INVESTIGATING EVOLUTIONARY RELATEDNESS AND CHEMICAL INHERITANCE IN YOUNG STELLAR OBJECTS WITHIN THE MONR2 MOLECULAR CLOUD. Rachel L. Smith[1,2,3] and A.C.A. Boogert[4]. [1]NC Museum of Natural Sciences (rachel.smith@naturalsciences.org), [2]Appalachian State University, [3]UNC-Chapel Hill, [4]Infrared Telescope Facility, Institute for Astronomy, University of Hawaii.

Introduction: Astronomical observations of young stellar objects (YSOs) are windows into protoplanetary chemistry, and are critical for informing models of the solar nebula. In particular, high-resolution near-infrared observations of the rovibrational bands of CO have enabled the precise evaluation of carbon and oxygen isotopes for a range of YSO environments, informing models of CO self-shielding in disks [1-3], supernova inheritance in the nebular cloud [4], and CO exchange between ice and gas reservoirs [3]. Massive YSOs provide additional insight into rare environments of star and planet formation, and chemistry that cannot be easily probed with low-mass YSOs. For instance, recent work connected to this study revealed variability in [^{12}CO]/[^{13}CO] ratios in very short time scales, suggesting that there could be significant and dynamic heterogeneity in certain carbon reservoirs in YSOs, which in turn could be a sign of chemical inheritance from the parent cloud to the disk [5,6].

The MonR2 molecular cloud is located $\sim$ 778 pc from the Sun in the constellation Monoceros, and is one of the closest regions of massive star formation, with YSOs in a range of local environments. This region provides a unique opportunity to observe binary systems and isolated cores within the same parent cloud, thus enabling an exploration of chemical relatedness within gravitationally-bound systems, as well as a comparisons of YSOs in multiple configurations with isolated cores originating from the same cloud. As many of these YSOs are CO-rich, containing the four observable isotopologues of CO (^{12}C^{16}O, ^{13}C^{16}O, ^{12}C^{18}O and ^{12}C^{17}O), we are able to evaluate the oxygen reservoir in three-isotope space, alongside carbon isotopic trends for a single target.

Here we present new results in oxygen for the binary system, MonR2 IRS3 (A,B), and the compact, massive YSO, MonR2 IRS2. This work derives from our ongoing observational study of massive YSO environments using the high-resolution iSHELL spectrograph on NASA's Infrared Telescope Facility (IRTF).

Observations and Methods: CO rovibrational absorption spectra were obtained with NASA's IRTF observatory using the iSHELL instrument at very high spectral resolution (M: $R \sim 88,000$; K: $R \sim 78,000$). M bands ($v = 1-0$) were used to obtain optically thin ^{13}C^{16}O, ^{12}C^{18}O, and ^{12}C^{17}O, and K bands ($v = 2-0$) for ^{12}C^{16}O, ensuring that all analyzed line were similarly optically thin. Example spectra are shown in Fig. 1 for MonR2 IRS2 and MonR2 IRS3 (A,B) taken during 2019 and 2021 observing runs. Following the methods in [2] for spectrally resolved CO lines, column densities for each spectral line were obtained by fitting a Gaussian to the main CO component, and deriving optical depths using the mean line width from the ^{12}C^{18}O lines. Rotational analyses were used to calculate total isotopologue column densities and integrated gas temperatures using one- or two-temperature fits (examples in Fig. 2). Isotope ratios for a single YSO were derived from gas at similar temperatures.

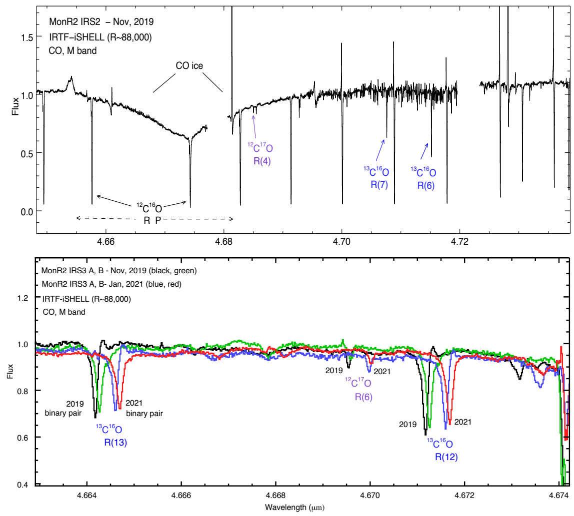

Figure 1: Selected portions of $M-$band spectra for embedded YSO MonR2 IRS2 [top] and zooms for two epochs of observations for binary YSOs MonR2 IRS3 (A,B) [bottom]. Observations were taken with IRTF-iSHELL ($R \sim 88,000$). Representative CO isotopologue lines are indicated. Spectra for MonR2 IRS3 are shifted for clarity in seeing the epochs.

Results and Discussion: Results for the oxygen isotopes derived from the CO isotopologues observed toward the massive MonR2 YSOs are shown in Fig. 3, with data normalized to the local ISM. We find clear ^{16}O excesses for both epochs of MonR2 IRS3 (B) and for the one epoch thus far observed for MonR2 IRS2. Within 1σ, these values fall on or very close to the slope-1 line, and thus signatures of CO self-shielding can be inferred for these targets. For both epochs of MonR2 IRS3 (A), we find ^{16}O depletion, also close to the slope-1 line. We see little variation between epochs in MonR2 IRS3 (A,B), suggesting that the oxygen signatures are robust over at least short periods.

The YSOs in the MonR2 IRS3 binary (A,B) are separated by $0.65''$, which, while gravitationally bound, corresponds to a separation of several hundred AU.

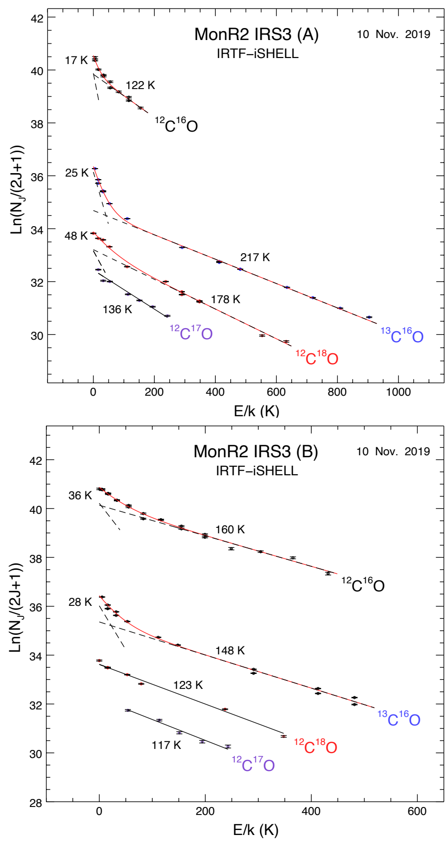

Figure 2: Rotational analyses for the 2019 epoch for binary MonR2 IRS3 (A,B) in this study. Distribution of data determined the use of one- or two-temperature fits for the isotopologues. Error bars are 1σ, E_J is the J^{th} rotational state energy, k is the Boltzmann constant.

Each component is further thought to be evolving in differing local environments, with component A possibly surrounded by a dense circumstellar disk [7,8], and component B not likely to have a disk but possibly the source of a high-velocity molecular outflow [7]. Recent observations suggest that MonR2 IRS2 could have a warped disk with an ionizing wind [9]. Our results reveal that the chemical pathways for oxygen in the binary also likely vary, with signatures of CO self-shielding in the non-disk binary component (B). We find almost identical signatures in MonR2 IRS2, which may also be evolving within a local ionizing environment. This disparity in YSOs within the same parent cloud, as well as disparate oxygen signatures for the two YSOs with potential disks, together point to a scenario of inheritance of CO self-shielding signatures from the parent cloud gas to the disk, with possible later processing in the complex disk environments characterizing massive YSOs; i.e., photochemistry in locally ionizing environments could be maintaining CO self-shielding. These results form a consistent picture with earlier findings of variability in

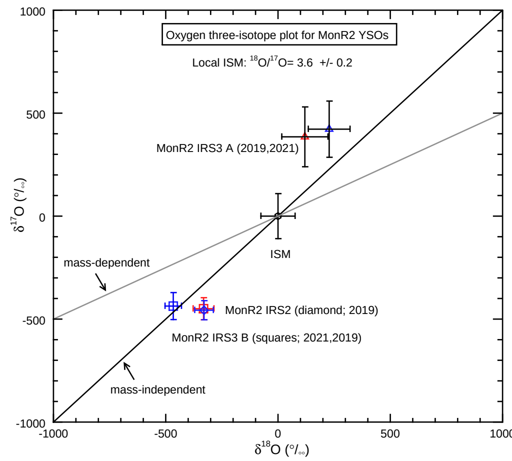

Figure 3: Oxygen three-isotope plot for the MonR2 YSOs in this study. Observing epochs (2019 and 2021) are shown for the binary MonR2 IRS3 A (triangles) and B (squares), and one epoch is shown for MonR2 IRS2 (blue diamond). Data were normalized to the local ISM, with $^{18}O/^{17}O$ = 3.6 ± 0.2 [10]. Error bars are 1σ. Mass-independent and mass-dependent fractionation lines are shown.

[$^{12}C^{16}O$]/[$^{13}C^{16}O$] for several massive YSOs that suggest inheritance from heterogenous gas reservoirs followed by mixing [5,6]. These results are also consistent with recent models of nebular inheritance of oxygen and heterogeneous gas reservoirs [11,12].

Conclusions: Within the MonR2 cloud complex, we find signatures of CO self-shielding in one member of a YSO binary without a known disk, and in a compact ionizing YSO with a potential warped disk. We find mass-independent but ^{16}O-depleted gas in the second member of the binary pair. These results show that members of gravitationally-bound YSOs can have disparate chemical evolutionary pathways. Results further suggest inheritance of CO self-shielding from the parent cloud to the disk, with complex processing and mixing as the YSO evolves, perhaps coupled with inheritance from heterogenous cloud reservoirs. Our observations help corroborate recent nebular models.

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