MODEL ATMOSPHERES OF AGB STARS: DYNAMICS, MOLECULES AND DUST

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Abstract. The atmospheres and circumstellar envelopes of AGB stars are characterized by complex physical phenomena like shock waves caused by stellar pulsation or formation of molecules and dust which often lead to a heavy mass loss and have a strong influence on IR properties as observed by ISO. To allow a physical interpretation of various observations we have constructed improved dynamical model atmospheres of long-period variables. In this contribution we mainly investigate the dependence of the atmospheric structure and its variability on stellar pulsation, molecular opacities and time-dependent dust formation. IR spectra resulting from our models are discussed in detail by Loidl et al. (1997b) and compared to ISO-SWS spectra obtained by Hron et al. (1997).

1. Introduction

In atmospheres of asymptotic giant branch (AGB) stars and, in particular, of those which show large amplitude pulsations (long-period variables; LPVs) the density-temperature structure is highly dependent on dynamical effects (i.e. pulsation, shock waves and stellar wind). At the same time, however, the formation of molecules and dust grains (line blanketing, levitation, backwarming) plays a very important role. One of the major challenges in today's numerical modelling of AGB stars is to take all of these effects into account simultaneously.

The stellar pulsation creates strong shocks in the atmosphere which increase the scale height, influence the formation of molecules and provide high densities in the cool outer layers of the extended atmosphere and circumstellar envelope, often allowing efficient dust formation. Due to its large opacity, the dust is accelerated by the strong radiation field of the star which leads to a slow but massive outflow. Furthermore, the blocking of radiation by dust causes higher temperatures below the dust layers (backwarming), thus influencing the formation of molecules and new dust grains.

Recent instrumental developments have lead to a dramatic quantitative and qualitative increase of observational data on AGB stars, demonstrating the shortcomings of standard model atmospheres. The variations of molecular features and photometric colours reflect the effects of shock waves running through the stellar atmosphere which cannot be reproduced by hydrostatic models (e.g. Aringer et al 1997, Alvarez & Plez 1997).

On the other hand, considerable progress has been achieved in the dynamical modelling of atmospheres and circumstellar envelopes of LPVs during the last few years (e.g. Fleischer et al. 1992, Höfner & Dorfi 1997). Winters et al. (1994) have presented IR light curves based on the models of Fleischer et al. (1992) which show a qualitative agreement with observations. Windsteig et al. (1997) have discussed the mid- and far-IR properties of the models presented by Höfner & Dorfi (1997), finding that the synthetic IRAS colours are consistent with observations.

In this contribution we present improved time-dependent dynamic model atmospheres for C-rich LPVs which show a better agreement with preliminary ISO SWS results (Hron et al. 1997) than synthetic spectra based on our previous models (Loidl et al. 1997a). We mainly concentrate on aspects concerning the structure of the atmosphere while the resulting synthetic spectra are discussed by Loidl et al. (1997b).

2. Modelling Method

We solve the coupled system of grey radiation hydrodynamics and time-dependent dust formation employing an implicit numerical technique. Details about the modelling method can be found in various papers (cf. Höfner et al. 1995, Höfner & Dorfi 1997 and references therein). The dynamical calculations start with a hydrostatic initial model which is calculated using the hydrostatic limit case of the grey radiation hydrodynamics equations (including a variable Eddington factor) and which can be directly compared to standard model atmospheres. The stellar pulsation of the LPV

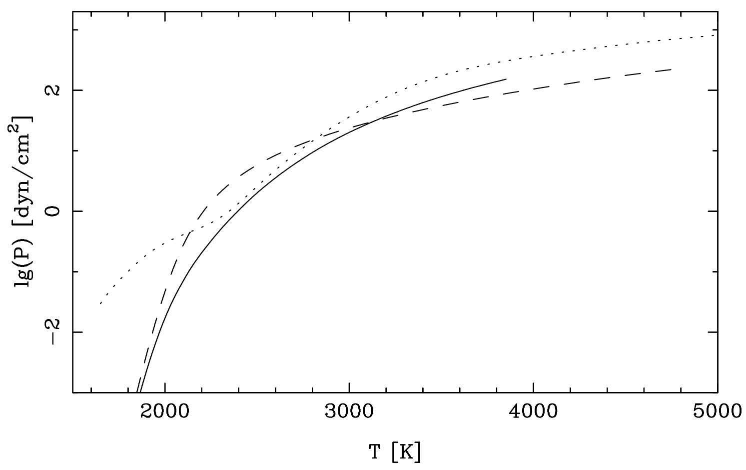

Figure 1. Atmospheric structure (gas pressure vs. temperature) of hydrostatic models: the grey initial models of R7OS14 (based on Planck mean molecular absorption coefficients; full line) and of K7U4 (calculated with a constant gas absorption coefficient of $10^{-2}\,\mathrm{cm}^2/\mathrm{g}$; dashed; cf. Loidl et al. 1997a) as well as a MARCS model atmosphere with similar stellar parameters (based on full monochromatic opacity sampling of the same molecular data as in model R7OS14; dotted).

is simulated by a variable boundary (piston) located beneath the stellar photosphere.

The dynamical calculation yields the structure of the atmosphere and circumstellar envelope (density, temperature, degree of condensation, etc.) as a function of time. These results are used as input for a detailed radiative transfer code to produce synthetic spectra (cf. Loidl et al. 1997b).

The models presented here have been improved compared to those in Höfner & Dorfi (1997) by introducing a more realistic treatment of the gas opacity. The constant value of the absorption coefficient (used in many dynamical models in the literature) is replaced by Planck mean absorption coefficients which are based on the SCAN molecular line data (Jørgensen 1997). We find that the gas opacity used in the dynamical calculation plays a crucial role with regard to the near-IR properties of the models.

The stellar parameters are chosen in accordance with the models of Höfner & Dorfi (1997) to allow a direct comparison. Note that no attempt is made here to model a particular object.

3. Results

In the following discussion we concentrate on one particular model (refered to as R7OS14) with the following parameters: $T_* = 2880$ K, $L_* = 7000\ L_\odot$,

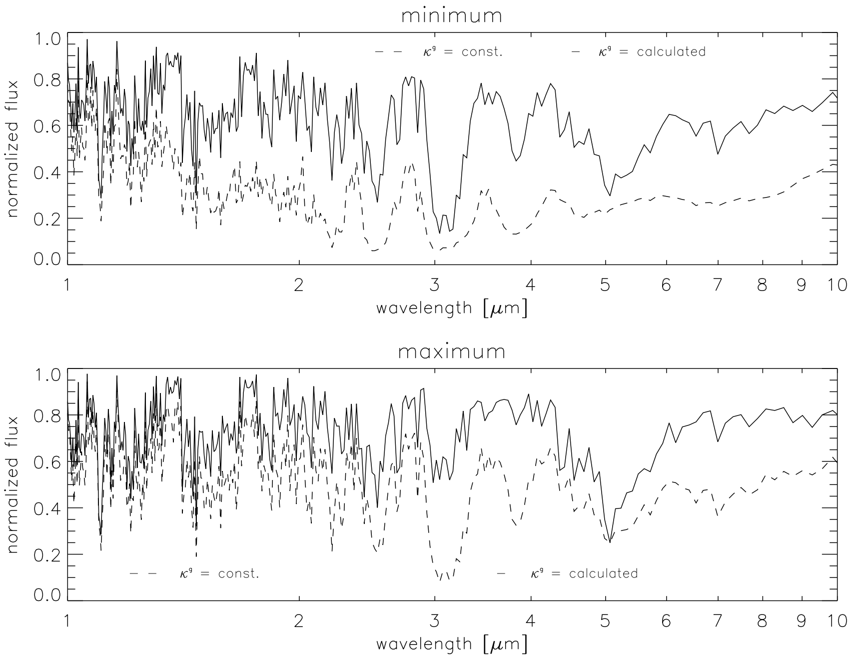

Figure 2. Synthetic spectra of models R7OS14 (full line) and K7U4 (dashed) at minimum and maximum light (cf. Loidl et al. 1997b for details).

$M_* = 1\ M_\odot$ (corresponding to $\log(g) = -0.6$), $\varepsilon_C/\varepsilon_O = 1.4$, a pulsation period of 390 days and a piston velocity of 4 km/s. A model with similar parameters but a constant gas absorption coefficient of $10^{-2}\ cm^2/g$ (K7U4) was investigated by Loidl et al. (1997a) with respect to synthetic IR spectra and other observable properties.

Figure 1 shows the initial hydrostatic structures of R7OS14 (full line) and of K7U4 (dashed) as well as a standard model atmosphere with similar parameters (obtained with the MARCS code; dotted). The new model R7OS14 (based on mean molecular opacities) approaches the MARCS atmosphere quite closely in the temperature region where the bulk of the near-IR molecular features forms. On the other hand, model K7U4 (calculated with a constant gas absorption coefficient of $10^{-2}\ cm^2/g$) has a much higher gas pressure (i.e. a higher density) in this critical zone. This is due to the fact that the gas absorption coefficient in the outer parts of model R7OS14 is considerably higher than in model K7U4.

The higher density in K7U4 for temperatures below about 3000 K leads to stronger molecular features in the spectra based on this model. Fig. 2 shows synthetic spectra of the dynamic models R7OS14 (full line) and

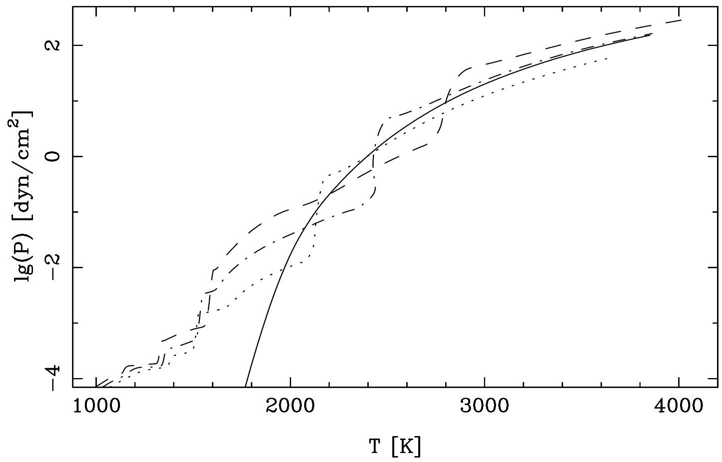

Figure 3. Atmospheric structure (gas pressure vs. temperature) of model R7OS14 at different phases (0.50: dashed; 0.75: dash-dotted; 1.00: dotted) and of the corresponding hydrostatic initial model (full line); phase 0.5 corresponds to minimum light, 1.0 to maximum light.

K7U4 (dashed) at two different phases. The spectra resulting from model R7OS14 are in much better agreement with preliminary results from ISO SWS spectra (Hron et al. 1997) than are the spectra of K7U4 (Loidl et al. 1997a). Note in this context that C-rich synthetic spectra obtained with models based on a constant gas absorption coefficient of $2 \cdot 10^{-4}\,\mathrm{cm}^2/\mathrm{g}$ – introduced by Bowen (1988) and used by many time-dependent calculations in the literature – exhibit far too strong molecular features due to the much higher overall density of such models.

Figure 3 shows the atmospheric structure of model R7OS14 at three different phases (dashed: 0.50, dash-dotted: 0.75 and dotted: 1.0) in comparison to the corresponding hydrostatic initial model (full line). The “steps” in the pressure correspond to shock waves. Their propagation through the atmosphere can be seen by tracking the progress of individual features from higher pressures and temperatures to lower ones (i.e. from right to left) with increasing time (phase 0.5 to 1.0). Apart from this local variations of pressure and temperature the shock waves also lead to a levitation of the outer layers of the atmosphere. Below a certain temperature (in this case about 2000 K) the pressure is at any time significantly higher than in the corresponing hydrostatic model.

4. Conclusions

We have found that both, the gas opacities used for the dynamic calculations and the shock waves created by the stellar pulsation, have a dramatic influence on the time-dependent atmospheric structure of our models and the resulting synthetic spectra. Employing Planck mean gas absorption coefficients based on molecular data (in contrast to a constant value as often used in similar models) provides reasonably realistic background structures which are modified by the running shock waves in a way which cannot be simulated with a sequence of standard hydrostatic model atmospheres.

Synthetic spectra based on our new models show a good qualitative agreement with observations, regarding the strengths and temporal variations of molecular features and photometric colours (cf. Loidl et al. 1997b, Hron et al. 1997). Due to the crude (i.e. grey) treatment of radiative transfer in the dynamical calculation and its consequences for the atmospheric structure, today's state–of–the–art dynamical models are still far from being a solid base for a detailed quantitative analysis, but we have presented here some progress towards a more realistic modelling of LPV atmospheres.

A reliable interpretation of high-quality observational data (as obtained e.g. with ISO) requires a new generation of model atmospheres based on a simultaneous solution of detailed frequency-dependent radiative transfer and time-dependent dynamics, including the opacities of complex molecules and the formation of dust grains.

Acknowledgements

This work is supported by the *Fonds zur Förderung der wissenschaftlichen Forschung* (FWF), project numbers J01283-AST and S7308-AST.

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