THE CARBON ISOTOPE RATIO OF THE SUN AND IMPLICATIONS FOR THE SOLAR NEBULA. J. R.
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Introduction: Carbon isotopes in the Sun and planetary materials are of central importance to understanding solar system formation. Genesis has not yet reported a C isotope ratio for the solar wind. Measurement of solar wind implanted in lunar regolith silicate grains yielded a $\delta^{13}C \sim -105 \pm 20$ ‰ (1-σ), from which a bulk solar ratio of $\sim$ -150 to -100‰ was inferred [1]. Ion microprobe measurements of TiC grains in a CAI in the Isheyevo meteorite found $\delta^{13}C = 1.1 \pm 7$‰ [2], a value indistinguishable from Earth mantle C. Previous observations of CO absorption in the solar photosphere yielded C isotope ratios either consistent with terrestrial, $\delta^{13}C \sim -30 \pm 45$ ‰ [3], or highly enriched relative to terrestrial, $\delta^{13}C = 110 \pm 14$ ‰ [4].

A reanalysis of shuttle-based observations of CO in the photosphere made significant progress by eliminating line blends of CO isotopic species with the tails of $^{12}C^{16}O$ lines, and by using a 3-D hydrodynamic model atmosphere of the Sun [5]. However, the literature values for the oscillator strength (*f*-value) scale for CO rovibrational transitions left a 60‰ range of uncertainty. Recently, we resolved these differences in *f*-values and derived a $^{13}C/^{12}C$ ratio of $\delta^{13}C = -48 \pm 7$‰ for the photosphere [6]. C isotope ratios are poorly constrained in the solar system, but the Sun is light compared to inner solar system materials (Fig. 1). Here, we explore models of ^{13}C enrichment in the solar nebula.

Enrichment of terrestrial planet ^{13}C: The origin of the enrichment of the terrestrial planets in ^{13}C is a central question, as is the enrichment of O isotopes [7]. We present here a preliminary evaluation of mechanisms that could produce enrichment of ^{13}C in the inner solar system. The ^{13}C enrichment could be a result of chemical processing in the solar nebula or parent molecular cloud, or could result from fractionation that accompanied accretion, differentiation, and atmospheric degassing during planet formation. We focus on a nebular or parent cloud origin.

As for O isotopes, self-shielding during CO photodissociation will produce an enrichment in the minor isotopes in the dissociation products. To address the fate of C atoms produced from CO photodissociation, we compute the chemical lifetimes of various C-containing species at the UV surface of a minimum mass solar nebula. This gives us a rough idea of the fate of the C atoms, and is done in lieu of a full photochemical model. We include the production of

electronically-excited C atoms, $C(^1D)$, which immediately react with H_2 to produce CH radicals. Figure 2 shows chemical lifetimes for a small subset of C species, including CH. If C atoms are ionized primarily by the protosun (with a $1/r^2$ decrease in ionization rate), there is a chance that C_2 (and high C chain species) can be formed, thus preserving a ^{13}C enrichment due to self-shielding. This result, however, depends strongly on H atom abundance. This simple model shows that preservation of a self-shielding-derived ^{13}C enrichment in the solar nebula may or may not have occurred.

Inheritance from the parent cloud: Another possibility for explaining the C isotope enrichment of the inner solar system is inheritance of ^{13}C-enriched C grains. CO self-shielding in molecular clouds has been observed [8], and could result in production of ^{13}C-enriched C grains. (We note that protoplanetary disks do not show clear evidence for CO self-shielding in $^{13}C/^{12}C$ [9]). Figure 3 shows a possible distribution of such C grains in the solar nebula.

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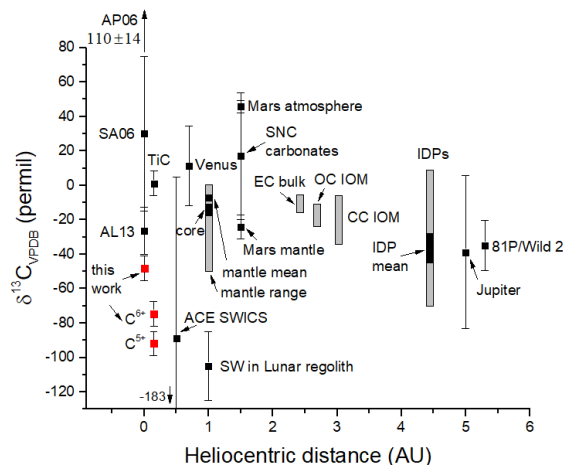
Figure 1. Carbon isotope ratios in the solar system. The value for CO in the Sun (red squares, 1-σ errors) reported here is among the lightest in the solar system for bulk materials, and lighter than previously reported values, AL13 [5] and SA06 [3]. The computed values for C^{5+} and C^{6+} ions in the solar corona (in red) are similar to solar wind in lunar regolith [1] and to ACE SWICS measurements, but differ from the ratio in TiC from Isheyevo [2]. Other reservoirs include Earth mantle diamonds (mean and range) and core estimate (Earth atmosphere is about 2‰ lighter than mantle mean), Venus atmosphere, Mars atmosphere, Mars mantle from SNC silicates, and SNC carbonates. Enstatite chondritic (EC) bulk C, ordinary chondrite (OC) insoluble organic matter (IOM), and carbonaceous chondrite (CC) IOM overlap with Earth mantle values. The Jupiter and interplanetary dust particle (IDP) ratios spans a wide range. Dust form comet 81P/Wild 2 had ratios clustering in a fairly tight range. The heliocentric distances shown for TiC, ECs, OCs, CCs, and IDPs are illustrative only. It should also be noted that the fraction of C in Earth's core could be as much as 90%, in which case the bulk Earth C isotope ratio would be approximately the core value. (The data references for this figure are in [6]).
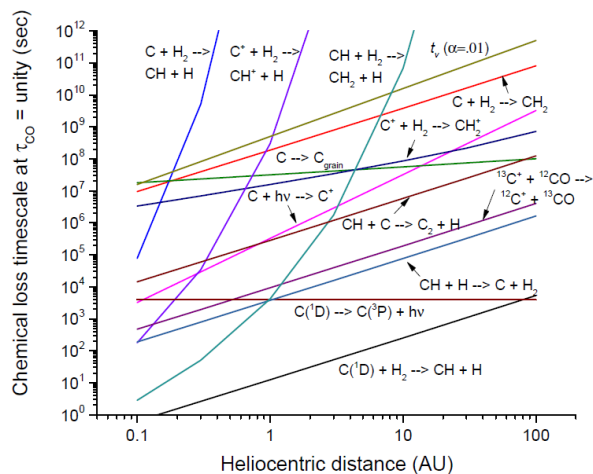

Figure 2. Chemical loss timescales for several carbon species computed at the FUV surface of the nebula and as a function of heliocentric distance. The figure shows that excited state carbon, $C(^1D)$, is lost to reaction with H_2 faster than for any other loss pathway. The C ionization reaction to form C^+ is FUV radiation from the protosun; nearby O stars can also be a significant source of FUV radiation. The timescale for the reaction $CH + H \rightarrow C + H_2$ was computed assuming an H/H_2

fraction = 0.01. This reaction returns C atoms to the gas in their ground state, allowing ionization and exchange to remove the C isotope self-shielding signature. Depending on the degree of dust settling and the CO fraction, the H/H_2 ratio can be higher or lower by a factor of ~ $10^2 – 10^3$. A much lower H/H_2 ratio allows the reaction $CH + C \rightarrow C_2 + H$ to sequester the self-shielding signature in C_2. Reaction of CH with H_2 also becomes much faster inside of 1 AU, providing another possible pathway for sequestering a C isotope self-shielding signature in larger molecules.
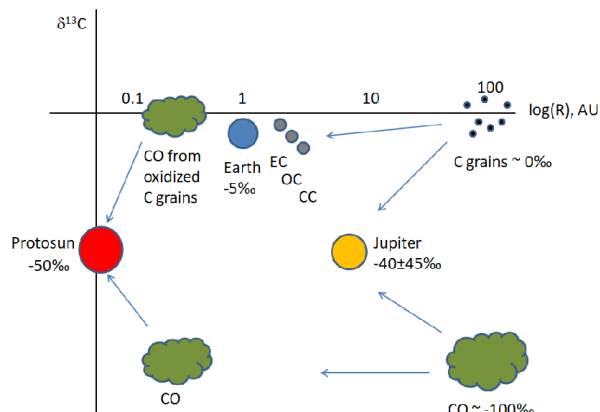

Figure 3. Illustration of one possible explanation for the difference between solar and terrestrial planet and asteroidal C isotopes. If, in the parent molecular cloud carbonaceous grains have a $\delta^{13}C_{PDB}$ values ~ 0‰ and CO has $\delta^{13}C_{PDB}$ ~ -100‰, and C is approximately equally distributed between grains and CO gas, then formation of Jupiter from both grains and gas would yield $\delta^{13}C$ ~ -50‰. Terrestrial planets and asteroids, formed primarily from planetesimals with C from C grains, would have $\delta^{13}C$ ~ 0‰. If C grains were converted to CO gas in the hot, inner solar nebula, the total accreted CO gas would yield a solar $\delta^{13}C$ ~ -50‰, as reported here. The cause of the C isotopic ratio difference in grains and dust of the parent cloud may have been a result of self-shielding in the parent cloud exposed to a high FUV radiation field, as, e.g., observed in Ophiucus [8].