**OXYGEN ISOTOPES AND THE ACCRETION OF THE TERRESTRIAL PLANETS:** Cyrena A. Goodrich and Michael J. Drake, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, U.S.A.

**INTRODUCTION.** It has become a paradigm of solar system formation that towards the end of accretion gravitational interactions between the objects destined to become the terrestrial planets and Moon to Mars-sized objects resulted in high relative velocities between these bodies, and highly eccentric orbits [1,2]. Thus, there was substantial mixing within at least the inner solar system, such that the assembled planets obtained material from a range of semi-major axes. This model provides an explanation for a variety of physical properties of the inner planets. For example, the high angular momentum of the Earth-Moon system is explained by origin of the Moon during impact of a Mars-sized body with the Earth [3]. It also accounts for some compositional characteristics such as the depletion of iron and volatile elements in the Moon. Here we use oxygen isotopic compositions to further examine this model.

**OXYGEN ISOTOPES OF SAMPLED SOLAR SYSTEM OBJECTS.** Figure 1 shows the oxygen isotopic compositions of sampled solar system bodies [4]. All materials fractionated from an initially homogeneous source would plot along a mass fractionation line of slope ~one-half on this standard three-isotope plot. For example, all terrestrial and lunar samples (and also enstatite chondrites and achondrites) plot on one such line. Samples of differentiated meteorites from the howardite - eucrite - diogenite suite (and also the mesosiderites and the main group of pallasites) fall on a parallel line which is displaced to more $^{16}O$-rich compositions by about 0.4‰. The shergottite - nahklite - Chassigny (SNC) meteorites (which are believed to be samples of Mars) fall on a parallel line displaced towards more $^{16}O$-poor compositions by about 0.6‰.

In contrast, all primitive materials have oxygen compositions which define much steeper trends, with slopes of ~ one (for example, C2-C3 carbonaceous chondrites, and chondrules from unequilibrated ordinary chondrites). These slopes have been interpreted as representing the admixture of variable amounts of $^{16}O$-rich material into the solar system at the time of nebular condensation and accretion [5]. Thus, different parts of the solar system probably had different oxygen isotopic compositions at the time of planet formation due to inefficient mixing of the $^{16}O$-rich component. It is not known, however, whether oxygen isotopic composition varied smoothly, discontinuously, or chaotically as a function of heliocentric distance. Nevertheless, if SNC meteorites are from Mars, we know the current isotopic composition of oxygen in two of the terrestrial planets.

**DYNAMICS OF ACCRETION OF THE TERRESTRIAL PLANETS.** Wetherill [2] has conducted calculations based on three variations of his earlier work [1] and has kept track of the provenance of planetesimals which accreted to make the final simulated terrestrial planets. In one set of calculations, he used 500 bodies of initial mass $2.52 \times 10^{25}$ g distributed between 0.6 AU and 1.2 AU, initial eccentricities between 0 and 0.02, and initial inclinations between 0 and 0.01. Assumptions were made concerning the partitioning of impact energy between internal heating and overcoming the gravitational binding energy to cause disruption. Different calculations led to varying outcomes, but the resulting simulated planets broadly resembled the terrestrial planets, with four or five planets distributed between about 0.4 AU and about 1.8 AU. Figure 2 shows the provenances of planetesimals residing in the final planets for one simulation. We use these provenances to investigate the range and distribution of oxygen isotopic compositions necessary to produce the observed offset in $^{16}O$ between the Earth-Moon system and Mars.

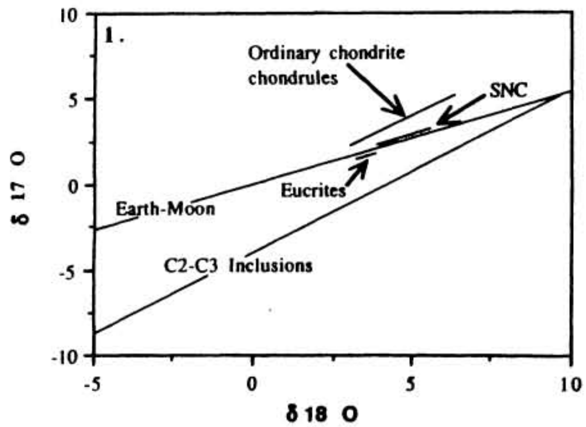
**MIXING CALCULATIONS.** If carbonaceous chondrite reservoirs were present only in the outer part of the inner solar system (beyond about 4 AU), then the plausible range of oxygen isotopic compositions in planetesimals available to be accreted to the terrestrial planets extends from the eucrites to the most $^{16}O$-poor chondrules in the unequilibrated ordinary chondrites. For the purposes of our calculations, we have assumed mixing along a line of slopeone, constrained to pass through the bulk Earth-Moon oxygen isotopic composition [6], with end-members designated E and O (Fig. 3). We considered three different distributions of oxygen isotopic composition along this line: (i) a linear variation with semi-major axis, with E at 0.6 AU and O at 1.2 AU; (ii) a square of semi-major axis variation; and (iii) a step function, with E between 0.6 AU and 1.0 AU, and O between 1.0 AU and 1.2 AU. In all cases (e.g. Fig. 3) the oxygen isotopic compositions calculated for Earth and Mars are too poor in $^{16}O$ and the differences between them are too small.

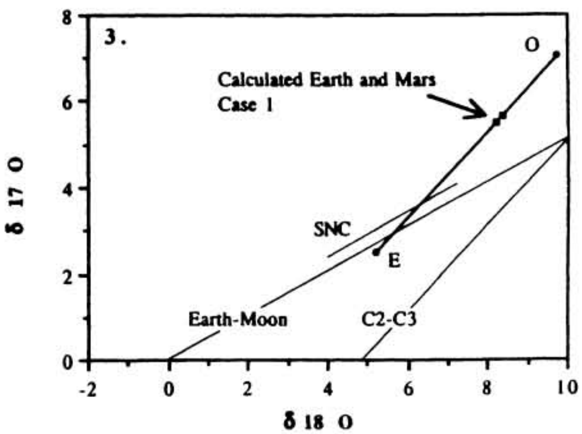
Alternatively, we can force the simulated Earth and Mars to fit the bulk Earth-Moon point and the intersection of the slope one mixing line with the SNC trend, and ask if the range of required oxygen isotopic compositions is plausible. The range of oxygen isotopic compositions required in the linear distribution case exceeds that retained in any sampled body (Fig. 4), and requires a component as rich in $^{16}O$ as some of the calcium-aluminum inclusions in the C3V carbonaceous chondrite Allende. The $^{16}O$-poor component exceeds any sampled solar system body or component of any meteorite. Similar conclusions hold for the other distributions, although the ranges of oxygen isotopic composition required are less extreme.

**CONCLUSIONS.** None of the tested regular distributions of oxygen isotopes within the range of observed inner solar system compositions can account for the oxygen isotopic compositions of Earth and Mars in the context of the Wetherill model. There are several possible explanations for this. First, the distribution of oxygen isotopes in the nascent solar system may not have been regular. Second, we have examined only one outcome of the Wetherill calculations. Perhaps other simulations would negate our conclusions. Third, perhaps the Wetherill model for the accretion of the terrestrial planets is not correct.

*This work was supported by NASA grant NAG 9-39.*

***References:*** (1) G.W.Wetherill (1985) *Science* **228**, 877. (2) G.W. Wetherill (1988) *Mercury* (U. of Az. Press), 670. (3) Benz *et al.* (1989) *Icarus* **81**, 113. (4) R.N. Clayton *et al.* (1976) *GCA* **30**, 10; R.N. Clayton *et al.* (1985) *Protostars and Planets II* (U. of AZ Press), 755. (5) R.N. Clayton *et al.* (1973) *Science* **182**, 485. (6) R.N. Clayton *et al.* (1976) *GCA* **40**, 1475.

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