CONSTRAINTS ON THE TIMESCALES AND DISTANCES OF SOLID MIGRATION IN THE SOLAR NEBULA FROM METEORITE PALEOMAGNETISM.

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Introduction: Solid objects ranging in size from mm-scale calcium-aluminium-rich inclusions (CAIs) to km-scale planetesimals are thought to have migrated throughout the early solar system [1,2]. Although these migrations have been proposed to have played key roles in generating the present day architecture of the solar system and forming planetary bodies, their timescales and distances are poorly constrained.

One reason for this limited understanding stems from difficulties in recovering the formation distances of meteorite components and parent bodies from laboratory measurements. Recently, paleomagnetic measurements have been proposed as a method of recovering these distances [3]. Models of our nebula suggest that the magnetic field it supported decreased in intensity by orders of magnitude over distances of tens of AU from the Sun [4]. Paleointensities recovered from the natural remanent magnetisation (NRM) carried by material old enough to have recorded a remanence of this field could therefore be used to constrain its formation distance. We applied this approach to LL chondrules, bulk CM chondrites and comet 67P [3], all of which yielded formation distances within error of independent estimates [5]. We also applied this approach to the Tagish Lake C2 chondrite, which yielded a formation distance of >13 AU [3], indicating the distal formation of some meteorite parent bodies.

The prolonged thermal and aqueous history of Tagish Lake means it recorded a chemical remanent magnetisation (CRM) of the time-averaged, stable component of the nebular field. The weak intensity of this component limits accurate paleointensity recovery, restricting our formation distance constraint to a lower limit. Additionally, the nature of CRM acquisition introduces uncertainties in the recovered paleointensity.

These issues could be overcome studying a meteorite that was briefly heated on its parent body within the lifetime of the nebula. This meteorite will have recorded a thermoremanent magnetisation of the intense, instantaneous (stable for periods of ~100 y) component of the nebular field [4], permitting accurate paleointensities to be recovered from thermal demagnetisation of this sample. These measurements could provide additional evidence that some meteorite parent bodies formed at large heliocentric distances as well as accurate constraints on these distances. With this goal, we measured the NRM carried by the metamorphosed C2 chondrite WIS 91600, which bears spectral, mineralogical and isotopic similarities to Tagish Lake [6-8].

Results: We recovered paleointensities from 7 mutually-oriented subsamples of WIS 91600 (12 - 37 mg) using in-field, zero-field double heating. The NRM of these subsamples consists of low (<200 ˚C, LT) and high temperature (200 - 390 ˚C, HT) components. Five subsamples displayed minimal alteration during heating. The average LT paleointensity of these subsamples is 32.9 ± 10.2 µT, consistent with WIS 91600 carrying a viscous terrestrial overprint. The average HT paleointensity is 4.0 ± 2.6 µT (1σ). This value and alternating field demagnetisation measurements indicate this remanence dates from heating on the parent body.

Discussion: *Nature of the field that magnetised WIS 91600.* A number of fields in the early solar system could have magnetised chondrites. The field that magnetised a specific chondrite depends on its peak temperature, cooling timescale and time of heating.

The concentration of thermally labile elements [8] and our thermal demagnetisations indicate WIS 91600 was heated to 400 - 500 ˚C. The size of Fe-Ni-S microstructures indicate WIS 91600 then cooled to ~200 ˚C in <10 hours [9]. This thermal history suggests WIS 91600 was heated by an impact. Impact shock waves are expected to have heated chondrite matrix [10]. This heat then diffused into cold, neighbouring chondrules, which we calculate led to both matrix and chondrules in WIS 91600 reaching a re-equilibrated temperature of >400 ˚C in <2 s before it cooled as a whole over a few hours as discussed above. This short time and high temperature rule out transient (<10 s) impact-generated fields as the source of the HT remanence.

The textures of aqueously-altered carbonaceous chondrites indicate that their parent bodies experienced multiple low-energy impacts during alteration [e.g., 11]. Some carbonates in these meteorites appear to have precipitated shortly after these impacts [12,13]. Mn-Cr dating of these carbonates in weakly (≤200 ˚C) and moderately (~200 - >500 ˚C) heated CM, CI and C2 chondrites suggest these impacts occurred between ~3.6 - 5.0 My after CAI formation [14]. WIS 91600 displays compositional and textural similarities to these moderately-heated chondrites [8], implying it was also likely heated by one of these impacts. Hence, WIS 91600 likely underwent heating and cooling within the lifetime of the nebula (~3.8 - 4.8 My after CAI formation [15]) and before asteroid cores could likely have generated dynamo fields [16]. The HT remanence in WIS 91600 is therefore likely a record of the instantaneous component of the nebular field.

Formation distance of the WIS 91600 parent body. Magnetohydrodynamical models predict that the instantaneous component of the nebular field reached 4.0 μT at ~10.5 AU [4] (Fig. 1), indicating that the WIS 91600 parent body formed distally, likely a few AU closer to the Sun than the Tagish Lake parent body [3].

Planetary migration. WIS 91600 likely came to Earth from the asteroid belt. Our recovered formation distance therefore suggests that the WIS 91600 parent body migrated from ~10.5 AU to 2 - 3 AU sometime before coming to Earth. The only processes that have been proposed to have caused such motion are gas giant migrations [e.g., 1]. Our recovered formation distance therefore supports at least one major planetary migration event in the history of our solar system.

Chondrule and CAI migration. WIS 91600 contains chondrules and CAIs. CAIs are generally believed to have formed within 1 AU of the Sun. The average O isotope composition of type I chondrules in WIS 91600 [17] is very similar to that in CO and CM chondrules [18], indicating they likely originated from a common reservoir (possibly present at ~3 - 4 AU) and probably formed at similar times (≲3.0 My after CAI formation) [5]. The extent and nature of aqueous alteration in WIS 91600 suggest that its parent body accreted at a similar time as those of the CM and CI chondrites (~3.0 - 3.5 My after CAI formation) [14]. Our observations therefore support the efficient outward migration of thermally-processed, mm-sized solids from <1 - 4 AU to ~10.5 AU in 0.5 - 3.5 My.

Ice migration. The typical O isotope compositions of bulk distal meteorites (WIS 91600 [7], Tagish Lake [19] and CI chondrites [20], proposed to originate from >15 AU [5]) are δ^{18}O = 15 - 20 and δ^{17}O = 8 - 10, distinct from those of most other carbonaceous chondrites. Hence, the O isotope composition of carbonaceous chondrite material reflects its formation distance, with distal material being enriched in ^{17}O and ^{18}O.

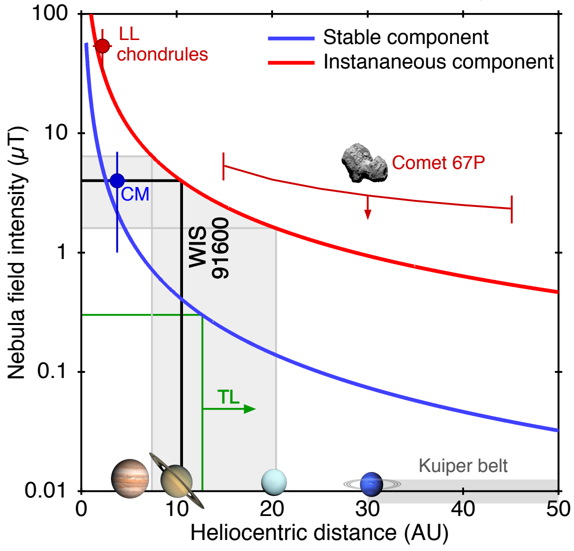

Fig 1. Model intensities of both components of the nebular field with heliocentric distance [4]. Recovered paleointensities and formation distance constraints of LL chondrules, bulk CM chondrites, comet 67P, Tagish Lake (TL) and WIS 91600 are included [3,5].

The O isotope compositions of bulk CO and CM chondrites [20] plot on a line on the triple O isotope diagram with slope ~0.7 that extends from the average O isotope composition of type I chondrules in these groups (δ^{18}O ≈ -5, δ^{17}O ≈ -8 [18]) to that of the bulk distal meteorites. The O isotope composition of bulk CR chondrites plot on a similar line [21] that extends from a different average type I chondrule isotope composition (δ^{18}O ≈ 0 and δ^{17}O ≈ -2.8 [22]). More aqueously altered material in all of these groups tends to plot at higher ^{17}O and ^{18}O values along these lines, with the extensively altered matrix in the CM chondrites and CR1 GRO 95577 plotting at the highest values along each line [20,21]. Therefore, the addition of water to pristine CM, CO and CR material moves its O isotope composition along these lines towards that of the bulk distal meteorites. This observation suggests that some of the ice accreted into the CM, CO and CR parent bodies originated in the distal reservoir from which WIS 91600, Tagish Lake and the CI chondrites formed and that this ice had migrated to ~3 - 4 AU by ~3.0 - 3.5 My after CAI formation.

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