Paleomagnetic Evidence for Formation of Ryugu in the Distal Solar System

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Paleomagnetic studies of meteorites have demonstrated that the solar nebula generated a magnetic field that likely played an important role in accretion during the early solar system [1]. The nebular field reached intensities of 54 ± 21 μT at heliocentric distances of 1-3 AU [2] and 101 ± 48 μT at 3-7 AU [3], and likely decayed by ~3-4 million years (Ma) after the formation of calcium aluminum-rich inclusions (CAIs) [4-7]. However, with the possible exception of Tagish Lake and Wisconsin Range (WIS) 91600, these studies have been restricted to meteorites that formed at distances <7 AU [8, 9]. Tagish Lake is of particular interest as its arrival to Earth from the asteroid belt implies that its parent body had been inwardly scattered, perhaps due to the formation and migration of the giant planets [9, 10].

The returned samples from asteroid (162173) Ryugu by the Hayabusa2 mission currently provide the best opportunity to study the nebular field in the distal solar system as the parent body may have experienced aqueous alteration at distances up to ~20 AU [11]. These particles are also high-quality targets for paleomagnetic investigations as they are: 1) in pristine condition since careful sample handling limits the possibility of magnetic and terrestrial contamination, which can lead to the creation of ferromagnetic minerals that mask the primary record of the particles, and 2) contain single-vortex framboidal magnetite which can retain magnetic records over the age of the solar system [12]. If the magnetite shows evidence of magnetization produced by an ancient field, the source of the field could have been the nebular field or a dynamo on the parent body. The latter case is of particular interest since this would imply that the parent body was partially differentiated with a carbonaceous chondritic crust [13]. Our current understanding of the lifetime of the nebula suggests that if the natural remanent magnetization (NRM) was acquired < 4 Ma, the source of the field was the nebula while a younger age would be indicative of a parent body dynamo. Initial Mn-Cr dating on carbonates that are thought to have formed at the same time as the magnetite yielded an age of 3.1 – 6.8 Ma after the formation of CAIs [14], but more recent dating on carbonates using the same dating system and improved calibrations suggests alteration occurred < 1.8 Ma after CAI formation [15].

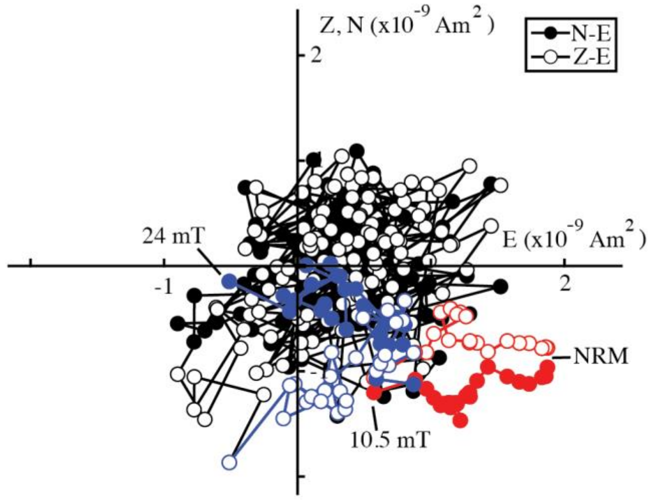

Figure 1: Orthographic projection of endpoints of NRM vectors on the northeast (N-E) and up-east (Z-E) planes during alternating field demagnetization of particle A0397. The LC component is shown in red, the MC component in blue, and the HC range in black. No components are observed >24 mT.

An initial paleomagnetic study of two Ryugu particles concluded that the particles formed in a > ~40 - 400 μT nebular field [14, 16]. However, this magnetization may be post-sampling contamination because: 1) magnetite can have coercivities up to 300 mT, but the NRMs of previously studied samples were unblocked to only 30 mT; 2) the previously studied samples had been analyzed with an electron microprobe which may have imparted a weak isothermal remanent magnetization (IRM); and 3) initial analysis of MasMag magnetometer data suggested that a boulder on Ryugu did not possess a measurable magnetization ($< 3 \times 10^{-6}$ Am^2 kg^{-1} at the m-scale) [17], yet the moment per unit mass of the reported samples is well above this limit (2.14×10^{-5} Am^2 kg^{-1}).

To address the origin and nature of NRM in Ryugu, we conducted an additional paleomagnetic analysis on three previously unstudied Ryugu particles: A0397, C0085b, and C0006. These samples have not been previously studied using a microprobe or instrument with a strong magnet prior to our paleomagnetic analysis.

Alternating field (AF) demagnetization of the NRM in A0397 to 400 mT in steps of 0.5-1 mT revealed two non-origin trending components (Fig. 1), a low coercivity (LC) component that unblocked between 0 and 10.5 mT and a medium coercivity (MCs) component that unblocked between 11 and 23.5 mT. Above >24 mT is a high coercivity (HC) range in which no NRM components are observed. AF demagnetization of C0085b to 400 mT revealed three NRM components: an LC component that unblocked between 0 and 12.5 mT, and two MC components that unblocked between 13 and 19 mT and 19.5 and 23.5 mT, respectively. The second MC component was origin-trending. As before, above >24 mT is a HC range containing no stable NRM. AF demagnetization of C0006 to 80 mT conducted in 5-10 mT steps revealed a non-origin trending LC component that unblocked between 0 and 20 mT with no apparent components in the HC range above 20 mT.

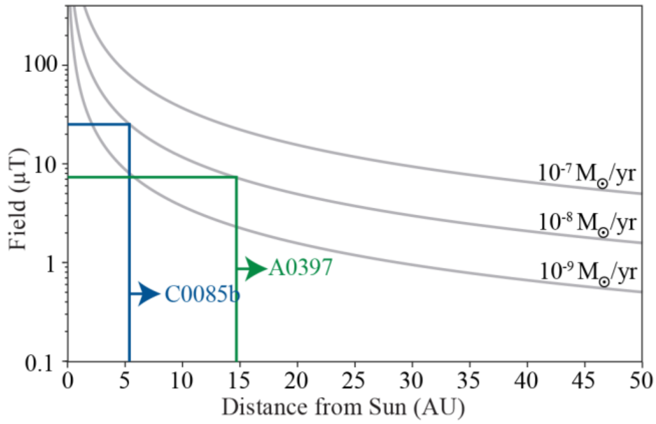

Figure 2: Predicted midplane nebular field assuming accretion around a solar mass star and that the nebular field and disk rotation are aligned. Accretion rates are given at the right-hand side for each curve. Colored lines represent constraints on heliocentric distance at which aqueous alteration occurred based on upper paleointensity limits from particles C0085b and A0397.

Paleointensities estimated via the anhysteretic remanent magnetization (100 μT bias field and 260 mT AC field) method for the LC components are 125.8 ± 28.9 (95% confidence interval, as for all below), 694.6 ± 145.5 and 44.8 ± 69.5 μT for A0397, C0085b, and C006 respectively. The MC paleointensity for A0397 is 45.6 ± 31.6 μT, while the two MC paleointensities for C0085b are 36.0 ± 44.4 and 62.3 ± 134.7. Importantly, the HC paleointensities are all also consistent with null paleofields: 26.4 ± 30.6 μT for C0085b, 7.4 ± 9.2 μT for A0397, and 8.8 ± 16.4 μT for C0006. This indicates that there are magnetic recorders with coercivities >24 mT in the particles that are capable of recording an ancient field but instead formed in the presence of a null or weak field.

Experiments conducted to determine the susceptibility of A0397 to viscous (VRM) remagnetization from prolonged exposure to an Earth-strength field indicate that the total moment gained over 4.5 years (initial sampling to NRM demagnetization) could account for 98% of the combined LC and MC components. We therefore suggest that the source of the LC and MC components in our samples are overprints, most likely a VRM from sitting in Earth's field and the field produced by spacecraft engines (10s of μT [16]) since sampling. The non-origin trending nature of the two A0397 components further indicate that they are not primary. We suggest that the previously reported strong paleointensities are due to a weak IRM from the electron microprobe as ratio of NRM to saturating IRM is >10% and the components are not origin trending as well.

Our results have profound implications for the history of the Ryugu parent body. Taking the alteration age to be < 1.8 Ma after CAI-formation, our most stringent upper paleointensity limit of 7.4 μT indicates that alteration occurred at heliocentric distances >15 AU for typical accretion rates during the main lifetime of the nebula of 10^{-8} M⊙ yr^{-1} (and >5 AU for the lower range of accretion rates during the main lifetime of the nebula) (Fig. 2). Given Ryugu's current location (~1 AU), the parent body may have been scattered inward prior to catastrophic disruption, but after experiencing aqueous alteration, due to influence from the giant planets in a similar manner to that proposed for the parent body of Tagish Lake. Our results therefore provide further evidence that the formation and migration of the giant planets led to a major reconstructing of the organization of the solar system.

References

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