CONSTRAINTS ON CHONDRULE GENERATION, DISK DYNAMICS, AND ASTEROID ACCRETION FROM THE COMPOSITIONS OF CARBONACEOUS METEORITES. J. F. J. Bryson[1] & G. A. Brennecka[2], [1]Department of Earth Sciences, University of Oxford, Oxford, UK. [2]Lawrence Livermore National Laboratory, Livermore, CA, USA.

Introduction: The elemental and isotopic compositions of meteorites are expected to reflect several key processes that acted in the protoplanetary disk, including the migration of gas and dust throughout the disk, the formation of chondrules, and the accretion of the first planetary bodies. However, the specific origins of these various compositions are currently poorly constrained, limiting our understanding of these processes and the early evolution of the Solar System.

Here, we explore these origins by applying an inverse mixing model to a compilation of previously measured elemental and isotopic compositions of carbonaceous (CC) meteorites (chondrites and iron meteorites) and their components. We find that the compositional dichotomy among non-carbonaceous (NC) and CC meteorites [1] is rooted in the mixture of different materials throughout the protoplanetary disk. We also uncover near-identical Cr isotopic signatures among chondrules in most CC chondrites, helping to elucidate the generation of these enigmatic objects.

Methods: We examined the elemental and isotopic compositions of refractory and main component elements in CC chondrites (Ti and Cr, respectively; [2-5]) and CC iron meteorites (Mo and Ni, respectively; [3,6]). We also examined the elemental concentrations of six plateau volatile elements (Bi, Ag, Pb, Zn, Te, & Sn) in CC chondrites [7]. We explored whether all of these compositions can be expressed as mixtures of different materials found in the protoplanetary disk, namely bulk NC chondrite material, calcium-aluminum-rich inclusion (CAI) material, and CI chondrite material. When we found this to be the case, we recovered the proportions of each of these materials that make up the compositions of these meteorites.

Results: *Refractory elements:* Following ref [3], the elemental and isotopic compositions of refractory elements in CC chondrites lie on mixing curves between NC and CAI material, arguing that the compositions of these elements in these meteorites originate from mixing these materials. The amount of CAI material ranges from ~2.5 - 6 wt% depending on the group.

Main component elements: The elemental and isotopic compositions of Cr in CC chondrites also lie on a mixing curve; however, this curve extends from NC to CI material for this element (Fig. 1). This argues that CI material must be a third endmember in the bulk compositions of CC chondrites. The amount of CI material in these meteorites varies from ~50 – 90 wt% depending on the group. The low concentration of Cr in

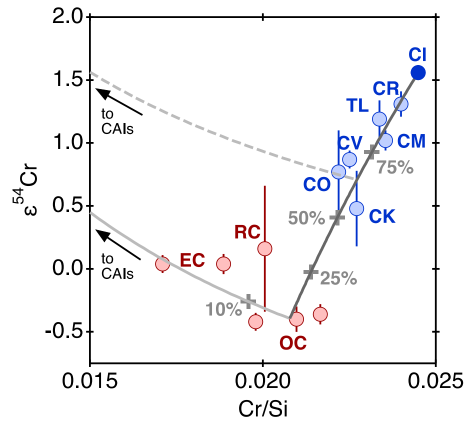

Fig 1. The ε^{54}Cr and Cr/Si values of CC and NC chondrites. The dark gray line represents mixing between OC and CI material. The solid light gray line represents mixing between OC and CAI material. The dashed line represents the mixture of CI, OC, and CAI material that recreates CO chondrites.

CAIs means that the low abundance of CAI material identified from the refractory element analysis is not expected to introduce resolvable changes to the Cr isotopic and elemental compositions of CC chondrites (Fig. 1). As such, the compositions of main component and refractory elements together argue that CC chondrites are a mixture of NC, CAI, and CI material, in varying proportions.

This result is supported by the joint ε^{50}Ti and ε^{54}Cr values of CC chondrites [8], which we find can be expressed as mixtures of very similar proportions of NC, CAI, and CI material as those recovered from the joint elemental and isotopic composition of each of these elements individually. Additionally, the Δ^{95}Mo and ε^{62}Ni values of CC iron meteorites exhibit very similar patterns to the joint ε^{50}Ti and ε^{54}Cr values of CC chondrites and can also be expressed as mixtures of NC, CAI, and CI material with proportions that occupy the same ranges as those recovered from CC chondrites.

Plateau volatile elements: Whereas mass dependent isotopic compositions of plateau volatile elements have been measured for many NC chondrites and exhibit large variations, this variability is likely due primarily to parent body metamorphism, so does not aid in the current study [7, 9-11].

On the other hand, the elemental compositions of plateau volatile elements in NC chondrites are often much less variable. The compositions of these elements are approximately flat in both NC and CC chondrites at a value that is characteristic of each group [12]. Chondrules exhibit concentrations of these elements that are ~13 wt% those found in matrix [7]. As such, the plateau volatile element concentration of a chondrite is expected to reflect the amounts of chondrules and matrix in the meteorite.

Coupled with our main component element analysis, this result indicates that bulk CC chondrites could have been generated either through the mixture of distinct populations of dust and gas with NC and CI isotopic compositions from which chondrules then formed, or through the mixing of CI dust and bulk NC chondrite material (i.e., a mixture of NC chondrules and NC dust dominated by chondrules). In the latter case, the amount of CI material in CC chondrites recovered from the elemental concentrations of plateau volatile elements varies from ~0 – 75 wt% depending on the group.

Discussion: *The origin of CAI material in CC meteorites:* The composition and mineralogy of CAIs argue that these objects formed close to the Sun shortly after it ignited [13]. The proportions of CAI material recovered from CC iron meteorites indicate that some CAIs had migrated into the CC reservoir by the accretion ages of the parent bodies of these meteorites (~1 – 1.5 Myr after CAI formation; [14]), arguing for outward migrations speeds of ≳2 – 4 AU Myr^{-1} [15] for some mm-sized objects in the early disk.

The origin of CI material in CC chondrites: The bulk main component and plateau volatile element compositions of CC chondrites and iron meteorites can be expressed as mixtures of NC and CI material. To explore the origin of this CI component, we derived a mixing model between bulk NC chondrite material and CI dust. We find that the proportions of CI material recovered from main component and plateau volatile element concentrations, as well as matrix mass fraction, follow the expected trends for this mixing, arguing that CC chondrites are mixtures of bulk NC chondrite material with CI dust and some CAI material.

Moreover, this mixing trend finds that chondrules in CM, CO, CV, and TL (Tagish Lake) chondrites all share near-identical average proportions of CI material, arguing that these objects were all generated in the same environment in the disk. Additionally, the abundances of matrix in these groups indicate that new chondrules did not form in the CC reservoir. Instead, these isotopic signatures and abundances argue that pre-existing NC chondrules were remelted in the CC reservoir, during which they were able to exchange material with their surrounding dust and gas to generate CC chondrules. This generation mechanism is consistent with the O-isotopic composition of relict grains in CC chondrules, which indicate that the precursors to these chondrules had NC-like isotopic compositions [16].

CI-like material has been proposed to be associated with the distal disk [15, 17, 18]. Differences in the bulk isotopic compositions of CC meteorites demonstrate that the amount of this CI-like material varied within the CC reservoir, arguing that this distal material migrated throughout the outer disk. As such, the abundance of this material is expected to have evolved over space and time. Hence, our recovered similarity in CC chondrule isotopic composition indicates that these objects were generated over a limited spatial extent and short time interval, arguing for their production through a localized event in the disk rather than continuous processes such as bow shocks, nebula lightning, planetary motion, etc.

The CR chondrites do not follow the expected trends in elemental and isotopic composition for mixing between bulk NC chondrite and CI material. This argues for a different generation mechanism of the constituents of CR chondrites, and for the formation of new CR chondrules in the CC reservoir. This could have been due to an impact between asteroid-sized bodies that melted matrix material, leading to new chondrules [19].

The proportion of CI material in CC iron meteorites: Together, CC iron meteorites and CC chondrites provide a time-resolved record of the amount of CI material throughout the CC reservoir. Using new accretion ages of CC iron meteorite parent bodies (that we derive from the calculated Al concentration of their chondritic precursor recovered from their Mo isotopic compositions), the proportion of CI material decreases as age decreases among CC iron meteorites and increases as age decreases among CC chondrites. These trends argue either for a change in the predominant direction of the motion of dust and gas in the NC and CC reservoirs (from outwards between ~0 – 2 Myr after CAI formation, to inwards at ≳2 Myr after CAI formation) or an evolution of the radial distance at which CC parent bodies accreted (from relatively distal and time varying for CC iron meteorite parent bodies, to relatively proximal and approximately constant for CC chondrite parent bodies).

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