OBSERVATIONS OF CARBON MONOXIDE VARIABILITY IN MASSIVE YOUNG STELLAR ENVIRONMENTS AND IMPLICATIONS FOR NEBULAR RESERVOIRS.

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Introduction: Astronomical observations of young stellar objects (YSOs) provide a unique window into protoplanetary chemistry. In particular, high-resolution near-infrared spectroscopy in the rovibrational bands of CO have enabled the precise evaluation of carbon and oxygen isotopes for a range of YSO environments, with implications for the early solar nebula [1-7], including insights into CO self-shielding [1,3,5], supernova inheritance in the nebular cloud [4], and chemical interchange between CO ice-gas reservoirs [5]. Considerations of how YSOs vary over time can also provide greater insight into YSOs as analogues for the solar nebula and exoplanetary systems. While each spectral observation is a snapshot in a several-million-years timescale, YSOs have interestingly been observed to vary in several important parameters over timescales of months to a few years. For example, observations of late-stage solar-type disks reveal up to 50% variability in infrared (IR) fluxes, possibly due to the stellar companions or magnetic fields [8], and 70% of Class I and II YSOs studied in Orion show IR variability in amplitude, possibly due to gas extinction or warps in disk geometry [9]. Significant light-curve variations have further been found in YSOs of the Lynds 1688 region, attributed to possible structural changes in the inner disk [10], and IR photometric variability in nearly 100 YSOs in Cygnus observed over a few years could be due to changes in disk dynamics [11]. An initial analysis of archival data of low-mass YSOs from the VLT-CRIRES archive shows variability in CO column densities of 23% to 134% observed from a few months to within 3 years apart, and gas-temperature variations of 42% to 116% [12].

Here we present initial results from a new and ongoing observational study that utilizes the high-resolution iSHELL spectrograph on NASA's Infrared Telescope Facility. This work is intended to determine variability on CO observed in similar bandpasses over several epochs for a set of massive YSOs across the Galaxy.

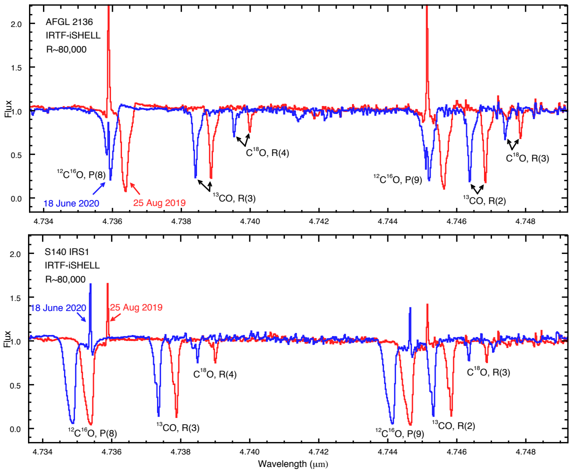

Figure 1: Portions of $M-$band spectra of two epochs for massive YSOs, AFGL 2136 (top) and S140 IRS1 (bottom) observed with IRTF-iSHELL ($R \sim 80,000$). Observations took place in 2019 (shifted right, red) and 2020 (shifted left, blue), approximately one-year apart. Representative CO isotopologue lines are marked. Spectra are shifted for clarity in seeing the epochs (Smith & Boogert, new data).

Observations and Methods: CO rovibrational absorption spectra were obtained with NASA's IRTF observatory with the iSHELL instrument at very high spectral resolution ($R \sim 80,000$, 3.75 km/s) in the $M-$bands ($v = 1-0$) for optically thin $^{13}C^{16}O$ (^{13}CO), $^{12}C^{18}O$ ($C^{18}O$), and $^{12}C^{17}O$ ($C^{17}O$), $K-$bands ($v = 2-0$) for $^{12}C^{16}O$, ensuring that all analyzed lines are similarly optically thin. Example IRTF spectra observed in 2019 and again in 2020 are shown for two massive YSOs in Fig. 1. Following the methods in [3] for spectrally resolved CO lines, molecular column densities for each YSO were obtained by fitting each spectral line with a Gaussian and deriving optical depths using the mean line width from the $C^{18}O$ lines. Assuming a Boltzmann distribution, a rotational analysis was used to derive final total isotopologue column densities and integrated excitation temperatures using one- or two-temperature models (examples shown in Fig. 2).

Results and Discussion: Our new findings for massive YSOs observed less than one year apart show that total ^{13}CO column densities vary most significantly (more than 33%) which also affects [^{12}CO]/[^{13}CO] ratios (varying from 12% to 33%; Fig. 3), and [^{13}CO]/[$C^{18}O$] ratios for both massive YSOs (15% to 30% change) and low-mass YSOs (53% to 63%) from our preliminary analysis prior to this work (Fig. 4). Gas temperatures show much less variation (13% or less) and variation in column densities for the other isotopologues is also less apparent. These findings thus far suggest that differences in variability between isotopologue reservoirs could signify disparate chemical pathways. Further, a recent study reports a large spread in $\Delta^{17}O$ variation in CAIs as a signature of in-

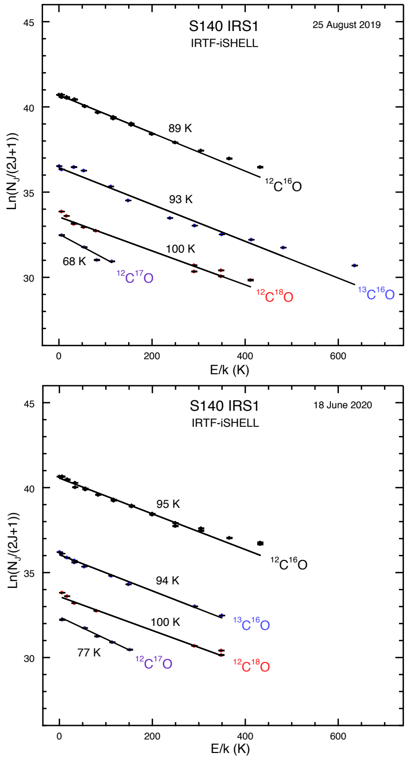

Figure 2: Rotational analyses for two epochs of observations for massive YSO, S140 IRS1 observed with IRFT-iSHELL (Smith & Boogert, new data) showing a single-temperature best-fit model for all isotopolgues. Error bars are 1σ, E_J is the J^{th} rotational state energy, k is the Boltzmann constant.

heritance of isotopic heterogeneity from the protosolar molecular cloud [13], and our findings of short-term variability and isotopic heterogeneity along various YSO lines-of-sight could further support a paradigm of heterogenous mixing from parent clouds for solar nebular analogues prior to planet formation.

Conclusions: Initial findings from our massive YSO observational survey and supported with low-mass YSO data from preliminary work suggest that CO reservoirs, in particular ^{13}CO and its ratios with respect to ^{12}CO and ^{12}C^{18}O, can vary significantly in abundance over short timescales, with variations possibly due to physical variations from wind and/or radiation. These results could also be additional signatures of inheritance of isotopic heterogeneity from the parent cloud in the early solar nebula, and short-term chemical variability should be explored further in nebular models. This ongoing observational study using IRTF-iSHELL will add statistical significance to these initial findings, which could also be further explored in interdisciplinary work with solar system materials.

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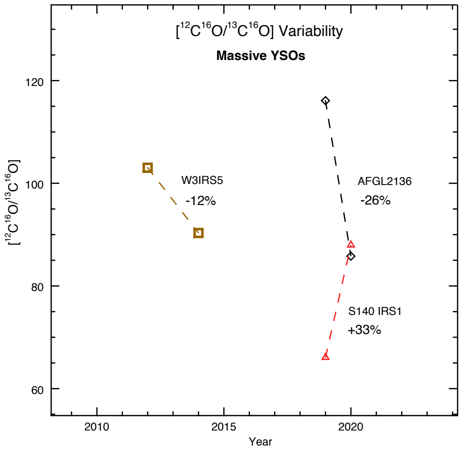

Figure 3: Plot of variability found in [^{12}CO]/[^{13}CO] between two epochs for massive YSO, W3IRS5, observed with Keck-NIRSPEC ($R \sim 25,000$) [Smith and Blake, in prep.], and for massive YSOs, AFGL 2136 and S140 IRS1 observed with IRTF-iSHELL ($R \sim 80,000$) in this new study.

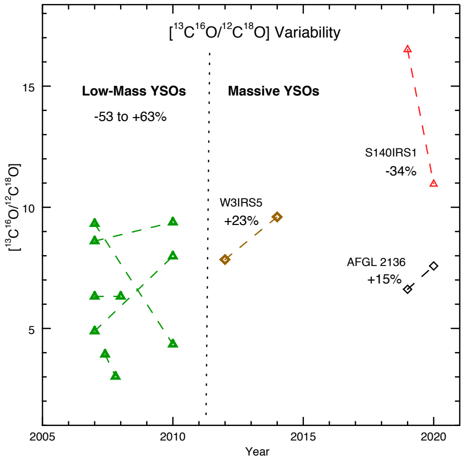

Figure 4: Plot of variability found in [^{13}CO]/[C^{18}O] for several low-mass YSOs observed with VLT-CRIRES as part of a preliminary archival analysis on variability, and massive YSOs in the current study showing two epochs. W3IRS5 was observed with Keck-NIRSPEC; AFGL2136 and S140IRS1 were observed with IRTF-iSHELL.

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