

## THE CARBON ISOTOPE COMPOSITION OF THE SUN: IMPLICATIONS FOR SOLAR SYSTEM FORMATION

J. R. Lyons<sup>1</sup>, E. Gharib Nezhad<sup>2</sup>, T. R. Ayres<sup>3</sup> <sup>1</sup>School of Earth and Space Exploration, Arizona State University, 781 S. Terrace Rd, Tempe, AZ 85281, USA; [jimlyons@asu.edu](mailto:jimlyons@asu.edu); <sup>2</sup>School of Molecular Sciences, Arizona State University, Tempe, AZ 85287, USA; [e.gharibnezhad@asu.edu](mailto:e.gharibnezhad@asu.edu); <sup>3</sup>Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA; [thomas.ayres@colorado.edu](mailto:thomas.ayres@colorado.edu).

**Introduction:** Measurements by the Genesis mission have shown that solar wind oxygen is depleted in the rare isotopes, <sup>17</sup>O and <sup>18</sup>O, by approximately 80‰ and 100‰, respectively, relative to Earth's oceans, with inferred photospheric depletions of 60‰ for both isotopes [1]. This is similar to the isotopically lightest, and oldest, condensates in chondritic meteorites [2], [3]. Direct astronomical measurements of CO absorption lines in the solar photosphere have previously yielded a wide range of O isotope ratios, with the most recent result [4] finding an <sup>18</sup>O depletion of 0 to 60‰. We have reanalyzed the line intensities, and obtained new results from direct measurement of photospheric oxygen and carbon isotope ratios [5], [6]. Our analysis yields an <sup>18</sup>O-depletion in the photosphere of  $\delta^{18}\text{O} = -51 \pm 11\%$  relative to VSMOW. This result confirms the inferred photospheric values from the Genesis mission [1], and provides the first accurate direct measurement of photospheric O isotope ratios ( $\delta^{17}\text{O}$  is less precise due to the low SNR of C<sup>17</sup>O lines). From the same analysis we find a carbon isotope ratio of  $\delta^{13}\text{C} = -48 \pm 7\%$  (1- $\sigma$ ) for the photosphere. This result differs from  $\delta^{13}\text{C} \sim 0\%$  found for TiC in CAIs in Isheyevo [7]. Computing the fractionation from the corona to the solar wind due to inefficient Coulomb drag, we find  $\delta^{13}\text{C} = -74\%$  and  $-91\%$  for C<sup>6+</sup> and C<sup>5+</sup>, respectively, in the solar wind. The result for C<sup>5+</sup> overlaps with the reported 1- $\sigma$  range for solar wind implanted in lunar regolith grains [8]. Our photospheric result for  $\delta^{13}\text{C}$  implies that the primary bulk reservoirs of carbon on the terrestrial planets are enriched in <sup>13</sup>C relative to the bulk material from which the solar system formed.

**C isotope fractionation in solar nebula:** The enrichment of the terrestrial planets in <sup>13</sup>C could be a result of chemical processing in the solar nebula, or could result from fractionation that accompanied accretion, differentiation, and atmospheric degassing during planet formation; here we focus on the former. Nebular C isotopes can be affected by many processes including CO self-shielding (as proposed for O isotopes), ion-molecule chemistry, CO ice formation in the outer nebula, loss of CO in surface disk winds, and incomplete oxidation of C grains in hot regions of the nebula. C atoms are ionized in a continuum at wavelengths  $\leq 110$  nm, so that ionization of atomic C accompanies CO dissociation (unless C is optically thick). Once ionized, a rapid ion-molecule exchange reaction,  $^{12}\text{CO} + ^{13}\text{C}^+ \rightleftharpoons ^{13}\text{CO} + ^{12}\text{C}^+ + 35 \text{ K}$  [9], acts to erase any <sup>13</sup>C excess in C<sup>+</sup> at high temperatures, and at lower temperatures produces enrichments in <sup>13</sup>CO and <sup>12</sup>C<sup>+</sup>. CO photolysis also yields C atoms in the C(<sup>1</sup>D) excited electronic state. Most CO photodissociation proceeds by the spin-allowed reaction,  $\text{CO} + h\nu \rightarrow \text{C}(\text{^3P}) + \text{O}(\text{^3P})$ . Velocity-map imaging measurements show that approximately 8% of CO follows a spin-forbidden pathway [10],  $\text{CO} + h\nu \rightarrow \text{C}(\text{^1D}) + \text{O}(\text{^3P})$ . The C(<sup>1</sup>D) is highly reactive, forming CH radicals upon collision with H<sub>2</sub>. Analysis of the chemical reaction timescales shows that reaction with H<sub>2</sub> is faster by a factor  $\sim 10^3$  than the next fastest process, radiative relaxation, in the inner solar nebula, and is comparable in timescale to radiative relaxation beyond  $\sim 50$  AU. Subsequent reactions of CH may lead to sequestration of C in larger molecules, e.g., by the reaction  $\text{CH} + \text{H}_2 \rightarrow \text{CH}_2 + \text{H}$ , or by  $\text{CH} + \text{C} \rightarrow \text{C}_2 + \text{H}$ , with possible preservation of the CO self-shielding isotope signature in the products. However, CH also reacts rapidly with H atoms, which returns C to its ground state, leaving it susceptible to ionization and exchange. The fate of CH is thus strongly dependent on the local H/H<sub>2</sub> ratio. A full assessment of the effects of CO self-shielding on C isotopes requires detailed nebular chemistry modeling, including atomic excited states.

**C isotope fractionation in clouds:** C isotope fractionation is well known in molecular clouds [11], and has also been observed recently in protoplanetary disks [12]. In molecular clouds towards Ophiucus, CO self-shielding was clearly responsible for the high <sup>12</sup>CO/<sup>13</sup>CO ratio observed at  $\zeta$  Oph, and in part attributable to the gentle FUV environment [11]. This suggests the possibility that <sup>13</sup>C-rich grains, formed in the parent cloud, could be inherited by the solar nebula, preferentially contributing C to terrestrial planets. In protoplanetary disks, high <sup>12</sup>CO/<sup>13</sup>CO ratios are also often seen, but are generally not correlated with the high C<sup>16</sup>O/C<sup>18</sup>O ratios associated with CO self-shielding, suggesting that other processes, such as CO ice formation, may be at work in these protoplanetary systems [12].

**References:** [1] McKeegan K. D. et al. 2011. *Science* 332, 1528-1532. [2] Clayton R. N. et al. 1973. *Science* 182, 485. [3] Liu M.-C. et al. 2009. *Geochimica et Cosmochimica Acta* 73, 5051. [4] Ayres T. R. et al. 2013. *Astrophysical Journal* 765, 46. [5] Lyons J. R. et al. 2017, *Lunar & Planetary Science Conference*, abstract 2309. [6] Lyons J. R. et al. (submitted). [7] Meibom A. et al. 2007. *Astrophysical Journal* 656, L33-L36. [8] Hashizume K. et al. 2004. *Astrophysical Journal* 600, 480-484. [9] Woods P. M. and Willacy K. 2009, *Astrophysical Journal* 693, 1360-1378. [10] Gao, H. et al. 2013, *Journal of Physical Chemistry A* 117, 6185-6195. [11] Federman S. R. et al. 2003, *Astrophysical Journal* 591, 986-999. [12] Smith R. L. et al. 2015, *Astrophysical Journal* 813, 120.