

After removing the 20 nm slice, the cross sectional surface is imaged using the SEM. By locating the fiducial mark the region of interest can be repeatedly and accurately located. Image optimization occurs before taking the final SEM image.

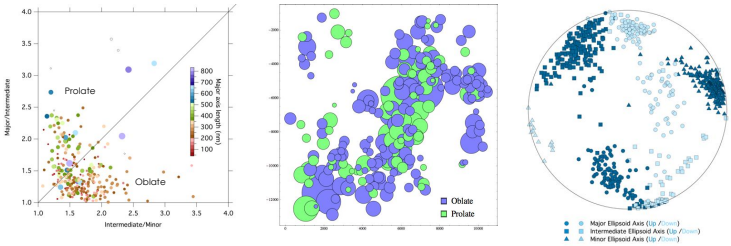
The final high resolution back scattered electron images are saved, and the routine is repeated to produce the full 261 image stack presented here.

Reconstruction



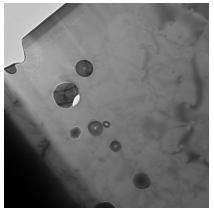
The SEM image stack is aligned, segmented, and realigned using the image processing tools in FIJI.[2] Once stack alignment is finalized the BoneJ plugin[3] is used to generate quantitative particle analysis.

Quantitative Metrics



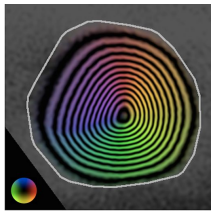
The best fit ellipsoids produced by BoneJ show us that the majority of the particles are oblate with average radii of 268 nm x 212 nm x 124 nm. The average prolate particle radii equals 327 nm x 174 nm x 123 nm. From the stereogram we can see that the particle orientations posses a strong directional anisotropy which is reflected in a measured magnetic anisotropy.

Lorentz Imaging



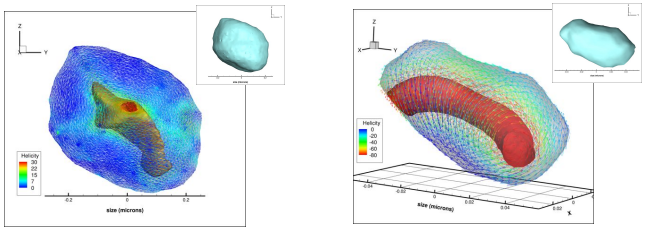
Dark or light spot in centre of particle indicates vortex core of an SV state

Holography



Magnetic induction map of single vortex particle produced using electron holography.

Micromagnetic Modeling



Particle geometries from the tomographic reconstruction were used to generate finite-element meshes and used as input to micromagnetic simulations. The two particles modeled both show vortex states. The left hand particle is the particle closest to the average prolate particle size. The right hand particle is the smallest prolate particle. The 'wings' emerging from the vortex core in the left hand grain are along the expected direction of a domain wall between the 010 and 001 easy directions. These wings are precursors to full domain walls and the first time such structures have been modeled. For the right hand particle, the vortex core is dominated by the shape anisotropy.

References

1. Fu, R. R. et al. Solar nebula magnetic fields recorded in the Semarkona meteorite. Science (80-.). 346, 1089–1092 (2014).
2. Schindelin, J. et al. Fiji: an open-source platform for biological-image analysis. Nat. Methods 9, 676–82 (2012).
3. Doube, M. et al. BoneJ: Free and extensible bone image analysis in ImageJ. Bone 47, 1076–9 (2010).
4. NanoPaleoMagnetism Project Website: https://wserv4.esc.cam.ac.uk/nanopaleomag/

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