The Carbon Isotope Composition Of The Solar Photosphere

J. R. Lyons1, E. Gharib Nezhad2, T. R. Ayres3
1School of Earth and Space Exploration, Arizona State University, 781 S. Terrace Rd, Tempe, AZ 85281, USA; jimlyons@asu.edu; 2School of Molecular Sciences, Arizona State University, Tempe, AZ 85287, USA; e.gharibnezhad@asu.edu; 3Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA; thomas.ayres@colorado.edu.

Introduction: Measurements by the Genesis mission have shown that solar wind oxygen is depleted in the rare isotopes, $^{17}$O and $^{18}$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 $^{18}$O depletion of 0 to 60‰. This wide range resulted from an uncertainty in the intensity of the CO rovibrational lines as determined from two oscillator strength scales, Goorvitch (1994) [5] and Hure and Roueff (1996) [6]. We have reanalyzed the line intensities, and present new results from direct measurement of photospheric oxygen and carbon isotope ratios.

CO line intensities: CO rovibrational transitions dominate the mid-IR spectral features of the photosphere. Using the shuttle-borne ATMOS (with resolution $\omega/\Delta\omega\sim150,000$), thousands of CO fundamental ($\Delta v=1$) and first-overtone ($\Delta v=2$) lines of the solar spectrum have been recorded with high signal-to-noise ratio [7]. A direct-fit method has been used to calculate a more accurate dipole moment function [8], from which we computed new oscillator strengths and line intensities. In the radiative transfer model for the solar photosphere, CO lines of similar lower state energy are co-added to reduce the radiative transfer computation required. Sixteen snapshots from a 3-D hydrodynamic atmosphere model are used to more accurately capture the temperature variation associated with convections cells at the base of the photosphere [4]. The O abundance ($\sim 610$ ppm) is first determined from $^{12}$C$^{16}$O lines (with resolution $\omega/\Delta\omega\sim150,000$), thousands of CO fundamental ($\Delta v=1$) and first-overtone ($\Delta v=2$) lines. Isotopic abundances are then computed separately.

Results and Conclusions: The analysis yields an $^{18}$O depletion in the photosphere of $\delta^{18}$O = -51 ± 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 (δ$^{15}$O has a higher uncertainty due to the low SNR of C$^{17}$O lines). From the same analysis we find a carbon isotope ratio of $\delta^{13}$C = -48 ± 7‰ (1-σ) for the photosphere. This result differs from $\delta^{13}$C ~ 0‰ found for TiC in [9]. Computing the fractionation from the corona to the solar wind due to inefficient Coulomb drag [10], we find $\delta^{13}$C = -74‰ and -91‰ for C$^{6+}$ and C$^{5+}$, respectively, in the solar wind. The result for C$^{5+}$ overlaps with the reported 1-σ range for solar wind implanted in lunar regolith grains [11]. Our photospheric result for $\delta^{13}$C implies that the primary bulk reservoirs of carbon on the terrestrial planets are enriched in $^{13}$C relative to the bulk material from which the solar system formed. Self-shielding of CO may have contributed to this process via C(1D) formation from ~95-100 nm. C(1D) rapidly reacts with H$_2$ to form CH, thereby avoiding formation of the C ion and subsequent exchange with CO, which erases the $^{13}$C enrichment in C atoms produced during CO self-shielding. Carbon isotopes are also affected by ion-molecule reactions, and by condensation of CO in the cold, outer nebula, effects that need to be evaluated with models. As with O and N isotopes, it is possible that photochemical processes enriched the nebula in the rare carbon isotope, relative to the bulk starting material.