AN OBSERVATIONAL SURVEY OF PROTOPLANETARY CARBON IN YOUNG STELLAR SYSTEMS ACROSS THE GALAXY.

R. L. Smith[1,2], G. A. Blake[3], A. C. A. Boogert[4], and K. M. Pontoppidan[5].
[1]North Carolina Museum of Natural Sciences, [2]Appalachian State University, Department of Physics & Astronomy, (rachel.smith@naturalsciences.org), [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 absorption spectroscopy of the rovibrational transitions of carbon monoxide (CO) gas toward young stellar objects (YSOs) enables precise evaluation of carbon and oxygen isotopes in these systems, providing insight into protoplanetary processes [1-6]. Meaningful comparisons can be made between solar system materials and young stellar gas, furthering our understanding of phenomena that could have affected chemistry in the early solar nebula, including CO self-shielding [3,6], supernova enrichment [4], and interplay between $^{12}C^{16}O$ ice and gas reservoirs [5,6]. Such data also enable the assessment of potential differences in chemical pathways between isolated cores and low-mass binary systems separated within a few hundred AU [5].

In contrast to their solar- (low-) mass counterparts, massive YSOs (>~ 8 solar-masses) are bright (~ 10^3 to 10^5 solar-luminosities) and trace high-UV fields, permitting observations over a significant range of Galactocentric radii (R_{GC}). Further, massive YSOs are particularly valuable targets for evaluating protoplanetary and prebiotic carbon chemistry, since precise abundances of gas-phase $^{12}C^{16}O$ (^{12}CO) and $^{13}C^{16}O$ (^{13}CO) isotopologues can be compared to ice-phase $^{12}C/^{13}C$ derived from CO and CO_2 ice reservoirs along a single line of sight. Here we present our survey of massive YSOs at R_{GC} of ~ 4.5, 6, 9 and 10 kiloparsecs (kpc) obtained with the Keck telescope. This presentation will also include massive YSOs to be observed with Keck prior to this conference, including objects at R_{GC} = 8, 7, and 0.5 kpc, and the Galactic center, completing this survey of protoplanetary carbon along a Galactic gradient.

Observations and Methods: Our present CO gas-phase data set includes 15 massive YSOs and one low-mass, bright solar-type YSO, obtained with the NIRSPEC instrument at high spectral resolution (R~25,000, 12 km s^{-1}) on the Keck telescope. We obtained fundamental (υ=1−0) absorption spectra for ^{13}CO, $^{12}C^{18}O$ and $^{12}C^{17}O$ isotopologues, and first overtone (υ=2−0) spectra for ^{12}CO lines, ensuring that all lines in this study were sufficiently optically thin. Equivalent widths for each line were derived using polynomial + Gaussian fits. Doppler broadening, integrated gas temperatures, and total molecular column densities were determined using curve-of-growth and rotational analyses for each YSO target. Our customized IDL pipeline and codes were used for all data reduction and analyses.

Results: Three of the massive YSOs in our sample -- AFGL 2136 (R_{GC} = 6.1), NGC 7538 IRS 9 (R_{GC} = 9.4), and W3 IRS5 (R_{GC} = 9.7) -- reveal lower [^{12}CO]/[^{13}CO] derived from cold or single-temperature warm gas, as compared to solid-phase [$^{12}CO_2$]/[$^{13}CO_2$] (ratios from [7]). In contrast, the massive YSO W33A (R_{GC} = 4.5) shows higher [^{12}CO]/[^{13}CO] in both warm and cold gas compared to the [$^{12}CO_2$]/[$^{13}CO_2$] ice. Elias 29, a complex solar-type YSO, reveals dramatically higher [^{12}CO]/[^{13}CO] (228±21) compared to solid [$^{12}CO_2$]/[$^{13}CO_2$] (81±3.7), which could be due to the distinct radiation and velocity fields in this YSO [8]. Taken together, our results thus far suggest a more complicated chemical pathway for CO_2 than direct origination from a CO reservoir as has been assumed [9]. We find several similarities between our massive YSOs and the low-mass YSOs surveyed with the CRIRES instrument [6]: the massive YSOs reveal disperson in [^{12}CO]/[^{13}CO] gas from the Galactic trend, resembling the [^{12}CO]/[^{13}CO] heterogeneity found toward the low-mass YSOs; for massive YSOs modeled with two temperature regimes, [^{12}CO]/[^{13}CO] ratios from warm gas are consistently higher than those from cold gas, a trend we also see in the low-mass YSOs; and in both massive and low-mass YSOs, CO gas-phase reservoirs may be similarly affected by CO ice. These comparisons thus far suggest that protoplanetary carbon may follow similar pathways in systems ranging in mass and UV field. Finally, our [^{12}CO]/[^{13}CO] ratios for W3 IRS5 (103±4) and W33A (158±11 [warm gas], 83±6 [cold gas]) are significantly higher than those obtained from radio observations of $^{12}C^{18}O$ and the doubly-substituted $^{13}C^{18}O$ (66±4 and 39±1, respectively [10]), which could be due to the higher photodissociation rate for $^{12}C^{18}O$ [11].

Conclusions: Our high-resolution observations of CO gas toward massive and complex YSOs across the Galaxy thus far suggest that carbon chemistry may be more complex than previously assumed, with CO_2 potentially not originating from CO. Further, we find similar trends in [^{12}CO]/[^{13}CO] for massive and solar-type YSOs with respect to carbon isotopic heterogeneity and dispersion from the predicted Galactic trend, warm vs. cold gas ratios, and potential influence of CO ice abundance on the gas-phase CO carbon isotope ratios; these findings suggest that carbon may follow similar chemical pathways in a wide range of protoplanetary environments. Our upcoming Keck observations focusing on massive YSOs in the Galactic center and R_{GC} ~ 7 and 8 kpc should put these results in a more complete context, and provide additional insight for protoplanetary and prebiotic carbon models.

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