ISO-SWS OBSERVATIONS AND MODEL ATMOSPHERES OF CARBON- AND OXYGEN-RICH AGB VARIABLES

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ABSTRACT

The ISO-SWS spectra of several representative carbon- and oxygen-rich AGB variables (R Aql, R Cas, T Dra, V Cyg, V CrB and R Scl) were obtained at several phases of their pulsational cycle. This allows us to study the molecular features and the dust emission of these objects as a function of stellar parameters as well as pulsational phase.
The observational data are compared with synthetic molecular spectra based on hydrostatic models (MARCS) and on dynamical atmospheres, which include such phenomena as pulsation, mass loss and dust formation. Some aspects of the SWS spectra like their variations can only be explained by dynamical atmospheres.
To be able to analyse also the targets with significant mass loss, we also included a dust component in the synthetic spectra. On the basis of these synthetic spectra we also investigate the influence of molecular features on the interpretation of the dust emission and vice versa. This is of special importance in the 8 to 16 micron region.

Key words: ISO; infrared astronomy; AGB stars.

1. MODEL SPECTRA

Synthetic spectra of cool AGB stars have usually been calculated using classical model atmosphere programs like the MARCS code (Gustafsson et al. 1975). These models are very sophisticated concerning wavelength dependent radiative transfer with a detailed treatment of molecular opacities, continuum absorption and convection. Nevertheless, it is obvious that the atmospheres of very cool AGB stars are dominated by such phenomena as pulsation, shock waves and heavy mass loss, which can definitely not be described by a hydrostatic approximation. As a consequence classical hydrostatic models fail to reproduce the strength and variations of certain molecular features in such objects (e.g. Aringer et al. 1997 for SiO).

We have calculated spectra based on hydrostatic MARCS models as well as on dynamic models for dust formation and mass loss developed by Höfner et al. (Höfner & Dorfi 1997, Höfner et al. 1998) where pulsation is simulated by a moving piston at the inner boundary. Using a given temperature-pressure structure we have computed chemical abundances of molecular species (equilibrium), continuum absorption (routines from MARCS code) and molecular opacities (directly from linelists or from opacity sampling). For the calculation of the synthetic spectra the following species have been included in the molecular opacities: CO, SiO, OH, H_2O, CO_2 from HITRAN and TiO for the oxygen-rich stars and CO, C_2, CN, CH, HCN, C_3 and C_2H_2 for the carbon-rich ones. The dynamic models are characterized by the following set of parameters: stellar mass, luminosity, effective temperature of the hydrostatic initial model and the carbon-to-oxygen abundance (C/O) ratio as well as the piston period P and velocity amplitude Δu_P. All abundances except that of carbon are assumed to be solar. Our 'standard' model for C-rich stars has the following parameters: M = 1 $M_\odot$, L = 7000 $L_\odot$, T_{eff} = 2880 K, C/O = 1.4, P = 390 d and Δu_P = 4 km s^{-1}.

There are still some problems concerning the dynamic model atmospheres. First, they are calculated with a grey radiative transfer using mean opacities, which probably produces significant deviations from the correct structure, especially in the outer layers of the atmosphere where most of the water absorption comes from. Also, the piston as an inner boundary for the models does not represent a very satisfactory solution, because it introduces additional degrees of freedom. Finally, for the oxygen-rich case we did not include any dust in the computations.

2. OBSERVATIONAL DATA

Within our open time observing programs the spectral variations of a few representative AGB stars were monitored with the ISO-SWS (de Graauw et al. 1996). In Table 1 we list the major characteristics of our targets presented here.

For R Scl and R Cas we have multiple observations distributed over the pulsational cycle. The spectra were full grating scans (2.4 μm to 44 μm) with a typical resolution of 400 to 600. The pipeline processed

Table 1. Summary of targets

Name	Type	Spectrum	P[d]	dM/dt $[10^{-6}]$	Comment
R Scl	SRb	C6,5	370	<1	large amplit., detached shell
TT Cyg	SRb	C5,4e	118	0.01	small amplit., detached shell
V460 Cyg	SRb	C6,4	180	0.1	small amplit.
TX Psc	Lb	C6,2		0.1	small amplit.
TY Dra	Lb	M6-M8		0.2	small amplit.
SV Peg	SRb	M7	145	0.05	small amplit.,"red SRV"
g Her	SRb	M6	90	≤0.01	small amplit.,"blue SRV"
R Cas	M	M6e-M10e	430	2	large amplit.

data (mostly OLP versions 6.xx) were further reduced with ISAP and then rebinned to a resolution of 100. 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 agreement between spectra of the same star taken within a few days was generally better than 10%. There was also good agreement with (quasi-simultaneous) ground based and IRAS photometry.

First results on R Scl have been presented by Hron et al. (1998) and will serve as a reference for the other C-rich targets.

3. COMPARISON OF OBSERVATIONS AND MODELS

1. Carbon-rich stars:
Figure 1 shows observations of TX Psc (dash-dot), TT Cyg (dash), V460 Cyg (dash-triple-dot) and R Scl (full, dot) in the wavelength range between 2.3 and 4.4 μm and between 3.5 and 8 μm respectively (upper panel). In the lower panels a few model spectra are shown for comparison. The depths of the 3 and 3.8 μm C_2H_2 features compared to the 5.1 μm C_3 feature suggest a sequence of decreasing temperature: V460 Cyg → TT Cyg → TX Psc → R Scl (max) → R Scl (min). The ratio of the strength of the 4.6 μm CO to the 5.1 μm C_3 feature indicates a sequence of increasing C/O ratio: TX Psc → V460 Cyg → TT Cyg (→) R Scl.

When investigating stars with considerable mass loss a correction of the observed spectra for the dust emission is necessary. For this purpose we have fitted the ISO spectra with DUSTY models (Ivezić et al. 1997). Synthetic spectra including the molecular absorption were used as input radiation, the ratio of amorphous carbon to SiC was chosen to be 4:1 and a $1/r^2$ dust density law adopted. After removal of the 11 μm emission feature we subtracted the resulting dust continua from the observed spectra and normalised the corrected spectra by linear interpolation between the fluxes at selected "pseudo-continuum" points. Figure 2 shows the result for one example, V Cyg. The dust optical depth at 2.2 μm are indicated in the plot, the thick full lines give the best fit, the dotted lines an indication for the influence of this parameter on the depth of the molecular features. The thin full lines are synthetic spectra at similar phases for a dynamical model with 7000 $L_\odot$ and the dashed lines are for a model with 10000 $L_\odot$. The asterisks mark the wavelengths used for the normalisation. The agreement of the observations of V Cyg with dynamic models is comparable to the results found for R Scl (Hron et al. 1998). Depth and variation of the 14 μm and the 3 μm C_2H_2 features are comparable. The shape of the SiC feature is not well reproduced by the DUSTY models. These effects are most likely due to the influence of molecular features. This means that the interpretation of the 11 μm feature requires a proper treatment of molecules and dust.

2. Oxygen-rich stars:
As it turned out, many of our ISO-SWS spectra of O-rich AGB stars can be reproduced by a temperature sequence of hydrostatic models. This is demonstrated in Fig. 3 where we compare the observations of three AGB variables with synthetic spectra based on MARCS atmospheres. The temperatures have been selected to fit the overall energy distribution of the ISO-SWS spectra. It is obvious that the intensity of the CO, OH and water bands is described very well in all cases. Nevertheless, for some objects one has to adopt unrealistically low temperatures (T < 2600 K) in order to reproduce the observed data.
Using dynamic models we have been successful in reproducing the features of OH, CO and SiO, but we got much too weak water absorption. This can be explained by the large deviations introduced by the grey approximation for the radiative transfer in the outer layers of the atmosphere.
Finally, it should be mentioned that the CO_2 feature around 4.3 μm could not be fit at all. The observed bands are always much stronger than the synthetic ones. This might be due to an incomplete linelist or incorrect chemical data (molecular equilibrium abundances).

In order to investigate the contribution of the circumstellar dust we again used the DUSTY code of Ivezić et al. (1997). The upper panel of Fig. 4 illustrates the contributions of the individual dust constituents. The full model spectrum is divided by the theoretical photospheric continuum in order to visualize the corresponding deviations. Note the 30 % difference between the synthetic stellar spectrum and the theoretical continuum around 8 μm, a region that is used for the definition of the stellar continuum by many authors. The lower panels of Fig. 4 show two examples of our combined results using opacity sampling spectra based on hydrostatic model atmospheres as the input for the DUSTY radiative transfer code. The

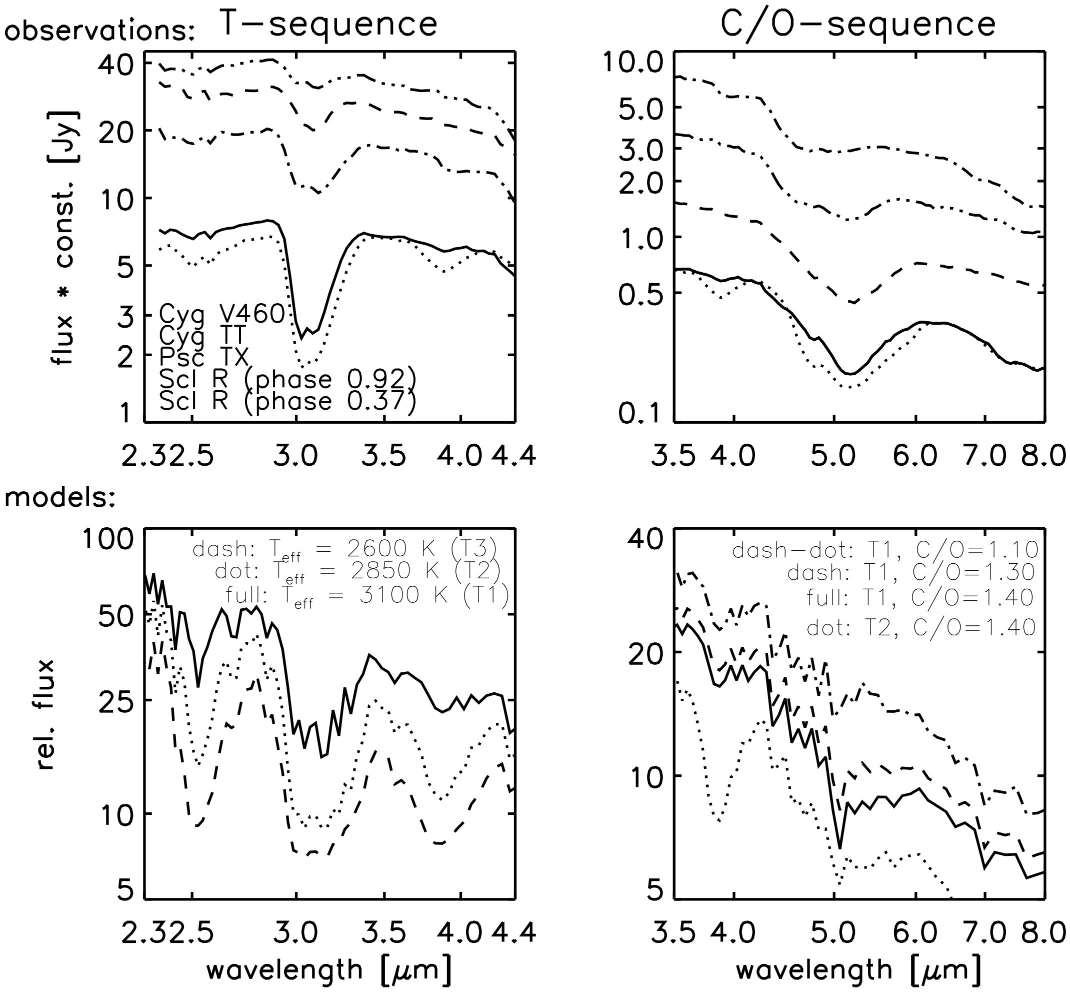

Figure 1. Five ISO-SWS spectra in the wavelength range between 2.3 and 4.4 μm and between 3.5 and 8 μm respectively (upper): dash-triple-dot: V460 Cyg, dash: TT Cyg, dash-dot: TX Psc, full: R Scl (0.92) and dot: R Scl (0.37). The lower panels show hydrostatic model spectra for different effective temperatures and different C/O ratios for comparison.

Lb variable TY Dra (left) can be reproduced with a dust shell consisting of a mixture of "astronomical silicates" and Mg(0.6) Fe(0.4) O on top of a hydrostatic 3000 K photosphere with $\log(g\,[cm/s^2]) = 0.0$. More information on the modelling is given in the figure. Also pure amorphous Olivine ($MgFeSiO_4$) could explain the observed spectral energy distribution. On the right hand side ISO observations and calculated spectra for two pulsational phases of the Semiregular variable SV Peg are shown. The small variation can be explained by a change of the effective temperature (3000 and 2900 K, resp.) of the model atmosphere. The contribution of the dust component is assumed to be constant between the two phases. The model parameters are again given in the figure.

A few conclusions can be drawn from the O-rich objects analyzed so far: For the modelling of the spectral energy distribution of circumstellar dust one requires good atmospheric models. A 2500 K blackbody gives wrong results for the dust component. The spectra of Semiregular and Irregular variables hardly can be reproduced using only "astronomical silicates". Most of these objects show indications of corundum and/or olivines. For the variable objects studied so far we found no indication of variable dust features but a strong influence of variable H_2O opacity. The rotation-vibration bands of CO_2 show a positive correlation with the 13 μm feature attributed to corundum.

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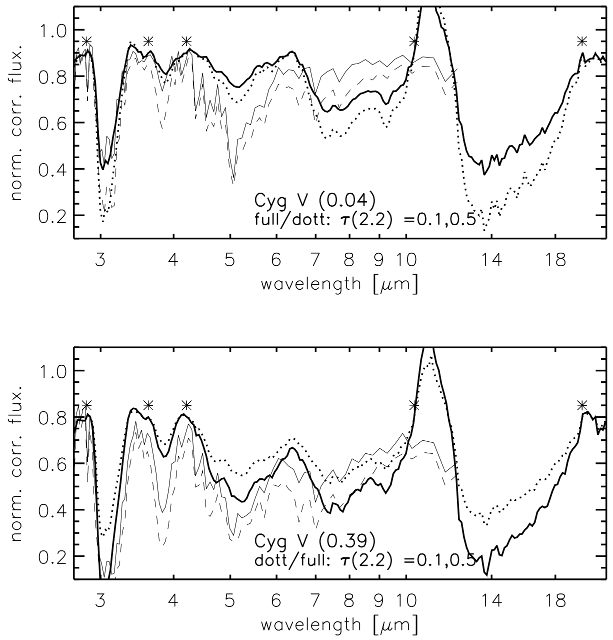

Figure 2. *ISO-SWS spectra of V Cyg taken near visual phases 0.04 (upper) and 0.39 (lower) compared to synthetic spectra. The observed spectra were normalised and corrected for continuous dust emission as described in the text. The dust optical depths at 2.2 μm are indicated in the plot, the thick full lines give the best DUSTY fit, the thick dotted lines an indication for the influence of this parameter on the depth of the molecular features. The thin full lines are the synthetic spectra at similar phases for a model with 7000 $L_\odot$, the thin dashed oes for a model with 10000 $L_\odot$. The asterisks mark the wavelengths used for the normalisation.*

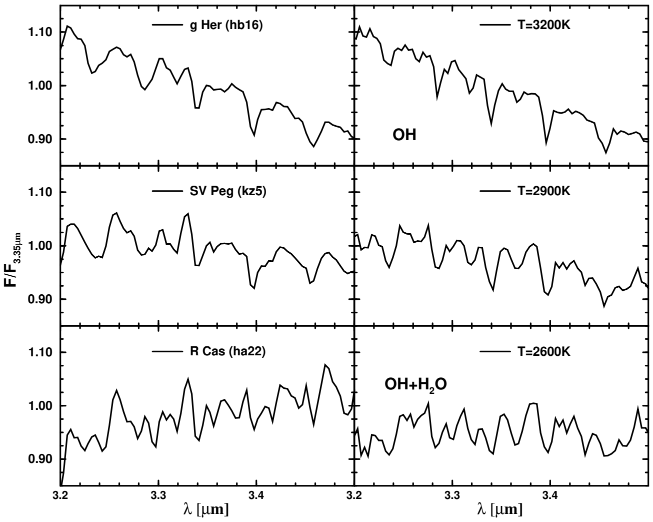

Figure 3. *ISO-SWS observations of the AGB variables g Her, SV Peg and R Cas compared with synthetic spectra for hydrostatic atmospheres with different temperatures, log (g[cm/s^2]) = 0.0, solar mass and chemical abundances. The resolution is between 300 and 400.*

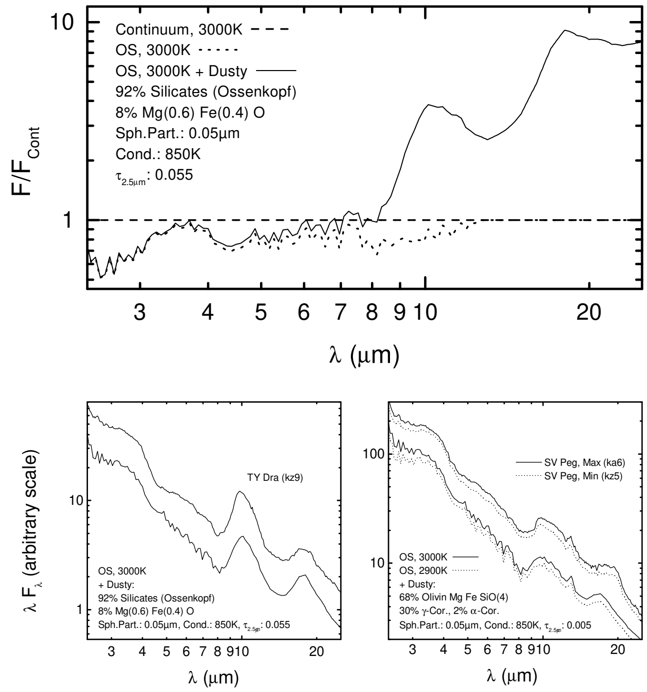

Figure 4. *Combined models using opacity sampling spectra based on hydrostatic model atmospheres as the input for the DUSTY radiative transfer code (see Sect.2).*

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