MODELING THE ELEMENTAL AND ISOTOPIC FRACTIONATIONS IN THE CARBONACEOUS CHONDRITES.

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Introduction: The bulk compositions of the chondritic meteorites exhibit elemental and isotopic variations that may help identify important processes that were operating in the early Solar System. Recently, it has been suggested that the formation of Jupiter's core < 1 Ma after Solar System formation created a barrier that impeded 'communication' between the inner and outer Solar System, with the carbonaceous chondrites (CCs) having formed beyond the orbit of Jupiter and all other chondrites (non-CCs: ordinary, Rumuruti, and enstatite) having formed inside of it [1, 2].

The basic features of the elemental fractionations amongst the chondrites have been understood for some time, but to date there have not been any attempts to quantitatively model them. The need for quantitative models has acquired greater importance with the discovery of nucleosynthetic isotopic anomalies in bulk meteorites that may have been produced by an unmixing of a homogeneous nebula or indicate a more spatially and/or temporally heterogeneous nebula than previously recognized [e.g., 2, 3, 4-6]. These nucleosynthetic anomalies are arguably the clearest evidence for a fundamental division between the CCs and non-CCs [7].

Here the results of quantitative modeling of the fractionations amongst the CCs [8, 9] are summarized. The fractionating components identified in the CC model are not able to reproduce the fractionations amongst the non-CCs, and they are described separately [10, 11].

Methods: A reduced X^2 fitting procedure was used to determine the minimum number of components that can explain all aspects of the bulk chemical and isotopic compositions of the CC groups. These components are: (1) a 'chondrule' (or chondrule precursor) component that evolved from an anhydrous and reduced (no FeO, etc.), but otherwise CI-like, material through partial loss of Fe,Ni metal and volatiles, probably early in Solar System history; (2) the CC-RI component, probably a composite of many different refractory materials, that has a bulk elemental composition that is AOA-like and is largely responsible for the nucleosynthetic isotope anomalies in the bulk CCs; (3) matrix that is compositionally CI-like, but anhydrous and reduced, and is primarily responsible for the contents of the most volatile elements used in the fits (e.g., S, Zn and Se); and (4) water, presumably accreted as ice, that hydrated and oxidized the CCs, and contributed to producing the range of bulk CC $\Delta^{17}O$ and $\delta^{18}O$ values.

Results and Discussion: The assumed components are an oversimplification of the complex aggregates that are the CCs. Yet, the fits are remarkably successful at reproducing the compositions of the main CC groups. Most features of the CC groups can be reproduced to within the estimated uncertainties in the bulk composi-

Fig. 1
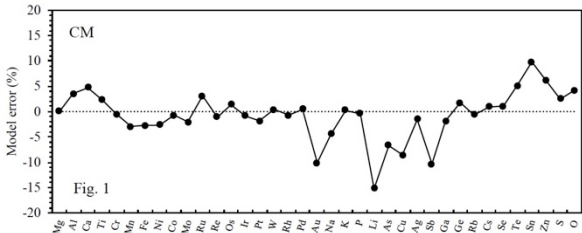
tions. What deviations there are do not exhibit any systematic behavior with volatility or chemical affinity.

Refractory inclusions: The addition of the CC-RI component can account for the enrichments in refractory lithophiles and siderophiles in the CCs, as well as all nucleosynthetic anomalies (Fig, 2). It has an AOA-like bulk composition with inferred $\Delta^{17}O\approx$-20 ‰,

Fig. 2
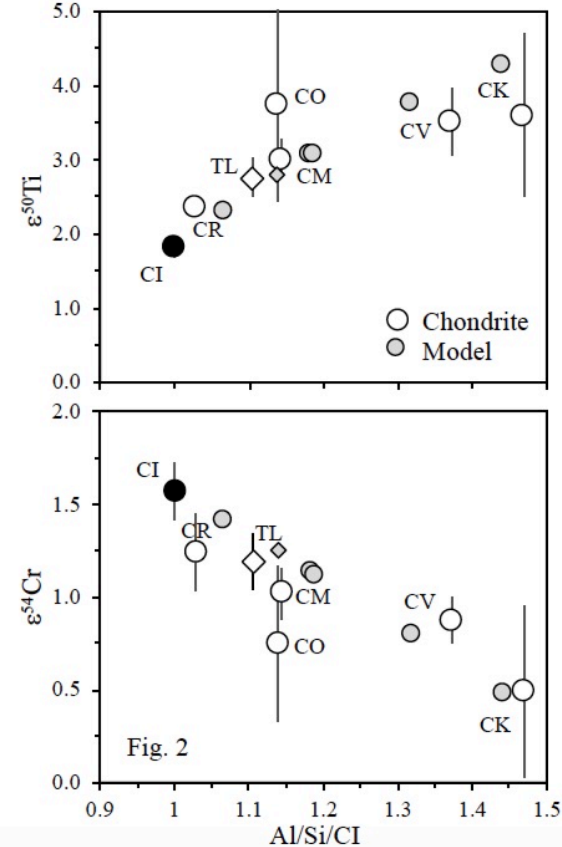
$\varepsilon^{48}Ca \approx 8$, and $\varepsilon^{50}Ti \approx 8$ that are consistent with most CAIs and AOAs. The most discordant result is its inferred $\varepsilon^{54}Cr \approx -10$ as all measured CAIs have positive values. It is possible that the CC-RI component is made of a more CAI-like sub-component that carries the positive $\varepsilon^{50}Ti$, and a less refractory sub-component (refractory accretionary rims?) that carries the negative $\varepsilon^{54}Cr$ and gives the CC-RI component its AOA-like bulk composition.

Chondrules: The fractional losses of the moderately and highly volatile elements from the 'chondrule' component are independent of lithophile or siderophile behavior and are consistent with their relative volatilities predicted by condensation models. The refractory siderophile-free composition of the Fe,Ni metal lost from the 'chondrule' component is also consistent with predictions of condensation models, and is inconsistent with the observed refractory-siderophile-bearing compositions of chondrule metal. Therefore, the volatile and metal loss from the 'chondrule' component probably predated chondrule formation.

The 'chondrule' component reproduces the average elemental compositions of separated Renazzo chondrules [12] fairly well. The abundances of the volatile elements Zn and Se are higher in the chondrules than predicted. If the measured Zn contents are a primary feature of CC chondrules, the fits will have overestimated matrix abundances. The fits cannot account for recycling of refractory inclusions during chondrule formation. In the CCs with higher refractory inclusion abundances than in the CRs, recycling of some of inclusion material will have contributed to the chemical diversity of their chondrules. The variations in the average $\Delta^{17}O$ and $\varepsilon^{54}Cr$ values of CC chondrules are broadly consistent with mixing of the 'chondrule' and CC-RI components in roughly their relative abundances in the bulk CCs. However, this is not the case for $\varepsilon^{50}Ti$ and $\varepsilon^{92}Mo$, perhaps because only the more ferromagnesian material in the CC-RI component was a significant component of CC chondrule precursors. The implications this might have, if correct, for mixing in the nebula and prior to chondrule formation must await identification of these materials in the meteorites.

Matrix: The assumption that matrix is CI-like is inconsistent with claims of chondrule-matrix complementarity. Nevertheless, the success of the fits suggests that the matrix was dominated by CI-like material, which would also explain the relatively uniform and CI-like abundances of organic C and presolar grains in the matrices of the most primitive CCs. The elemental evidence for complementarity may be the result of secondary chondrule-matrix exchange. The Mo and W isotopic evidence for complementarity may be an artifact of size-dependent metal-silicate segregation during chondrule formation and the physical disaggregation used to make chondrule and 'matrix' separates from a meteorite.

Water: Water plays an important role in reproducing the bulk O isotopic compositions, even in the CO,CV

Fig. 3
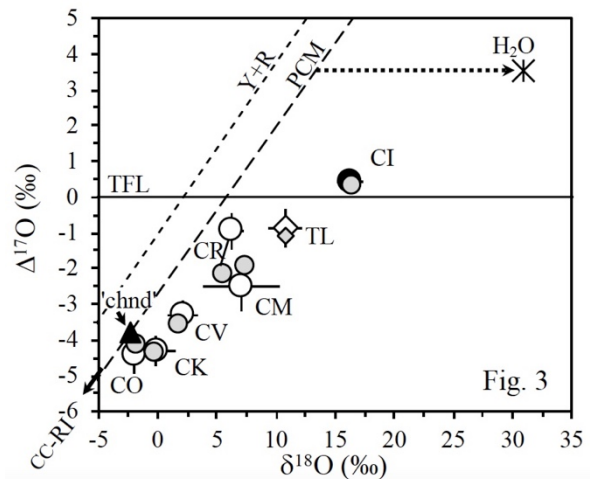
and CKs. The overall trend is reproduced by the fit, but the CRs (Renazzo) in particular could not be reproduced to within their error. The inferred $\Delta^{17}O=3.5$ ‰ for the CC water is consistent with most constraints from secondary phases in the CCs, but is slightly lower than some estimates for CM water. The large O isotopic mass fractionation of the water ($\delta^{18}O \approx 18$-21 ‰), relative to the PCM or Y+R lines, is consistent with ~89-95 % condensation of ice from a vapor under Rayleigh conditions at 150-170 K. There would also be a 50-110 ‰ enrichment in D associated with this process. This is not enough to explain the non-solar δD of CC water, requiring that there was an interstellar component to the CC water as models suggest that significant D enrichments in water are unlikely to be generated in the nebula.

The water seems to have been entirely accreted with the matrix with fairly constant and CI-like water/matrix ratios. Why apparently little or no water condensed onto chondrules is unclear. The inferred water/matrix (wt.) ratios of 0.2-0.4 are much less than the ratio of one that is often cited for the nebula, and suggests that most C was in CO and CO_2, and the abundance of CH_4 was low.

References: [1] Kruijer T.S. et al. (2017) *PNAS, 114*, 6712-6716. [2] Budde G. et al. (2016) *EPSL, 454*, 293-303. [3] Trinquier A. et al. (2009) *Science, 324*, 374-376. [4] Fischer-Gödde M. et al. (2015) *GCA, 168*, 151-171. [5] Van Kooten E.M.M.E. et al. (2016) *PNAS, 113*, 2011-2016. [6] Schiller M. et al. (2015) *GCA, 149*, 88-102. [7] Warren P.H. (2011) *EPSL, 311*, 93-100. [8] Alexander C.M.O'D. (2019) *GCA* In press. [9] Alexander C.M.O'D. (2018) *Meteor. Planet. Sci., 53*, A4. [10] Alexander C.M.O'D. (2019) *GCA* In press. [11] Alexander C.M.O'D. (2019), *LPSC, 50* Submitted. [12] Kong P. and Palme H. (1999), *GCA 63*, 3673-3682.