NEW MEASUREMENTS OF SILICON ISOTOPE RATIOS ACROSS THE GALAXY WITH IMPLICATIONS FOR GALACTIC CHEMICAL EVOLUTION.

N. N. Monson[1], M. R. Morris[2] and E. D. Young[1], [1]Department of Earth, Planetary, and Space Sciences, UCLA (nn.monson@ucla.edu; eyoung@ess.ucla.edu), [2]Department of Physics and Astronomy, UCLA (morris@astro.ucla.edu).

Introduction: While interstellar oxygen isotopes have been studied extensively [e.g., 5] the same is not true of the other light-element systems having three stable isotopes; ^{24,25,26}Mg and ^{28,29,30}Si. Magnesium does not lend itself to widespread interstellar observations, however silicon can be observed in molecular clouds at millimeter and submillimeter wavelengths. The silicon isotope system is largely analogous to that of oxygen, and galactic chemical evolution (GCE) necessitates that both systems evolve via comparable mechanisms. This makes silicon a potentially valuable benchmark for examining the methodologies used to measure galactic oxygen isotope ratios.

Presolar silicon carbide grains found in meteorites indicate that silicon in the solar system is isotopically aberrant with respect to simple GCE predictions. These grains are thought to have condensed out of the winds of ancient AGB stars and therefore representative of the interstellar medium (ISM) as it existed when those stars formed >> 5 Gyr. The disparate rates of nucleosynthesis between the primary nuclide ^{28}Si and secondary nuclides ^{29}Si and ^{30}Si leads to two predictions; that the primary to secondary isotope abundance ratio will rise *linearly* with time, and that the abundance ratio of secondary isotopes will remain *constant*. Thus, to first order, GCE would dictate that Solar [^{28}Si]/[^{29}Si] and [^{28}Si]/[^{30}Si] ratios, being representative of the ISM when the sun formed (i.e. 4.5 Gyr), be smaller than the [^{28}Si]/[^{29}Si] and [^{28}Si]/[^{30}Si] ratios found in presolar SiC grains, *but this is not observed.* This deviation from the simple GCE prediction is not well understood [1], and several hypotheses have been put forth to explain it, including an incomplete understanding of the influence of winds from AGB stars on the isotope ratios in the interstellar medium [2], and pollution of the stellar birth environment by a nearby Type-II supernova [3, 4]. Are these isotopic differences the result of a misunderstanding of GCE, or are they indicative of some extraordinary circumstances surrounding the birth of the solar system? In other words, *are we normal*?

The questions raised by the abundance trend of presolar SiC grains can be put into a galactic context and perhaps resolved if the present galactic isotope ratios are determined as a function of galactocentric radius (a rough proxy for time), as ratios of stable isotopes in the solar system can be placed in a galactic context only if the effects of time can be accounted for. In effect, GCE must be considered in any comparison between the solar system and either the ISM or any extrasolar planetary systems. Here we address this issue by reporting on the first new radio astronomy measurements of silicon isotope ratios across the galaxy in nearly 30 years.

The Case for Silicon: A number of silicon species, including SiC, SiS, SiCN, SiNC and SiH_4, all have at least one detection in a circumstellar envelope around an AGB star, but local nucleosynthesis and hence the potential for sample bias, makes these unsuitable proxies for the average interstellar abundances. This is not true for silicon monoxide, which is the most commonly observed silicon species in the ISM and is thought to dominate the gaseous silicon budget [6]. Despite SiO being an oxide, no knowledge of oxygen isotope ratios is required to extract silicon isotope ratios from observations. For these reasons, SiO is well suited for probing isotopic GCE, as the chance that observational measurements are not representative of the bulk silicon composition is minimized.

In previous radio astronomy work with silicon isotopes, investigators found that despite reasonable antenna temperatures (i.e. line intensities), the main isotopologue lines bordered on the optically thick regime ($\tau \approx 1$) in many sources [7, 8]. This, in combination with high system temperatures (i.e. low S/N ratios), made it difficult to determine galactic silicon isotope abundances to any useful degree of accuracy, and

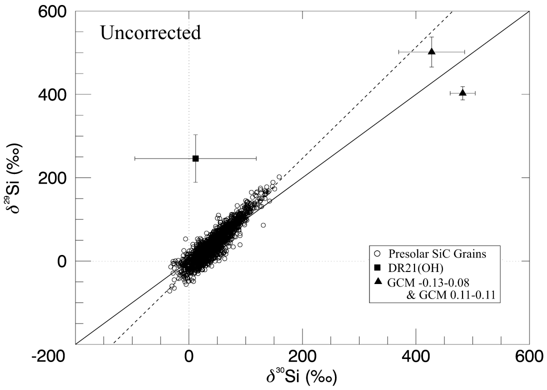

Figure 1: Uncorrected data for the three sources observed with the GBT. The solid line is the slope unity line predicted by GCE, and the dotted line represents the slope ≈ 4/3 regression line through the presolar SiC grains.

the issue was largely forgotten. However, modern high-resolution, low-noise receiver systems are sufficiently sensitive to permit rare isotope emission lines to be resolved with reasonable integration times. With these tools at our disposal, it is now feasible to determine variations in [^{29}SiO]/[^{28}SiO] and [^{30}Si]/[^{28}SiO] with accuracy and precision sufficient to address optical depth effects and determine what, if any, silicon isotope gradient exists in the galaxy.

Observations: Initial observations of the vibrational ground-state, $J = 1 \rightarrow 0$ pure-rotational transition of the three silicon isotopologues of SiO were carried out at the Robert C. Byrd Green Bank Telescope (GBT) in May of 2013. Three sources, DR21(OH), GCM -0.13-0.08 and GCM 0.11-0.11 have been observed to date. Extraction of isotope ratios from the raw data was done via a novel vectorized calibration routine and a series of line profile integrations performed by a suite of purpose built IDL and Fortran programs written by the first author.

DR21(OH), a high-mass star-forming region located within the Cygnus X molecular cloud complex, shows no evidence of optical depth in the main isotope emission line, however the rare isotope lines suffer from poor signal-to-noise ratios. The two galactic center sources, GCM -0.13-0.08 and GCM 0.11-0.11, both show evidence of appreciable optical depth in the main isotope emission line profiles, however both sources have good signal to noise ratios, and the lines are well resolved thanks to the ample resolution afforded by the GBT's FFT spectrometer backend. Using a series of simple radiative transfer codes to generate synthetic spectra, the optical depth at the center of the observed main isotope lines can be shown to be of order unity for both sources.

Discussion: Correcting for the effects of optical depth effectively destroys the galactocentric isotope gradient indicated by the raw data (Figures 1 and 2), as all three sources fall within error of one another with respect to δ^{29}Si. Although a marginal gradient in δ^{30}Si does remain, it seems likely that this is an artifact of the comparatively poor signal-to-noise ratio in the observed ^{30}SiO emission lines. Even if this small discrepancy in ^{30}Si was accepted as physical, a paltry 200‰ pales in comparison to the 3000‰ gradient seen in oxygen [3].

Preliminary results appear to support the argument that optical depth was responsible for previous evidence of a galactocentric silicon isotope gradient [7]. If true, significant revision of our understanding of the stable isotopic effects of GCE will be undoubtedly be necessary. There are, however, other phenomena that could be affecting the observed isotopic ratios. To date, the *modus operandi* when reducing the data has been to assume uniform excitation of all three species (this is not strictly true, as we correct for a small but significant discrepancy between the excitation temperatures of the three isotopologues as a consequence of the slightly disparate Einstein A coefficients). While there is no obvious evidence to suggest this is an invalid assumption, it is conceivable that weak inversions within a source [c.f., 9] or an enhanced radiation field within one of the line profiles could cause divergent excitation of the three isotopologues. Should this be the case, it would affect the extracted isotope ratios in a manner largely indistinguishable from optical depth effects, and may explain the apparent lack of a galactocentric silicon isotope gradient. Revisiting the three sources previously observed with the GBT and observing higher order transitions will help to properly constrain the excitation temperature of all three species, however this effort is still in progress.

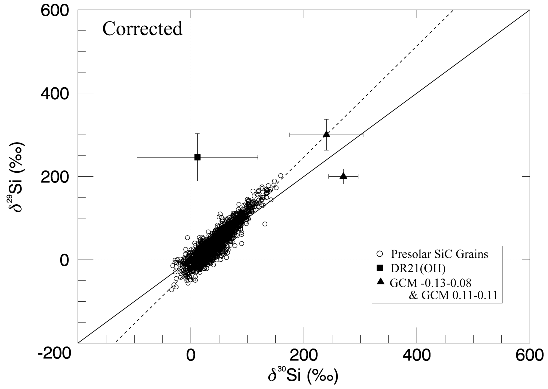

Figure 2: Calculated silicon isotope ratios after correcting for optical depth effects. The solid and dotted lines are the same as in Figure 1.

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