SOLAR SYSTEM OXYGEN ISOTOPE RATIOS RESULT FROM POLLUTION BY TYPE II SUPERNOVAE. E. D. Young[1,2] , M. Gounelle[3], R. Smith[1] , M. R. Morris[4], and K. M. Pontoppidan[5], [1]Department of Earth and Space Sciences, University of California Los Angeles (UCLA), Los Angeles, CA 90095, USA, [2]Institute of Geophysics and Planetary Physics, UCLA (eyoung@ess.ucla.edu), [3]Laboratoire d'Étude de la Matière Extraterrestre, Muséum National d'Histoire Naturelle, 57 rue Cuvier, CP52, 75005 Paris, France, [4]Department of Physics and Astronomy, UCLA, [5]Hubble Fellow, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.

Introduction: For decades it has been known that solar system $^{18}O/^{17}O$ is peculiar with respect to Galactic values. Rocks of the solar system have $^{18}O/^{17}O$ of approximately 5.2 while values for CO, OH, and HCO^+ in giant molecular clouds across the Galaxy are consistently 3.5 +/– 0.3 [1, 2]. This difference cannot be explained by Galactic chemical evolution (GCE), which results in a constant $^{18}O/^{17}O$ with time, and a satisfactory explanation for the disparity has proven elusive. The standard view has been that there may be a systematic error between the absolute ratios obtained by radio astronomy and those measured by mass spectrometry [3], however the latter yield absolute oxygen isotope ratios accurate to fractions of per cent while the difference in question is 30%. Systematic errors in the radio astronomy measurements can be addressed by measuring isotopologue ratios using a different method.

Here we report new infrared absorption measurements of oxygen isotope ratios in individual young stellar objects (YSOs) that confirm the previous radio observations of giant molecular cloud gas. These new data show that the typical Galactic $^{18}O/^{17}O$ of ~3.5 is not only an average over the parsec scale but pertains to the scale of single YSOs as well. These new, high-spatial-resolution data underscore the disparity between solar and extrasolar $^{18}O/^{17}O$ ratios. We show that this discrepancy is best explained by ~30% pollution (atomic units) of the proto-solar molecular cloud by intermediate mass (~20 $M_\odot$) type II supernovae ejecta.

Observations: Smith et al. [4] report detection of four CO isotopologues, $^{12}C^{16}O$ (CO), $^{13}C^{16}O$ (^{13}CO), $^{12}C^{18}O$ ($C^{18}O$) and $^{12}C^{17}O$ ($C^{17}O$), in two YSOs. High-resolution 4.7 μm fundamental and/or 2.3 μm overtone ro-vibrational absorption bands for CO were obtained for the disk surrounding the primary pre-main sequence type II young stellar object VV CrA from the Corona Australis star forming region using CRIRES on the VLT at ESO's Paranal Observatory. The object is ~ 170 pc from the Sun. Lower resolution data were obtained for a more massive embedded young stellar object, IRAS 19110+1045, using NIRSPEC on the Keck II telescope. This source resides 6 kpc from the Sun (and a similar distance from the Galactic center, D_{GC} ~ 6 kpc). Details of the data collection and processing are provided by Smith et al..

Results: The new infrared (IR) absorption data for the young stellar objects are compared with earlier radio and UV astronomical observations in Figure 1. The new data are within 1σ of the slope-1 line in oxygen three isotope space defined by the previous radio and UV data. This slope-1 line is a consequence of GCE since both ^{17}O and ^{18}O are secondary nuclides while ^{16}O is a primary nuclide. With these new measurements the GCE line for oxygen is now defined by radio, UV, and IR observations and is unlikely to be a spurious artifact. Rather, it is a robust reflection of the oxygen isotopic composition (and evolution) of the present-day Galaxy at a range of scales.

Discussion: Also shown in Figure 1 is a compilation of pre-solar grain data showing that the mode of pre-solar grain oxygen isotope data is on the oxygen GCE line (slope-1 line). The key observation is that solar system oxygen isotope ratios representing the full range of observed ratios in meteorites and planets are depleted in ^{17}O relative to the oxygen GCE line by nearly 300 ‰ (30%). Although the high solar $^{18}O/^{17}O$ value has been interpreted as an unexplained ^{18}O excess, the relationship between local interstellar medium (ISM) and solar values in Figure 1 is most consistent with a paucity of ^{17}O; GCE effects over the past 4.6 billion years could account for an increase in $^{18}O/^{16}O$ of the solar system relative to Galactic values (~400 ‰ over the past 4.6 Gyr [3]) but the expected equivalent shift to higher $^{17}O/^{16}O$ is not evidenced, precluding GCE as the explanation.

Supernovae pollution. Previous work has shown that the $^{18}O/^{17}O$ of type II supernovae ejecta varies systematically with mass of the progenitor star [5]. In Figure 2 we show the isotopic compositions of model SNe II ejecta [6] compared with Galactic and solar system values. It is clear from the plot that pollution of typical Galactic oxygen by ejecta from intermediate-mass SNe II (~15 $M_\odot$ to 25 $M_\odot$) can explain the high $^{18}O/^{17}O$ of the solar system. At this writing we see no other plausible explanation for the 30 % deficit in $^{17}O/^{16}O$. For example, mass fractionation at very low temperatures might be invoked, but the starting composition for mass fractionation on this plot would have to have been at unrealistically high D_{GC} of ~ 15 kpc [3] (Figure 1).

Astrophysical environment. Mass balance arguments preclude contamination from a single SNe. Rather, we suggest that the pollution was the result of overlap of two generations of star formation. The first, initiated approximately 10 to 12 Myr prior to solar system formation, produced multiple stars in the ~15 $M_\odot$ to 25 $M_\odot$ mass range that exploded just prior to solar system formation. A star forming region composed of 1000 $M_\odot$ of stars is expected (based on a Salpeter initial mass function and a total gas mass of $10^5 M_\odot$) to produce 35 stars that end their life as type II SNe, and of these, approximately 10 will be in the intermediate mass range. Together these stars release many solar masses of oxygen. Supernova shock fronts sweep up molecular cloud material to form polluted margins between H II regions that would exhibit anomalous isotope ratios. The next generation of star formation that formed the Sun is likely to have been triggered in these polluted "superbubble" margins. An analogous process of overlapping generations of star formation may be ongoing today in the Scorpius-Centaurus region [7].

Collateral isotopic effects. The suggestion that oxygen isotopes provide robust evidence for SNe II pollution of the protosolar cloud can be tested using the implied collateral effects for other nuclides. The next most robust signals should come from carbon and neon isotopes (nitrogen will be affected by photochemistry and so difficult to assess). The solar system is high in $^{12}C/^{13}C$ as compared with ISM values, and the carbon isotopes are generally consistent with oxygen isotopes in implying tens of per cent of pollution. Neon isotopes are more difficult to interpret because of the uncertainties in ISM ratios. Using Galactic cosmic rays (GCRs) as surrogates for the ISM suggests that solar Ne may be enriched in ^{20}Ne relative to ^{22}Ne, qualitatively consistent with expectations from the pollution scenario.

Whether or not this pollution that affected the light stable isotopes was also responsible for the abundances of short-lived radionuclides in the solar system is left as an open question. We note that if the same pollution that affected oxygen was also the source of short-lived radionuclides, free decay times between SNe II explosions and solar system formation was no greater than 2 to 3 Myr.

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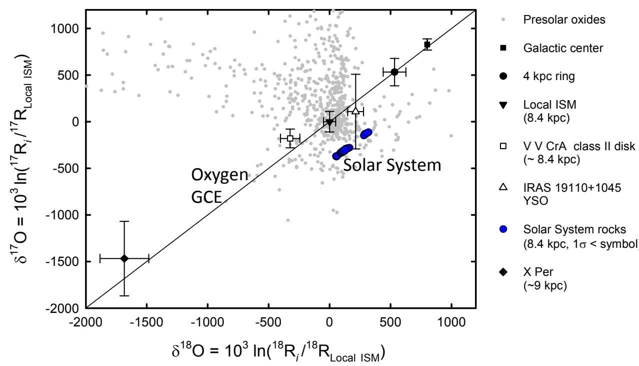

Figure 1. Logarithmic oxygen three-isotope plot comparing Galactic and solar system oxygen isotope ratios. New data for young stellar objects are shown in open symbols. Previous molecular cloud data are shown in filled black symbols. Solar system values are in blue and pre-solar grains are shown as grey dots. The extreme X Per cloud value is interpreted as being the result of photochemical self shielding [8].

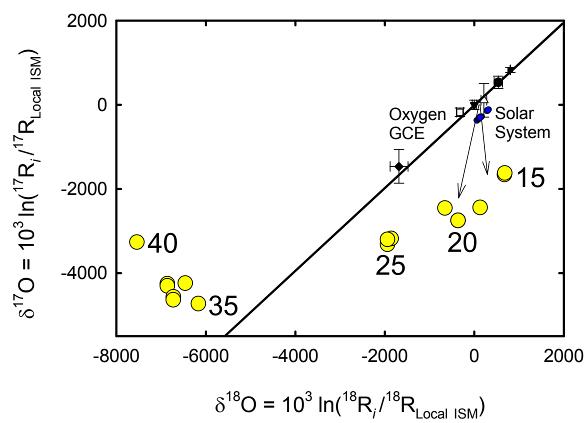

Figure 2. Comparison of oxygen GCE, solar system, and model SNe II ejecta. Numbers refer to solar masses of progenitor stars for the SNe ejecta. We suggest that the solar system paucity in ^{17}O is a result of pollution by intermediate-mass SNe II as shown by the arrows.