EVIDENCE FOR PLANETARY MIGRATION IN THE EARLY SOLAR SYSTEM FROM METEORITE PALEOMAGNETISM

J. F. J. Bryson[1,2], B. P. Weiss[2], E. A. Lima[2], J. Gattacceca[3], W. Cassata[4], [1]Department of Earth Sciences, University of Cambridge, Cambridge, UK, [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [3]CEREGE, CNRS/Université d'Aix, Aix-en-Provence, France, [4]Lawrence Livermore National Laboratory, CA, USA.

Introduction: At least two major planetary migrations events have been proposed to have occurred within the first ~1 Gyr of our solar system. The first is the Grand Tack [1], which involves the early growth and gas-driven migration of Jupiter and Saturn, and the second is the Nice model [2], which involves the late, sudden outward migration of the outer solar system bodies as Jupiter and Saturn passed through their 1:2 resonance. Despite the enormous impact these events would have had in shaping the architecture of our solar system, relatively little direct evidence for either event has been gleaned from the meteorite record. As both events are predicted to have been capable of transporting small bodies that formed in the outer solar system into the asteroid belt, one key observation that would elucidate these migrations is the identification of meteorites derived from the present-day asteroid belt that originally formed beyond the orbit of Jupiter. However, reliable and direct estimates of the formation radii of meteorite parent bodies are sparse [3]. Furthermore, estimates of the formation time and radii of meteorite parent bodies would provide vital constraints on the rates, distances and mechanisms by which chondrules and calcium-aluminium-rich inclusions (CAIs) were transported throughout our young solar system.

With this goal, we conducted paleomagnetic measurements of the Tagish Lake meteorite. The absorption spectra [4], isotopic signature [5] and composition [6] of this meteorite suggest that its parent body likely formed relatively far from the Sun. Moreover, the measured age of carbonate formation in Tagish Lake of ~4 Myr after CAI formation [7] indicates that the formation of magnetic phases in this meteorite during the aqueous alteration of its parent body likely occurred while our nebula was still generating a magnetic field [8, 9]. As the intensity of this field is predicted to have decreased with distance from the Sun [10], the paleointensity recovered from Tagish Lake could be used to constrain the formation radius of its parent body.

Samples and Methods: The Tagish Lake meteorite is an ungrouped C2 carbonaceous chondrite that fell on January 18th 2000. Magnetite is abundant in this meteorite and is found as nm-scale crystals organised into framboids, stacks of µm-sized platelets and µm-sized spherules [11]. The grains in the framboids display vortex magnetic domain states [12], which are extremely stable remanence carriers [13]. When magnetic phases form in the presence of a magnetic field, they can acquire a chemical transformation remanent magnetisation (CTRM) whereby grains preferentially form with their magnetic moments aligned in the direction of the field. The extent of this directional bias can be measured at the present day using routine paleomagnetic methods and can be used to constrain the intensity of the ancient field that imparted the remanence.

We obtained a pristine sample of Tagish Lake from U. Alberta that had fusion crust along one edge and extended up to 12 mm from the fusion crust. We cut multiple, mm-sized, mutually-orientated subsamples from the sample at increasing distance from the fusion crust. We demagnetised the natural remanent magnetisation (NRM) of 8 subsamples using alternating field (AF) methods. We constrained their paleointensities and paleomagnetic fidelity by applying and subsequently demagnetising anhysteretic remanent magnetisations (ARMs) with a range of bias fields (thermal equivalent fields of 15, 1.5 and 0.15 µT). We conducted Thellier-Thellier measurements on 4 subsamples, heating the subsamples in air. The AF subsamples spanned the range of possible distances from the fusion crust, while all of the Thellier-Thellier subsamples originated from >2 mm from the fusion crust.

Results: All the subsamples demagnetised using AF methods (expect for one that had fusion crust along one face) only contained a low coercively (LC) component to their NRM that was blocked up to 6.5 - 42 mT depending on the proximity of the subsample to the fusion crust. All of the subsamples still contained a component of their 15 µT and 1.5 µT ARMs in the higher coercivity (HC) AF range. Two of the subsamples (TL-4 and TL-8a) also still contained a component of the 0.15 µT ARM in the same coercivity range.

We constrained the paleomagnetic fidelity of our AF subsamples by attempting to recover the bias fields of the applied ARMs using the same method that we used to constrain the paleointensity of the field that imparted the NRM [14]. Two of our subsamples (TL-4 and TL-8a) had sufficiently high fidelities that we were able to recover the bias field intensity within a factor of 2 for the 0.15 µT ARM, implying that these subsamples are capable of providing reliable paleointensity estimates down to this field intensity.

The absence of a NRM in the same coercivity range in which the 0.15 µT-equivalent ARMs persisted in TL-4 and TL-8a implies that these subsamples experienced fields with intensities weaker than this value.

Indeed, the average paleointensity calculated across the HC range in these subsamples is 0.05 ± 0.07 µT.

The subsamples in our Thellier-Thellier experiments altered on heating above ~200 - 300 ˚C and did not provide reliable paleointensity constraints.

Discussion and Implications: Aqueous alteration of carbonaceous chondrites was a protracted process, certainly lasting >1 year and most likely lasting for 10^5-10^6 years [15]. Petrological observations indicate that magnetite formed during the earliest stages of this process on the Tagish Lake parent body [11]. Magnetite I-Xe ages predate carbonate Mn-Cr ages in other carbonaceous chondrites by ~1-2 Myr [7, 16], suggesting that magnetite possibly formed ~3 Myr after CAI formation in Tagish Lake. We are in the process of acquiring magnetite I-Xe ages of Tagish Lake to obtain a precise age of CTRM acquisition in this meteorite.

The magnetic field generated by our nebula contained a weak component that was directionally-stable across the lifetime of the nebula [8], which has been constrained from paleomagnetic measurements to have been >3 - 3.5 Myr after CAI formation [8, 9]. Consequently, Tagish Lake likely acquired a CTRM while the nebula was still generating a magnetic field, yet it experienced field intensities ≤0.15 µT. The intensity of the stable component of the nebula field is predicted to have only reached these low values at distance ≥20 AU from the Sun (for a ratio of thermal to magnetic pressure in the mid-plane of the disc of 10^{-5}) [10], implying that the Tagish Lake parent body formed in the outer solar system (Fig 1). According to the Grand Tack model [1], bodies that formed at these distances constitute a significant fraction of the present-day Kuiper belt. It is therefore feasible that Tagish Lake is a piece of a comet. Indeed, our formation radii and field limit agree extremely well with those of comet 67P [17].

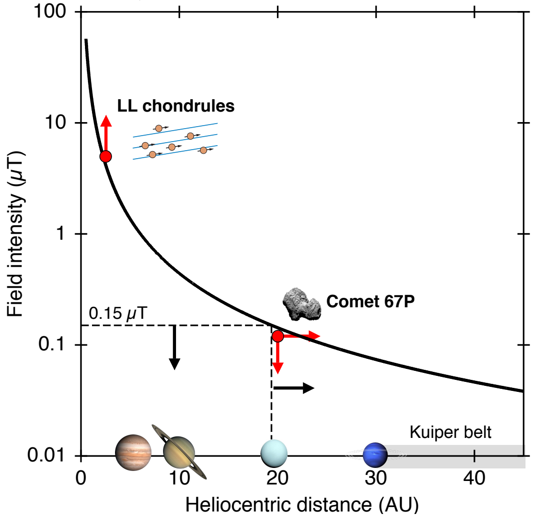

Figure 1. Predicted intensity of the stable component of our nebula field with heliocentric distance [8].

The well-documented fall of the Tagish Lake bolide allowed its pre-impact orbit to be calculated, which indicates that Tagish Lake made its way to Earth from the asteroid belt [18]. Coupled with our paleomagnetic constraint that the Tagish Lake parent body formed at ≥20 AU, this observation supports the migration of this body from the Kuiper belt to the asteroid belt. The only processes that have been proposed to have caused such inward transport are migrations of the gas giants. If Grand Tack was responsible for this transport, it is possible that Tagish Lake would have experienced the dying moments of the nebula magnetic field [19]. The absence of any pre-terrestrial remanence in our Tagish Lake sample suggests that this scenario is less likely, leaving the migrations in the Nice model as perhaps the more likely process [20].

Tagish Lake contains aqueously-altered chondrules (0.25 - 1 mm large) and CAIs (200 - 300 µm large) [9]. Our results therefore imply that these planetary components were present at distances ≥20 AU (in agreement with observations of the Stardust mission [21]) at times earlier than the accretion age of the Tagish Lake parent body (≲4 Myr after CAI formation [7]). CAIs are thought to have only formed within ~1 AU of the Sun and gas densities are thought to have been too low to permit chondrule formation in the outer solar system [22]. Hence, our observations support the efficient outward transport (from ≲1 AU to ≥20 AU within ≲4 Myr) of the first solids that formed in our solar system.

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