Asymptotic Giant Branch Stars
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Atmospheric Structure and Mass Loss of O-rich Long Period Variables. A Confrontation of Models with ISO-SWS Observations

B. Aringer, F. Kerschbaum, J. Hron, T. Posch and W. Windsteig

Institut für Astronomie, Univ. Wien, Vienna, Austria

U.G. Jørgensen and S. Höfner

Niels Bohr Institute, Univ. Obs. Copenhagen, Copenhagen, Denmark

Abstract. We present ISO-SWS observations of cool oxygen-rich AGB variables and compare them to synthetic molecular and dust spectra based on hydrostatic and dynamic model atmospheres.

1. Modelling

1.1. Hydrostatic and dynamic model atmospheres

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). This is done by a program called COMA (Copenhagen **O**pacities for **M**odel **A**tmospheres) producing opacities as a function of wavelength and radius, which are then used as an input for a spherical radiative transfer code. The following species have been included into the molecular opacities: CO, SiO, OH, H_2O, CO_2 from HITRAN and TiO. As an example of the results we show the normalized spectra of hydrostatic models with T = 2 600 K and T = 3 400 K in Fig. 1. It is obvious that the molecular absorption increases at lower temperatures.

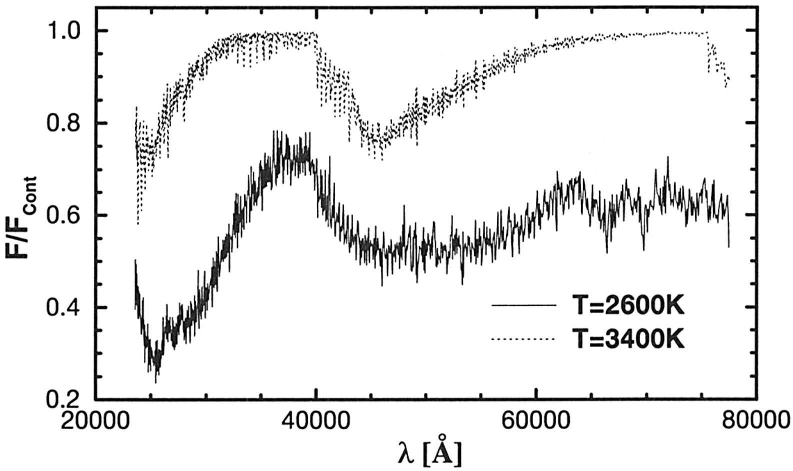

Figure 1. Normalized synthetic infrared spectra for two hydrostatic atmospheres with different temperatures (2600 and 3400 K), $\log(g\,[\mathrm{cm/s^2}]) = 0.0$, solar mass and chemical abundances. The resolution is about 900.

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.

1.2. Radiative transfer with DUSTY

In order to investigate the contribution of the circumstellar dust we used the publicly available radiative transfer code DUSTY (Ivezić et al. 1997). In contrast to the approach chosen by most authors we did not take blackbodies as the central light sources, but the synthetic spectra discussed above.

The upper panel of Fig. 3 illustrates the contributions of the individual constituents. The final model spectrum is divided by the theoretical photospheric continuum in order to visualize the corresponding deviations. Note the 30 % difference between the stellar spectrum and the theoretical continuum around 8 μm, a region that is used for the definition of the stellar continuum by many authors.

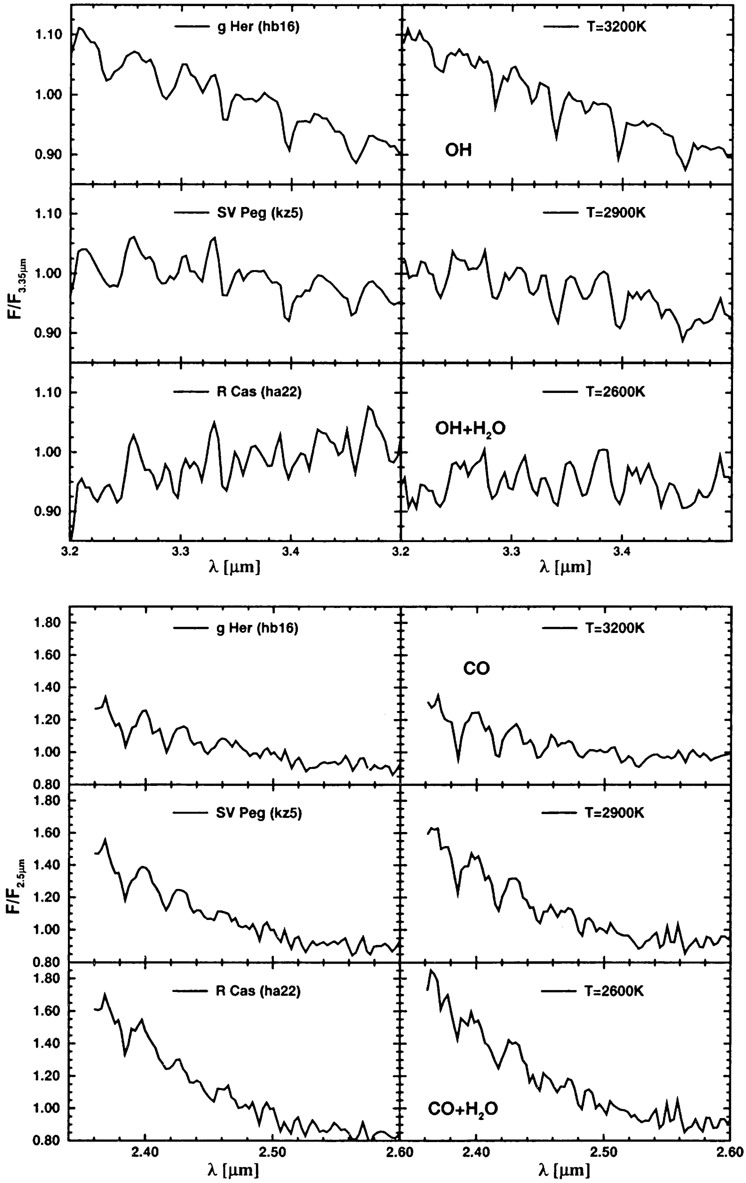

Figure 2. ISO-SWS observations of the AGB variables g Her, SV Peg and R Cas compared with synthetic spectra for hydrostatic atmospheres with different temperatures, log (g [cm/s^2]) = 0.0, solar mass and chemical abundances. The resolution is between 300 and 400.

2. Observations

Observational material of 5 open time ISO projects (*fkerschb.orichsrv/orichsrl/ zzagb2pn* and *jhron.varlpv/varlpv2*) was used for our work. We tried to cover on one hand a large number of representative O-rich AGB variables of different pulsational properties (Mira, SRa, SRb, Lb, and OH/IR) and on the other hand to monitor a smaller subsample in order to study the spectral changes. In total we were able to observe 22 objects at least once. For 10 of them we could take between 2 and 7 individual spectra at different pulsational phases.

We used ISO-SWS (de Graauw et al. 1996) with full grating scans (2.4 μm to 44 μm, AOT01 and speed 2, typically) and a typical resolution between 400 and 600. The pipeline processed data products (OLP 6) were further reduced with ISAP and for the circumstellar modelling 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 connection of the individual bands which introduces an additional uncertainty was done by multiplying the longer wavelength band in order to fit overlapping regions. For flux levels below 100 Jy the correction was applied additively.

3. Results

3.1. Stellar atmospheres

As it turned out, large fractions 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. 2 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 ($T < 2\,600$ K) in order to reproduce the observed data. In addition, the low resolution of our ISO spectra ($R < 1\,000$) does not always allow a distinction of the bandheads from the local continuum also dominated by molecular absorption. Thus, effects like the observed weakness of the SiO bands compared to theoretical predictions from hydrostatic models will not appear in our data.

We want to emphasize that due to their limited spectral resolution ISO-SWS data can only be reproduced using molecular linelists which are complete concerning the overall opacity. This is especially true for water where we have taken approximately 20 000 000 lines into account. At the moment such complete lists can only be obtained from theoretical calculations, and not from any experimental database.

Using dynamic models we have been successful in reproducing the bandheads 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

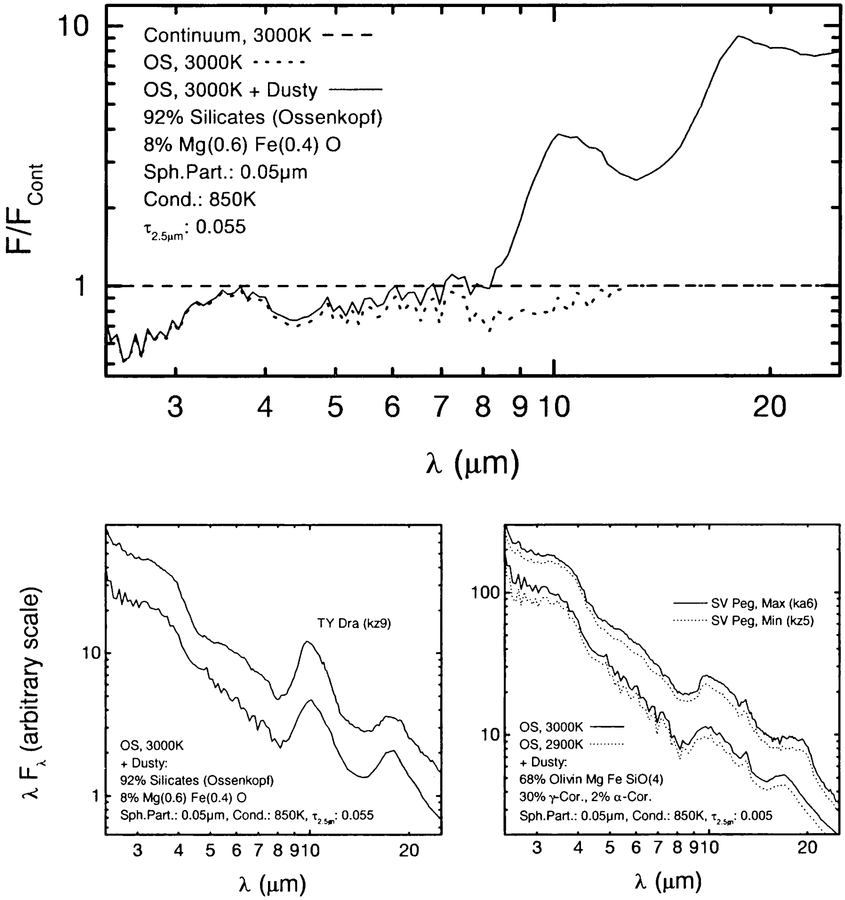

Figure 3. Combined models using opacity sampling spectra based on hydrostatic model atmospheres as the input for the DUSTY radiative transfer code.

ones. This might be due to an incomplete linelist or incorrect chemical data (molecular equilibrium abundances).

3.2. Circumstellar material

The lower panels of Fig. 3 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 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 3 000 K photosphere with $\log(g\,[\mathrm{cm/s^2}]) = 0.0$. 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 (3 000 and 2 900 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 objects analyzed so far: in order to reproduce the spectral energy distribution of circumstellar dust one requires atmospheric models reproducing the molecular absorption. The "canonical" 2 500 K blackbody gives wrong results for the dust component. As an example, in all objects with optically thin circumstellar shells one needs a significantly weaker dust emission to explain the observations since part of the 8–9 μm feature contrast originates from the underlying atmospheric molecular absorption by SiO and H_2O.

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 as a function of phase, e.g. the Mira star R Aql, we found no indication of changing dust features but a strong influence of the time-dependent H_2O and SiO absorption. It should be noted that due to the small size of our sample and the uncertainties of the models we cannot exclude variations of the dust emission. However, we want to emphasize again that such studies require modelling of the molecular "background".

Finally, we want to mention that the intensity of the rotation-vibration bands of CO_2 increases with a stronger 13 μm feature attributed to corundum (compare also with Ryde et al. 1999).

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More information on this contribution can be found at:
http://rigel.astro.univie.ac.at/~aringer/agb98/agb98.html

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