Line Dancing of CO_2 in Mira Atmospheres

Dana Baylis-Aguirre[1], Michelle J. Creech-Eakman[1], Tina Güth[2]

(dana.baylis@student.nmt.edu)

[1]New Mexico Institute of Mining and Technology

[2]New Mexico State University,

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Introduction and Purpose

Introduction: A key topic in stellar physics deals with the production of dust and molecules, and how stars return material to their environments. Understanding circumstellar enrichment affects many facets of astrophysics from star and planet formation to galaxy evolution. Dust and molecules significantly affect their environments, but our understanding of their formation 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 insight can be gained from studying the circumstellar environments (CSE) 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 oxygen-rich (M-type) Mira variables taken with phase, using the high resolution module of Spitzer's *Infrared Spectrograph* (IRS) (R$\sim$ 600 [4]). 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 [3].

The spectra include a plethora of CO_2 ro-vibrational, Q-branch bandheads (Figures 3, 4). I created a 2-slab model using the non-local thermodynamic equilibrium (NLTE) radiative transfer code, RADEX [7] to determine the density and temperature of the gas in each slab and added the results together to globally fit the 3 brightest Q-branch bandheads at 13.87 μm, 14.98 μm, and 16.18 μm. To model the desired transitions in the mid-IR I have built a custom molecular file for CO_2 in the 10-20 μm 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.**

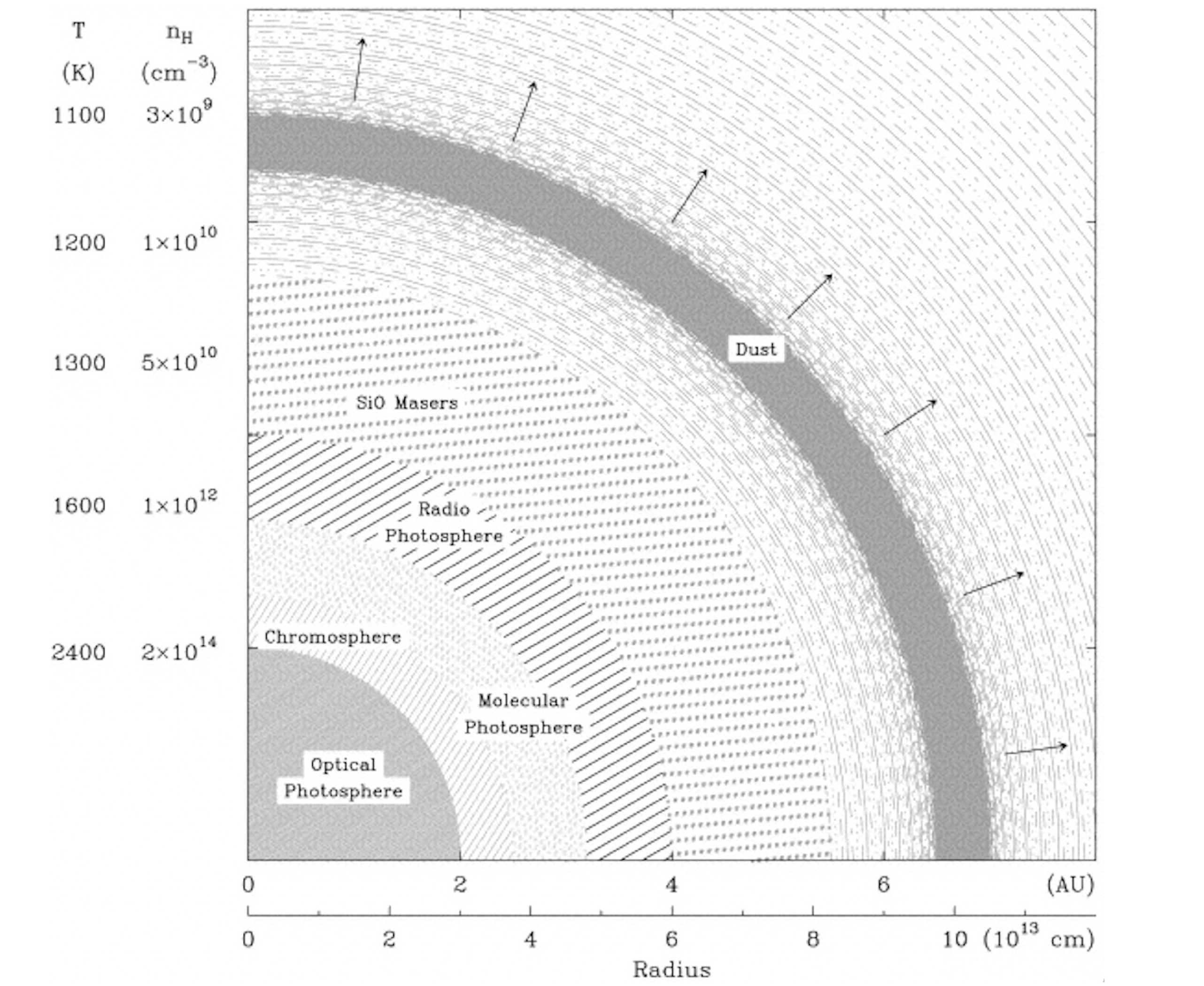

Figure 1: Illustration of Mira variable [6]. Mira atmospheres are dynamic; the CSE is perturbed by pulsational shocks. We approximate this bubbling cauldron using concentric slabs of material. The CO_2 gas is extended throughout the atmosphere, and will most likely require multiple slabs to model.

RADEX CO_2 Molecular File

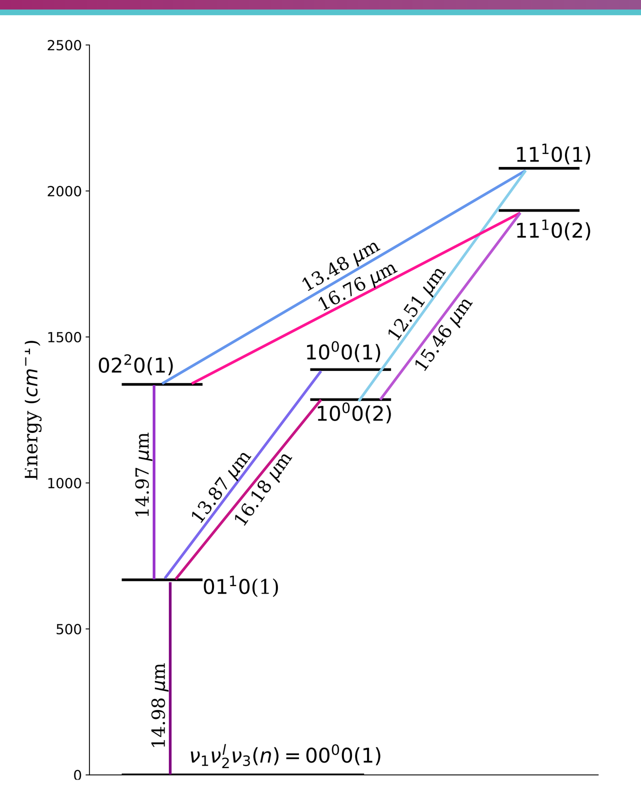

Figure 2: The 8 transitions included in molecular file. Note color of transition matches resulting spectra in Figure 5.

I have built a custom molecular file for RADEX that includes 8 CO_2 ro-vibrational transitions in the mid-IR (Figure 3). Each vibrational state contains up to J=50 rotational levels. The file includes 818 radiative transitions, and 20,000 collisional rate coefficients. All Einstein A coefficients, transition wavelengths, and energy levels were taken from HITRAN [5]. I extrapolated collisional rate coefficients similar to [2], 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.

Mid-IR Slab Spectrum of CO_2

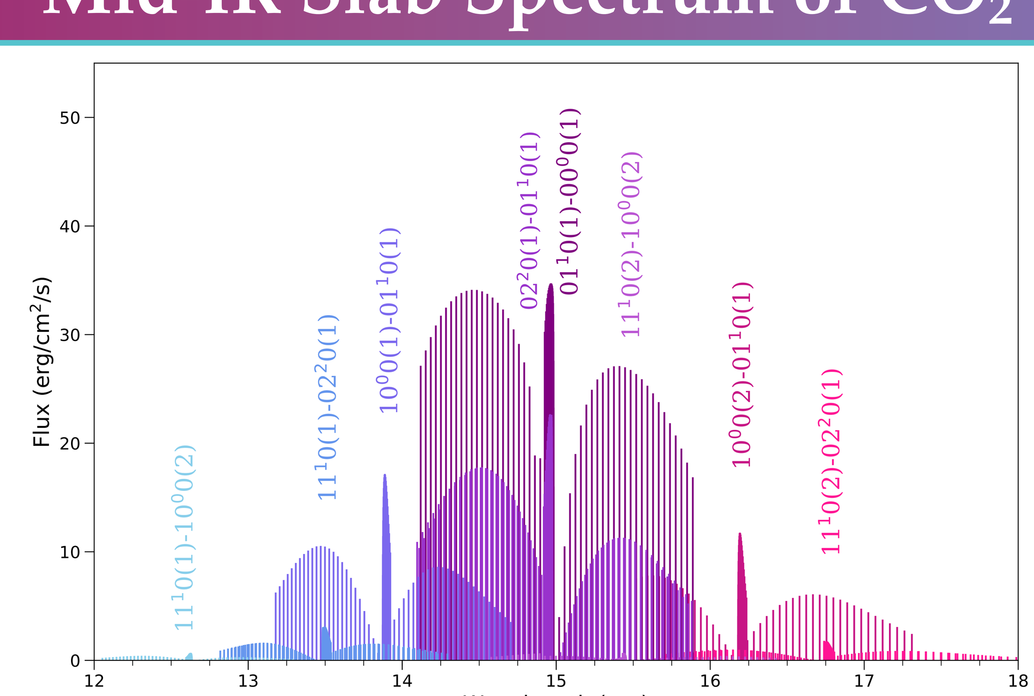

Figure 5: Slab spectrum of CO_2 calculated with RADEX. Parameters: density: 10^{17} cm^{-3}; Kinetic Temperature: 1000 K; CO_2 column density: 10^{17} cm^{-2}.

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

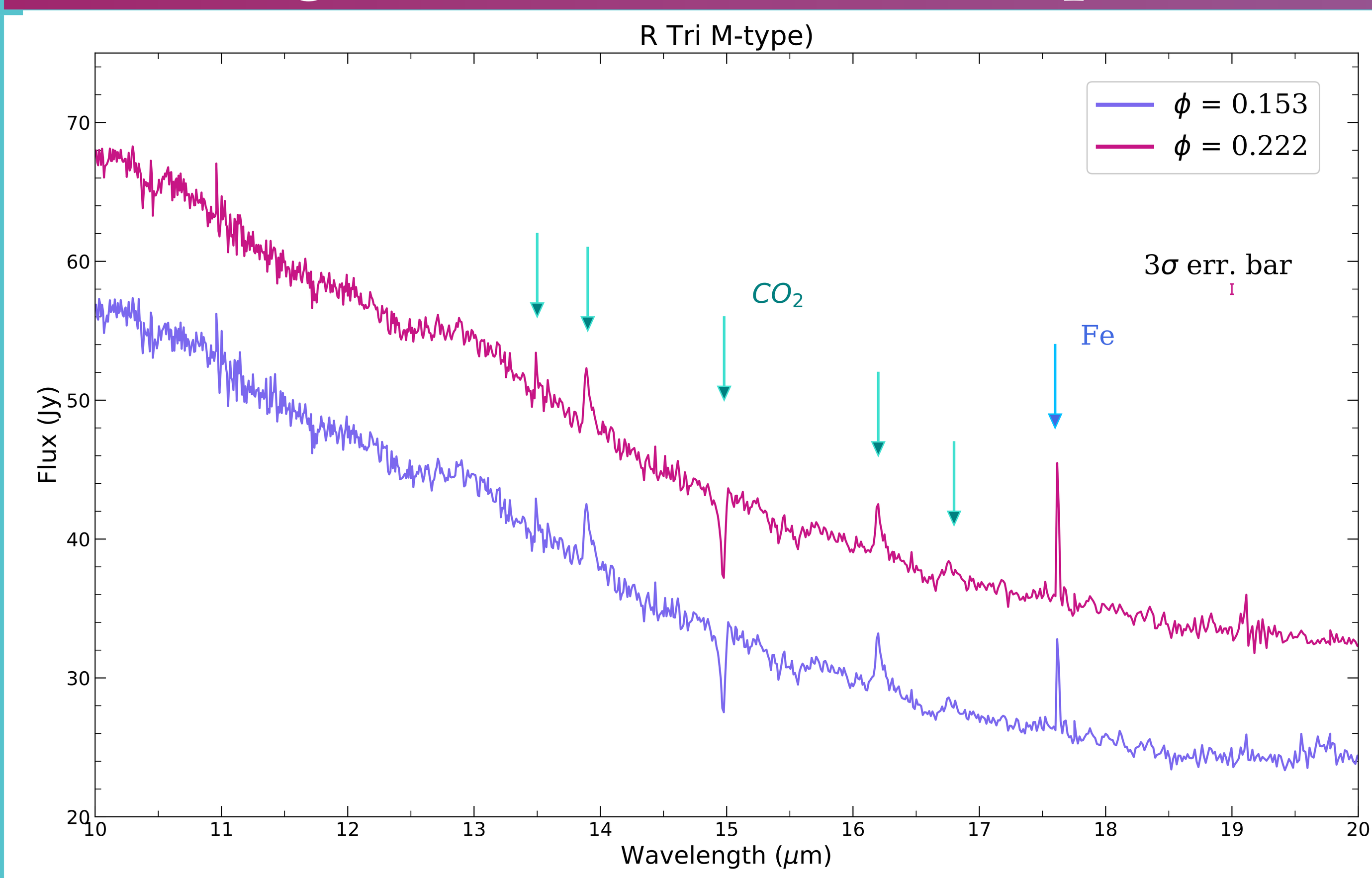

Figure 3: Spitzer spectrum for M-type Mira variable *R Tri*. Note that the top spectrum has been artificially offset by 8 Jy for clarity.

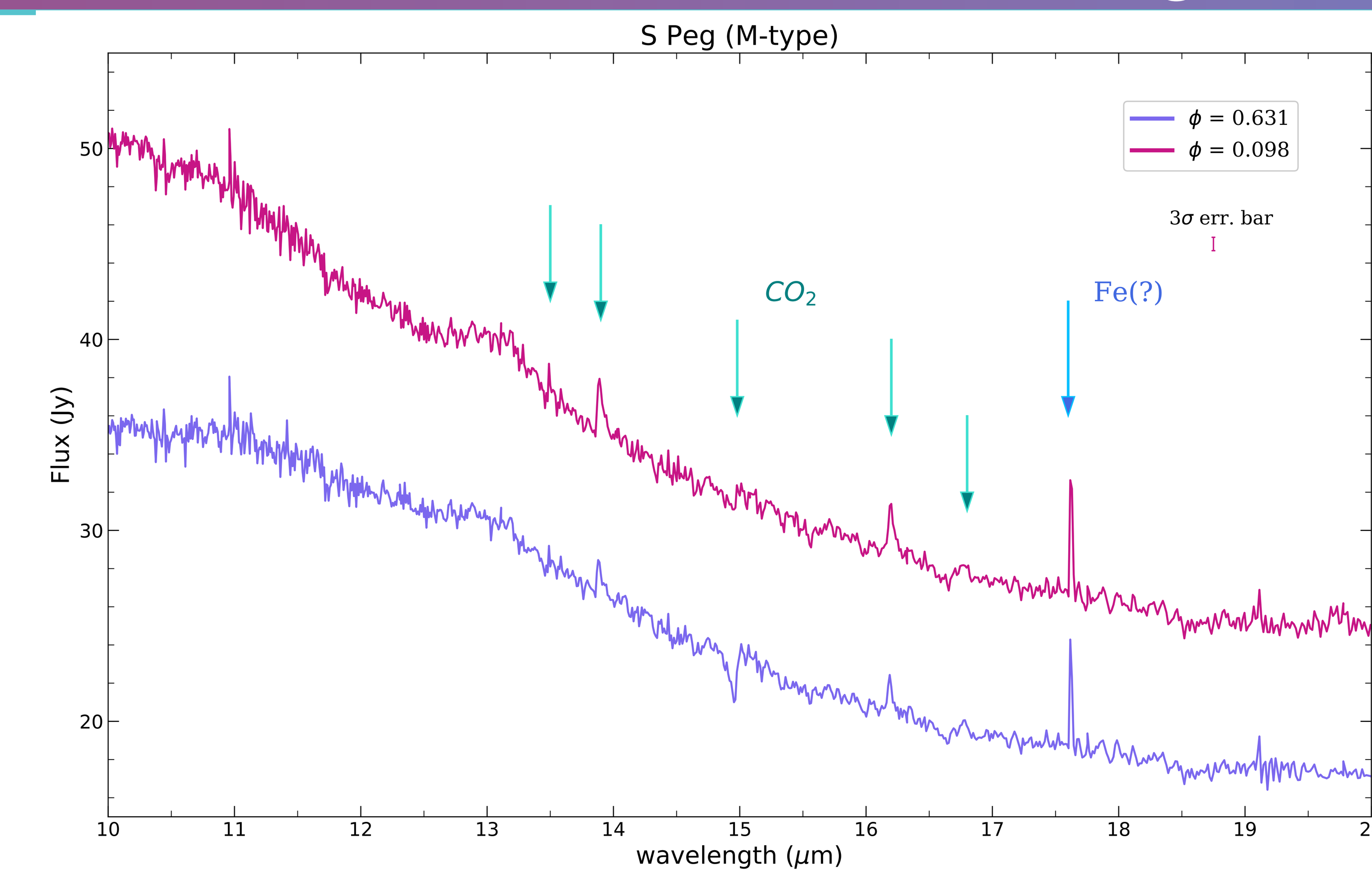

Figure 4: Spitzer spectrum of M-type Mira variable *S Peg*. The top spectrum is offset by 5 Jy for clarity.

Examples of RADEX Fits

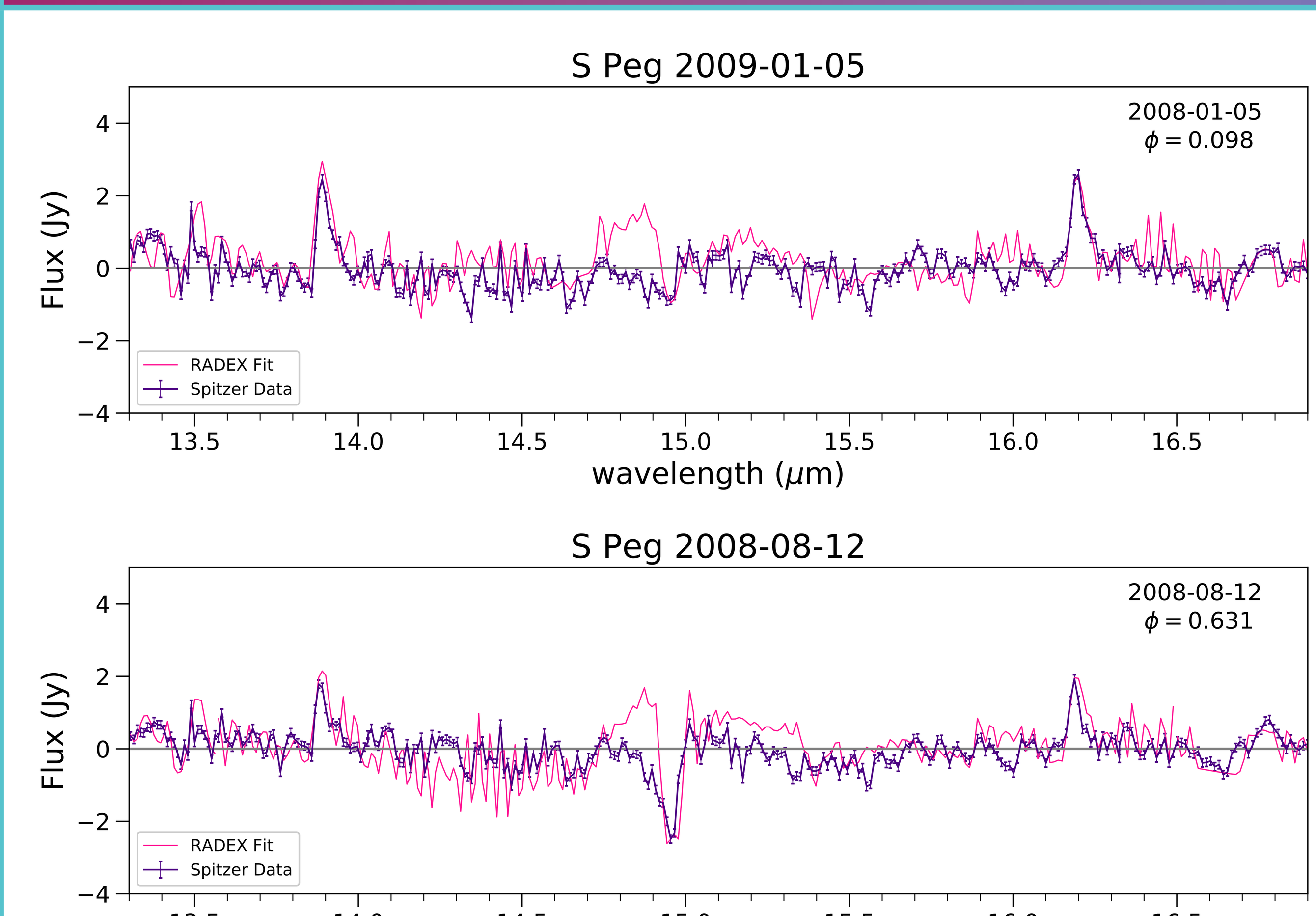

Figure 6: RADEX results for 15 μm feature in S Peg. The change in intensity is most likely tied to shocks associated with the pulsation of the star. Additional hot bands are needed to fit the left wing of the feature. Further results from RADEX fits of 2 Miras are presented in Table 1.

Results and Future Work

Table 1: Results of RADEX models of CO_2 slabs in 2 Mira variables.

Target	T_{kin}(K)	N (cm^{-2})	R (R_*)	ϕ
R Tri 2008-09-07				
13.87 μm (E) & 16.18 μm (E)	600 ± 50	$5\times10^{17} \pm 0.5\times 10^{17}$	3.5 & 2.9	0.153
14.98 μm (A)	550 ± 50	$2.25\times10^{16} \pm 0.05\times 10^{16}$	4.1	0.153
R Tri 2008-10-02				
13.87 μm (E) & 16.18 μm (E)	600 ± 50	$4.50\times10^{17} \pm 0.5\times 10^{17}$	3.5 & 2.9	0.222
14.98 μm (A)	550 ± 50	$2.40\times10^{16} \pm 0.05\times 10^{16}$	4.1	0.222
S Peg 2008-12-08				
13.49 μm (E) & 16.76 μm (E)	1400 ± 50	$7.5\times10^{16} \pm 0.5\times 10^{16}$	4.5 & 4.5	0.631
13.87 μm (E) & 16.18 μm (E)	500 ± 50	$5.5\times10^{17} \pm 0.5\times 10^{17}$	3.8 & 3.4	0.631
14.98 μm (A)	750 ± 50	$2.40\times10^{16} \pm 0.05\times 10^{16}$	2.6	0.631
S Peg 2009-01-05				
13.49 μm (E) & 16.76 μm (E)	1400 ± 50	$1.0\times10^{17} \pm 0.25\times 10^{17}$	4.3 & 4.7	0.098
13.87 μm (E) & 16.18 μm (E)	500 ± 50	$5.5\times10^{17} \pm 0.5\times 10^{17}$	3.7 & 3.1	0.098
14.98 μm (A) vw	750 ± 50	$1.55\times10^{16} \pm 0.5\times 10^{16}$	2.3	0.098

- The custom built file for CO_2 accurately creates a 2-slab model that can globally fit the 3 bright Q-branch bandheads in our Spitzer spectra; see [1] for full paper on R Tri.
- The cool temperature of the CO_2 gas at a few R_* could indicate a "refrigeration zone" where silicate dust can form within a few R_*.
- We will re-observe hot bands at high resolution with EXES on SOFIA which will allow us to determine stronger constraints on the temperature and density.

References

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