# The Lines They Are A'Changing

## A Spitzer Study of Mid-Infrared Spectral Lines in Mira Variable Atmospheres


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## Introduction and Purpose

**Introduction:** A fundamental question in modern astrophysics deals with the production of dust and molecules, and how stars enrich their environments. Understanding this enrichment affects many facets of astrophysics including star and planet formation and galaxy evolution. Molecules and dust contribute significantly to their environments, but our understanding of how they are created is, at best, still rudimentary. We know a large fraction of material returned to the interstellar medium (ISM) is preferentially formed at the latest stages of stellar evolution.

Much of the answer lies in the complex behavior of Asymptotic Giant Branch (AGB) stars, which are low to intermediate mass stars ($0.8 - 8\ M_{\odot}$) in the final stages of their evolution. AGB stars are characterized by H and He shell burning above a degenerate C/O core. Mira variables are AGB stars that regularly pulsate $200 - 500$ days. These pulsations create shock waves that propagate through the atmosphere contributing to mass loss rates as high as $10^{-6} - 10^{-4}\ M_{\odot} yr^{-1}$. We track these pulsations with phase, $\phi = 0 - 1$; the star is brightest optically at $\phi = 0$. The cool temperatures (2500-3500 K) allow for the existence of molecules and dust in the atmosphere, and the pulsations help loft this material into the surrounding environment (Figure 1). These conditions make Mira atmospheres perfect laboratories for studying how evolved stars enrich their circumstellar environments.

**Purpose:** My dissertation focuses on analyzing mid-IR spectra of 14 oxygen-rich (M-type) Mira variables taken with phase, using the high resolution module of Spitzer's *Infrared Spectrograph* (IRS) (R$\sim$ 600 [3]). This is a unique, rich data set due to multiple observations of each star and the high SNR from quick exposure times to prevent saturation of the detector. For data reduction see [2].

The spectra include a plethora of $CO_2$ ro-vibrational, Q-branch bandheads (Figures 3, 4). I am using the non-local thermodynamic equilibrium (NLTE) radiative transfer code, RADEX [6] to determine the density and temperature of the gas and how they change with the pulsation of each star. The program is designed to work with a text file of molecular data; to model the desired transitions in the mid-IR I have built a custom molecular file for $CO_2$ in the 10-20 $\mu$m range (for details see below). **Studying the physics of these $CO_2$ lines will provide key insight to how Mira variables create molecules and enrich their local environments.**

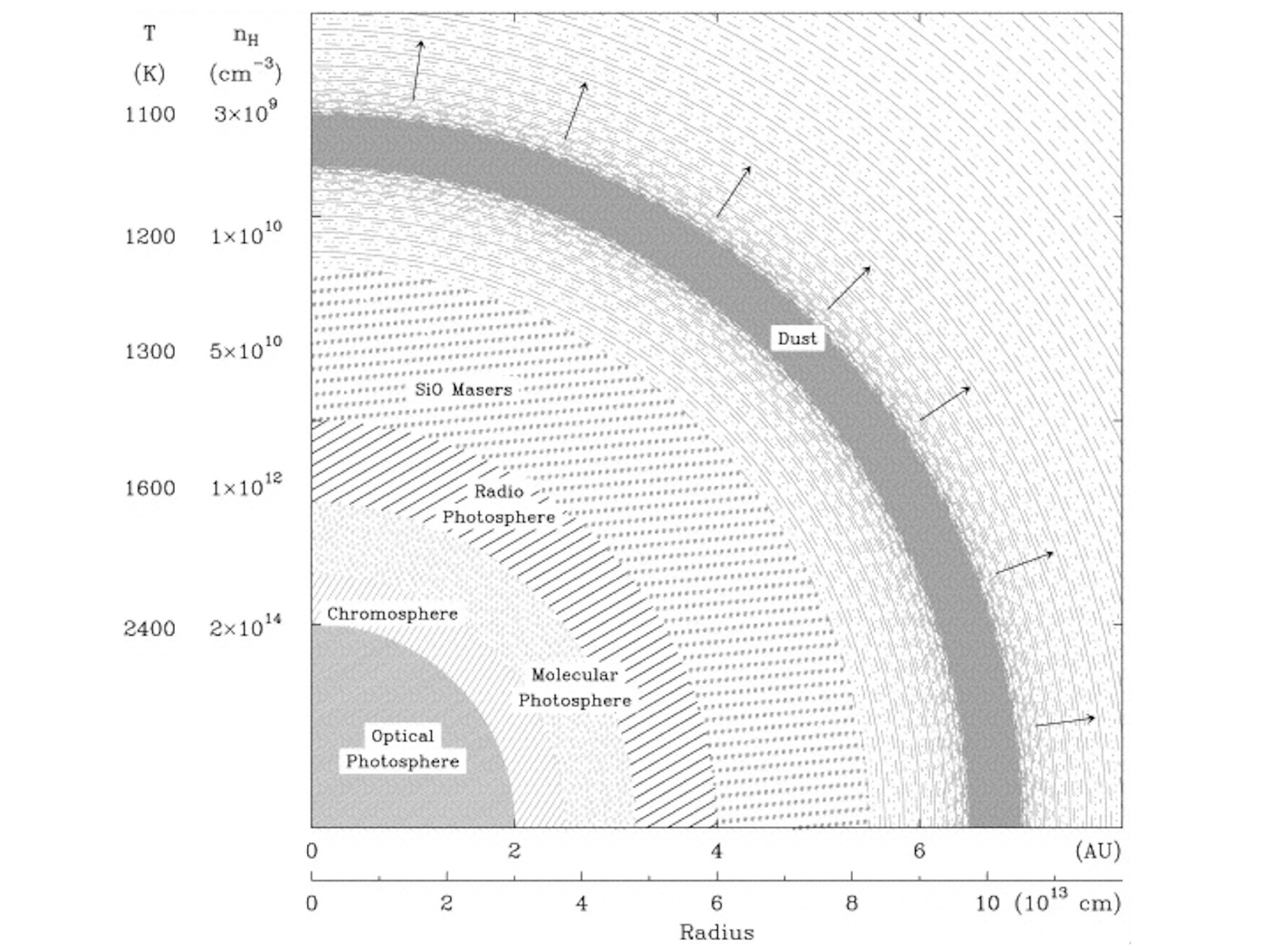


**Figure 1:** Illustration of Mira variable [5]. Mira atmospheres are dynamic; the gas and dust are constantly perturbed by pulsational shocks. We approximate this bubbling cauldron using concentric slabs of material. The $CO_2$ gas is extended throughout the atmosphere, and will most likely require multiple slabs to model.

## RADEX $CO_2$ Molecular File

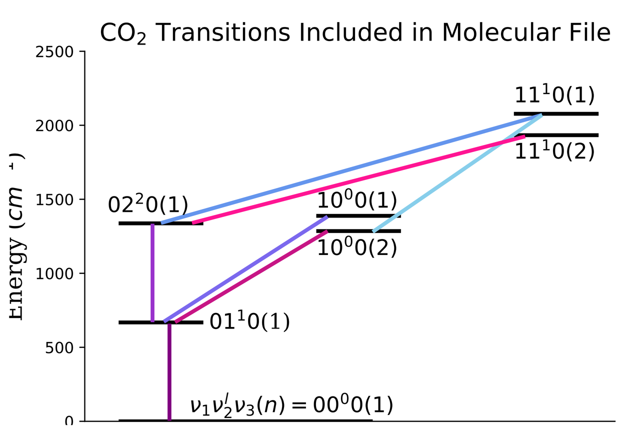


**Figure 2:** The 7 transitions included in molecular file. Note color of transition matches resulting spectra in Figure 5.

I have built a custom molecular file for RADEX that includes 7 $CO_2$ ro-vibrational transitions in the mid-IR (Figure 2). Each vibrational state contains $J = 50$ rotational levels. The file includes 743 radiative transitions, and 18,000 collisional rate coefficients. All Einstein A coefficients, transition wavelengths, and energy levels were taken from HITRAN [4]. I extrapolated collisional rate coefficients similar to [1], which involves calculating the conditional probability that a full state-to-state transition will occur. A sample slab spectrum of $CO_2$ is shown below in Figure 5, and examples of RADEX fitting Spitzer spectra are shown in Figure 6.

## High Resolution Mid-IR Spectra of $CO_2$ in Mira Variables R Tri and S Peg

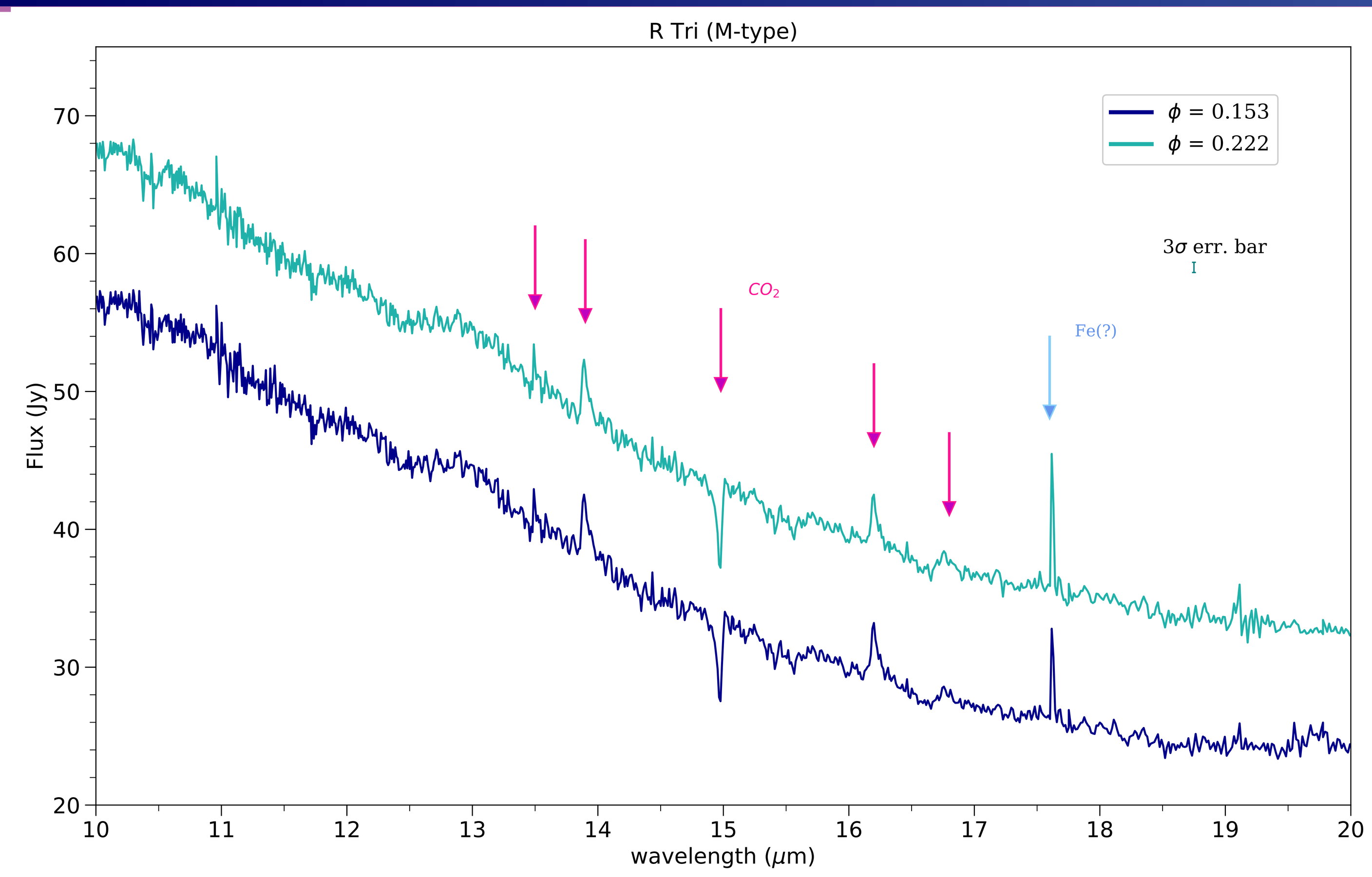


**Figure 3:** Spitzer spectrum for M-type Mira variable *R Tri*. Note that the top spectrum has been artificially offset by 8 Jy for clarity.

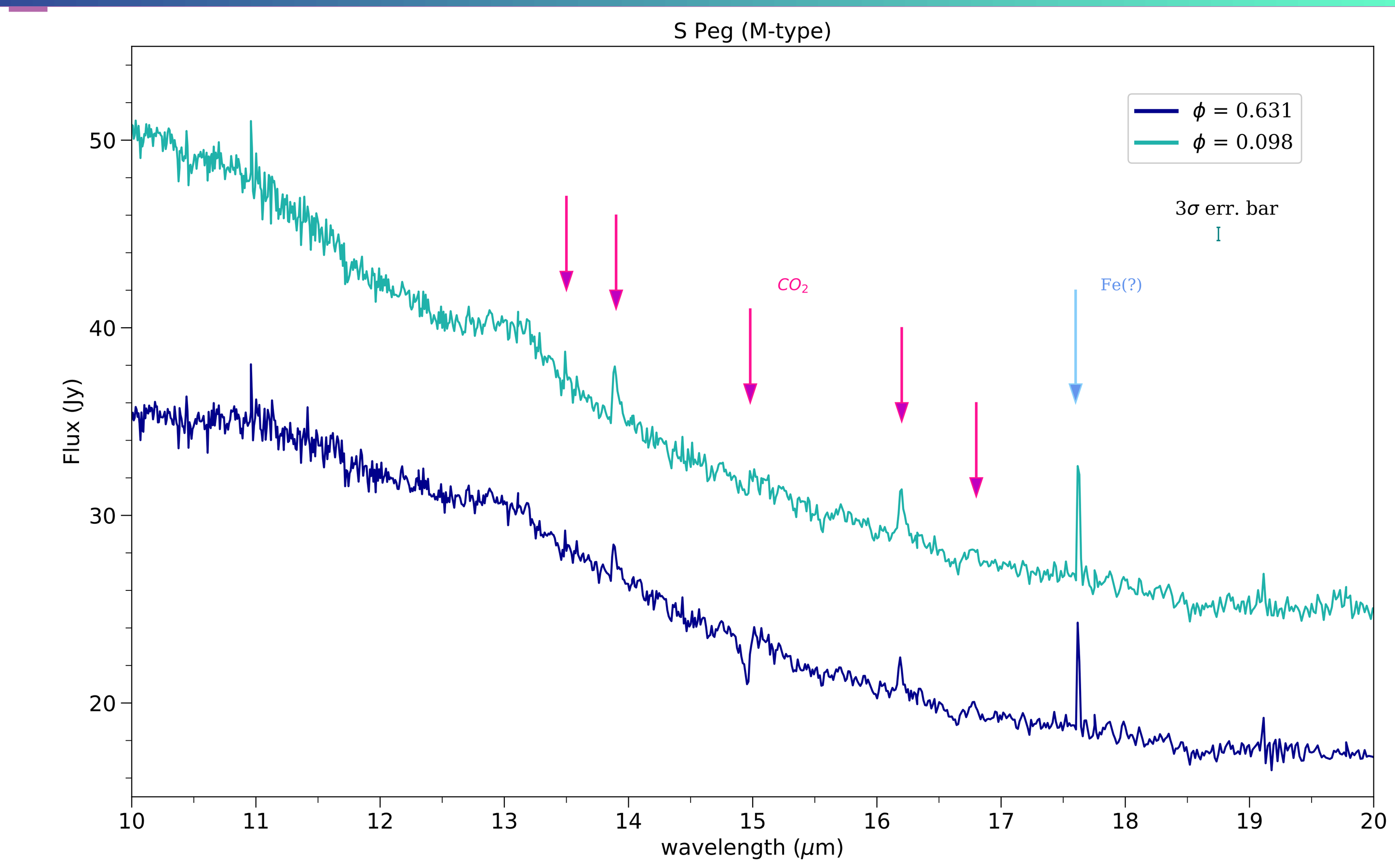


**Figure 4:** Spitzer spectrum of M-type Mira variable *S Peg*. The top spectrum is offset by 5 Jy for clarity.

## Mid-IR Slab Spectrum of $CO_2$

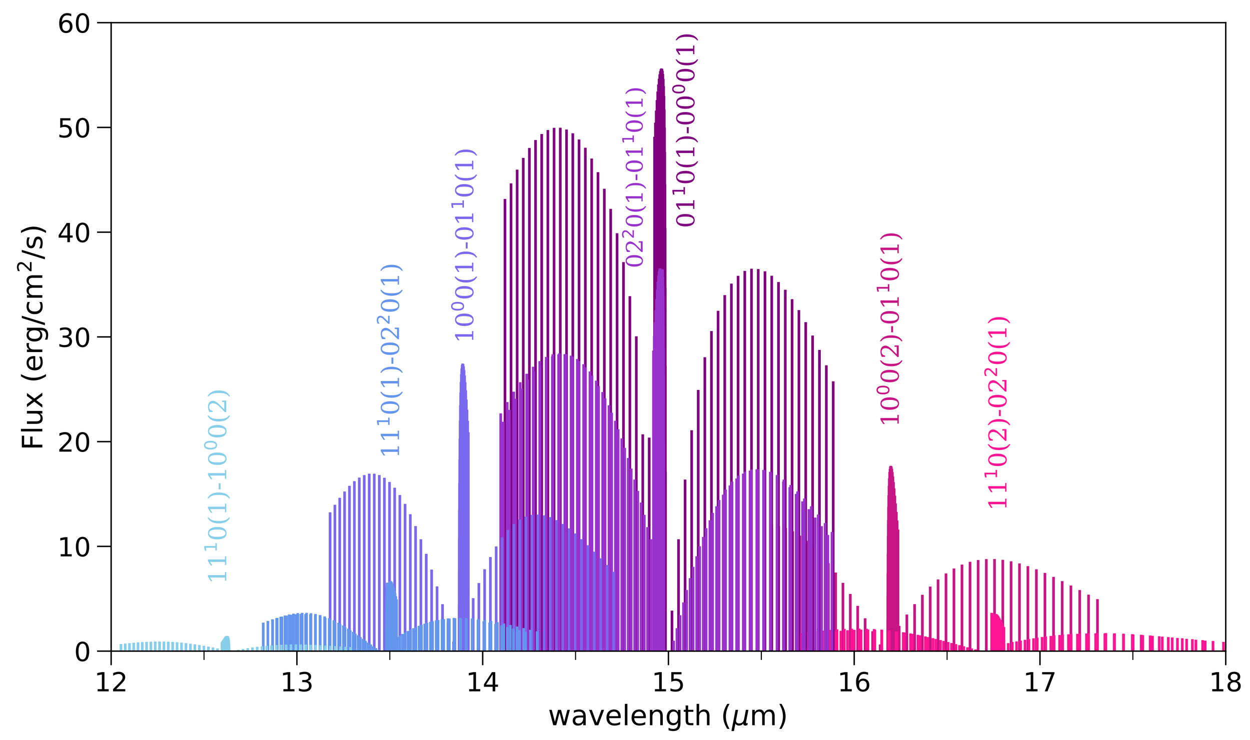


**Figure 5:** Slab model spectrum of $CO_2$ calculated with RADEX. Parameters: density: $10^{17}$ cm$^{-3}$; Kinetic Temperature: 1000 K; $CO_2$ column density: $10^{17}$ cm$^{-2}$.

## Examples of RADEX Fits

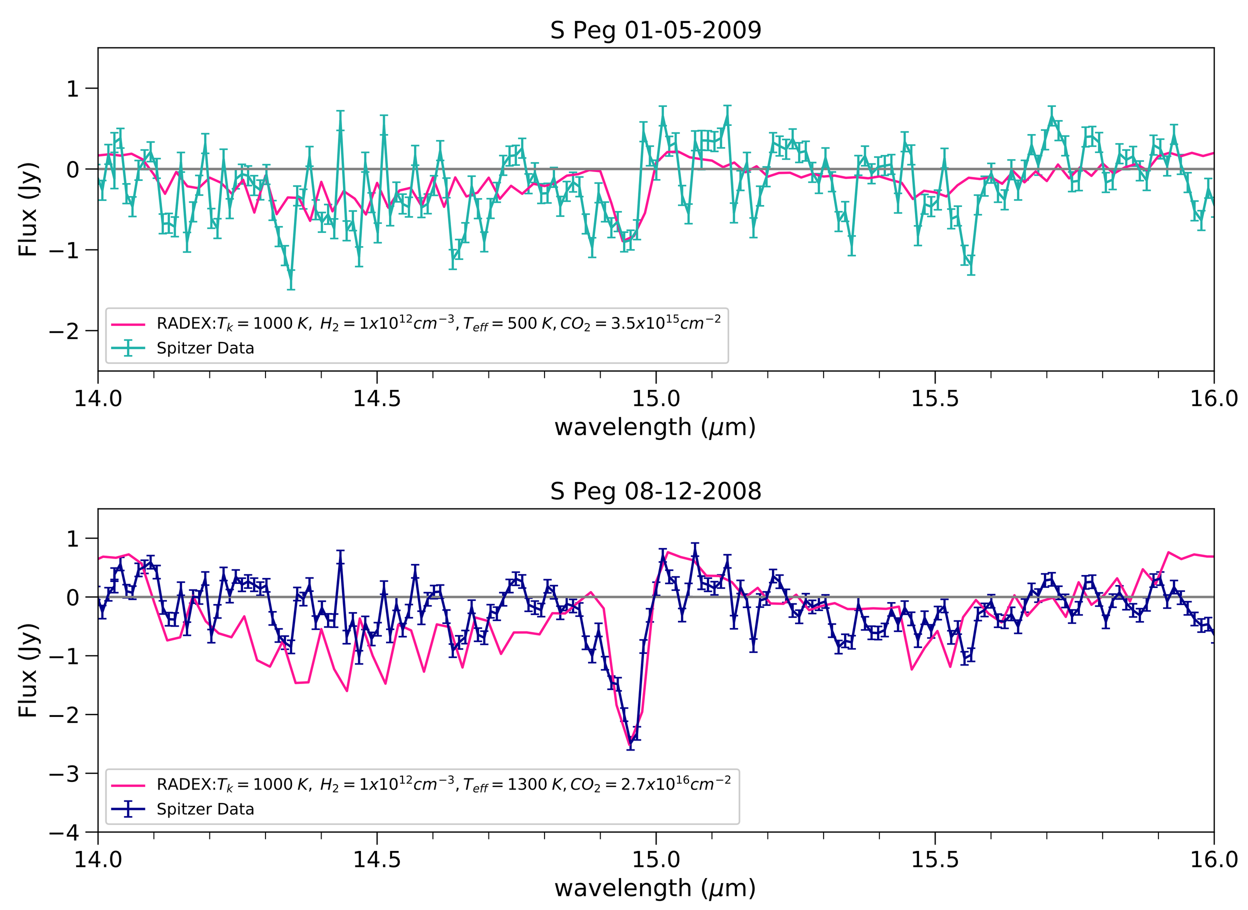


**Figure 6:** RADEX results for 15 $\mu$m feature in S Peg at $\phi = 0.098$ (top) and $\phi = 0.631$ (bottom). The change in density is most likely tied to the pulsation of the star. Further results from RADEX fits of 3 stars are presented in Table 1.

## Results and Future Work

**Table 1:** Results of RADEX models of $CO_2$ slabs in 3 Mira variables.

| Star | Line | $\phi$ | Col. Density (cm$^{-2}$) | T (K) |
|---|---|---|---|---|
| S Peg | 15 $\mu$m | 0.631/0.098 | 2.7x$10^{16}$/3x$10^{15}$ | 1000/1000 |
| S Peg | 13.8, 16.2 $\mu$m | 0.631/0.098 | 3x$10^{17}$/1.4x$10^{17}$ | 500/600 |
| R Tri | 15 $\mu$m | 0.153/0.222 | 1x$10^{16}$/1.1x$10^{16}$ | 550/500 |
| R Tri | 13.8, 16.2 $\mu$m | 0.153/0.222 | 2x$10^{17}$/2x$10^{17}$ | 700/600 |
| S Ser | 15 $\mu$m | 0.620/0.671 | 1.4x$10^{16}$/1x$10^{16}$ | 800/800 |
| S Ser | 13.8, 16.2 $\mu$m | 0.620/0.671 | 1.8x$10^{17}$/1.4x$10^{17}$ | 600/600 |

- The custom built file for $CO_2$ accurately models the ro-vibrational Q-branch bandheads in our Spitzer spectra
- There is evidence for 2 slabs of $CO_2$ gas; the 15 $\mu$m results indicates a hot layer close to the star, while the 13.8, 16.2 $\mu$m lines indicate a denser, slightly cooler layer further out.
- I will finish modeling the $CO_2$ lines in the remaining stars to confirm that $CO_2$ gas is extended in Mira atmospheres, and check for phase dependent behavior of the gas.

## References


[1] Bosman A.D., et al., 2017, A&A 601, A36
[2] Creech-Eakman, M. J., et al 2012, Astron. Review, 7,4
[3] Houck, J. R. et al. 2004, SPIE, 5478, 62
[4] Gordon, I. E., et al., 2013, JQSRT, 203, 3-69
[5] Reid, M. J., & Menten, K. M., 1997, ApJ, 476, 327
[6] Van der Tak, F.F.S., et al., 2007, A&A 468, 627-635


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