ANALYSIS OF INFRARED SPECTRA OF CARBON STARS OBSERVED BY THE ISO SWS

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1. Introduction

Infrared spectra of carbon stars are of great importance in understanding the stellar evolution at the asymptotic giant branch (AGB). The analysis of elemental abundances of carbon, nitrogen, and oxygen, which is indispensable to understand the nuclear processes in AGB stars, can be done based on high-resolution infrared spectra. In addition, infrared spectra of carbon stars bring us information on the physics and chemistry in the circumstellar envelope.

We present analysis of infrared spectra of visual carbon stars based on newly developed spherical model atmospheres. Before comparing predicted spectra with the observed, we determine elemental abundances of carbon and oxygen from high-resolution spectra acquired with a Fourier transform spectrometer (FTS). Since the atmospheric structure of carbon stars is very sensitive to the chemical composition, the determination of chem-

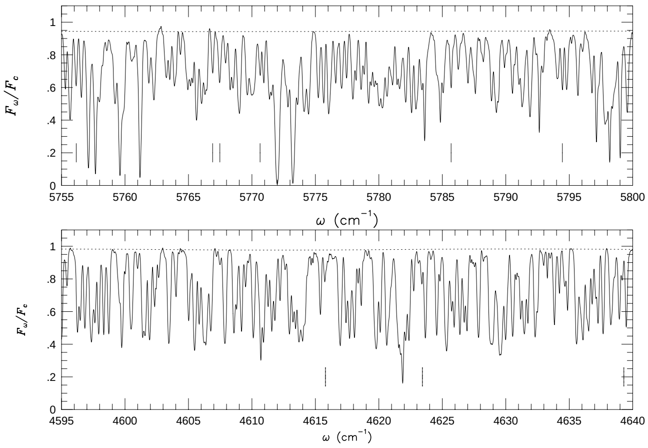

Figure 1. A portion of the observed spectrum of TX Psc. Upper panel: H-band spectrum. The ticks represent the CO second overtone lines used in the analysis. Lower panel: K-band spectrum. The ticks represent the C_2 Phillips system lines used in the analysis. The dotted lines in both panels represent the continuum level which is determined by drawing an envelope over the peaks in the spectral region studied

ical composition is needed prior to comparison of predicted spectra with observations.

We then compare synthetic spectra with observations by the ISO SWS as well as by the ground-based photometry or spectrophotometry. The model atmospheres used in the abundance analysis are tested by these photometric and spectrophotometric observations, and used to define the photospheric contribution in the observed spectra. The outer atmosphere or the inner circumstellar envelope is probed based on the CO fundamental and first overtone bands.

2. Analysis of elemental abundances of carbon and oxygen in carbon stars

Elemental abundances of carbon and oxygen, and their isotopic ratios are crucial information to understand the formation of carbon stars. However, the analysis of chemical composition in carbon stars is never well-established. For example, we analyzed $^{12}C/^{13}C$ ratios from CN lines around 8000 Å for more than 100 carbon stars (Ohnaka & Tsuji 1996) and found a systematic discrepancy from the result by Lambert et al. (1986). In the present work, we present a re-analysis of the same spectral data that they analyzed. The data were originally obtained by Lambert et al. (1986) with the FTS at the Kitt Peak National Observatory. The archived data were kindly made us available by Dr. K. H. Hinkle. The spectra cover from 4000 to 6600 cm^{-1} (2.5 – 1.5 μm) with spectral resolution of $R = 9.4 \times 10^4$ to

TABLE 1. Comparison of the oxygen abundances and the C/O ratios derived by Lambert et al. (1986) (LGEH86) and by the present work (O97). 'PP' denotes the analysis based on the plane parallel models, while 'SS' denotes models in spherical symmetry

	[O/H]			C/O		
Star	O97 (SS)	O97 (PP)	LGEH86	O97 (SS)	O97 (PP)	LGEH86
TX Psc	−0.006	−0.096	−0.10	1.140	1.160	1.027
BL Ori	−0.068	−0.182	−0.29	1.311	1.394	1.039
V Aql	−0.010	−0.152	−0.20	2.479	2.825	1.25

5.7×10^4. The signal-to-noise ratios are also satisfactory, typically about 100. We selected three stars from the sample of Lambert et al. (1986): TX Psc, BL Ori, and V Aql. Figure 1 shows a portion of the observed spectrum of TX Psc in the H- and K-bands. We determined oxygen abundance from the CO second overtone lines and carbon abundance from the C_2 Phillips system lines.

In order to determine C and O abundances self-consistently, we made a grid of model atmospheres with different carbon and oxygen abundances. With each model, we calculate the corrections for the molecular abundance by comparing equivalent widths predicted from the model atmosphere with the observed ones. Then we interpolate the carbon and oxygen abundances with which the corrections for the molecular abundance of CO and C_2 should be zero. The analysis was done with model atmospheres in two different geometries: plane parallel and spherical atmospheres. Details of the model atmospheres and the analysis can be found in Ohnaka (1997).

The resulting abundances of carbon and oxygen in three carbon stars are given in Table 1, together with the result by Lambert et al. (1986). The result of oxygen abundances is in fair agreement. However, the result of carbon abundance shows severe disagreement with those of Lambert et al. (1986). The C/O ratios derived in the present work are higher than their values, and especially C/O ratio more than 2 is derived for V Aql. One of the possible reasons for such a discrepancy is the difference of model atmospheres used in the analyses of both authors, but further investigation should be done to clarify the discrepancy and to establish C/O ratios in carbon stars.

Though C/O ratios in carbon stars still controversial, the C/O ratios derived in the present work are quite consistent with $^{12}C/^{13}C$ ratios derived by Ohnaka & Tsuji (1996) from a view point of carbon star formation. In the current scenario of carbon star formation, K and M giants evolve to

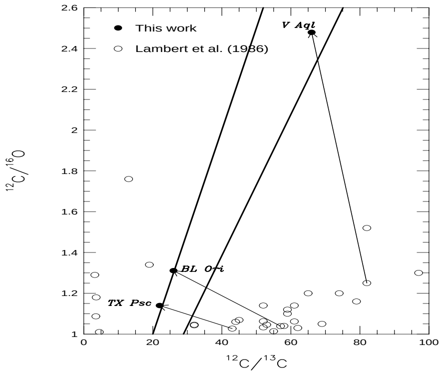

Figure 2. C/O ratios determined in the present work are plotted against $^{12}C/^{13}C$ ratios derived by Ohnaka & Tsuji (1996) (filled circles), together with the results by Lambert et al. (1986) (open circles). The solid lines represent predictions from the carbon star formation scenario in which K and M giants evolve to carbon stars by addition of ^{12}C. The difference of the result between Lambert et al. (1986) and the present work is represented by the arrow for each star

carbon stars by addition of ^{12}C synthesized in the thermal pulse. If this scenario is correct, there should be a correlation between $^{12}C/^{13}C$ ratio and C/O ratio along the evolution from K and M giants to carbon stars. The analyses of carbon and oxygen abundances as well as $^{12}C/^{13}C$ ratio in K and M giants were done by Smith & Lambert (1985, 1990), therefore, we can calculate C/O ratio and $^{12}C/^{13}C$ ratio which K and M giants would have when they became carbon-rich. In Fig. 2 we plot C/O ratios against $^{12}C/^{13}C$ ratios for the three carbon stars, together with such a prediction. As can be seen in the figure, the C/O ratios and $^{12}C/^{13}C$ ratios in the three stars are quite consistent with the simple picture of carbon star formation mentioned above.

3. Comparison of synthetic spectra with observations

Once carbon and oxygen abundances are determined, we can construct a model atmosphere adjusted to each program star and generate synthetic spectra.

Figure 3 shows the comparison of emergent flux from the model atmosphere adjusted to TX Psc with a photometric observation in Johnson et al. (1985). A glance of the figure reveals that the observed spectral energy distribution is fairly reproduced, though the match is rather poor for the strong absorption feature due to CN around 1.5 μm. It should be kept in mind, however, that the effect of molecular opacity is incorporated in the calculation of model atmospheres not on a line-by-line basis: we employed

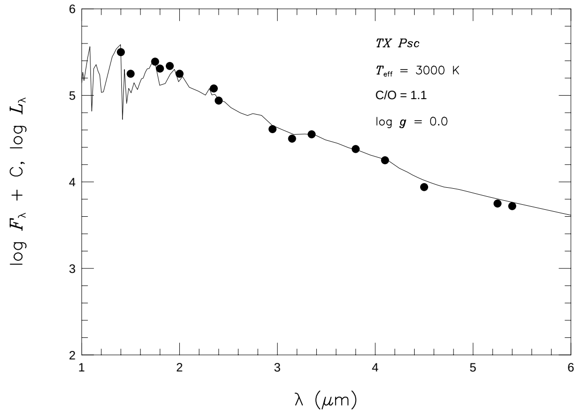

Figure 3. Comparison between emergent flux from the model atmosphere for TX Psc (solid line) and a photometric observation in Johnson et al. (1985) (filled circles)

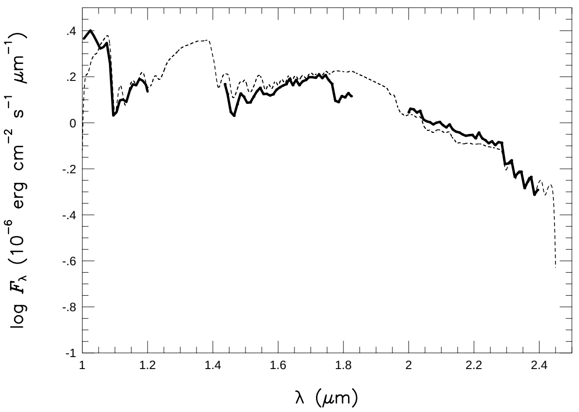

Figure 4. Comparison between a synthetic spectrum (dashed line) and the spectrum observed by Lázaro et al. (1994) for TX Psc (solid line)

the Band Model method of which details are described in Tsuji (1994).

However, a synthetic spectrum generated based on that model shows a rather good agreement with observations. Figure 4 shows the comparison between the synthetic spectrum for TX Psc and a spectrophotometric observation by Lázaro et al. (1994). Lines of the CO second and first overtone bands, the C_2 Phillips system, and the CN red system are included in the calculation of the synthetic spectrum. The match between the calculation and the observation is rather good, though not perfect. The slight disagreement might be attributed to the temporal change of molecular absorption feature, since two spectra of TX Psc in Lázaro et al. (1994) acquired at different epochs show such temporal variation.

The contribution from the circumstellar envelope becomes more significant in the wavelength region longer than 4 or 5 μm. In Fig. 5 we show

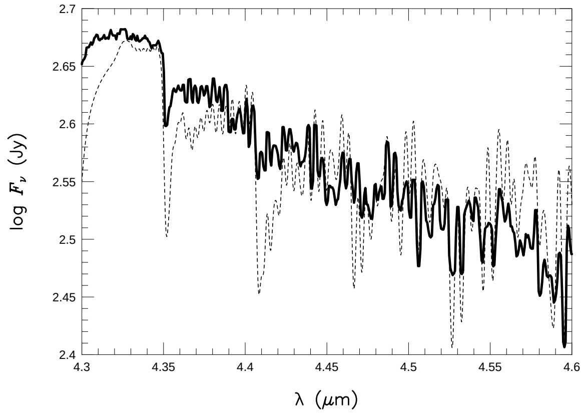

Figure 5. Comparison between the synthetic and observed spectra of the CO fundamental bands for TX Psc. The solid line represents the observation by the ISO SWS AOT6, while the dashed line a prediction based on the model atmosphere adjusted to TX Psc

the CO fundamental bands in TX Psc observed by the ISO SWS AOT06, together with a spectrum predicted from the model adjusted to this star. It is obvious that the observed CO fundamental bands are much weaker than predicted. It can be interpreted as due to filling in by the emission from an extra-component above the photosphere. In fact, the existence of such a component has been implied by intensity anomalies in low excitation lines of the CO first overtone bands: we found in the FTS spectra that the low excitation lines ($\chi < 0.6$ eV) are much stronger than predicted. The analysis of such absorption excess (Ohnaka 1997) revealed the existence of warm molecular envelope with excitation temperature of 1500 K (TX Psc) and 950 K (V Aql), and with CO column density of $\log N_{\rm CO} = 20$ cm^{-2}. As the next step, further investigation on the emission excess in the CO fundamental bands should be done to see if it can also be explained by the warm molecular envelope. And larger number of stars should be analyzed to clarify how the properties of the warm molecular envelope are related to the stellar parameters such as effective temperature and chemical composition.

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