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The Pulsation of M-type Miras: Multi-Epoch ISO-SWS Observations and Dynamical Models

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Abstract. We present time series of observed and synthetic ISO-SWS spectra of oxygen-rich Mira variables covering the wavelength range between 2.36 and 7.75 μm. The calculations are based on new dynamical models, which have been computed with a non-grey radiative transfer taking into account all relevant molecular opacities. It turns out that many features in the ISO spectra of cool long period variables which could not be reproduced within the framework of classical hydrostatic model atmospheres nor with grey dynamical calculations can now be understood without any additional assumptions. This is especially true for the water bands, which dominate the opacity in the infrared range of M-type Miras.

1. Observations

Observational material taken from five open-time ISO projects (*fkerschb.orichsrv/orichsrl/zzagb2pn* and *jhron.varlpv/varlpv2*) was used for this work. The data include 22 representative O-rich AGB variables of different pulsational properties. In addition, for a subsample of 10 Mira and Semiregular stars between 2 and 7 individual spectra corresponding to different phases are available, which allow us to study the spectral changes as a function of time. All data were produced by the ISO-SWS instrument with full grating scans covering the wavelength range between 2.4 and 44 μm with a typical resolution between 300 and 500 depending on frequency (AOT01 and speed 2). The pipeline processed data products (OLP 7) were further reduced with the ISO Spectral Analysis Package ISAP. 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. As an example we present in Fig. 1 spectra of R Cas taken at different phases. More details concerning the observations can be found in Aringer et al. (2000).

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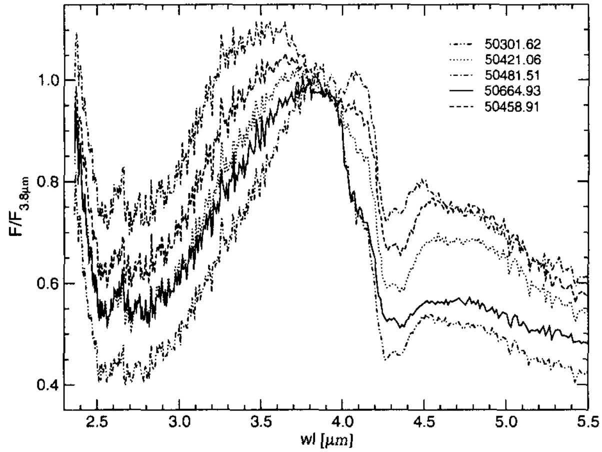

Figure 1. The observed ISO-SWS spectrum of R Cas at different times. The flux is normalized to the value at $3.8\,\mu$m.

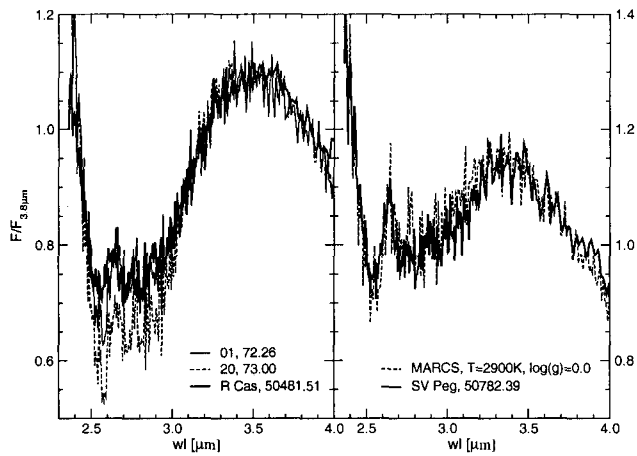

Figure 2. A comparison of observed and calculated ISO-SWS spectra which are normalized to the flux at $3.8\,\mu$m. In the left panel data of R Cas and two phases of a dynamical model (see text) are shown. The indicated phases (72.26, 73.0) correspond to the oscillating inner boundary (piston). In the right panel a spectrum of SV Peg is compared to a hydrostatic MARCS model with $\log(g\,[\mathrm{cm\ s^{-2}}]) = 0.0$ and $T_{\rm eff} = 2900\,$K.

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2. Model Spectra

In order to compare our ISO data of oxygen rich stars to synthetic spectra we have computed cool and extended hydrostatic atmospheres with different temperatures using an improved version (Jørgensen et al., 1992) of the MARCS code with spherical radiative transfer routines. In addition, we have also produced synthetic spectra based on a time sequence of a dynamical model, which allows us to study the effects of pulsation and shock waves. In contrast to earlier attempts (e.g. Aringer et al., 1999), we were able to use atmospheric structures belonging to a new generation of dynamical calculations, which have been constructed with a non-grey radiative transfer taking into account all relevant molecular opacities. A description of these models can be found in the contribution by Höfner et al. (Höfner et al., these proceedings). The stellar parameters are $T_* = 2790\,K$, $L_* = 10000\,L_\odot$ and $M_* = 1\,M_\odot$ for the initial model and $P = 525\,d$ as well as $\Delta u_P = 2\,kms^{-1}$ for the inner boundary (piston).

Our synthetic spectra cover the wavelength range between 0.5 and 20.0 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 $\xi = 2.5\,km\ s^{-1}$. The opacities of water have been updated according to Jørgensen et al. (2001). In order to compare the theoretical results to the observations the original resolution of 300000 was reduced to the value of the ISO-SWS data (300 to 500).

3. Results

As it has already been discussed in Aringer et al. (2000), the ISO-SWS observations of Semiregular stars can be very well reproduced by synthetic spectra based on hydrostatic atmospheres. The temporal variations of these objects are only small and can be simulated by models of different effective temperatures. As an example we show in the right panel of Fig. 2 data for SV Peg compared to a 2900 K MARCS atmosphere. It should be mentioned in this context that even in the relatively warm Semiregular stars the model structures as well as the spectra in the ISO-SWS range are very much dominated by water absorption. Thus, a complete and realistic treatment of the water opacity is crucial for the investigation of our ISO data, as it was pointed out by Jørgensen et al. (2001). At the moment it is not possible to fit the region between 4.2 and 4.5 μm where a strong CO_2 band is situated. This is most probably due to the fact that we have no complete linelist for this molecule.

For the cool Mira stars the situation is quite different. As it is demonstrated in Fig. 1 those objects show huge spectral variations with time. We see a general trend that in the studied Mira variables the most intense water (broad depression between 2.5 and 3.0 μm) and SiO (bands between 4.0 and 4.2 μm) absorption appears around the time of the light minimum (e.g. R Cas, 50301.62), while the weakest water bands and SiO emission are observed around the maximum (e.g. R Cas, 50481.51). Nevertheless, we want to emphasize that due to the limited number and time coverage of the ISO data it is not clear, if the spectral changes follow the pulsation cycle exactly. The very strong H_2O depression corresponding to extremely cool temperatures far below 2000 K as well as the SiO emission which we observed at some phases cannot be explained by classical hydrostatic atmospheres.

In the left panel of Fig. 2 we compare an observation of R Cas with spectra calculated for two phases of the dynamical model mentioned above. In contrast to previous results derived from computations based on grey atmospheres, which always produced much too weak water bands, the agreement is quite good. At this point it should be noted that the used model was not designed to fit the specific stellar parameters of R Cas. It was chosen as a typical example of a cool mass-losing Mira star.

It is seen that the dynamical computation predicts a variation of the water features. And in some cases we even got SiO emission, which is in qualitative agreement with the observations. Thus, we are optimistic that with the new generation of dynamical models it will become possible to reproduce also the ISO-SWS spectra of the coolest Mira stars. However, for all of the atmospheres calculated up to now the predicted water absorption during the phases around minimum light is still too weak. This is mainly due to the fact that, in contrast to carbon stars, models for oxygen rich objects do not include dust formation (see Aringer et al., 1999) and therefore do not produce a considerable mass loss forming cool dense shells.

4. Future Work

There are two major improvements concerning the computation of synthetic spectra for cool AGB variables that we plan for the near future. First, we will do experiments with different methods to include a dust opacity into the models for oxygen rich objects. This seems to be crucial in order to understand the water absorption in stars with significant mass loss. First tests with a very simple (and grey) opacity law for the dust as introduced by Bowen (1988) have already been performed. However, this can only be regarded as a first step towards a more realistic description. Second, we plan to generate a complete linelist for the CO_2 molecule which will allow us to cover also the 4 to 5 μm region in our investigations.

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