NEW INSIGHTS ON THE ORIGIN OF THE SOLAR SYSTEM ^{12}C/^{13}C RATIO USING PROTOSTELLAR OBSERVATIONS AND RADIATIVE TRANSFER MODELING.

Rachel L. Smith[1], Klaus M. Pontoppidan[2], Edward D. Young[1,3], and Mark R. Morris[4], [1]Department of Earth and Space Sciences, University of California Los Angeles (UCLA) (rsmith@ess.ucla.edu), [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, [3]Institute of Geophysics and Planetary Physics, UCLA, [4]Division of Astronomy and Astrophysics, Department of Physics and Astronomy, UCLA

Introduction: The ^{12}C/^{13}C ratio in the solar system is thought to be $\approx 87-89$ $[1-4]$, values that are noticeably higher than the local interstellar medium (ISM; $\approx 62-69$; $[4-6]$). Galactic chemical evolution (GCE) models have been used to explain this apparent discrepancy [6, 7]; these models assume that the solar system ^{12}C/^{13}C ratio reflects the local ISM ≈ 4.6 Gya, and similarly that ^{12}C/^{13}C abundance ratios in young stellar objects (YSOs) observed today should represent their local clouds.

We have derived CO isotopologue abundance ratios toward several protostars, representing embedded young stellar objects (YSOs), disks and molecular clouds. We find ^{12}CO/^{13}CO ratios ranging from $\approx 84-160$; values which are significantly higher than the local ISM, implying that YSOs may not represent their parent clouds, which would impact current GCE model assumptions.

Observations: We present several new observations of CO isotopologues toward low-mass YSOs in local star-forming regions. Observations of the 4.7 μm $(v = 1-0)$ and 2.3 μm $(v = 2-0)$ CO rovibrational absorption spectra were obtained with the Cryogenic Infrared Echelle Spectrograph (CRIRES) on the Very Large Telescope at very high resolution ($\lambda/\Delta\lambda \approx$ 95,000 $\approx$ 3 km s^{-1}); a small subset of these data has been reported [8, 9]. Spectra of the 4.7 μm bands for the embedded YSO, IRS 63 (Ophiuchus), and the HL Tau (Taurus) circumstellar disk are shown in Figure 1.

Methods: Total column densities for the observable CO isotopologues were calculated by summing the measured column densities of observed rotational states and assuming a Boltzmann distribution for the remaining states at the best-fit temperature derived from the observed lines. Given the high spectral resolution of CRIRES, the line profiles can be used directly in computing the column densities for each line, following [8]. To help validate this technique and define the parameter spaces for various YSO morphologies for which accurate isotope abundance ratios may be derived, we have begun using the RADLite ray-tracing code developed by Pontoppidan et al. [10] to generate model spectra, analyses of which are then compared to the protostellar observations.

Results and discussion: Rotational plots for IRS 63− a disk surrounded by a protostellar envelope−and the HL Tau disk, are shown in Figure 2. The excitation temperature (T) of the gas is determined from the negative reciprocal of the slopes of their respective best-fit lines. Two-temperature fits best capture the distribution of the data. Figure 3 shows rotational plots derived using RADLite. Initial results from these models show that the temperature trends observed in embedded objects and disks can be generally reproduced by the models (compare with Figure 2). Isotope ratios input into the models were accurately retrieved, further validating results from the observations.

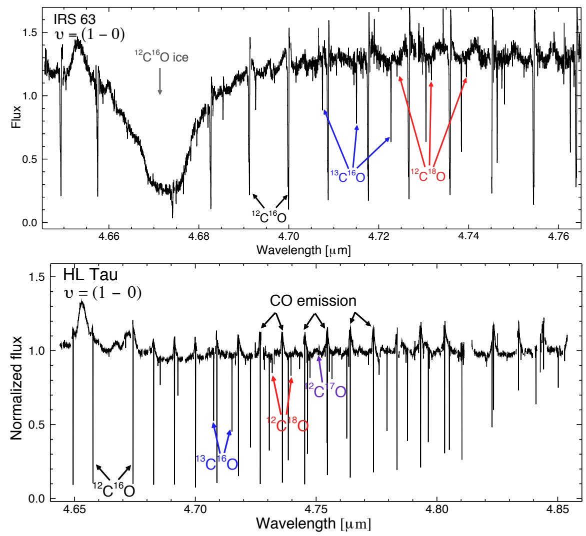

Figure 1: Infrared 4.7 μm $(v = 1-0)$ CO rovibrational bands toward the embedded Ophiuchus YSO, IRS 63 (top) and the circumstellar disk surrounding HL Tau, in Taurus (bottom). In each spectrum, representative isotopologues are marked within the forest of narrow CO absorption lines. IRS 63 shows the broad ^{12}C^{16}O ice band often seen in embedded YSOs; in HL Tau, low-level ^{12}C^{16}O emission lines from hot gas near the inner disk are noted.

Figure 4 shows the ^{12}CO/^{13}CO derived for the objects in our CRIRES data set, along with published ^{12}C/^{13}C ratios, versus Galactocentric radius (R_{GC}). Measurements of high ^{12}C/^{13}C in diffuse regions of the Ophiuchus cloud have been attributed to CO photochemistry (black arrows; [11, 12]). In our study, heterogeneity in the Ophiuchus cloud is found by virtue of the high ^{12}CO/^{13}CO in the cloud-tracing object, IRS 51, as compared to the lower value derived for the foreground cloud traced by the DoAr24E binary system. While we find signatures of CO self-shielding in the oxygen isotopes for VV CrA [8], HL Tau, IRS 43 and RNO 91, CO photochemistry does not explain the

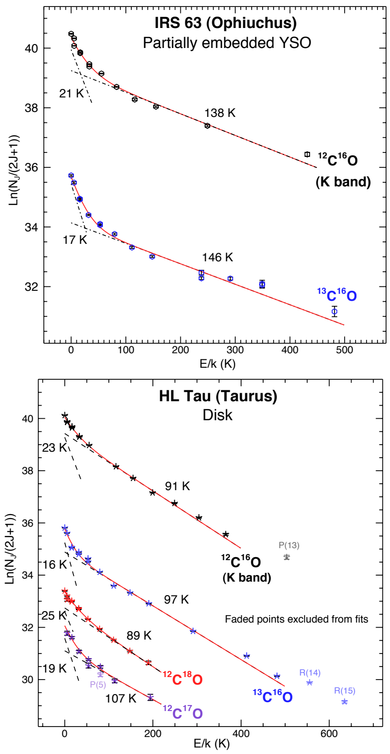

Figure 2: Rotational plots for IRS 63 and HL Tau. E_J is the energy of the J^{th} rotational state, k is the Boltzmann constant, and N_J is the column density obtained for each line. Error bars are 1σ.

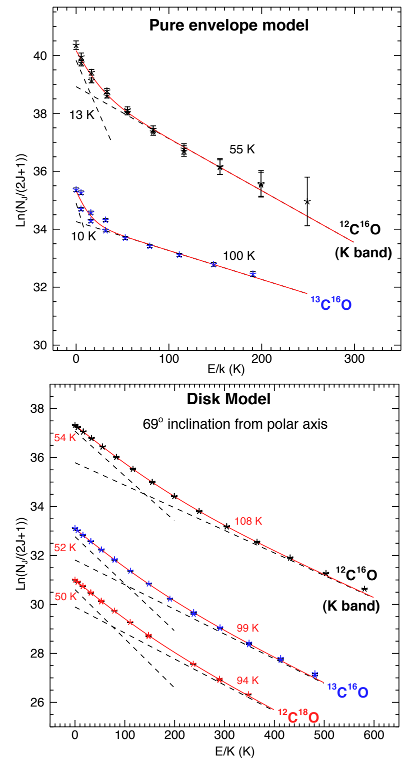

Figure 3: Rotational plots derived from spectra generated using the RADLite ray-tracing code, showing that the general temperature distribution for an envelope and a disk can be reproduced by the models.

trends in the carbon isotopes. Initial comparisons between column densities in CO ice [15] and our data suggest that fractionation between CO in the solid and gas phases may obtain high gas-phase ^{12}CO/^{13}CO, similar to what we observe.

Conclusions: We find high ^{12}CO/^{13}CO toward several protostars and clouds. Our results indicate that GCE models may be insufficient for explaining the solar system-ISM ^{12}C/^{13}C discrepancy, and that cloud heterogeneity may be an important factor in understanding early solar system chemistry. Initial evaluation of CO in gas and ice suggests that high ^{12}CO/^{13}CO may be achieved by fractionation between gas and ice.

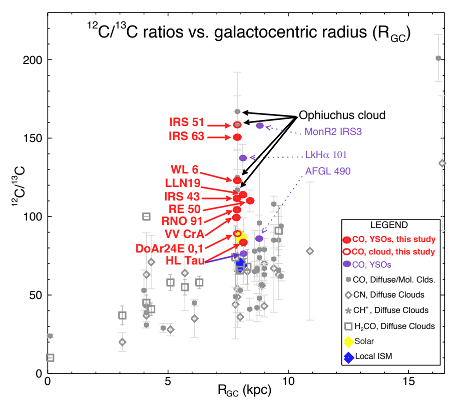

Figure 4: Compilation of published ^{12}C/^{13}C ratios vs. R_{GC} (kpc). Data from our study (red dots; left-side labels) show ^{12}C/^{13}C ratios that are significantly higher than the ISM (68 ± 15; [6]) and solar system (86.8 ± 3.8; [1]). The black arrows indicate high ^{12}C/^{13}C in diffuse regions of Ophiuchus [11, 12]. YSO data for MonR2 IRS3, LkHα, AFGL 490 [13] and HL Tau (lower value; [14]) are marked (purple).

References: [1] Scott P. C. et al. (2006) *Astron. Astrophys. 456*, 675-688. [2] Coplen T. B. et al. (2002) *Pure Appl. Chem. 74*, 1987-2017. [3] Clayton D. D. and Nittler L. R. (2004) *Annu. Rev. Astron. Astrophys. 42*, 39-78. [4] Wilson T. L. (1999) *Rep. Prog. Phys. 62*, 143-185. [5] Langer W. D. and Penzias A. A. (1993) *ApJ 408*, 539-547. [6] Milam S. N. et al.(2005) *ApJ 634*, 1126-1132. [7] Prantzos N. et al.(1996) *Astron. Astrophys. 309*, 760-774. [8] Smith R. L., Pontoppidan K. M., Young E. D., Morris M. R. and van Dishoeck E. F. (2009) *ApJ 701*, 163-175. [9] Smith R. L. et al. (2010) *41st LPSC*, 2254. [10] Pontoppidan et al. (2009) *ApJ 704*, 1482-1494. [11] Federman S. R. et al. (2003) *ApJ 591*, 989-999. [12] Lambert D. L. et al. (1994) *ApJ 420*, 756-771. [13] Goto et al. (2003) *ApJ 598*, 1038-1047. [14] Brittain et al. (2005) *ApJ 626*, 283-291. [15] Pontoppidan et al. (2003) *Astron. Astrophys. 408*, 981-1007.