THE STABLE ISOTOPE CASE FOR SUPERNOVA ENRICHMENT OF THE SOLAR SYSTEM BIRTH ENVIRONMENT BY SEQUENTIAL STAR FORMATION.

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Introduction: Recognition of the importance of sequential enrichments of nuclides in star-forming regions experiencing repetitive "collect and collapse" is emerging in both the astronomical and cosmochemical communities . In general one finds support for the concept that short-lived radionuclides (SLRs) could have been enriched relative to steady-state interstellar medium values by nuclear debris from both strong pre-Wolf Rayet stellar winds and supernovae in a giant molecular cloud complex [1]. At least three generations of star formation overlapping spatially may be required to explain the details of the isotopic composition of the solar system. The degree to which stable isotope enrichments would occur by these processes depends critically on production factors, particularly the gross yields from type II SNe, and the masses, and hence evolution times, of stellar sources. Consideration of both stellar wind and explosion yields, as well as the local composition of the ISM 4.6 Gyr before present, provides for a degree of decoupling between SLRs and stable isotopes.

Supernova Enrichment: Enrichment of the solar system birth environment by type II sypernova (SN II) ejecta [2] 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. For example, winds tend to produce too little oxygen of disparate composition to effect substantial regional changes in $^{18}O/^{17}O$.

Previous work emphasized the importance of the variation in oxygen isotopic composition of SNe II ejecta as a function of progenitor mass [3]. Using the most recent models for supernova yields [4, 5], 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 $M_\odot$ [2]. In other words, the source of oxygen that enriched the solar birth environment was 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 [6]. 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). Because the B stars that comprised the sources of high-^{18}O oxygen evolved for 10 to 20 Myr prior to explosion, they must have represented an earlier generation of star formation compared with that which made the Sun.

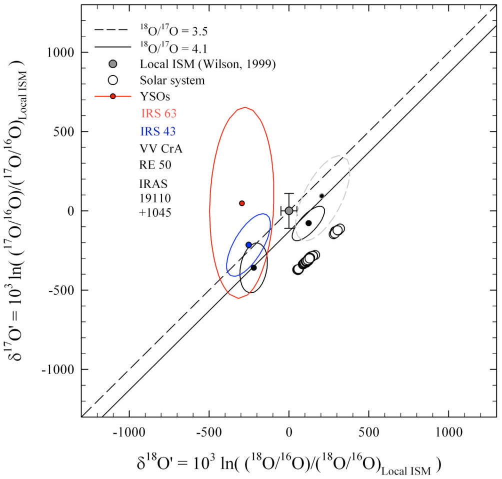

Figure 1. Oxygen three-isotope plot (with δ relative to local ISM of Wilson [9]) comparing CO around YSOs, the ISM (lines) and the solar system. IRS 63 and IRS 43, YSOs from the ρ Ophiuchus region, are new additions to the data set for YSOs. Modified after [10] with more recent data added as shown in [11] and in Smith et al. (in prep.).

Collatoral Effects: The same mass fraction of SNe II ejecta that explains solar system oxygen isotope ratios would also explain the apparent excess in ^{28}Si in the solar system [7] and would have negligible effect on the solar C isotope ratios relative to the present ISM. It could account for maximum estimates of solar system initial $^{60}Fe/^{56}Fe$ with a free decay time of order 10 Myr, though the requirement for $^{60}Fe/^{56}Fe$ in excess of steady-state ISM values is presently unclear. Such a scenario also effectively decouples ^{26}Al from $^{18}O/^{17}O$ enrichment. This is beause: 1) a likely source of ^{26}Al was strong stellar winds from a star greater than ~30 $M_\odot$ proximal to the birth place of the solar system; 2) the free decay time defined by the explosion of the soures of high $^{18}O/^{17}O$ oxygen is many half lives of ^{26}Al; and 3) the winds that were the source of ^{26}Al would have had little effect on oxygen isotopes of the ISM material that coalsesced to form the solar system parental molecular cloud.

The Galactic Chemical Evolution Alternative: Gaidos et al. [8] have suggested an alternative explanation for the disparity between solar and present-day Galactic $^{18}O/^{17}O$. They posit that Galactic chemical evolution (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 distribtuion of oxygen isotopes in the Galaxy as it requires a slope of ~3 in oxygen three isotope space, contrary to the slope-1 line defined by CO observations across the Galaxy (Figure 2). The GCE model of [8] 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 as a proxy for time. Figure 3 shows that the most recent CO isotopologue ratios as a function of R_{GC} are consistent with R_{GC} as a proxy for time, as commonly asserted for metallicity.

References: [1] M. Gounelle, et al., *ApJ* 694 (2009) L1. [2] Young E.D., Gounelle M., Smith R.L., et al. (2011) *The Astrophysical Journal* 729:43. [3] Gounelle M. and Meibom A. (2007) *The Astrophysical Journal 664*, L123-L126. [4] Woosley S. E. and Heger A. (2007) *Physics Reports 442*, 269-283. [5] Rauscher T., Heger A., Hoffman R. D. *et al.* (2002) *The Astrophysical Journal 576*, 323-348. [6] Brasser R., Duncan M. J. and Levison H. F. (2006) *Icarus 184*, 59-82. [7] Alexander C. M. O. D. and Nittler L. R. (1999) *The Astrophysical Journal 519*, 222-235. [8] Gaidos E., Krot A. N. and Huss G. R. (2009) *Astrophysical Journal Letters 705*, L163-L167. [9] Wilson T. L. (1999) *Reports on Progress in Physics 62*, 143-185. [10] Smith R. L., Pontoppidan K. M., Young E. D. *et al.* (2009) *The Astrophysical Journal 701*, 163-175. [11] Young E.D., Pontoppidan K.M., Smith R.L., et al. LPSC 2010.

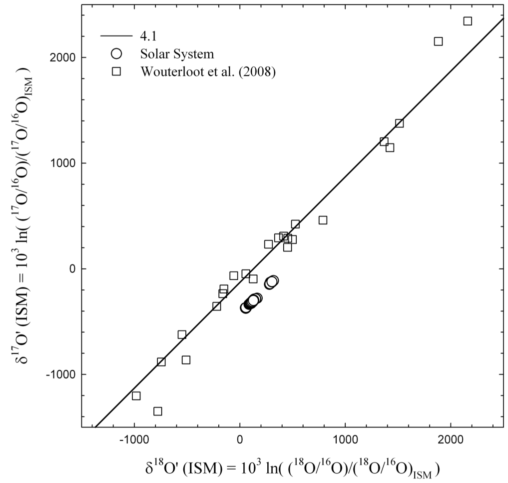

Figure 2. Slope-1 line defined by Galactic reservoirs of CO compared with solar values (after [10]).

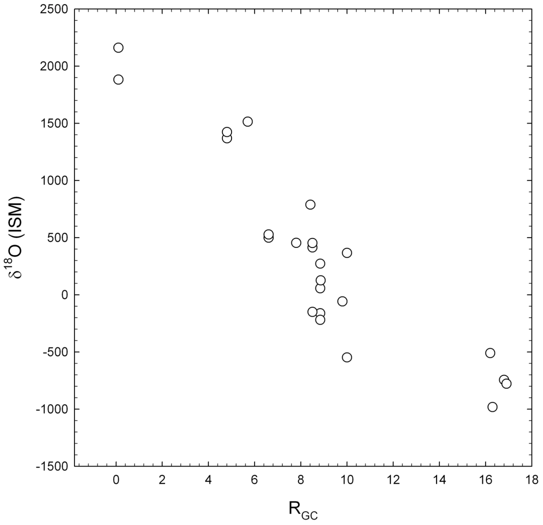

Figure 3. Plot of distance from the Galactic center (RGC) vs. $^{18}O/^{16}O$ in CO gas of the ISM (after [10]).