HIGH-PRECISION $C^{17}O$, $C^{18}O$ AND $C^{16}O$ MEASUREMENTS IN YOUNG STELLAR OBJECTS: ANALOGUES FOR CO SELF-SHIELDING IN THE EARLY SOLAR SYSTEM.

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Introduction: The oxygen isotope anomaly in the Solar System, defined as a mass-independent correlation between $[^{16}O]/[^{18}O]$ and $[^{16}O]/[^{17}O]$ among rocky bodies, has defied explanation since its discovery [1]. One leading explanation is CO self-shielding [2], whereby the isotopologues of CO are shielded from further photodissociation by far ultraviolet (FUV) radiation in proportion to their abundances. Thus, $C^{17}O$ and $C^{18}O$ are more rapidly destroyed than $C^{16}O$. While isotope-selective photodissociation is known to occur in molecular clouds [3,4,5], and possibly in the HL Tau disk [6], conclusive evidence in circumstellar disks is lacking. Until recently, searching for oxygen isotope fractionation in protoplanetary disks has been difficult due to the minimum required $\sim$10% accuracy in CO isotopologue measurements. Recently, the advent of improved astronomical instrumentation has permitted precise comparisons between isotope ratios in protoplanetary systems and meteorites. Here we report new, very high-resolution infrared observations of four CO isotopologues – $C^{16}O$, ^{13}CO, $C^{18}O$ and the rare species, $C^{17}O$ – in two YSOs, and evidence for CO self-shielding in a circumstellar disk.

CO self-shielding model: CO photodissociation models predict that circumstellar disk surfaces should preserve isotope selectivity [7,8], suggesting that the outer disk regions will exhibit $C^{17}O$ and $C^{18}O$ deficits relative to $C^{16}O$ as a consequence of CO self-shielding. Precise observations of CO isotopologue ratios in disks can test these models for the oxygen isotope anomaly.

Observations: We observed the 4.7 μm fundamental and 2.3 μm overtone ro-vibrational CO absorption spectra in two YSOs: VV CrA, a binary T Tauri star in the Corona Australis molecular cloud, and Reipurth 50, a stage I, embedded, intermediate-mass FU Ori star in the Orion Molecular Cloud. The very high-resolution ($\lambda/\Delta\lambda \approx 95\,000$) spectra were obtained with the newly implemented Cryogenic Infrared Echelle Spectrograph (CRIRES) on the Very Large Telescope (VLT) in Chile. The fundamental bands shown in Figure 1 illustrate the forest of narrow absorption lines due to CO gas. We believe this is the first reported detection of $C^{17}O$ in infrared absorption [9].

Results and discussion: Derived rotational excitation diagrams are shown in Figure 2, where the sub-level column densities, $N_J/(2J+1)$, are plotted against the energy of the state J compared to the linear best-fit expected for a single-temperature gas. For each isotopologue, the excitation temperature (T) of the gas is determined from the negative reciprocal of the slopes of their respective lines. The range of gas temperatures along the line of sight toward both objects can be seen from the different slopes between the low-J ($J \leq 3$) and higher-J transitions; we expect this trend for geometries where the gas is heated by the central star. Best-determined column densities originate from the higher temperature regime for both objects. Ratios derived for VV CrA are: $[C^{16}O]/[C^{18}O] = 680 \pm 40$; $[C^{16}O]/[C^{17}O] = 2800 \pm 300$, and $[C^{18}O]/[C^{17}O] = 4.1 \pm 0.4$. For Reipurth 50, we find $[C^{16}O]/[C^{18}O] = 510 \pm 30$; $[C^{16}O]/[C^{17}O] = 2300 \pm 150$, $[C^{18}O]/[C^{17}O] = 4.4 \pm 0.2$. While the

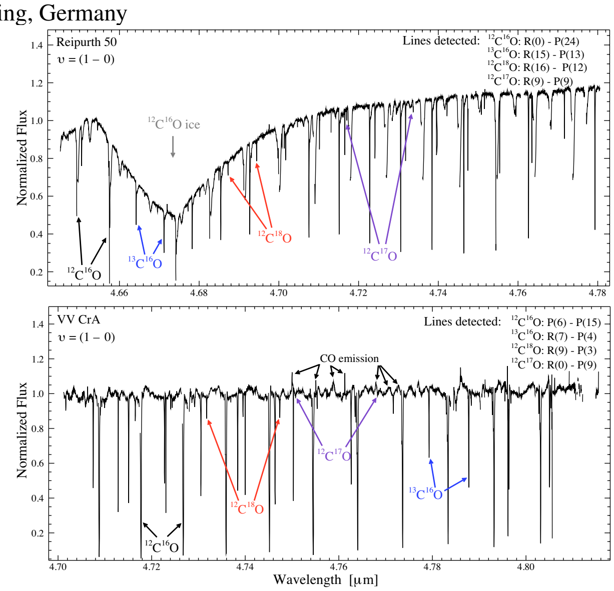

Figure 1: Infrared spectra of the CO fundamental ro-vibrational bands toward Reipurth 50 and VV CrA. Representative absorption lines due to various CO isotopologues are indicated. Also noted are the broad emission lines from hot CO gas in the inner disk of VV CrA, and the known solid CO feature in Reipurth 50.

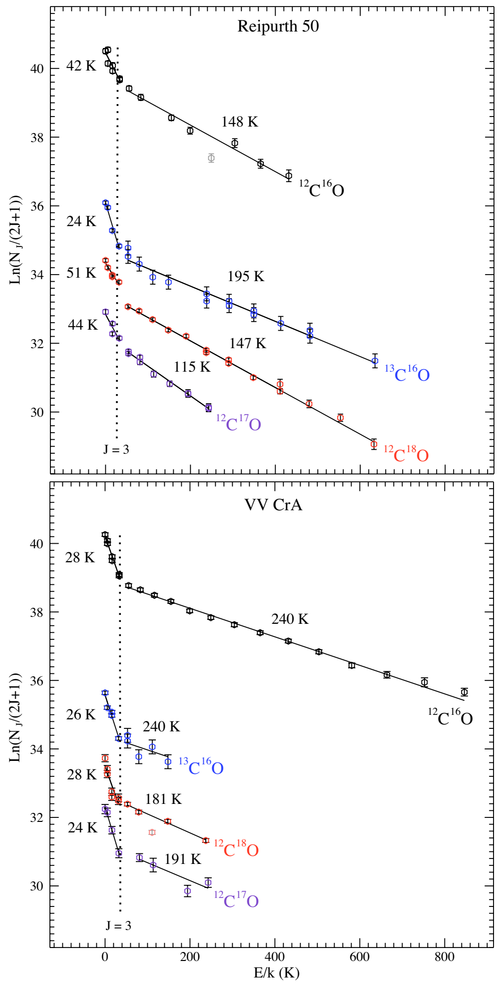

Figure 2: Rotational plots for Reipurth 50 and VV CrA. Error bars are 1σ. E_J is the energy of the J^{th} rotational state above the ground rotational state, and k is the Boltzmann constant. Faded symbols were not included in the fits.

$^{12}C/^{13}C$ ratios for both objects are nearly twice the expected interstellar medium (ISM) ratio of 69 ± 6 [10], our data suggest a decoupling of carbon and oxygen isotope effects during CO photolysis.

Our results are further summarized in Figure 3, where the $[^{16}O]/[^{18}O]$ and $[^{16}O]/[^{17}O]$ ratios of our objects are compared to the local ISM. The mass-independent trend seen in VV CrA can be most easily explained by photochemical enhancement of the more abundant $C^{16}O$ molecule relative to the rare isotopologues. Reipurth 50 does not exhibit a mass-independent fractionation effect. One possible explanation for the higher fractionation in the VV CrA disk versus the Reipurth 50 envelope is that a photochemical deficit in $C^{17}O$ and $C^{18}O$ relative to $C^{16}O$ may require at least 10^5 years to proceed in a circumstellar environment, as predicted by models [8], and require a combination of factors such as disk geometry, grain growth and vertical mixing [9].

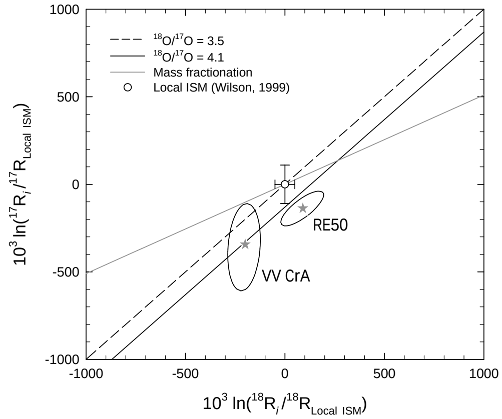

Figure 3: Comparison of oxygen isotope ratios between the ISM and CO surrounding the two YSOs (stars). Solid and dashed lines show assumed mass-independent fractionation for the $^{18}O/^{17}O$ ratio, as indicated. The mass-dependent fractionation line is shown in grey. $^{18}R_i = [C^{18}O]/[C^{16}O]$. Ellipses represent 95% confidence limits.

Conclusions: Using high-resolution data from CRIRES, we demonstrate that measurement of $[C^{16}O]/[C^{18}O]$ and $[C^{16}O]/[C^{17}O]$ in CO is possible with the precision necessary to distinguish photochemical effects from mass-dependent isotope fractionation. Results for VV CrA are explained by CO photochemistry, imparting viability to CO self-shielding as an explanation for the Solar System oxygen anomaly. Our ongoing analyses of disks and envelopes should help solidify this conclusion by distinguishing potential self-shielding in objects in discrete evolutionary stages.

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