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

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Introduction: Measurements by the Genesis mission have shown that solar wind oxygen is depleted in the rare isotopes, 17O and 18O, 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 18O 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 18O-depletion in the photosphere of $\delta^{18}O = -51 \pm 11$‰ 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 ($\delta^{17}O$ is less precise due to the low SNR of $^{17}$O lines). From the same analysis we find a carbon isotope ratio of $\delta^{13}C = -48 \pm 7$‰ (1-$\sigma$) for the photosphere. This result differs from $\delta^{13}C \sim 0$‰ found for TiC in CAIs in Isheyevka [7]. Computing the fractionation from the corona to the solar wind due to inefficient Coulomb drag, we find $\delta^{13}C = -74$‰ and -91‰ for C6+ and C5+, respectively, in the solar wind. The result for C5+ overlaps with the reported 1-$\sigma$ range for solar wind implanted in lunar regolith grains [8]. 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.

C isotope fractionation in solar nebula: The enrichment of the terrestrial planets in $^{13}$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 $\lesssim 110$ nm, so that ionization of atomic C accompanies CO dissociation (unless C is optically thick). Once ionized, a rapid ion-molecule exchange reaction, $^{12}$CO + $^{13}$C $\rightarrow$ $^{13}$CO + $^{12}$C + 35 K [9], acts to erase any $^{13}$C excess in C relative to the bulk material from which the solar system formed.

CO photodissociation proceeds by the spin-forbidden reaction, CO + hv $\rightarrow$ C(2P) + O(3P). Velocity-map imaging measurements show that approximately 8% of CO follows a spin-forbidden pathway [10], CO + hv $\rightarrow$ C(2D) + O(3P). The C(2D) is highly reactive, forming CH radicals upon collision with H2. Analysis of the chemical reaction timescales shows that reaction with H2 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 CH + H2 $\rightarrow$ CH2 + H, or by CH + C $\rightarrow$ C2 + 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/H2 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 $^{12}$CO/$^{13}$CO ratio observed at $\zeta$ Oph, and in part attributable to the gentle FUV environment [11]. This suggests the possibility that $^{13}$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 $^{12}$CO/$^{13}$CO ratios are also often seen, but are generally not correlated with the high C16O/C18O ratios associated with CO self-shielding, suggesting that other processes, such as CO ice formation, may be at work in these protoplanetary systems [12].