SUB-MILLIMETER SCALE IMAGING OF MAGNETIZATION IN THE ALLENDE CV CHONDRITE: IMPLICATIONS FOR THE STRUCTURE OF THE SOLAR NEBULA

R.R. Fu[1], M.W.R. Volk[1], Dario Bilardello[2], Guy Libourel[3,4], Geoffroy Lesur[5], and Oren Ben Dor[1,6] [1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA USA. [2]Department of Earth and Environmental Sciences, University of Minnesota, Minneapolis, MN, USA. [3]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, Nice, France. [4]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, HI, USA. [5]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France. [6]Department of Physics, Harvard University, Cambridge, MA, USA. (rogerfu@fas.harvard.edu).

Nebular, dynamo, or impact-generated magnetic fields: The paleomagnetic record of the Allende CV chondrite has been extensively investigated to understand the nature of magnetic fields in the early solar system. Studies conducted in multiple laboratories have consistently found that Allende was magnetized in an ancient field of ~10-60 μT intensity [1-3]. Researchers have interpreted these strong magnetizations observed in Allende as a record of magnetic fields sustained by nebular gas [1], core dynamo magnetic fields on the CV parent body [2], and short-lived impact-generated magnetic fields [4].

Each interpretation, if correct, would have different implications for the planet formation process. The intensity of solar nebula magnetic fields may be diagnostic of the role that magnetism played in controlling the accretion rate of the protoplanetary disk and setting up nebular turbulence that may have led to planet formation [5]. Alternatively, the presence of a core dynamo on the CV parent body would imply that some chondritic parent bodies were partially differentiated into a metallic core, silicate mantle, and unmolten chondritic crust [6]. Finally, a record of impact-generated magnetic fields would provide the first natural evidence of a new process for generating magnetic fields on planetary bodies with broad implications for the interpretation of paleomagnetic and crustal remanence observations [4].

Predictions for fine-scale magnetization patterns: These different interpretations for the observed magnetizations in Allende make distinct, testable predictions for the distribution of magnetization at the sub-millimeter scale. In the case of a long-lasting magnetic field generated by the protoplanetary disk or core dynamo, a thermoremanent magnetization (TRM) affecting Allende is expected to magnetize all different ferromagnetic grain populations in including Fe-sulfide, magnetite, and FeNi metal (Fig 1; [7]). In the simplest scenario, such a TRM should be observed in both the porous matrix and chondrules.

However, paleomagnetic measurements of separated chondrules and matrix fragments showed that most chondrules do not carry the strong, unidirectional magnetization that has been interpreted to be a dynamo field record (hereafter, the MT component). Previous authors [7] attributed this heterogeneity to preferential removal of a pre-existing, spatially uniform remanence during the late alteration of ferromagnetic phases in chondrules [4]. If true, this scenario would predict that only specific ferromagnetic minerals that escaped later alteration should carry MT magnetization.

In contrast, such a chondrule-matrix dichotomy in natural remanent magnetization (NRM) properties can be simply explained in the impact hypothesis. Due to the short-lived nature of impact-generated magnetic fields, a record of such fields can only be preserved as a rapidly quenched TRM in the porous matrix due to heterogeneous shock heating [4]. In this case, all grain populations *in the matrix* should carry the MT component regardless of mineralogical context.

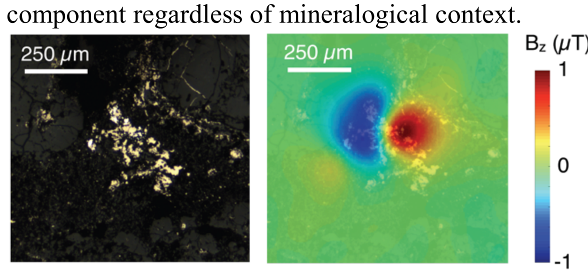

Figure 1: *Reflected light optical image and overlaid QDM magnetic field image of FeNi metal (awaruite) and Fe-sulfide association in the Allende matrix.*

Overview of methods: To help distinguish between the above-described scenarios, we conducted a suite of paleomagnetic experiments using the quantum diamond microscope (QDM) to image the sub-millimeter distribution of magnetization. We summarize the results of these experiments below.

We performed all experiments on a well-characterized section of Allende previously studied by Carporzen et al. (2011) and Fu et al. (2014) [2,7]. The previous studies had established that the sample has not been exposed to contaminating artificial magnetic fields and provide a reference direction and demagnetization spectrum for the MT component.

Experiment 1: Thermal demagnetization of NRM shows that matrix metal lacks MT magnetization. We imaged the NRM in Fe-sulfide and FeNi metal-rich regions of the matrix and performed stepwise thermal demagnetization to 600˚C (Fig. 1).

These experiments show that FeNi metal assemblages in both matrix and chondrule contexts carry NRM with scattered directions while sulfide NRM directions are consistent with that of bulk samples (Fig. 2). This observation that metal assemblages in Allende matrix do not carry the MT magnetization suggests that preferential impact heating of the matrix alone cannot explain the magnetization pattern in Allende.

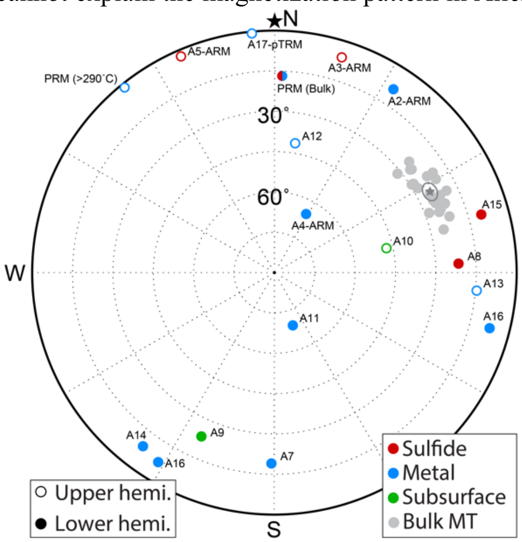

Figure 2: *Equal area stereonet diagram showing fitted NRM component directions and the direction of laboratory imparted remanence. Number adjacent to data points denote isolated source ID and symbol color denotes composition. Star denotes bias field direction in laboratory remagnetization experiments.*

Experiment 2: ARM, pTRM, and PRM acquisition experiments show that both metal and sulfide assemblages can acquire unidirectional remanence. We imparted an anhysteretic remanent magnetization (ARM) with 300 mT AC field, a series of partial TRM up to 400˚C, and a pressure remanent magnetization in 1.8 GPa hydrostatic pressure on Allende samples and imaged the change in magnetization in FeNi and sulfide assemblages. These experiments showed that ferromagnetic carriers of all mineralogies can acquire a unidirectional remanence in a uniform bias field. This result rules out large differences in thermal or shock remanence susceptibility to explain the lack of MT magnetization in FeNi metals.

Experiment 3: Thermal demagnetization of ARM shows that sulfides and FeNi metals have a Curie points at 284˚C and 539˚C. By tracking the decrease in source magnetic moment using repeated bulk sample measurements and QDM imaging during thermal demagnetization, we were able to identify the Curie temperatures of individual mineralogical assemblages. The 284˚C Curie temperature of the sulfide phases is consistent with the reported 290˚C maximum unblocking temperature of the MT component, which removes the main argument in favor of a partial TRM origin in previous studies [2,7]. Further, the higher Curie temperature of the FeNi metals implies that the MT component is unlikely to be a TRM because such a scenario would predict the presence of unidirectional magnetization in metal assemblages, which is not observed (see above).

Discussion and Conclusion: Our combined experiments show that the MT magnetization is carried exclusively by Fe-sulfide phases and that a magnetizing event of thermal or shock origin is expected to magnetize the FeNi metal. Because we observe no such FeNi remanence, we propose that the MT component is a chemical remanent magnetization (CRM) carried by Fe-sulfides. Because the capacity for CRM acquisition depends completely on the chemical transformation in question, a CRM may simultaneously result in a uniform unblocking temperature up to the Curie temperature and the exclusion of other ferromagnetic phases from carrying the MT component.

If we accept a CRM origin for the MT component, the timing of the recorded magnetic field then coincides with the aqueous alteration of the Fe-sulfide phases. Although these minerals in Allende have not been directly dated, Mn-Cr and I-Xe dating of secondary minerals in other CV chondrites and of magnetite in Allende have yielded early formation ages between 3.0±0.5 and 4.2±0.8 My after CAIs [8-10].

These early ages imply that the MT magnetization may have been acquired in the presence of solar nebula magnetic fields, although an early dynamo source cannot be ruled out. If the high ≥20 μT paleointensities reported for the MT component indeed reflect nebular magnetic fields, these values are approximately one order of magnitude stronger than nebular paleointensities recovered from other carbonaceous chondrites. Taken together, these data imply the presence of heterogenous magnetic field environments in the outer disk, suggests a central role for magnetic instabilities in disk accretion and the presence of ring and gap structures in the outer solar system.

References: [1] Sugiura, N. et al. (1979) *PEPI* 20, 342. [2] Carporzen, L. et al. (2011) *PNAS* 108, 6386. [3] Emmerton, A. et al. (2011) *JGR* 116, E12007. [4] Muxworthy, A.R. et al. (2017) *MAPS* 1. [5] Klahr, H. et al. (2018) in *Protoplanetary Disks: Setting the Stage for Planetesimal Formation*. [6] Weiss B.P. and Elkins-Tanton, L.T. (2013) *Annual. Rev. EPS.* 41, 21.1. [7] Fu, R.R. et al. (2014) *EPSL* 404, 54. [8] Doyle et al. (2015) *Nat. Comm.* 6, 7444. [9] MacPherson et al. (2017) *GCA* 201, 260. [10] Pravdivtseva et al. (2013) *44th LPSC*, 3104.