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Synthetic spectra for pulsating red giants: status, limitations and applications

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Abstract. We present hydrostatic and dynamic model atmospheres and synthetic spectra for pulsating red giants (M- and C-types). Based on a comparison of these models with various sets of observations we summarize the successes and limitations of the models and the influence of fundamental stellar parameters on the spectral appearance.

1. Pulsating red giants

The photospheres of stars on the Asymptotic Giant Branch (AGB) are characterized by (at least) three important physical phenomena: (i) cool temperatures, allowing the formation of molecules and dust; (ii) pulsations, leading to strong temporal and radial variations in the structure of the atmosphere and (iii) a stellar wind, driven by the pulsations and radiation pressure on dust, causing very extended atmospheres. Some or all of these phenomena are also relevant for the most luminous Red Giant Branch stars. The luminosity and mass loss of pulsating red giants make them interesting targets for galactic studies. But although these stars are the oldest known group of variable stars and hence huge sets of data exist, detailed models of light curves or spectral variations are just emerging. Modelling the atmospheres and the spectral appearance of pulsating red giants is thus still one of the major challenges for stellar astrophysics.

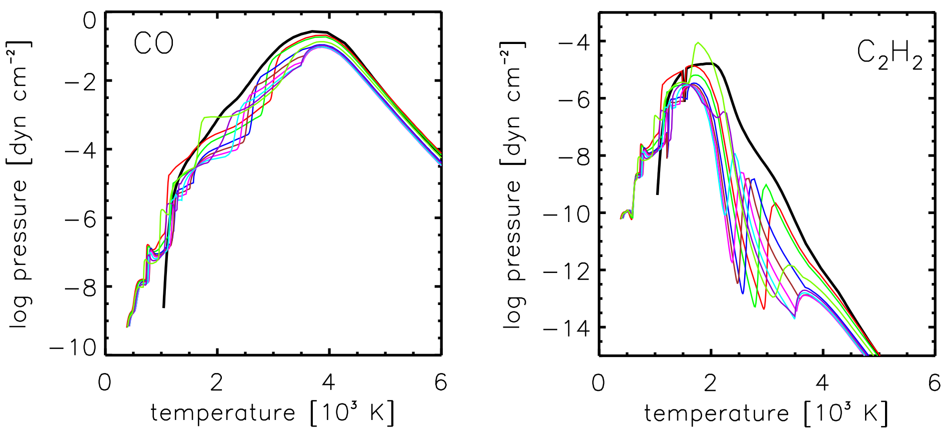

Figure 1. Partial pressures for CO and C_2H_2 versus temperature for a dynamical model representative of a C-rich mira. The thick black lines denote the hydrostatic initial model, the thin lines are for different phases of the dynamical model (Gautschy-Loidl 2001).

2. Model atmospheres and synthetic spectra

Red giant model atmospheres may be grouped into three categories: 'classical', i.e. hydrostatic and dust-free models, 'dynamical', i.e. taking into account the effects of pulsation and 'dusty', i.e. one of the previous including circumstellar dust. An overview of existing models and possible problems can be found in Plez (1999) and Höfner (1999a).

The model atmospheres used in this work are either computed with an improved version of the MARCS code (Jørgensen et al. 1992) or with the latest generation of dynamical models by Höfner (1999b, 2001). The dynamical models are obtained by combining time-dependent hydrodynamics with frequency-dependent radiative transfer. The stellar pulsation is simulated by applying a variable inner boundary moving sinusoidally with a velocity amplitude Δu_p and a period P. The luminosity variation follows from the variable inner radius and the assumption of constant flux at this radius.

The molecular abundances are computed on the basis of equilibrium chemistry. Opacities are treated in the opacity sampling approximation or as line lists and they include most of the molecular species relevant for the range of pressures and temperatures, i.e. CO, TiO, SiO, OH, CH, C_2, CN, H_2O, CO_2, C_3, HCN, C_2H_2 and others. For H_2O, C_2, C_3, HCN and C_2H_2 improved opacity data are used (Jørgensen et al. 2000, 2001). The radiative transfer is done either in plane parallel or spherical geometry.

A major difficulty is the treatment of dust formation and dust emission, especially when the dust emission is not dominating the spectrum. For M-type stars, where the formation process is still poorly known, our models currently either omit the dust or we use a purely photospheric spectrum as the central source for a superposed model of the dusty envelope (e.g. Aringer et al. 1999a). For stars with weak mass loss this approximation should be acceptable out to the mid-IR since the dust formation takes place in regions where not much emission from molecular rotational-vibrational transitions is expected anymore. For C-type stars, a detailed description of dust formation is included (moment method, Gauger et al. 1990). Due to the considerable uncertainties in the treatment of the dust we will restrict the comparison with observations to cases where dust plays only a minor role. Until now, the spectral synthesis does not include velocity fields.

From our sets of hydrostatic models alone two important conclusions can be drawn: due to the strong interaction between molecular absorption and atmospheric structure and due to the competition between different molecular species, no simple relations between atomic abundances and the strengths of molecular features can be expected. Furthermore, there may be ambiguities or degeneracies in the relations between stellar parameters and spectral features or photometric indices. Examples can be found in Jørgensen et al. (2000) or Hron et al. (2000). The hydrodynamical models generally show an enhanced molecular opacity in the outer regions (mostly due to polyatomic molecules) and strong temporal and spatial variations in the molecular abundances (Fig. 1). The pulsation amplitude has the strongest influence on the atmospheric structure and spectral appearance (e.g. Loidl et al. 1999).

3. Observational data

The best constraints for our models come from observations probing wide parts of the photosphere at different phases of the pulsation cycle. Thus time series extending over a wide wavelength range and with good spectral resolution are needed. Since data-sets fulfilling these conditions are more or less non-existent, in general information from optical and IR-data obtained at different phases has to be combined. Very valuable data sets for our purposes so far have been the archival data of the Kitt Peak Fourier Transform Spectrometer (e.g. Lebzelter & Hinkle 2001), our time series obtained with ISO-SWS (e.g. Hron et al. 1998) and the low-resolution optical and infrared spectra of Lançon & Wood (2000).

4. Comparing models and observations

So far, our models were compared to well observed pulsating red giants in the solar neighborhood (e.g. Aringer et al. 1999b, 2001 for M-stars and Jørgensen et al. 2000, Gautschy-Loidl 2001 for C-stars; Fig. 2) and to stars in the galactic bulge (Schultheis 1998). They have also been used to analyse narrow-band photometry of AGB-stars in Local Group Galaxies (Nowotny et al., this volume).

The main result of this comparison is that hydrostatic model atmospheres can well reproduce visual to mid-IR spectra and narrow-band colours of stars with temperatures above 3000 (C-stars) to 3300 K (M-stars), with bolometric amplitudes below a few 0.1^{mag} and with small mass loss. The hydrostatic models can and should thus be used to derive fundamental stellar parameters. However, the predicted effects of parameters like metallicity or surface gravity are generally small and comparable to the observed temporal variations in the molecular features. Furthermore, almost all features are sensitive to more than one parameter.

For stars not fulfilling the above conditions, dynamical models are needed for a reasonable description of the observations. Using hydrostatic models results e.g. in different temperatures from different molecular features or fails to reproduce the observed strengths and variations of various molecular features (e.g. Aringer et al 1999a,b, Gautschy-Loidl 2001). While for the previous generations of models, the agreement was rather qualitative, the latest generation starts to give also quantitative agreement: SiO and H_2O features in M-type Mira variables and a so far unidentified feature at 1.53μm in C-stars can be reproduced (Figs. 3 and 4). The largest differences between models and observations are found in the outermost parts of the atmosphere. Ongoing improvements therefore concern the molecular opacities, the treatment of dust and the inclusion of velocity fields for spectral synthesis.

To establish a link between observed pulsating red giants and the model categories mentioned in Sect. 2, the classification scheme of M-type AGB-variables by Kerschbaum & Hron (1992) provides a rough guideline. The spectra of blue semiregular variables are well reproduced with hydrostatic atmospheres without dust, red semiregular variables need dusty hydrostatic (and in some cases also dynamical) models and synthetic spectra for Mira variables have to be based on dynamical and dusty model atmospheres.

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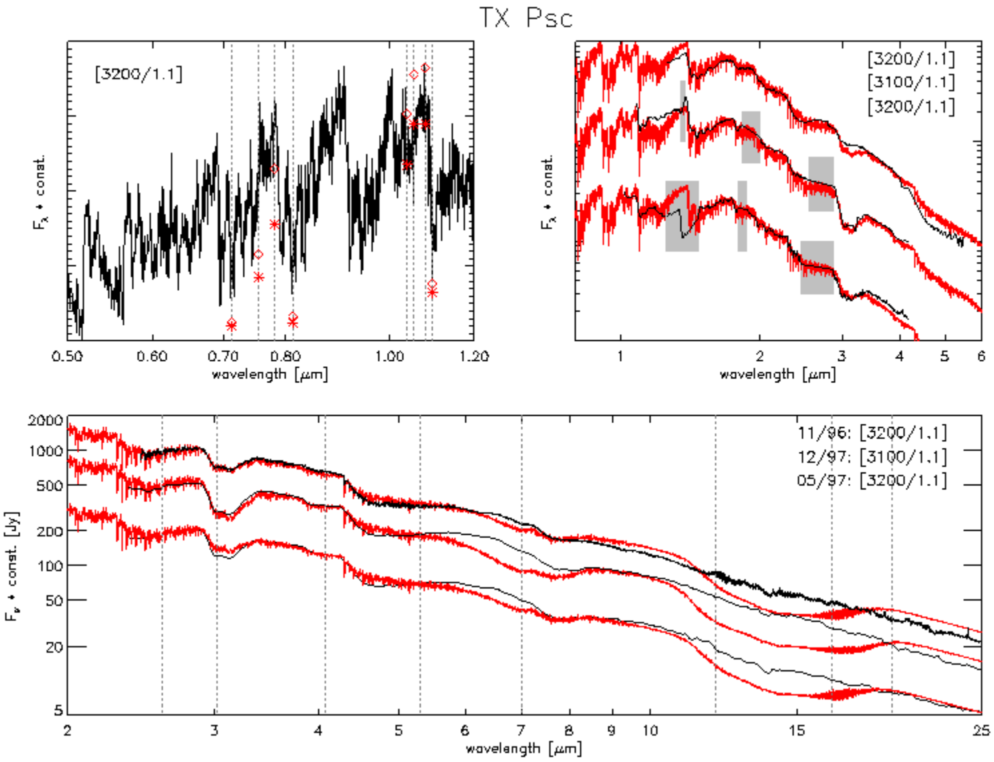

Figure 2. Comparison of various observations of the C-type semiregular variable TX Psc with synthetic spectra based on hydrostatic models. The effective temperature and C/O ratio of the models is given within square brackets. Upper left: symbols denote observed narrow-band photometry, the black curve is the model spectrum. Upper right: black curves are KAO and ground based near IR-spectra, grey curves are models. The shaded areas are regions affected by bad transmission of the earth's atmosphere. Lower panel: ISO-SWS spectra (black) and models (grey). See Gautschy-Loidl (2001) and Jørgensen et al. (2000) for details.

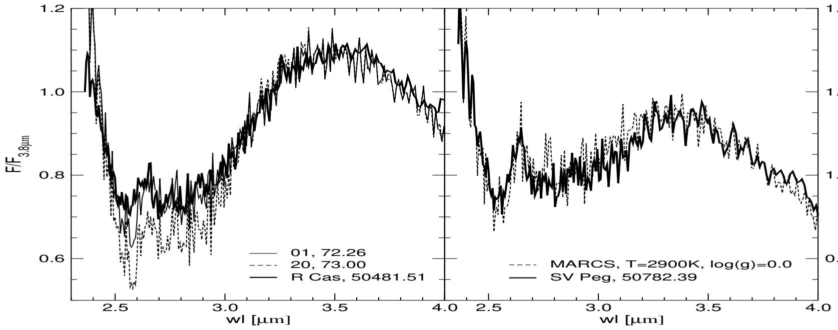

Figure 3. A comparison of observed ISO-SWS and calculated spectra for two M-type stars. The spectrum of SV Peg, a semiregular variable, can be well reproduced by a hydrostatic model with the parameters indicated (right panel). For the mira variable R Cas (left panel) one ISO-SWS spectrum (thick line) is compared to two phases of a dynamical model (Aringer et al 2001).

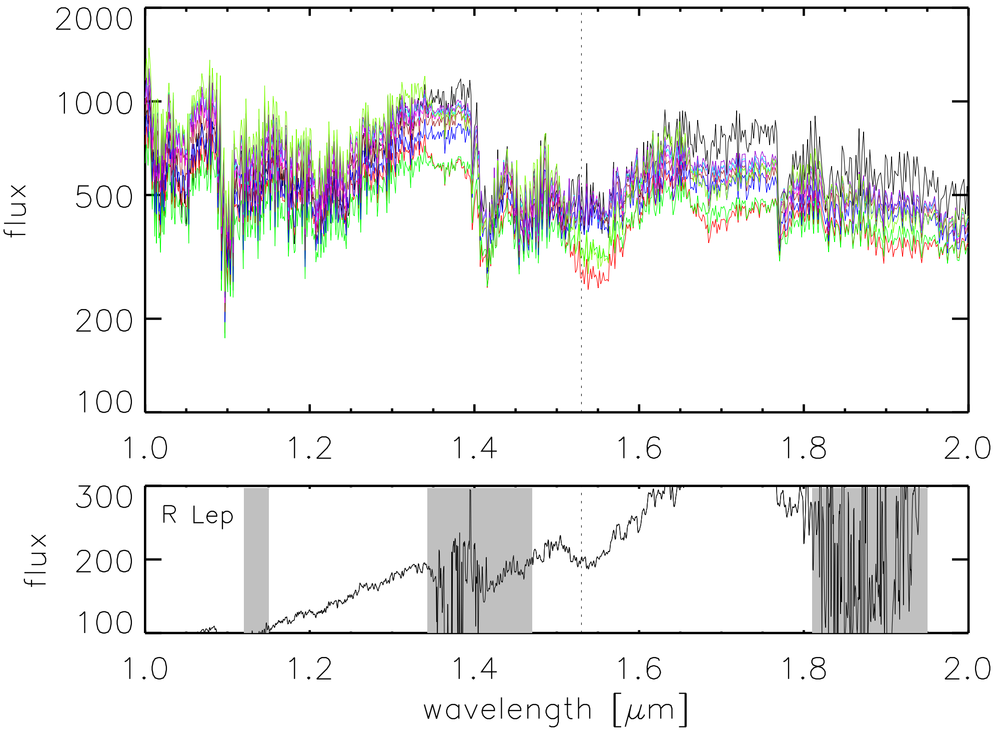

Figure 4. Observed near IR spectrum of the C-type mira variable R Lep (lower panel) compared to synthetic spectra at several phases of a dynamical model atmosphere (upper panel). The dotted line marks the blue edge of the 1.53μm feature observed in C-type Miras. The corresponding feature in the model spetra is due to a C_2H_2 and HCN combination band. The shaded regions are affected by a bad transmission of the earth's atmosphere, hence observations are uncertain there. See Gautschy-Loidl (2001) for details.