CONSTRAINTS FROM ISOTOPIC DICHOTOMY OF METEORITES AND FROM A TRANS-JOVIAN ORIGIN FOR CARBONACEOUS CHONDRITES ON THE ORIGIN OF CHONDRITIC COMPONENTS

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Introduction: Mass-independent isotopic variations for O, Cr, Ti, and Ni in meteorites define two well-separated clusters: carbonaceous chondrites and some differentiated meteorites in one cluster, and all other meteorites in the other [1]. Warren [1] speculated that the two clusters formed in the outer and inner Solar System, respectively. Coincidentally, a mechanism for deriving these two populations of planetesimals was proposed by Walsh et al. [2]. In their Grand Tack model, Jupiter's migration initially emptied and then repopulated the main asteroid belt with S-type planetesimals from the belt and C-types from beyond Jupiter. Evidence for the "Warren gap" on the $^{17}\Delta$O *vs.* ε^{54}Cr plot has since strengthened as the number of distinct types of analyzed meteorites including ungrouped ones has increased from 26 to 42, e.g. ref., [3]. Equally important, iron meteorites define the same two isotopic reservoirs, carbonaceous and non-carbonaceous, on a plot of ε^{95}Mo *vs.* ε^{94}Mo showing that the isotopic dichotomy existed from <1 Myr after CAIs when iron meteorite bodies accreted to 3−4 Myr after CAIs when CR chondrites accreted [4,5]. Isotopic constraints and Jupiter formation models can help explain how chondritic components formed.

Ca-Al-rich inclusions: If CAIs formed close to the protosun, why are they much more abundant in C chondrites, which formed furthest from the Sun? How did they survive in the disk for 3 Myr? Some authors argue that CAIs and chondrules formed near the Sun and were transported outwards via X-winds [6] or disk winds [7,8]. Other models invoke outwards turbulent flow of CAIs at the disk midplane [9] or aerodynamic redistribution of chondritic components and early formation of C chondrites [10]. Given that (*i*) the O isotopic compositions of CAIs and chondrules show that they formed in different disk regions [11], (*ii*) Al-Mg radiometric ages of chondrules in C chondrites are mostly younger than those in LL chondrites [12], and (*iii*) CAIs were present where C chondrite chondrules formed [13], we favor distribution of CAIs outside the disk. We envisage that CAIs were transported by disk winds to the outer solar system and drifted inwards due to gas drag until they piled up outside proto-Jupiter's orbit. Once Jupiter reached 10 M_E it generated a pressure bump preventing inwards drift of mm-cm sized particles including ice [14].

Bulk chondrite refractory element abundances: Our proposed scenario for CAIs explains why C chondrites are enriched in refractory elements, why bulk compositions of CV chondrites show type II REE patterms, why thulium is depleted in the inner solar system relative to C chondrites [15], and why C chondrites are enriched in ε^{50}Ti [16]. CAIs are enriched in ε^{50}Ti, about half have type II REE patterns, which lack the most-refractory REE save for thulium which is enriched ~10-fold relative to neighboring REE.

Chondrules and matrices: Formation of C chondrites beyond Jupiter can account for the near-simultaneous formation of chondrules in LL and CO chondrites and oxygen isotopic and chemical data showing that there was virtually no mixing between these two reservoirs. Chondrules in CM, CO, CR, CV, and ungrouped C chondrites have O isotopic compositions that lie along the PCM slope-1 line with a significant range of Δ^{17}O values, typically from -6‰ to -1‰ [17]. By contrast, chondrules in LL, H, R, K, and E chondrites show small ranges of Δ^{17}O values and define mass fractionation trends near the terrestrial fractionation line [18]. This reflects mixing of ^{16}O-rich amoeboid-olivine inclusions that accompany CAIs as well as ^{17,18}O-rich water [17], neither of which are abundant in the inner solar system [14]. Matrices and chondrules originated in the same regions.

Discussion and implications: The asteroid belt is a "cosmic zoo" containing planetesimals from all over the solar system: E chondrites and achondrites from <2 AU, C chondrites from beyond Jupiter, and P and D asteroids from trans-neptunian orbits, which were added during the LHB [19]. Because of early protoplanetary growth <1 Myr after CAIs, the disk was carved into separated zones before chondrites formed and multiple chondrule-forming mechanisms operated across the disk [8]. Comet Wild 2 chondrule fragments probably formed in the outer solar system. Planetesimals from beyond Jupiter were probably mixed into the asteroid belt when Jupiter reached 40 $M_{E,}$ started to migrate, and scattered planetsimals into and out of the asteroid belt [2]. A Grand Tack is needed to explain why the belt is severely depleted in mass and now contains subequal masses of C and S asteroids: depletion preceded addition of C-type (and S-type) asteroids. CB chondrites formed during the Grand Tack [20], consistent with OC clasts in CBs.

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