NEW OBSERVATIONS OF CO ISOTOPOLOGUES TOWARD MASSIVE PROTOSTARS: AN EXPANDED VIEW OF MOLECULAR RESERVOIRS IN THE GALAXY. Rachel L. Smith[1,2], Geoffrey A. Blake[3], A. C. Adwin Boogert[4], Klaus M. Pontoppidan[5], Alexandra C. Lockwood[3], [1]North Carolina Museum of Natural Sciences (rachel.smith@naturalsciences.org), [2]Appalachian State University, Department of Physics and Astronomy, [3]California Institute of Technology, Division of Geological and Planetary Sciences,[4]SOFIA/USRA, NASA Ames, [5]Space Telescope Science Institute.

Introduction: High-resolution near-infrared observations of carbon monoxide (CO) gas in absorption have been shown to be powerful tools for the precise derivation of C and O isotope ratios toward solar-type, low-mass protostars within $\sim$ 1 kiloparsec (kpc) of the Sun [1-3]. Results thus far have revealed signatures of CO self shielding – supportive evidence for this process on disk surfaces [2,3,6] – and significant heterogeneity in [^{12}CO]/[^{13}CO], with possible interplay between CO ice and gas reservoirs as a cause [3-5,6]. Precise ratios of [^{12}C^{18}O]/[^{12}C^{17}O] toward low-mass young stellar objets (YSOs) have also been used to argue for supernova enrichment in the early solar system [7], and our recent comparison between low-mass binary systems and embedded protostars suggest carbon isotopic homogeneity within a few hundred AU [6].

As part of our new observational survey of massive YSOs, we present initial results of CO isotopologue abundances toward the highly luminous ($\sim$ 7$\times$10^{4}L$_{\rm Sun}$) protostar AFGL 2136 in the Juggler Nebula, $\sim$2 kpc from the Sun and a Galactocenteric radius (R$_{\rm GC}$) of 6.1 kiloparsecs (kpc). We compare these results to other CO reservoirs in this and similar YSOs. Unlike most low-mass objects, bright, massive protostars are observational tracers of regions with high-UV fluxes and several isotopic systems, and span a larger range in R$_{\rm GC}$. Our new CO$_{\rm Gas}$ values provide robust comparisons to solid CO and CO$_2$ reservoirs along the same lines of sight, shedding light on key protostellar chemical pathways [8,9].

Observations and Methods: Fundamental ($v = 1 - 0$) and first overtone ($v = 2 - 0$) spectra toward five massive protostars were obtained with the NIRSPEC instrument (R$\sim$ 25,000) on the Keck II Telescope (Mauna Kea, HI). Spectra were reduced using our customized IDL pipeline; portions of these for AFGL 2136 are shown in Figure 1. The ($v = 1 - 0$) ^{12}C^{16}O lines are saturated and show complex profiles, so ($v = 2 - 0$) lines are used for analyzing ^{12}C^{16}O.

Equivalent widths (W_ν) were determined using a polynomial + Gaussian fit to each isotopologue line (examples in Figure 1). For ^{12}C^{18}O and ^{12}C^{17}O lines, column densities for each rovibrational line (N_J) were calculated directly using the optically-thin relation, $W_\nu = (\pi e^2/mec^2) f_J N_J$ [10], with f_J representing the absorption oscillator strength for the $J^{\rm th}$ transition. A rotational analysis (Figure 2, top) of the more robust ^{12}C^{18}O lines was used to constrain a temperature in the curve of growth [10], necessary to find the N_J for the potentially saturated ^{12}C^{16}O and ^{13}C^{16}O lines by relating the Doppler line broadening (b) to W_ν. A preliminary curve of growth using a fixed temperature of 130 K (slightly higher than ^{12}C^{18}O following trends found in our earlier data), is shown in Figure 2 (bottom). Total column densities were derived from the rotational analysis (Figure 2 (top), which assumes a Boltzmann distribution for the gas [1-3, 14]).

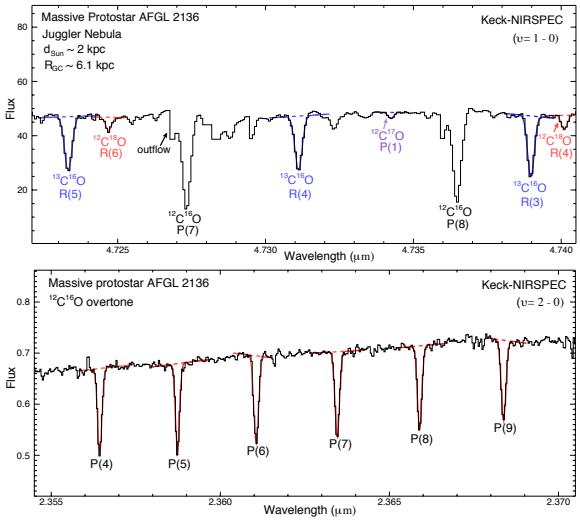

Figure 1: Portions of CO fundamental rovibrational bands toward the massive protostar, AFGL 2136, obtained with Keck-NIRSPEC. Representative CO isotopologue absorption lines are marked. Lines show overlaid model fits, used to derive equivalent widths for each line. (Top): Fundamental band ($v = 1 - 0$) band, where lines for all four CO isotopolgues were observed. (Bottom): First overtone ($v = 2 - 0$) band; several ^{12}C^{16}O are lines are marked.

Results and discussion: An initial [^{12}CO]/[^{13}CO] of $\sim$ 76$\pm$8 for AFGL 2136 is plotted against R$_{\rm GC}$ of $\sim$ 6.1 kpc (Figure 3). Unlike the dispersion found in our low-mass sources (R$_{\rm GC}\sim$ 8kpc), AFGL 2136 follows the predicted Galactic trend for [^{12}C/^{13}C], consistent with the pattern found in solid [^{12}CO$_2$]/[^{13}CO$_2$] toward other massive protostars [8]. Further, the [^{12}CO]/[^{13}CO] of $\sim$ 76 $\pm$ 8 is lower than the solid [^{12}CO$_2$]/[^{13}CO$_2$] of 107$\pm$8 for this object [8], following the systematic trend suggested for a few other massive protostars[8]. We find a [^{12}C^{16}O]/[^{12}C^{18}O] of $\sim$ 1700 $\pm$ 180, suggesting that CO self shielding may be influencing the oxygen ratios, yet without a robust abundance of [^{12}C^{17}O] a mass-independent trend cannot be determined. The weak CO ice feature observed

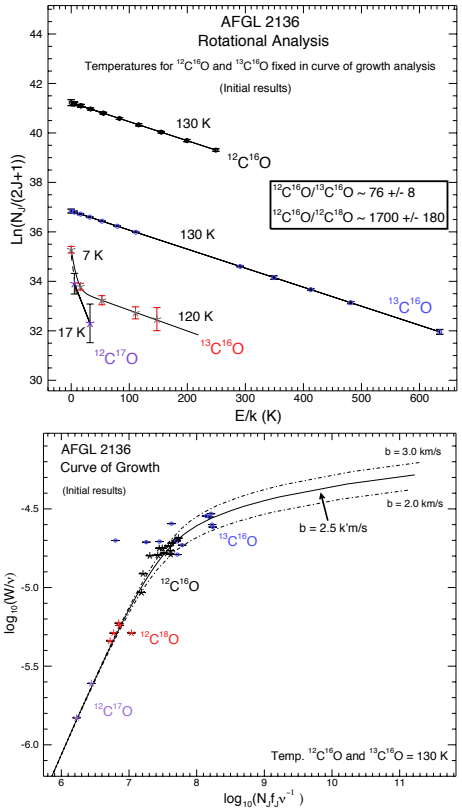

Figure 2: Preliminary analysis for AFGL 2136. (Top): Rotational analysis. Error bars are 1σ. E_J is the energy of the J^{th} rotational state, and k is the Boltzmann constant. (Bottom): Curve of growth showing the N_J determination for the $^{12}C^{16}O$ and $^{13}C^{16}O$ lines based on a Doppler line broadening (b) value of 2.5 km/s and a temperature of 130 K.

in AFGL 2136 [11] further enables comparison of the CO ice fraction vs. the $[^{12}CO]/[^{13}CO]$ in the gas (Figure 4). These results so far support the potential observational trend between CO ice and $[^{12}CO]/[^{13}CO]$ gas as a possible explanation for the $[^{12}CO]/[^{13}CO]$ dispersion seen in our low-mass sample. Continued analysis of our data will help further evaluate these potential trends.

Conclusions: Preliminary results for $[^{12}CO]/[^{13}CO]$ toward the massive YSO AFGL 2136 suggest that massive protostars may show less carbon isotopic dispersion in distinct molecular reservoirs than found in low-mass objects. Our findings support the possible interplay between CO ice and gas seen in our low-mass sample, as well as the possible real isotopic discrepancy between CO_{Gas} and $CO_{2\,(Ice)}$ in massive objects. This ongoing survey of massive protostars should help constrain the evaluation of protostellar C and O reservoirs – links to key chemical pathways in these evolving systems.

References: [1]Brittain S.D. et al. (2005) *ApJ 626*, 283-291.[2]Smith R.L. et al. (2009) *ApJ 701*, 163-175.[3]Smith R.L. et al. *ApJ, submitted*.[4] Pontoppidan K.M. (2006) *A&A 453*, L47.[5]Young E.D. and Schauble E.A. *42nd LPI, 1608*, 1323.[6] Smith R.L. et al. (2013) *44th LPI, 1719*, 2698.[7]Young E.D. et al. (2011) *ApJ, 729*, 43.[8] Boogert A.C.A. et al. (2000) *A&A 353*, 349-362.[9] Boogert A.C.A. et al. (2002) *ApJ 577*, 271-280.[10]Spitzer L. J. (1978) Physical Processes in the Interstellar Medium. [16] Pontoppidan K.M. et al. (2003) *A&A 408*, 981-1007.[12] Milam S.N. et al. (2005) *ApJ 634*, 1126-1132.[13] Scott P.C. et al. (2006) *A&A. 456*, 675-688.[14] Goto M. et al. (2003) *ApJ 598*, 1038-1047.[15] Federman S.R. et al. (2003) *ApJ 591*, 989-999.[16] Lambert D.L. et al. (1994) *ApJ 420*, 756-771.[17] Thi W.-F. et al. (2006) *A&A 449*, 251-265.

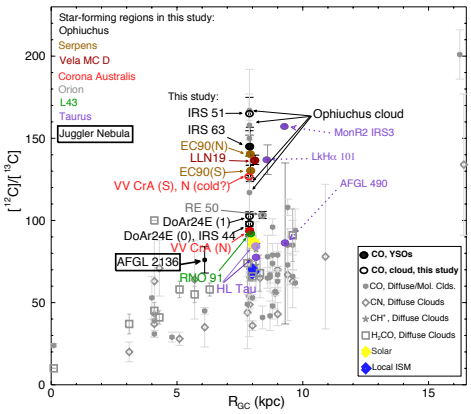

Figure 3: Ratios of $[^{12}C]/[^{13}C]$ vs. R_{GC} (kpc), including data from the literature and CO_{Gas} from our high-resolution surveys (left labels, filled dots [2,3,6]). AFGL 2136 is boxed at 6.1 kpc. (Top, left): Color-coded molecular clouds associated with each protostar. Values for local ISM ($\sim$ 68 [12]), solar system $\sim$ 87 [13] are shown, with HL Tau from [1] and 3 embedded protostars [14] indicated (purple; right-side labels). Black arrows: diffuse $[^{12}CO]/[^{13}CO]$ gas in Ophiuchus [15,16].

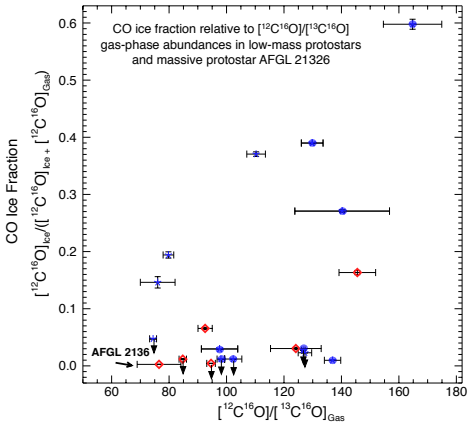

Figure 4: Comparison of the CO ice fraction with $[^{12}C]O/[^{13}CO]_{Gas}$. AFGL 2136 value (bottom left) is shown with our low-mass sample [3,6]. Blue stars: cold-gas isotope ratios from regimes where warm gas (red diamonds) was also observed. Blue ovals: objects where *only* cold gas was observed. Total CO ice values were derived from pure CO ice optical depths [11,17]. Arrows: 3σ upper limits on ice.