OXYGEN ISOTOPIC CONSEQUENCES OF GIANT PLANET MIGRATION. Edward D. Young[1], David C. Rubie[2], and David P. O'Brien[3], [1]Dept. of Earth and Space Sciences, University of California Los Angeles, USA (eyoung@ess.ucla.edu), [2]Bayerisches Geoinstitut, Universität Bayreuth, Germany (dave.rubie@uni-bayreuth.de), [3]Planetary Science Institute, Tucson, Arizona, USA (obrien@psi.edu).

Introduction: A profound consequence of the discovery of extrasolar planets has been greater appreciation for the role of giant planet migration as a determining factor in the architecture of planetary systems in general. This extends to our own solar system, where it is likely that the gas and ice giants moved radially with respect to the Sun early in solar system history. Although we cannot know precisely how these events unfolded, dynamical models serve as guides. One criticism of these models has been that they do not result in testable hypotheses that can be used to assess their veracity. A means to redress this problem is to imbue the dynamical models with chemical and isotopic systematics that can produce results to be compared with present and future observations. This is one of the goals of the ERC "ACCRETE" project (http://www.accrete.uni-bayreuth.de/). Rubie, O'Brien, Morbidelli and others have been examining the consequences of the "Grand Tack" model [1] for core-mantle differentiation of the terrestrial planets [2]. In this study we consider the oxygen isotopic consequences of terrestrial planet formation in the context of the Grand Tack scenario.

Models: We calculate the oxygen isotopic compositions of terrestrial planets accreted following the passage of Jupiter and Saturn through the inner solar system. We use the Grand Tack n-body simulation SA154-767. The initial conditions include 36 embryos distributed from 0.7 to 3 AU and 1500 planetesimals distributed from 0.7 to 13 AU. The majority of bodies are not accreted. Compositions are assigned to bodies based on their initial locations. Based on core-formation modeling, the inner region (<1.1 AU) is characterized by 99.9% of total iron being initially reduced and 22% of Si dissolved in Fe metal. Beyond 1.1 AU we impose a linear gradient in the fraction of iron as FeO such that FeO = total Fe at the H_2O snow line. We explore variations in the position of the snow line, beyond which bodies contain 20 wt% H_2O (~60% by volume). In this model, Mars is dominantly an embryo that originates at 2.2 AU. A reasonable fit to Earth and Mars oxidation states is obtained with the snow line at ca. 4 AU (e.g., 7.95 wt% FeO for Earth's mantle). At the same time, the model Mercury is consistently more oxidized than current constraints imply. Moving the snow line inward increases mantle FeO values and reduces Earth's mantle SiO_2 concentration.

Oxygen Isotopes: We consider the oxygen isotopic composition of bodies in the solar system to be the consequence of mixing between silicate dust and water, consistent with recent models based on self shielding of CO [3-6]. Variations between high $\Delta^{17}O$ water and low $\Delta^{17}O$ dust occurred by a myriad of processes within the gaseous solar nebula (isotope exchange, evaporation and recondensation) and within parent bodies (water-rock reactions, secondary mineral growth). Whole-rock meteorite $\Delta^{17}O$ values range from ~ –4 to +2 ‰ and we take this as the range in planetesimal bulk values excluding water ice but inclusive of the effects of water-dust exchange (thus allowing for a pre-exchange $\Delta^{17}O$ value for dust comparable to CAIs or solar). Water ice is thought to be higher in $\Delta^{17}O$ than rock in primitive solar system bodies. Values recorded in aqueous alteration products range from ~ +3 to +100 ‰ [7, 8]; we use this range for the H_2O component of planetesimals. In addition, we include FeO as a third oxygen isotope reservoir representing oxidation products with higher $\Delta^{17}O$ values of 0 to 2 ‰ (e.g., LL vs. H chondrite). Initial bulk oxygen isotope values are assigned to planetesimals and embryos based on their compliments of silicate, FeO and water. The isotopic compositions of these components are varied using uniformly distributed random numbers with the ranges cited above. Results shown here are for 1000 random draws, comprising Monte Carlo simulations of possible oxygen isotope outcomes for the SA154-767 Grand Tack simulation (genealogy of the planets remains fixed, only the isotope values change).

Results: The results show that where source materials for terrestrial planet formation are disturbed by giant planet migration, a simple monotonic variation in $\Delta^{17}O$ does not occur despite the relatively simple structure of high $\Delta^{17}O$ beyond the water snow line and lower values interior to the snow line. The difference in $\Delta^{17}O$ between Mars and Earth (0.3 ‰), the only planetary-scale oxygen isotope observable available at present, is best matched with the snow line at ~ 4 to 5 AU (Figures 1, 2). This also happens to be the best fit for the oxidation state of Earth's mantle in this scenario based on the core formation models.

With the water snow line at 2.5 AU, Earth, Mars and Venus on average have similar $\Delta^{17}O$ values when Earth has the terrestrial value of 0 ‰; Mars typically has a value of ~ 0.0 +/- 0.15 ‰ relative to Earth, Venus is essentially identical to Earth, and Mercury has a value of ~ −0.1 +/− 0.05 ‰ (Figure 1). When the snow line is at 5 AU $\Delta^{17}O$ values for Mars are ~ 0.25 +/− 0.15 ‰, Venus is ~ 0.15 +/− 0.15 ‰, and Mercury is ~ 0.05 +/- 0.05 ‰ relative to Earth (Figure 2). With the water line at 6 AU Mercury and Earth have identical $\Delta^{17}O$ values, Mars is ~ 0.15 +/- 0.05 ‰, and Venus is ~ 0.10 +/- 0.05 ‰ (not shown). We note that the minimum $\Delta^{17}O$ for Earth relative to the surrounding terrestrial planets in these simulations is similar to the trend for FeO contents.

The effects of the position of the snow line on $\Delta^{17}O$ of Mars relative to Earth is as follows: Earth receives more H_2O-bearing material with high $\Delta^{17}O$ when the snow line is proximal to the formation region of Earth. In order to compensate to produce Earth's $\Delta^{17}O$ value, silicate must be lower in $\Delta^{17}O$. Mars is essentially an embryo originating at 2.2 AU and the reduction in silicate $\Delta^{17}O$ has a relatively large effect on this embryo.

Discussion: If giant planets migrated radially in the early solar system, the region of their rocky/icy core formation is uncertain. Accordingly, the usual arguments that Jupiter formed at 5 AU because the water snow line enhanced dust surface densities sufficiently to promote core formation are less compelling. Nonetheless, models for the distribution of accretion disk temperatures suggest that the snow line should have resided at 5 to 6 AU with accretion rates near $10^{-7}\,M_{\odot}\,yr^{-1}$ and at 2 to 3 AU with accretion rates of about $10^{-8}\,M_{\odot}$. The oxygen isotope results presented here are consistent with the higher accretion rates within the context of the Grand Tack simulation.

These calculations provide examples of the types of observations that could be arbiters for competing scenarios. For example, on the basis of oxygen isotopes we can exclude planet accretion from planetesimals formed with a water snow line within the the middle of the present-day asteroid belt *if* Jupiter and Saturn moved through the inner solar system as envisioned in the Grand Tack model. Conversely, a snow line at 4 to 5 AU is consistent with the relative $\Delta^{17}O$ values of Earth and Mars as well as the oxidation state of the terrestrial mantle. In this case, the *prediction* is that Mercury should have a $\Delta^{17}O$ value very similar to Earth (within 0.05 ‰) and Venus should have a value between those of Earth and Mars.

References: [1] Walsh K.J. et al. (2011) *Nature* 475, 206-209. [2] Rubie D.C. et al. (2012) *American Geophysical Union Fall Meeting*. V53G-03. [3] Lyons J.R. and Young E.D. (2005) *Nature* 435, 317-320. [4] Young E.D. (2007) *Earth and Planetary Science Letters* 262, 468-483. [5] Kuramoto K. and Yurimoto H., 2005. in *Chondrites and the Protoplanetary Disk*, A.N. Krot, E.R.D. Scott, and B. Reipurth, Editors., Astronomical Society of the Pacific: San Francisco. p. 181-192. [6] Yurimoto H. and Kuramoto K. (2004) *Science* 305, 1763-1766. [7] Sakamoto N. et al. (2007) *Science* 317, 231-233. [8] Choi B. et al. (1998) *Nature* 392, 577-579.

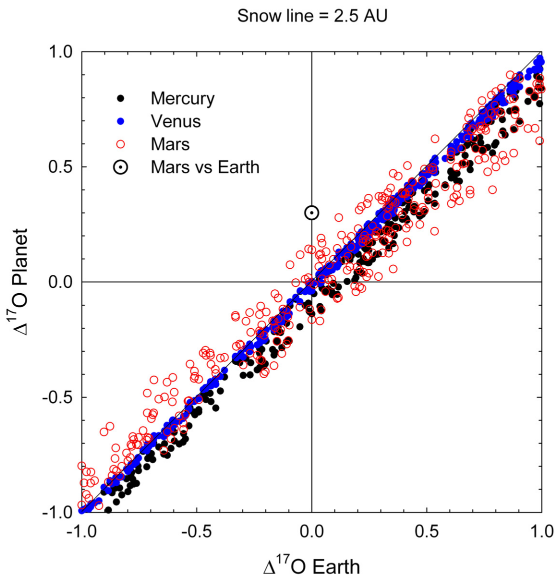

Figure 1. Results of 1000 simulations for the oxygen isotopic composition of terrestrial planets where the snow line is at 2.5 AU. Solar Mars vs. Earth is shown for reference.

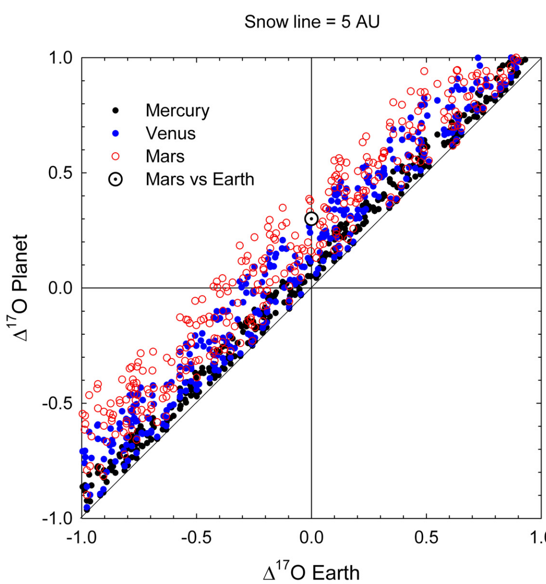

Figure 2. As in Figure 1 but with the snow line at 5 AU.