A WEAK SOLAR NEBULA MAGNETIC FIELD IN THE DISTAL SOLAR SYSTEM FROM RYUGU PALEOMAGNETISM. E. N. Mansbach¹, E. A. Lima¹, M. Sowell², J. L. Kirschvink²,3, R. R. Fu⁴, S. Cambioni¹, X-N. Bai⁵, J. B. Ream¹, C. Anal⁵, A. Kobayashi⁵,6, H. Hidaka⁵, B. P. Weiss¹, ¹Massachusetts Institute of Technology, Cambridge, MA, USA, ²California Institute of Technology, Pasadena, CA, USA, ³Kochi Advanced Marine Core Research Institute, Kochi, Japan, ⁴Harvard University, Cambridge, MA, USA, ⁵Tsinghua University, Beijing, China, ⁶Tokyo Institute of Technology, Meguro, Tokyo, Japan.

Introduction: Magnetic fields are thought to play a key role in driving angular momentum transport in protoplanetary disks (PPDs) via turbulence generation, a large-scale toroidal field, and/or disk winds [1]. They may also influence chondrule formation, planetesimal accretion and the radial transport of materials. Meteorite paleomagnetic studies indicate the presence of a nebular field in our solar system during the first 3 million years (Ma) after the formation of calcium aluminum-rich inclusions (CAIs), with an intensity of 20-70 µT at heliocentric distances of 1-3 AU [2] and 40-194 µT [3-5] at 3-7 AU. Assuming magnetic fields drive accretion, these field strengths correspond to accretion rates of $10^9$ - $10^7$ M⊙ yr⁻¹ (solar masses per year), consistent with astronomical observations of stellar accretion rates for PPDs during the main disk (class II) phase [6].

However, the existence and intensity of the nebular field in the distal (7 - 40 AU) solar nebula remain unknown. A unique opportunity to address this knowledge gap is provided by returned samples from Cb-type asteroid (162173) Ryugu by the Hayabusa2 mission [7]. These samples are important for two reasons: 1) Ryugu likely experienced alteration in the distal solar system as inferred from its chemical and isotopic compositions (e.g., [8, 9]); and 2) Ryugu experienced aqueous alteration at <2.93 Ma after CAIs as indicated by Mn-Cr chronometry [10], a time when the nebula was still present in the inner solar system. The aqueous alteration produced framboidal magnetite [11], which could have acquired a crystallization remanent magnetization (CRM) from the nebular field. The framboidal magnetite has been demonstrated to be in a stable magnetic domain state [12] and therefore should be able to record and retain a magnetization from the early solar system.

To determine the strength of solar system nebular field and the associated rate of magnetically driven accretion in the distal solar system, we present the results of a paleomagnetic study of three mm-sized Ryugu particles (A0397, C0006, and C0085b). We combine these results with a reanalysis of the alteration times and paleomagnetic record of two ungrouped chondrites, Wisconsin Range (WIS) 91600 and Tagish Lake, that also likely formed in the distal solar system [13, 14].

Fig. 1: Paleomagnetism of Ryugu. A) Orthographic projection of endpoints of NRM vectors on the northeast (N-E) and up-east (Z-E) planes for A0397. B) Moment (not normalized) versus AF level for the NRM and various ARM applications in sample A0397.

Results: Alternating field (AF) demagnetization of the natural remanent magnetizations (NRM) of A03397 (Fig. 1a) and C0085b revealed two weak components, denoted here as the low coercivity (LC) and medium coercivity (MC) components. The LC component unblocked by 10-15 mT depending on the sample and the MC component unblocked by 24 mT for both samples. The high coercivity (HC) range above the MC component had no recoverable NRM component. AF demagnetization of NRM for C0006 only revealed a non-origin trending LC component blocked to 20 mT.

We estimated the paleointensity of each component and the HC range by application and subsequent AF demagnetization of an anhysteric remanent magnetization (ARM) [100 µT bias field, and 145 mT
AC field] as a proxy for a CRM (Fig. 1b). The LC paleointensities for A0397, C0085b, and C0006 were 22.1 ± 5.1 μT (all uncertainties 95% confidence intervals), 118 ± 27.5 μT, and 7.9 ± 12.2 μT respectively. All paleointensities use updated CRM/ARM ratios from ref. [15]. The paleointensities of the MC components in A0397 and C0085b were 8.0 ± 5.5 μT and 3.6 ± 6.9 μT respectively. Like the latter, the paleointensities determined for the HC range of all three particles are indistinguishable from zero: 7.4 ± 9.3 μT (A0397), 26.3 ± 30.5 μT (C0085b), and 8.8 ± 16.5 μT (C0006).

**Discussion:** Our data indicate a weak or null field at the time of aqueous alteration assuming the scale of brecciation is not finer than the scale of alteration and that our particles constitute one clast each. We interpret the LC and MC components to be overprints due to exposure to the field of Earth and/or from the Hayabusa2 spacecraft since the components are generally not origin-trending and viscous remanent magnetization experiments indicate that a substantial portion (45-68%) of the components can be explained from prolonged low-intensity field exposure.

Considering that alteration occurred while the nebula was likely active, our strictest upper limit of 7.4 μT indicates the nebular field in the distal solar system was very weak. This upper limit is in stark contrast to the strong nebular field recorded in CO, CM and LL chondrites (e.g., [4]) (Fig. 2), and therefore supports the hypothesis that Ryugu and isotopically similar CI chondrites formed in a distinct region from other known chondrites [16]. Assuming a typical and spatially uniform accretion rate of 10^{-8}M_{\odot} yr^{-1}, the upper paleointensity limit suggests alteration at a heliocentric distance of >15 AU, consistent with the 13 – 25 AU formation distance independently inferred from chemical and isotopic studies of Ryugu [16].

We combine these results with paleointensities of Tagish Lake [14] and WIS 91600 [13]. Previous Mn-Cr dating on Tagish Lake dolomites suggested that these meteorites experienced alteration 3-4 Ma after CAIs [17], which spans the period over which the nebula might have dissipated. Accounting for the fractionation effects of Fe in dolomite compared to the calcite standard used in the original analysis, we estimate a refined age of <2.34 Ma after CAI formation [10].

We also update the previously reported Tagish Lake and WIS 91600 paleointensities to account for new results on ARM to CRM efficiency [15]. We find an upper limit for Tagish Lake of <0.9 ± 0.3 μT and a positive field detection of WIS 91600 as 5.1 ± 4.5 μT.

The field strength recorded by WIS 91600 indicates that the distal nebular field was capable of driving accretion at rates 8.0 × 10^{-10}M_{\odot} yr^{-1} to 6.2 × 10^{-8}M_{\odot} yr^{-1} at heliocentric distances 7 – 40 AU. Therefore, the results presented in our study of Ryugu combined with the updated ages and paleointensities of WIS 91600 and Tagish Lake suggest a faint distal nebular magnetic field capable of driving stellar accretion at rates consistent with those found by analyses of inner solar system meteorites.