THE OXYGEN ISOTOPIC CASE FOR SUPERNOVA ENRICHMENT OF THE SOLAR SYSTEM BIRTH ENVIRONMENT.

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Introduction: Infrared absorption measurements of CO oxygen isotopologue ratios from individual young stellar objects (YSOs) confirm that the solar system is anomalously high in $^{18}O/^{17}O$ compared with extra-solar oxygen in the Galaxy. The reason for this distinction between "typical" Galactic oxygen and solar system oxygen has been the subject of debate. Possibilities include: 1) dispersion in $^{18}O/^{17}O$ not previously recognized; 2) departures from the accepted understanding of Galactic Chemical Evolution (GCE) of oxygen; or 3) enrichment of the solar birth environment in ^{18}O relative ^{17}O by stellar ejecta. Consideration of our new YSO data [3], augmented with additional data shown here (Figure 1), and previous data for the ISM, suggests that the unusually high $^{18}O/^{17}O$ of the solar system cannot be explained by either GCE or the normal dispersion in the Galaxy. Rather, it is best explained by local enrichment from an earlier generation of star formation.

Data: Our survey of CO oxygen isotopologue ratios in YSOs now includes 5 objects: IRS 43, IRS 63, RE50, VV CrA, and IRAS 19110+1045. Data for the first four in this list were collected using CRIRES on the Very Large Telescope (VLT) at ESO's Paranal Observatory by KMP. The last datum in the list is from existing Keck II NIRSPEC observations (G. Blake and coworkers). Our method for arriving at isotope ratios has been described by Smith et al. [3]. CO carbon isotope ratios from the CRIRES targets are presented at this meeting (Smith et al.). The relatively large errors for extracted column densities from the few $C^{17}O$ lines (3) for IRS 63 result in a large uncertainty for that datum.

The essential conclusion from the data acquired thus far is that material surrounding newly formed individual stars is similar to previous measurements of the ISM in having $^{18}O/^{17}O$ of $\sim 4.0^{+0.2}_{-0.5}$. There is no evidence thus far for significant dispersion up to solar values of 5.2 +/– 0.2 (Figure 1).

Supernova Enrichment: Enrichment of the solar system birth environment by type II sypernova (SN II) ejecta offers a viable explanation for the unusually high $^{18}O/^{17}O$ of the solar system. Other sources of $^{18}O/^{17}O$ enrichment are generally of lower probability.

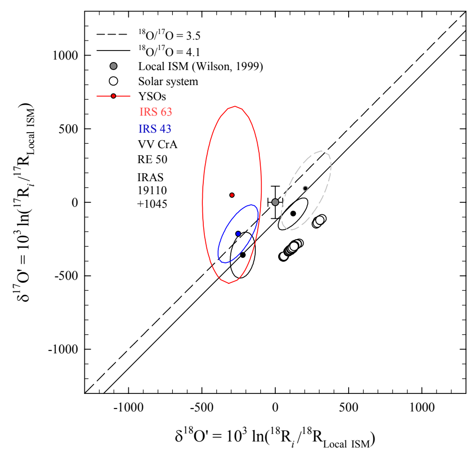

Figure 1. Oxygen three-isotope plot (with δ relative to local ISM of Wilson [1]) comparing CO around YSOs, the ISM (lines) and the solar system. IRS 63 and IRS 43, YSOs from the ρ Ophiuchus region, are new additions to the data set. ^{18}R and ^{17}R are $^{18}O/^{16}O$ and $^{17}O/^{16}O$, respectively.

For example, Wolf Rayet (WR) winds are unlikely because WR stars are in general more massive, and therefore more rare, than many stars that end their lives as SNe II. Also, the brief period of WR evolution (~ 10^5 yrs) and low rates of mass loss together limit the time-integrated mass of oxygen liberated.

Previous work emphasized the importance of the variation in oxygen isotopic composition of SNe II ejecta as a function of progenitor mass [4]. Using the most recent models for supernova yields [5, 6], it is clear that to obtain the solar oxygen isotopic composition from estimates of the composition of the local ISM 4.6 Gyr ago, the progenitor masses of the exploding stars that supplied the exogenous oxygen were < 20 $M_\odot$. In other words, the source of oxygen that enriched the solar birth environment was apparently one or more exploding B stars.

To the extent that B stars were the source of high $^{18}O/^{17}O$ in the solar system, we have an important constraint on the solar birth environment. A fundamental consequence of the stochastic nature of star formation and the nature of all proposed initial mass functions (IMFs) for star formation is that smaller clusters of stars produce fewer and smaller SNe II than do large clusters of stars. This effect can be quantified using published mass generation functions for stellar clusters [7]. Coupling this effect with SNe II yields shows that the cluster of stars that could have provided a source of suitably high $^{18}O/^{17}O$ to the solar system was most likely composed of order 500 stars (as opposed to > 1,000 stars) (Figure 2). These conclusions are robust with respect to SNe yield estimates.

Because the exploding B stars that comprised the sources of high-^{18}O oxygen evolved for 10 to 20 Myr, they must have represented an earlier generation of star formation compared with that which made the Sun.

Collatoral Effects: The same mass fraction of

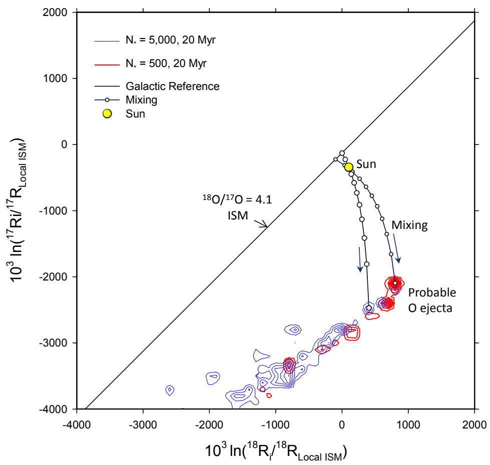

Figure 2. Oxygen three-isotope plot showing calculated mixing trends between an ISM 4.6 Gyr ago that must have had $^{18}O/^{16}O$ < $^{18}O/^{16}O$ of the ISM today and SNe II ejecta from a previous generation of star formation. Red contours show the probability density contours for ejecta from a cluster of 500 stars. Blue contours are for a cluster of 5,000 stars. The source of oxygen was most plausibly from a smaller cluster in order to yield high $^{18}O/^{17}O$ and high $^{18}O/^{16}O$.

SNe II ejecta that explains solar system oxygen isotope ratios would also explain the apparent excess in ^{28}Si in the solar system [8] and would have negligible effect on the solar C isotope ratios relative to the present ISM. It could account for solar system initial $^{60}Fe/^{56}Fe$ with a free decay time of order 10 Myr, but could not then account for the initial concentrations of ^{26}Al and ^{41}Ca because of the shorter mean lifetimes of these correlated short-lived nuclides.

The Galactic Chemical Evolution Alternative: Gaidos et al. [2] have suggested an alternative explanation for the disparity between solar and present-day Galactic $^{18}O/^{17}O$. They suggest that GCE results in substantial reduction in $^{18}O/^{17}O$ with time in the Galaxy. In their model, solar $^{18}O/^{17}O$ is high because it sampled the ISM 4.6 Gyr before present. We find this explanation to be at odds with the variation of oxygen

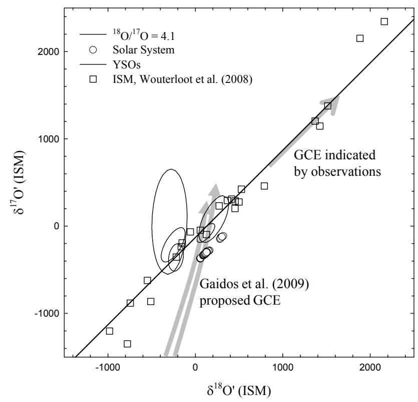

Figure 3. Comparison of GCE proposed in [2] and ISM and YSO data.

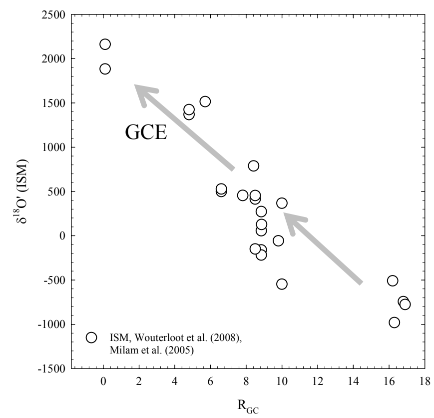

Figure 4. Plot of distance from the Galactic center (R_{GC}) vs. $^{18}O/^{16}O$ in CO gas of the ISM.

isotopes across the Galaxy. Figure 3 compares their proposed GCE trend with oxygen isotope ratios throughout the Galaxy. The GCE model of [2] does not account for the observations, and we are aware of no other credible explanation for the approximate slope-1 line defined by the observations other than GCE, with distance to the Galactic center (R_{GC}) serving as a proxy for time. Figure 4 shows that the most recent ISM CO isotopologue ratios vary systematically with R_{GC}, implying that R_{GC} is a proxy for time, as commonly asserted for metallicity.

References: [1] Wilson T. L. (1999) *Reports on Progress in Physics 62*, 143-185. [2] Gaidos E., Krot A. N. and Huss G. R. (2009) *Astrophysical Journal Letters 705*, L163-L167. [3] Smith R. L., Pontoppidan K. M., Young E. D. *et al.* (2009) *The Astrophysical Journal 701*, 163-175. [4] Gounelle M. and Meibom A. (2007) *The Astrophysical Journal 664*, L123-L126. [5] Woosley S. E. and Heger A. (2007) *Physics Reports 442*, 269-283. [6] Rauscher T., Heger A., Hoffman R. D. *et al.* (2002) *The Astrophysical Journal 576*, 323-348. [7] Brasser R., Duncan M. J. and Levison H. F. (2006) *Icarus 184*, 59-82. [8] Alexander C. M. O. D. and Nittler L. R. (1999) *The Astrophysical Journal 519*, 222-235.