Introduction: High-resolution near-infrared absorption spectroscopy of carbon monoxide (CO) gas has enabled precise comparisons between carbon and oxygen isotopic reservoirs toward low-mass (solar-type) young stellar objects (YSOs) within ~1 kiloparsec (kpc) of the Sun [1-3]. Supportive evidence for CO self-shielding on disk surfaces [2,3,4], and significant heterogeneity in gas-phase \([^{12}\text{CO}] / [^{13}\text{CO}]\) with possible interplay between CO ice and gas reservoirs [3,5,6], have been reported toward several local low-mass YSOs. Precise ratios of \([^{12}\text{C}]^{18}\text{O}] / [^{12}\text{C}]^{17}\text{O}\) have also been used to argue for supernova enrichment in the early solar system [7], and comparison between low-mass binary systems and embedded protostars is suggestive of carbon isotopic homogeneity within a few hundred AU [8].

Compared to solar-type YSOs, massive YSOs are observational tracers of regions with high-UV fluxes, span a larger observational range in Galactocentric radius \((R_{\text{GC}})\), and enable meaningful comparisons between carbon reservoirs observed along the same lines of sight. These targets therefore offer valuable insights on key protoplanetary and prebiotic carbon pathways. Here we present new results from our ongoing observational survey of CO isotopologues toward massive YSOs along a Galactic gradient, refining initial conclusions that CO gas follows predictive trends in massive YSOs as compared to low-mass counterparts [9].

Observations and Methods: We present new observations from our Keck-NIRSPEC (R ≈ 25, 000) survey for the massive YSOs, W33A – at \(R_{\text{GC}} = 4.5\) kpc, thus far this survey’s farthest source from the solar system – and the complex, bright solar-type YSO, Elias 29 \((R_{\text{GC}} = 7.8\) kpc); eight additional massive targets surrounding ~8 kpc have been reduced and are currently being analyzed. Luminosities range from \(\sim 1 \times 10^4\) to \(4.7 \times 10^5\) \(L_{\odot}\), and \(\sim 39L_{\odot}\) for Elias 29. Fundamental \((v = 1 - 0)\) and first overtone \((v = 2 - 0)\) rovibrational spectra were reduced using our customised IDL pipeline. Equivalent widths \(W_v\) for each line were computed using polynomial + Gaussian fits (spectra and sample fits are shown in Figure 1). For \(^{12}\text{C}^{18}\text{O}\) and \(^{12}\text{C}^{17}\text{O}\) lines, column densities \((N_j)\) were calculated using the optically thin relation, \(W_v = (\pi c^2/4 m_{\text{e}} e^2) f_j N_j\) [10]. For each YSO, a curve of growth (example, Figure 2 top) relating \(W_v\) to \(N_j\), was used in conjunction with the rotational analysis (examples, Figure 2 bottom) and Figure 3 to find the best-fit Doppler broadening parameter \((b)\), which in turn was used to derive \(N_j\) values for the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) lines. Total column densities for each isotopologue were then found using the best-fit \(b\) and derived rotational temperatures.

Results and discussion: Derived ratios of \([^{12}\text{CO}] / [^{13}\text{CO}]\) for the five analyzed massive YSOs thus far, AFGL 2136, MonR2 IRS3, NGC 7538 IRS9, W3 IRS5, and W33A, and the low-mass complex YSO, Elias 29 \((R_{\text{GC}} = 4.5\) to 9.7 kpc), are shown in Figure 4 against data from low-mass CRIRES studies [2,3] and data from the literature. We find that cold-gas \([^{12}\text{CO}] / [^{13}\text{CO}]\) \((T \sim 5\) to 60 K) shows some dispersion off the Galactic trend for \(^{12}\text{C}/^{13}\text{C}\), similar to what is found for many of the low-mass YSOs [3]. Four of the massive YSOs show lower cold/warm-gas \([^{12}\text{CO}] / [^{13}\text{CO}]\) compared to solid-phase \([^{12}\text{CO}_2] / [^{13}\text{CO}_2]\) [11], while W33A reveals significantly higher \([^{12}\text{CO}] / [^{13}\text{CO}]\) for both warm and cold gas compared to \([^{12}\text{CO}_2] / [^{13}\text{CO}_2]\) ice. Elias 29 – a complex YSO with potentially distinct radiation and velocity fields [15] – reveals a dramatically higher \([^{12}\text{CO}] / [^{13}\text{CO}]\) \((228 \pm 21)\) compared to solid \([^{12}\text{CO}_2] / [^{13}\text{CO}_2]\) \((81 \pm 3.7)\). These results suggest
Figure 2: Analysis for massive YSO, W33A. (Top): Curve of growth showing the best-fit $b$ value (11 km/s), as well as other comparison velocity curves. (Bottom): Rotational analysis. Error bars are 1σ, $E_J$ is the energy of the $J^{th}$ rotational state, $k$ is the Boltzmann constant.

Figure 3: Rotational analysis for low-mass YSO, Elias 29, for $b = 3$ km/s. Error bars are 1σ, $E_J$ is the energy of the $J^{th}$ rotational state, $k$ is the Boltzmann constant.

that CO$_2$ may not originate from CO reservoirs as previously assumed [12]. Further, we find that warm-gas [12CO]/[13CO] ratios are consistently higher than those from the cold gas when observed in the same target, suggesting that there may be similar temperature-dependent CO fractionation pathways in a range of YSO types. Finally, our [12CO]/[13CO] for W3 IRS5 (103 ± 4) and W33A (158 ± 11 and 83 ± 6) are significantly higher than those from radio observations of 12C$^{18}$O and the doubly-substituted 13C$^{18}$O (66 ± 4) [13], which could be due to the higher photodissociation rate for 12C$^{18}$O [14].

Conclusions: Our high-resolution observations of CO toward massive and complex YSOs across the Galaxy thus far reveal [12CO]/[13CO] gas-phase ratios which significantly vary from derived ice-phase [12CO]/[13CO], with varying degrees of dispersion off the general Galactic carbon trend. Our results suggest that CO$_2$ may not originate from CO, and complex outflow environments and radiation fields in both massive and low-mass YSOs should be considered in evolutionary models for protoplanetary and prebiotic chemical pathways.