PROBING THE OUTER ATMOSPHERE OF CARBON STARS - C_2H_2, HCN AND C_3 FEATURES IN THE SWS RANGE

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ABSTRACT

We have obtained ISO-SWS spectra of a number of carbon-rich AGB stars in the wavelength range 2.4 – 44 μm with a resolution of about 400. We compare these spectra with results of hydrostatic and dynamic model atmospheres. Of special interest are the features which are formed far out in the atmosphere like the C_2H_2, HCN and C_3 features. For these outer regions of the atmosphere deviations from hydrostatic structures are to be expected.

Key words: ISO – stars: AGB and post-AGB – stars: atmospheres stars: variables stars: carbon stars: radiative transfer

1. INTRODUCTION

A very sensitive probe for the outer atmosphere is the so called 14 μm feature which is due to HCN and/or C_2H_2. Hydrostatic model atmospheres predict a deep feature in this region. In C-stars with weak mass loss and small luminosity variations this feature is however very weak although other C_2H_2/HCN features in the SWS range can be fitted quite well with hydrostatic models. In a fully consistent model atmosphere calculation it is not possible to change the appearance of this feature without also changing the other features of C_2H_2 and HCN at shorter wavelengths. The observed weakness of this feature in C-stars with weak mass loss has led Jørgensen et al. (2000) to suggest that the molecular absorption at 14 μm is filled in with emission from cold dust distributed in clumps.

2. OBSERVATIONS

The observations were part of the solicited discretionary time program ZZAGB2PN of Kerschbaum et al. and obtained with the SWS (de Graauw et al. 1996). The spectra were taken with AOT01, i.e. they are full grating scans (2.4 μm to 44 μm). The speeds were either 1 or 2 which results in a typical resolution of 400 (Leech 1998). The pipeline processed data (OLP versions 7.01) were further reduced with ISAP. For all spectra a significant offset between the two scan directions was found in band 2C (7 μm to 12 μm) which was corrected by rejecting the scan direction with the higher flux.

The individual detectors and bands were combined by additive constants if the flux was below 100 to 200 Jy and by multiplicative corrections otherwise. Since some of the spectral features extend across more than one SWS-band and since we wanted to compare also the overall spectral shape, care had to be taken to minimise errors introduced by the band combination. For this reason we used band 2A (4.08 μm to 5.30 μm) as a flux reference. This band is well calibrated and has a wavelength range such that errors in its absolute flux are not propagated over too many bands. Our own data are complemented by additional spectra of some targets available in the ISO archive from other proposals. We also extracted the spectra of several calibration stars of earlier spectral type from the ISO archive. This allowed us to optimise the wavelength regions used for joining the bands and to check for systematic effects at the band limits. From the final spectra we computed flux densities in the L′ and the IRAS 12 μm and 25 μm filters. A comparison with ground based photometry (compiled from the literature) and the IRAS point source catalogue showed differences between $\pm 10\,\%$ and $\pm 20\,\%$, the differences at 25 μm generally being the largest. This is in agreement with the expectations from the flux variability of our targets, the calibration uncertainty of the SWS and the propagation of a flux error in our reference band to longer wavelengths.

3. MODEL ATMOSPHERES

The hydrostatic plane parallel model atmospheres are computed by use of an updated version of the original MARCS code (Gustafsson et al. 1975). Some of the improvements in the present version have been described by Jørgensen et al. (1992), Helling et al. (1996) and Jørgensen (1997). We treat the energy balance in the opacity sampling scheme and have adopted approximately 10000 frequency points for the radiative transfer computation. We include the molecules CO, CN, C_2, CH, CS, HCN, C_2H_2 and C_3 in the opacity together with continuum sources as described in Gustafsson et al. (1975).

The dynamic model atmospheres are described in Höfner (1999) and in the contribution of Höfner et al. (this volume). These models are characterized by the following set of parameters: stellar mass M, luminosity L, effective temperature $T_{\rm eff}$ of the hydrostatic initial model and the carbon-to-oxygen abundance ratio as well as the piston period P and velocity amplitude Δu_P.

4. SYNTHETIC SPECTRA

We have computed synthetic opacity sampling spectra including the molecules CO, CH, C_2, CN, HCN, C_2H_2 and C_3 in the wavelength range between 0.5 and 25 μm with a resolution of 20000. Due to the statistical character of the opacity sampling technique, it is necessary to average the opacity sampling spectrum over a number of frequencies before it can be compared to an observed spectrum. We rebinned the synthetic spectra to a resolution of 1000 for the comparison with the observations.

5. COMPARISON WITH OBSERVATIONS

In the case of moderately variable stars synthetic spectra resulting from hydrostatic models show good agreement with the observed spectra from the visual range until about 10 μm. Figure 1 shows a fit of the observed ISO-SWS spectrum of TX Psc with a model spectrum with an effective temperature of 3000 K, a luminosity of 5200 $L_\odot$ and a C/O ratio of 1.02. The light lines demonstrate the effect of a 5% error in flux band 2A (4.1 to 5.3 μm) propagated through the spectrum. Beyond 10 μm the observed spectra appear much more continuum-like than the synthetic photospheric spectra.

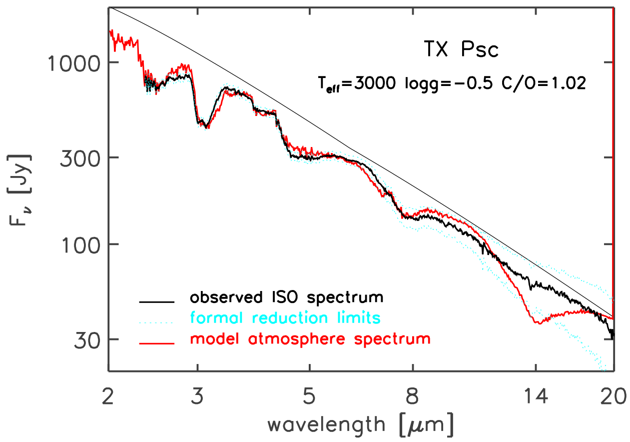

Figure 1. Comparison of observed (thick black line) and synthetic spectrum (thick grey line) for TX Psc. The light lines demonstrate the effect of a 5% error in flux band 2A (4.1 to 5.3 μm) propagated through the spectrum.

5.1. The 14 μm feature

The strongest predicted feature in the synthetic photospheric spectra in the long wavelength region is the so-called 14 μm band. It is dominated by absorption of C_2H_2 and HCN. In almost all carbon stars observed with ISO the 14 μm band is very weak (Yamamura et al. 1999, Jørgensen et al. 2000). Figure 2 shows simulations of the C_2H_2 bands in the 14 μm and the 3 μm region for the bright carbon star TX Psc. From top to bottom in the upper panel the spectra are: (1) the observed ISO-SWS spectrum (bold line), (2) the computed contribution of C_2H_2 to the spectrum if the spectrum forming gas was only 300 K (dotted line) warm, (3) a spectrum based on the C_2H_2 absorption coefficient at 630 K (dashed line), and (4) the full photospheric contribution of C_2H_2 to the spectrum (thin line). The 300 K spectrum shows a good agreement in the 13.7 μm region which represents the vibrational ground state part of the 14 μm band transition of C_2H_2. In the case of the 630 K spectrum one still sees a pronounced contribution from the vibrational ground state transition, but in addition a feature from 14 to 14.3 μm can be seen which also seems to be identifiable in the observed spectrum. There is only little resemblance between the observed and the computed photospheric spectrum. In a fully consistent model atmosphere calculation it is not possible to change the appearance of the 14 μm feature without also changing the other C_2H_2 and HCN features at shorter wavelengths. The lower panel of Fig. 2 demonstrates this for C_2H_2 in the 3 μm region, the denotions are the same as in the upper panel. These simulations only include the contribution of C_2H_2 to the bands, in the observed spectrum however HCN is contributing too which can be easily seen in the 3 μm region.

5.2. Discussion

To clarify the origin of the discrepancy in the feature depth we tested two possible scenarios.

On one hand we simulated combined dust and gas spectra by adding the emission from dust with low temperature to our photospheric spectrum. The idea is to see if the observed spectrum can be explained qualitatively by a relatively hot photospheric component which dominates the flux in the infrared below about 10 μm and a relatively cool emission (dust) component above the photosphere, which modifies the long-wavelength photospheric spectrum. We found it impossible to fill in the photospheric 14 μm band (such that a qualitative agreement with the observations in this region could be obtained) without also destroying the agreement between the observed and computed photospheric short-wavelength part of the SWS spectral region. A similar result is obtained if the blackbody is replaced by emission from a spherical dust envelope. The simulations indicate that the source of emission cannot cover the entire surface. We therefore tentatively suggest that the photosphere is obscured by clumps of dust-rich cool gas with a temperature of about 300 to 500 K which cover about 10% (the filling factor) of the surface area. The features seen at 13.7 μm,

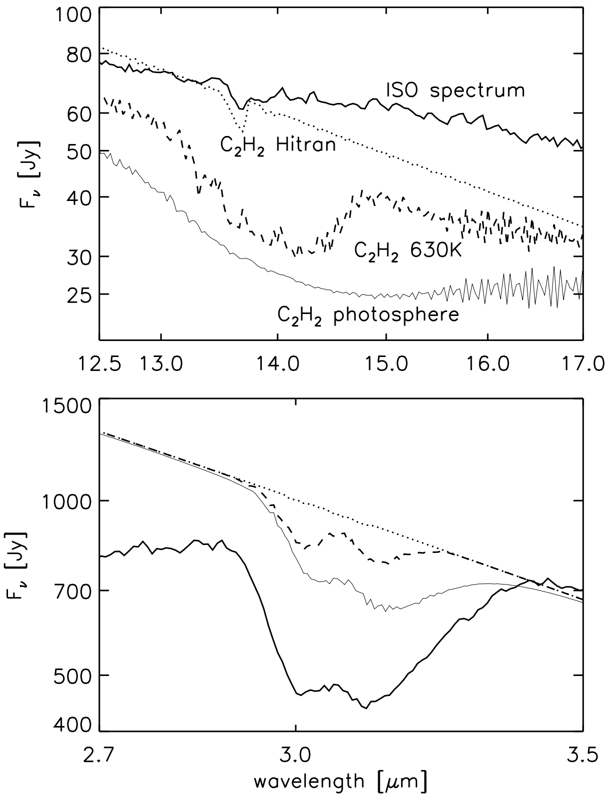

Figure 2. Simulations of the C_2H_2 bands in the 14 μm and the 3 μm region for the bright carbon star TX Psc (see text for details).

$14.0-14.3\,\mu$m, and possible other small discrete absorptions in the region, are due to C_2H_2 and HCN absorption in the very cool gas above the region of these clumps. However, we stress that this scenario is not a self-consistent, physical model computation, but a suggestion which quantitatively would be able to explain the observed spectra.

This scenario with an inhomogeneous atmosphere is in qualitive agreement with recent high angular resolution observations (e.g. Richichi et al. 1995) and with models of the ultraviolet spectrum of TX Psc (Jørgensen & Johnson 1991).

On the other hand we compared the spectra with dynamic model atmospheres. Figure 4 shows the result of such an attempt. Depending on the model parameters, the resulting synthetic spectra either show a pronounced 14 μm feature or it can be filled in with emission.

In Fig. 5 different phases of one dynamic model are plotted in order to demonstrate how the features can vary during a cycle. It shows that not only the 14 μm feature is affected, but also all other features which are formed in the outer regions where dynamics is important, especially the C_2H_2 (2.5, 3.0, 7 to 8, 14 μm) , HCN (3.0, 7 to 8, 14 μm) and C_3 (5.1 μm) features are filled in with emission.

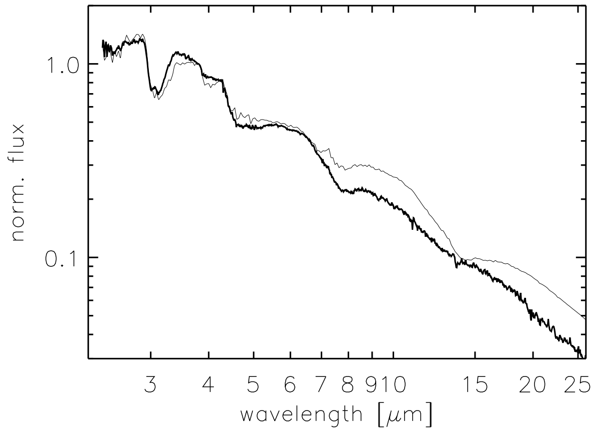

Figure 3. Comparison of the ISO-SWS spectrum of TX Psc (bold line) with a photospheric model spectrum including a 10% contribution from a 500 K blackbody.

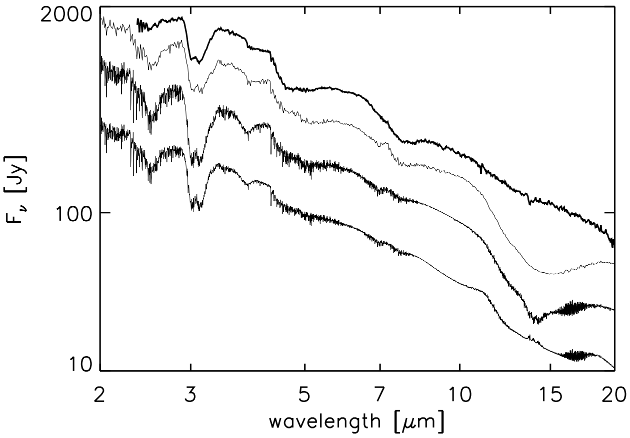

Figure 4. From top to bottom: ISO-SWS spectrum of TX Psc, best fit hydrostatic MARCS model, maximum light dynamic model with the same input parameters as the MARCS model ($T_{\rm eff}$ = 3000 K, C/O = 1.1, L = 5200 $L_\odot$, P = 337 days, $\Delta u_{\rm P}$ = 2 km/s) and a maximum light model of a dynamic model with higher luminosity and lower temperature ($T_{\rm eff}$ = 2900 K, C/O = 1.1, L = 7000 $L_\odot$, P = 337 days, $\Delta u_{\rm P}$ = 2 km/s).

Figure 6 shows two ISO-SWS spectra of the SRb variable V460 Cyg taken about 300 days (or 1.7 light cycles) apart from each other. One can recognise a variation of the 3 μm (due to C_2H_2 and HCN), the 5.1 μm (due to C_3) and the 7 μm (due to C_2H_2 and HCN) region. The difference in the slopes beyond 11 μm is probably due to the reduction uncertainties for stars with such low fluxes in this wavelength region. The present dynamical models predict stronger feature variations, but until now no attempt was made to “fit” a particular star. With a system-

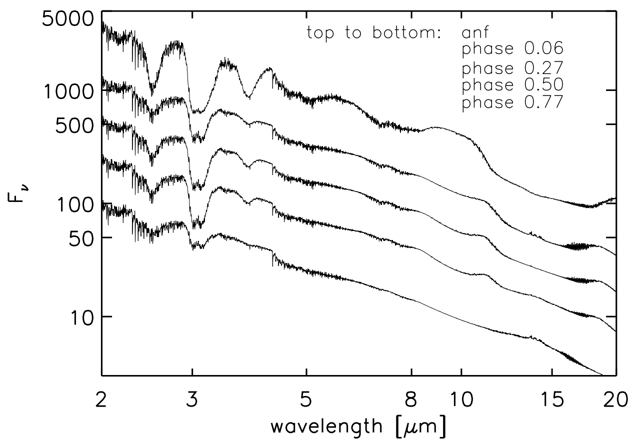

Figure 5. Hydrostatic initial model and four phases of a dynamic model with the parameters: $T_{\rm eff}$ *= 2900 K, C/O = 1.1,* $L = 7000\ L_\odot$*,* $P = 337$ *days,* $\Delta u_{\rm P} = 2$ *km/s). The 14* μ*m feature can be either very strong or be filled up by emission.*

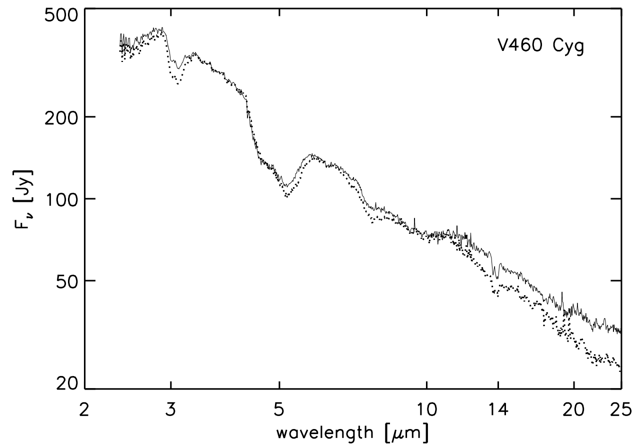

Figure 6. Two ISO-SWS spectra of the SRb variable V460 Cyg taken about 300 days apart from each other.

atic parameter study and variation it might be possible to fit the spectra. But certainly further investigations are necessary in order to test both hypotheses.

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