WHAT MATERIAL ACCRETED TO FORM THE EARTH? T. H. Burbine[1], R. C. Greenwood[2] and I. A. Franchi[2], [1]Department of Astronomy, Mount Holyoke College, South Hadley, MA 01075, USA (tburbine@mtholyoke.edu), [2]Planetary and Space Sciences, School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK.

Introduction: One unsolved question in planetary science is what was the dominant material that accreted to form the Earth. Enstatite chondrites and aubrites all fall close to the terrestrial fractionation line on the three-isotope oxygen isotopic plot (**Figure 1**) [1]. (Aubrites are achondrites that are believed to be the product of the melting and differentiation of enstatite chondrite-like material [2].) Dauphas [3] noted that enstatite chondrites and aubrites are isotopically similar to the Earth over a wide variety of isotopic systems. However, enstatite chondrites and aubrites have much lower bulk FeO-contents (< 1 wt%) than the primitive upper mantle (PUM) (~8 wt%) [4]. Javoy et al. [5] argued that the increasing temperature during the Earth's formation would have caused iron in the mantle to oxidize.

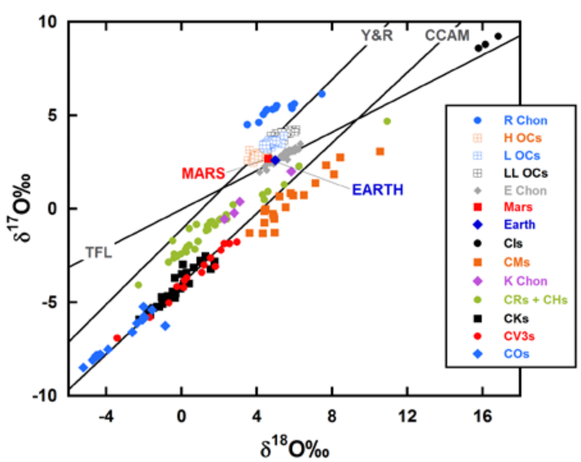

Figure 1. Oxygen isotope plot for the chondritic meteorite groups, the K chondrite grouplet, the Earth, and Mars. The terrestrial fractionation line (TFL), the Carbonaceous Chondrite Anhydrous Mineral (CCAM) line, and the Y&R (Young and Russell) [6] line are also plotted.

The estimated Mg/Si weight ratio for the PUM is much higher than the Mg/Si ratio for known chondrites [7] (**Figure 2**). Of known chondritic material, carbonaceous chondrites have Mg/Si ratios closest to that of the PUM. However, Warren [8] noted that the Earth is not isotopically similar to carbonaceous chondrites over a wide variety of isotopic systems. Enstatite chondrites have the lowest Mg/Si ratios of known chondrites. Incorporating Si into the core could resolve this apparent compositional difference between the chondrites and the PUM [7]. Additionally, this apparent compositional difference might be resolved if the PUM estimates are not representative of the bulk silicate Earth [7]. Another possible explanation is that the Earth is primarily composed of chondritic material not currently in our meteorite collections [9]. Dauphas [3] proposed that the Earth formed out of material isotopically similar to enstatite chondrites, but enriched in forsterite. Burbine and O'Brien [10] (**Figure 2**) found that no known mixture of chondritic material could match the chemical and isotopic composition of the bulk Earth. So what is the Earth made from? Could the Earth be composed primarily of chondritic material not currently found in our meteorite collections?

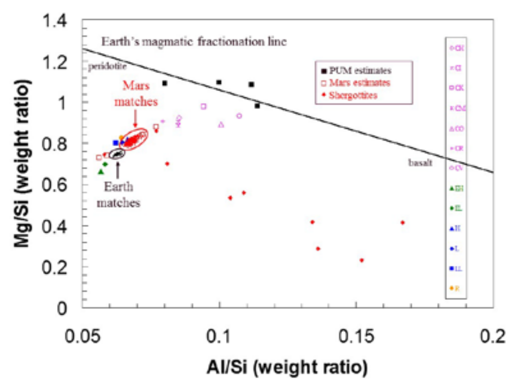

Figure 2. Plot of Al/Si versus Mg/Si weight ratios for chondritic meteorite groups (average values), estimated values for the PUM (black squares), estimated values for Mars (open red squares), and values for shergottite meteorites (red diamonds). The black line is the trend for terrestrial rocks, which is taken from Dreibus et al. [11]. Ellipses are drawn around the estimates of the composition of the PUM and Mars. The black dots are the matches for the Earth, and the red dots are matches for Mars. Figure is from Burbine and O'Brien [10].

Building Blocks of Mercury, Venus, and Mars: Estimates of the building blocks of the other terrestrial planets have also been done. The best chondritic analogs for Mercury's building material appear to be the enstatite chondrites [12] due to the low-FeO nature of Mercury's surface [13]. The building blocks of Venus are usually assumed to be similar to those of the Earth [14]. The "best" models for forming Mars contain a mixture of a number of different chondritic meteorite groups, but usually include a sizeable proportion of ordinary chondritic material (**Figure 2**) [10].

Condensation Sequence: Grossman [15] calculated a condensation sequence for minerals in the solar nebula. The highest temperature condensates (corundum, perovskite, melilite group, and spinel) are found in calcium-aluminum inclusions (CAIs), which are major components of CV and CO chondrites. CAIs are the oldest dated material found in our Solar System and appear to have been preferentially transported outward to the outer Solar System. Lower-temperature condensates (enstatite and FeNi metal) are major components of enstatite chondrites, while even lower-temperature condensates (ferrous olivines and ferrous pyroxenes) are major components of ordinary chondrites (H, L, and LL) with FeNi metal. (Enstatite chondrites have olivine compositions of $Fa_{<1}$. Equilibrated H chondrites have olivines with Fa_{16-20}, equilibrated L chondrites have olivines with Fa_{23-26}, and equilibrated LL chondrites have olivines with Fa_{27-32} [16].) Water, which would have condensed at even lower temperatures, is found in the hydrated silicates in carbonaceous chondrites.

One chondritic grouplet (K chondrites) have fayalite contents (Fa_4) intermediate between enstatite and H chondrites [17]. (Grouplets have less than five members.) K chondrites are named after the first identified member, Kakangari. However, K chondrites have bulk oxygen isotopic values that plot near CR chondrites (**Figure 1**), Mg/Si ratios that are slightly higher than H chondrites, and high matrix abundances that is similar to carbonaceous chondrites [17]. Therefore, chondrites intermediate in bulk FeO between enstatite and H chondrites and oxygen isotopic values that fall near the terrestrial fractionation line could have potentially formed.

Asteroid Belt: The asteroid belt shows a distribution of taxonomic classes that is roughly consistent with the condensation sequence [18,19]. Taxonomic classes that are primarily composed of material that would have condensed at higher temperatures tend to be found closer to the Sun than classes that contain material that would have condensed at lower temperatures. The interior part of the belt is dominated by E-type asteroids, which are believed to include the parent bodies of the aubrites. The middle part of the belt is dominated by S-complex bodies, which are believed to include the parent bodies of the ordinary chondrites. The outer part of the belt is dominated by C-complex bodies, which are believed to include the parent bodies of the carbonaceous chondrites. However, there are over 700,000 asteroids currently known and only ~120-132 identified possible meteorite parent bodies using both oxygen isotopic and mineralogical studies [20]. Therefore, a large number of chondritic meteorite types that are not currently found in our meteorite collections could potentially be present in the asteroid belt

Conclusions: The difficulty in making the Earth (and Venus) out of known chondritic material could potentially be solved by the existence of chondritic material not currently found in our meteorite collections. These chondrites would be intermediate in bulk FeO between enstatite and H chondrites and isotopically similar to enstatite chondrites. Models for forming the terrestrial planets should use a much larger array of starting materials than just the known chondritic meteorite groups. This material could still exist in the asteroid belt. However, this is a very unsatisfying explanation in many respects since this material has not been currently identified. The discovery and analysis of Mercurian and Venusian meteorites would also help us gain insight on potential building blocks for the terrestrial planets.

References: [1] Newton J. et al. (2000) *Meteoritics & Planet. Sci., 35,* 689-698. [2] Keil K. (2010) *Chemie der Erde, 70,* 295-317. [3] Dauphas N. (2017) *Nature, 541,* 521-524. [4] Robinson M. S. and Taylor G. J. (2001) *Meteoritics & Planet. Sci., 36,* 841-847. [5] Javoy M. et al. (2010) *EPSL, 293,* 259-268. [6] Young E. D. and Russell S. S. (1998) *Science, 282,* 452-455. [7] Palme H. and O'Neill H. St. C. (2014) In *The Mantle and Core* (Vol. 3), *Treatise on Geochemistry 2nd Ed.*, 1-39. [8] Warren P. H. (2011) *EPSL, 311,* 93-100. [9] Drake M. J. and Righter K. (2002) *Nature, 416,* 39-44. [10] Burbine T. H. and O'Brien K. M. (2004) *Meteoritics & Planet. Sci., 39,* 667-681. [11] Dreibus G. et al. (1998) *LPS XXIX,* Abstract #1348. [12] Namur O. et al. (2016) *EPSL, 439,* 117-128. [13] Nittler L. R. et al. (2011) *Science, 333,* 1847-1850. [14] Righter K. et al. (2006) In *Meteorites and the Early Solar System II,* 803-828. [15] Grossman L. (1972) *GCA, 36,* 597-619. [16] Weisberg M. K. et al. (2006) In *Meteorites and the Early Solar System II,* 19-52. [17] Weisberg M. K. et al. (1996) *GCA, 60,* 4253-4263. [18] Gradie J. and Tedesco E. (1982) *Science, 216,* 1405-1407. [19] DeMeo F. E. and Carry B. (2014) *Nature, 505,* 629-634. [20] Greenwood R. C. et al. (2017) *LPS XLVIII,* Abstract #2515.

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