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Nanopaleomagnetism: How to extract and understand ancient extraterrestrial magnetic signals from meteorites using synchrotron X-rays

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Magnetic signals recorded by meteorites provide invaluable information about the formation and evolution of our solar system. Before interpreting these signals, it is essential to understand how these signals are being recorded, and whether they are likely to be stable for billions of years. Over the last five years significant progress has been made in understanding the magnetic information recorded by iron-bearing meteorites. The bulk of meteoritic metal is kamacite ($Fe_{0.95}Ni_{0.05}$) which forms large mm-scale lamellae in the Widmanstätten pattern, a characteristic feature of slow-cooled iron meteorites. These kamacite lamellae are magnetically soft; they are multidomain and any magnetic information recorded is easily overwritten. Between the large-scale kamacite lamellae however, a range of microstructures form, including the cloudy zone. The cloudy zone consists of nanoscale islands of tetrataenite ($Fe_{0.5}Ni_{0.5}$) in an Fe-rich matrix. These tetrataenite islands are exceptional paleomagnetic recorders but their small size makes extracting paleomagnetic information experimentally challenging. X-ray photoemission electron microscopy (X-PEEM) allows the distribution of magnetization within the cloudy zone to be imaged with nanoscale resolution. This technique has been used to characterize the magnetic behavior of numerous meteoritic FeNi microstructures and has also been used to calculate paleointensities generated by planetesimal dynamos within the first 200 million years of solar system formation. Examples of studies on the IAB iron meteorites, the Main Group pallasites and the mesosiderites will be discussed.

Paleomagnetic signals have also been extracted from chondritic meteorites, which contain the first solids to have formed in our solar system. Paleomagnetic signals recorded by nanoscale Fe particles in dusty olivine grains in the Semarkona LL3.0 chondrite are interpreted as evidence for the strength of the solar nebula magnetic field. This record has significant implications for the evolution of the protoplanetary disk. Numerous microscopy studies have been conducted to verify the ability of these Fe particles to record stable paleomagnetic records from the earliest history of the solar system. Magnetic transmission X-ray microscopy (MTXM) has been used to image the nanoscale magnetic structure within individual Fe-particles from the Semarkona LL3.0 chondrite under applied laboratory fields and they are found to be stable in magnetic fields of at least 200 mT. MTXM has a significant advantage over electron microscopy techniques since imaging can be conducted under applied magnetic fields. This is very difficult to achieve using techniques such as Lorentz microscopy or electron holography as the applied magnetic field causes the electron beam to be deflected, defocusing the image.