DOES THE OXYGEN ISOTOPE DIAGRAM PROVIDE CLUES TO THE DISTRIBUTION OF METEORITIC MATERIAL IN THE EARLY SOLAR SYSTEM? T. H. Burbine[1] and R. C. Greenwood[2], [1]Department of Astronomy, Mount Holyoke College, 50 College Street, South Hadley, MA 01075, USA (tburbine@mtholyoke.edu), [2]Planetary and Space Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK.

Introduction: Following the pioneering studies of Robert Clayton [1], oxygen three isotope analyses have been widely used as a means of constraining the genetic relationships between meteorite groups. Most meteorites in the same group, particularly achondrites, tend to display coherent relationships on oxygen three isotope diagrams (**Figure 1**). Here we discuss how the distribution of different meteorite groups on the oxygen three isotope diagram may provide clues to their original location within the protoplanetary disk.

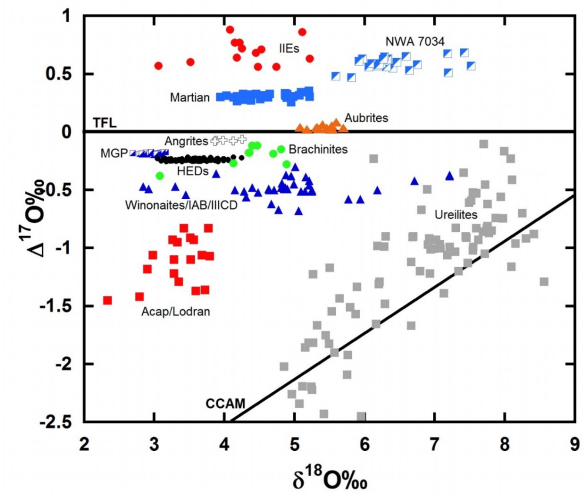

Figure 1. Oxygen three isotope diagram showing the distribution of the principal achondrite groups.

Models: Recent astrophysical models have focused on the dichotomy of isotopic compositions between two groups of material [2], which are labeled as the carbonaceous chondrite (CC) and non-carbonaceous (NC) groups (**Figure 2**). The CC group tend to have higher concentrations of nucleosynthetic isotopes (e.g., ε^{50}Ti, ε^{54}Cr). The NC group includes non-carbonaceous chondrites and most achondrites.

The isotopic differences are proposed [3-5] to be due to early infalling material in the solar nebula being enriched in nuclides produced in neutron-rich stellar environments. CAIs record these early-Solar System isotopic enrichments. This material would have been transported outwards through viscous spreading. The later infalling material, assumed to be depleted in neutron-rich nuclides, would tend to accumulate in the inner part of the disk and dilute the isotopic signature of the NC region.

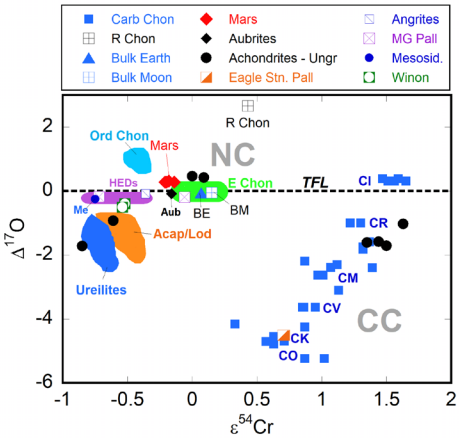

Figure 2. Plot of Δ^{17}O versus ε^{54}Cr for a range of meteorites. The plot is modified after Warren [2].

The formation of Jupiter's core would stop significant material exchange between the NC and CC regions and isotopic homogenization, resulting in the dichotomy that we see today. The NC meteorites would have formed in the inner Solar System and the CC meteorites would have formed in the outer Solar System. As Jupiter and Saturn migrated outwards during the later stages of the "Grand Tack" [6], CC parent bodies would have been scattered into the region now known as the asteroid belt.

Oxygen Isotope Diagram: A number of trends are apparent on the oxygen three isotope diagram (**Figures 1** and **2**). For example, the distance (Δ^{17}O) that the enstatite, ordinary, and R chondrites fall away from the terrestrial fractionation line (TFL) may be correlated with the sequence that these meteorites would have condensed out in the solar nebula [7].

Almost all carbonaceous chondrites fall below the TFL [1,8] (**Figure 2**). The CI and "CY" chondrites are exceptions and fall slightly above the TFL [1,8,9].

Almost all the meteorites that experienced melting also fall below the TFL [1,8] (**Figures 1** and **2**). These meteorites include the HEDs (howardites, eucrites, diogenites) and ureilites. The aubrites fall relatively near the TFL. Differentiated meteorites that fall above the TFL are relatively rare. Heating of these bodies is attributed to ^{26}Al.

Also, the aubrites and enstatite chondrites, which are the best analogs for the chondritic precursor of the aubrites, have virtually indistinguishable Δ^{17}O values

[10] and fall very near the TFL. Both aubrites and enstatite chondrites are extremely reduced.

Also, there is considerable overlap in oxygen isotopic space (**Figure 2**) between meteorites that fall in the CC region and those that fall in the NCC region [2]. While nucleosynthetic anomalies can be used to easily separate CC and NC meteorites, $\Delta^{17}O$ does not. The $\Delta^{17}O$ variations are usually assumed to be related to photochemical processes in the solar nebula [11].

Finally, refractory inclusions, which would have condensed out at extremely high temperatures [7] and very early in Solar System history, have extremely ^{16}O-rich compositions and, therefore, extremely negative $\Delta^{17}O$ values [12]. These inclusions include CAIs (calcium-aluminum-rich inclusions) and AOAs (amoeboid olivine condensates). CAIs are the oldest dated material in the Solar System [13].

Proposed Model: We propose that the location of a meteoritic group on the oxygen three isotope diagram could be a function of the original concentration of refractory inclusions incorporated into the body. The more negative the $\Delta^{17}O$, the higher concentration of refractory inclusions that the parent body received.

However, relict CAIs are relatively rare in chondrules [14] and refractory inclusions are also relatively rare in ordinary, enstatite, and R chondrites [15]. Could the majority of these inclusions incorporated into the chondrites be "destroyed" by parent body processes? Despite the proposed "destruction" of the CAIs, the bulk oxygen isotopic composition of the body would not be expected to change. Some refractory inclusions may have been extremely small, increasing the probability of their "destruction". The refractory inclusions we see today were either "lucky" or were incorporated late.

We assume that the NC chondrites formed in the inner Solar System and that carbonaceous chondrites formed in the outer Solar System. We assume that the formation location of the NC chondrites (in order of increasing distance from the Sun) would be enstatite, H, L, LL, and R chondrites. This sequence also increases in $\Delta^{17}O$, which could be due to each meteorite parent body receiving smaller fluxes of refractory inclusions with increasing distance from the Sun.

The negative $\Delta^{17}O$ values for most carbonaceous chondrites implies that the abundances of refractory inclusions incorporated by outer Solar System bodies were higher than those incorporated by bodies in the inner Solar System. The CI chondrites, which may have formed far from the Sun, would have incorporated the smallest flux of refractory inclusions of the carbonaceous chondrites, and, therefore, have a slightly positive $\Delta^{17}O$.

The observation that the aubrites and enstatite chondrites have virtually indistinguishable $\Delta^{17}O$ values may imply that bodies that formed in the same region of the Solar System may have accumulated similar abundances of refractory inclusions. These bodies would have similar $\Delta^{17}O$ values but the differentiated bodies would have melted due to either forming earlier or accumulating more ^{26}Al.

Could this observation imply that NC differentiated meteorites that formed with negative $\Delta^{17}O$ values formed in the outer Solar System from carbonaceous chondritic material, which also have negative $\Delta^{17}O$ values, and not in the inner Solar System? But why don't NC differentiated meteorites have nucleosynthetic anomalies consistent with carbonaceous chondrites? Maybe these bodies formed early in Solar System history and did not incorporate a significant fraction of interstellar dust with nucleosynthetic isotopic excesses. The carbonaceous chondrites would have formed later and incorporated more dust.

Or did the NC differentiated meteorites that formed with negative $\Delta^{17}O$ values just form from inner Solar System material that accumulated more refractory inclusions? This accumulation would have moved the resulting meteorites downwards on an oxygen three isotope diagram.

Conclusions: We propose a scenario where the distribution of meteorites on the oxygen isotope diagram is due to the early incorporation of refractory inclusions. Further modeling needs to be done to investigate this scenario in more detail.

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