A NEW GENERATION OF DYNAMICAL MODELS FOR LONG-PERIOD VARIABLES: A NEW ERA FOR THE INTERPRETATION OF ISO-SWS DATA OF COOL GIANTS

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ABSTRACT

We present synthetic ISO-SWS spectra of oxygen-rich cool giants for the wavelength range between 2.36 and 7.75 μm. These are based on hydrostatic as well as on completely new dynamical models which have been calculated with a non-grey radiative transfer including molecular opacities. It turns out that many features in the ISO spectra which could not be reproduced within the framework of classical model atmospheres can now be understood without any additional assumptions.

Key words: infrared: stars – stars: atmospheres – stars: late type

1. Observations of O-rich AGB variables

Observational material taken from five 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 spectra as a function of time. 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 covering the wavelength range between 2.4 and 44 μm (AOT01 and speed 2). The pipeline processed data products (OLP 7) were further reduced with the ISO Spectral Analysis Package ISAP (Sturm et al. 1998), and the typical resolution is between 300 and 500 depending on frequency (= position in ISO-SWS band, see Leech 1998 and Valentijn et al. 1996). 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 the overlapping regions. For flux levels below 100 Jy we have applied the correction additively.

2. Model Spectra

In order to compare our ISO data to synthetic spectra we have computed a small grid of cool and extended hydrostatic atmospheres using an improved version (Jørgensen et al. 1992) of the MARCS code (Gustafsson et al. 1975) with spherical radiative transfer routines from Nordlund (1984). In addition to the hydrostatic MARCS models we have also produced synthetic spectra based on the two dynamical atmospheres p5t288solu2 and p5t297solu2 (see Aringer et al. 1999). This allows us to study the effects of dynamical phenomena like pulsation, shock waves, dust formation and mass loss on the ISO-SWS observations.

Our synthetic spectra cover the wavelength range between 2.36 and 7.75 μm at a resolution of 300000. The spectra were calculated using COMA (Aringer 2000) and a spherical radiative transfer. We have included millions of molecular lines of CO, SiO, OH, H_2O and CO_2 assuming Doppler profiles and a microturbulent velocity of $\xi = 2.5$ km/s. In order to compare them to the observations their original resolution of 300000 was reduced to about 900 which corresponds to the maximum value that one might expect from our ISO-SWS data. As it has been said in the previous section, the real resolution of the observations is typically by a factor of 2 to 3 smaller depending on the frequency. Thus, for a direct comparison of theoretical and ISO spectra a further reduction of the resolution was necessary.

One of the main problems concerning our synthetic spectra based on dynamical models is that the latter are calculated using a grey radiative transfer. This does especially affect the appearance of features produced by molecules like H_2O which have a large influence on the atmospheric structure. A good example are the water bands in the near infrared where the absorption predicted by the theoretical computations is much too weak compared to the ISO-SWS observations (see Sect. 5). First dynamical models for carbon stars calculated with a non-grey radiative transfer have recently been published by Höfner (1999). A similar approach has now been successful for an oxygen rich object with the following parameters which was also used to produce a synthetic spectrum: $T_* = 2790$ K, $L_* = 10000\,L_\odot$ and $\mathcal{M}_* = 1\,\mathcal{M}_\odot$ for the initial model and $P = 525$ d as well as $\Delta u_P = 2$ km/s for the piston.

3. Hydrostatic Models and Observations

In order to get some informations about the stellar temperatures we have tried to fit the synthetic spectra calculated from a $T_{\rm eff}$-sequence of hydrostatic MARCS atmospheres to a representative set of ISO data in the range between 2.4 and 4.2 μm. This region is dominated by the intense molecular absorption from CO and water. We did not extend our study to longer wavelengths, because we wanted to avoid problems with the CO_2 feature around 4.4 μm where the opacity might be significantly underestimated in all models of cool stars (Aringer 2000). Some of the results can be seen in Figs. 1 to 4 where we show the observations together with synthetic spectra which represent the best fits in the different regions of the investigated frequency range. All spectra are normalized to the flux level at 3.3 μm, and the numerical resolution is set to 450 which corresponds approximately to the maximum value in our ISO-SWS data. In some parts of the studied wavelength range this is still too high by a factor of up to 1.5 producing minor artificial deviations on small scales. A good example for that kind of problems is the region around 4 μm where the SiO first overtone bands are situated. However, there is only an effect on narrow features and not on the general energy distribution which was used to define the temperatures.

Concerning the fit of spectra calculated from hydrostatic atmospheres we found four categories of ISO-SWS data:

1. g Her (1997-01-13): The spectrum can be very well reproduced by a MARCS model with an effective temperature between 3100 and 3200 K. This is definitely the highest value that we obtained for an object from our small sample (see Fig. 1).
2. g Her (1996-03-07), SV Peg (1996-05-08), SV Peg (1997-11-29): The ISO-SWS data of these Semiregular variables are still very close to the shown theoretical spectra which are based on hydrostatic atmospheres with temperatures between 2800 and 3100 K. Nevertheless, there is a clear trend that they tend to follow the cooler models at longer wavelengths and the warmer models at shorter wavelengths (see Fig. 2). This might be explained by two effects: Either the water opacity around 2.5 μm which was used in the calculations is much too small or we see deviations caused by dynamical phenomena. For three reasons we favor the latter explanation: First, water dominates the molecular absorption in the outer atmospheres of cool stars. As a consequence there exists some kind of regulation mechanism, and the structure in a consistently computed model is adjusted by a larger or smaller opacity in a way that the features do not change significantly. Second, the temperatures needed here in order to reproduce the observations are in general much lower than the values derived at shorter wavelengths from the TiO bands (Schultheis et al. 1999). This indicates that there are more severe problems which cannot be solved by simply increasing the opacity of a single molecule. And finally, the 2.5 μm water absorption seen in the next group of ISO data can be fit with the synthetic spectra, although the corresponding objects are very cool.
3. R Aql (1996-03-18), R Aql (1997-09-21), R Cas (1997-02-02): These spectra of Mira stars can be reproduced with very cool MARCS models having effective temperatures between 2600 and 2800 K. The only major deviation is an emission bump around 4.2 μm which seems to be caused by the SiO bands (see Fig. 3). Thus, we have an indication for SiO emission in Mira variables appearing at phases with relatively weak water absorption. It should be noted that this feature is situated very close to the border between ISO-SWS bands 1e and 2a around 4.06 μm which may introduce some errors concerning small scale structures and the overall slope in the spectra. Nevertheless, since the emission bump is larger than the expected errors and its appearance is correlated with the phase, we conclude that it is not an artefact. In addition, it can only be seen in Mira variables.
4. R Aql (1996-10-01), R Aql (1997-05-03), R Cas (1996-08-06), R Cas (1996-12-03), R Cas (1997-01-10): These data of Mira stars cannot be explained by synthetic spectra based on our grid of MARCS models. The water absorption is much too intense indicating a temperature significantly cooler than 2600 K which is not realistic for hydrostatic objects (see Fig. 4). As for the second group the explanation might be again a problem with the water opacity or the influence of dynamical phenomena. Both effects would be much stronger in cool Mira variables. However, due to the reasons that have already been discussed before we favor the second explanation.

star	date	phase	class
R Aql	1996-03-18	0.93	3 si
R Aql	1996-10-01	0.64	4 (si)
R Aql	1997-05-03	0.40	4
R Aql	1997-09-21	0.90	3 si
R Cas	1996-08-06	0.50	4 ext
R Cas	1996-12-03	0.79	4
R Cas	1997-01-10	0.88	4 (si)
R Cas	1997-02-02	0.93	3 si

Table 1. Visual phases and spectral class (see text) of the ISO observations of R Aql and R Cas. The appendix si indicates SiO emission which is seen in all type 3 spectra. (si) means that there is strong evidence for SiO emission in a spectrum of group 4. Extremely intense water absorption is marked with ext.

4. Variability

In Table 1 we list the phases of the different ISO-SWS observations of the Mira stars R Aql and R Cas taken from

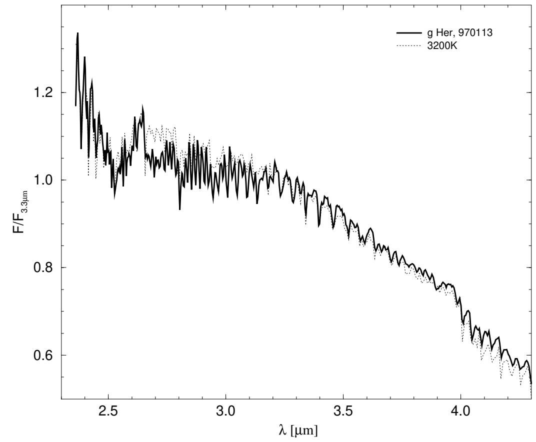

Figure 1. ISO-SWS data of g Her and synthetic spectrum based on a MARCS model with 3200 K, log $(g[cm/s^2]) = 0.0$, solar mass and chemical abundances. All spectra are normalized to the flux level at 3.3 μm, and the numerical resolution is set to 450.

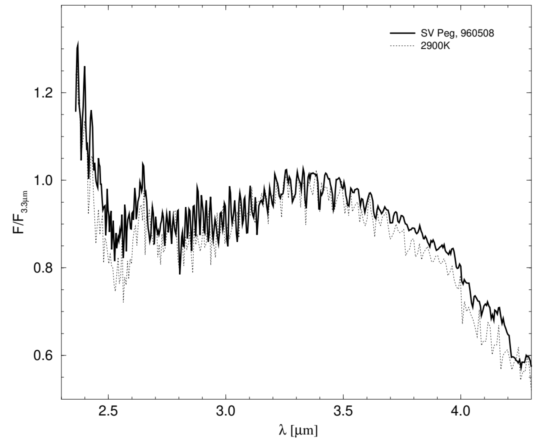

Figure 2. ISO-SWS data of SV Peg and synthetic spectrum based on a MARCS model with 2900 K, log $(g[cm/s^2]) = 0.0$, solar mass and chemical abundances. All spectra are normalized to the flux level at 3.3 μm, and the numerical resolution is set to 450.

their visual AAVSO light curves together with the group the corresponding spectrum belongs to. In addition we have included information on the appearance of SiO emission which is visible in all type 3 spectra, but maybe also in some of class 4. It is obvious that all data of type 3 were obtained close to the visual maximum between phase 0.9 and 1.0. On the other hand the spectra from our sample which belong to group 4 correspond to phases from 0.4 to 0.9. From Table 1 one can tell that there is a trend that

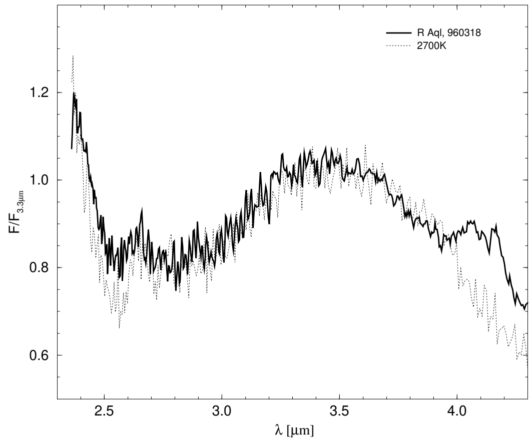

Figure 3. ISO-SWS data of R Aql and synthetic spectrum based on a MARCS model with 2700 K, log $(g[cm/s^2]) = 0.0$, solar mass and chemical abundances. All spectra are normalized to the flux level at 3.3 μm, and the numerical resolution is set to 450.

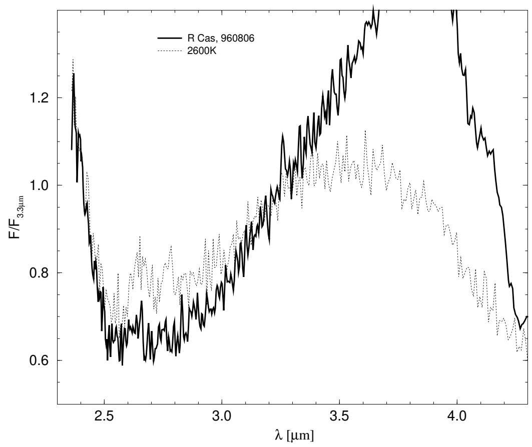

Figure 4. ISO-SWS data of R Cas and synthetic spectrum based on a MARCS model with 2600 K, log $(g[cm/s^2]) = 0.0$, solar mass and chemical abundances. All spectra are normalized to the flux level at 3.3 μm, and the numerical resolution is set to 450.

in the two studied Mira variables the most intense water and SiO absorption appears around the time of the light minimum, while the weakest water bands and SiO emission are observed around the maximum. At a given phase, R Cas always shows the stronger molecular absorption. Due to the small number of ISO spectra and objects used for this investigation we are only able to conclude something about general trends. In order to get further information on the behavior of the water and SiO features as a function of stellar properties and pulsational phase, this kind of study has to be extended to more stars and more observations per source. It should be noted that at least the SiO lines around 4 μm are not always correlated with the photometric variations (Aringer 2000).

5. Spectra from Dynamical Models

As one would expect the molecular features in dynamical atmospheres vary as a function of time depending on species and spectral frequency range. It should be noted that in the computed ISO-SWS data we even observe emission at certain phases. The latter usually appears at the longer wavelengths where the sphericity effects are in general more important, since most of the corresponding lines are formed in the outer regions of the stellar atmosphere. As it turns out there exists no phase where the dynamical atmosphere exactly reproduces the spectrum based on the hydrostatic initial model.

In general the spectra calculated from the dynamical atmospheres p5t288solu2 and p5t297solu2 have only a relatively weak molecular absorption, especially if they are compared with the results from MARCS models. This is mainly due to the fact that there are no intense water bands and it is absolutely not in agreement with the ISO observations of such cool giants. The best explanation for the much too weak water features in the synthetic spectra are deviations of the pressure-temperature structure which are produced by the grey radiative transfer used to construct the dynamical models (with Planck mean opacities). In the outermost parts of a grey atmosphere the density at a given temperature will be underestimated by orders of magnitude affecting in an oxygen-rich environment especially the bands of water. For the case of carbon stars this problem is discussed in more detail by Höfner (1999) where one can also find the first non-grey dynamical models.

As it has been mentioned in the end of Sect. 2, we could also calculate a synthetic spectrum based on a first oxygen rich prototype of dynamical atmospheres computed with a non-grey radiative transfer (see also Höfner et al., this conference). In comparison with typical results from p5t288solu2 and p5t297solu2, the water absorption around 2.5 μm is much more intense, while we find emission at longer wavelengths. This is demonstrated in Fig. 5. Concerning the spectra obtained from the coolest hydrostatic models, we get a different shape of the water features, especially of the blue wing of the 2.5 μm depression. In general, the new spectra match the ISO observations much better than any previous results from grey dynamical or MARCS atmospheres. However, we were still not able to reproduce the extremely intense water feature seen at several phases of R Cas. In this context it should be noted that at the moment only one oxygen rich new generation model is available which was not designed to fit a certain observed object.

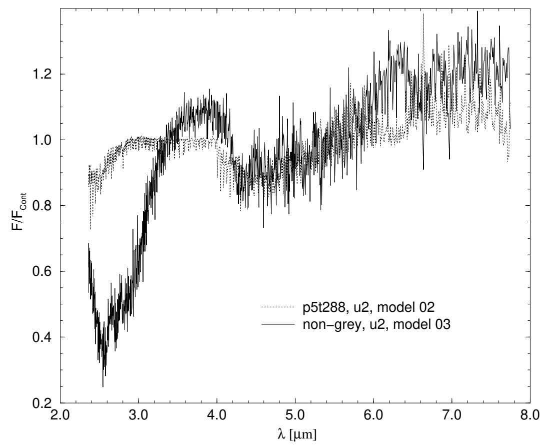

Figure 5. Synthetic spectra for the SWS range between 2.36 and 7.75 μm based on the dynamical atmospheres p5t288solu2 (T=2880 K, grey) and the new non-grey model mentioned in the text (T=2790 K). The spectra are normalized to a radiative transfer calculation without molecular opacities and have a resolution of 900.

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