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A new generation of dynamic model atmospheres for AGB stars: first results

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Abstract. Existing time-dependent dynamic model atmospheres for AGB stars suffer from the fact that they are based on grey radiative transfer which is a poor approximation for cool line-blanketed atmospheres. Therefore, frequency-dependent radiative transfer has been included into a well-tried radiation hydrodynamics code to obtain more realistic models. First results concerning the structure of such non-grey dynamical model atmospheres are presented in this paper. Due to computational reasons, the number of frequencies used in the radiative transfer has to be kept very low, typically around 50, but even with this restriction considerable improvements can be obtained compared to grey models.

Key words: stars: AGB and post-AGB – stars: variables – stars: atmospheres – hydrodynamics – radiative transfer

1. Introduction

Time-dependent dynamics is an essential ingredient for understanding the atmospheres of AGB stars. Stellar pulsation creates strong shock waves which modify the structure of the atmosphere. Locally, the passing shocks cause a temporal variation of the thermodynamical conditions, influencing the formation of molecules and dust grains. Globally, the effects of the shock waves can trigger the onset of a stellar wind.

Existing dynamical model atmospheres (cf. Höfner 1999 for a recent review) are based on grey radiative transfer. This assumption, however, is problematic for cool extended atmospheres which are strongly affected by line blanketing of molecules and it may lead to more or less unrealistic pressure-temperature structures. On the other hand, classical hydrostatic model atmospheres (reviewed e.g. by Gustafsson & Jørgensen 1994 and Gustafsson 1998) include a detailed treatment of radiative transfer and of the relevant microphysics. This makes them an important tool for investigating the photospheric spectra of non- or weakly pulsating giants. However, in situations where dynamics plays a decisive role this approach may lead to serious misinterpretations.

The impressive progress of observational techniques achieved during the last few years has led to a large amount of high-quality data on AGB stars: high resolution spectra (individual molecular bands originating in different atmospheric layers; line profile variations due to velocity fields), a wide wavelength coverage (simultaneous monitoring of molecular and dust features), high angular resolution (spatial structure of the atmosphere) and detailed monitoring of temporal variations of individual stars. This progress has to be accompanied by a similar improvement of models to develop a better understanding of AGB stars and to provide tools for a reliable interpretation of observational data.

In this paper a prototype calculation for a new generation of model atmospheres is presented. This model combines the advantages of time-dependent dynamics and non-grey radiative transfer. A frequency-dependent treatment of radiative transfer has been included into an existing radiation hydrodynamic code which has already been used to model the atmospheres and circumstellar envelopes of AGB stars (e.g. Höfner & Dorfi 1997, Höfner et al. 1998).

For computational reasons, the number of frequency points which can be handled in such a combined modelling of time-dependent dynamics and frequency-dependent radiative transfer is very limited. However, as demonstrated by Helling & Jørgensen (1998) for hydrostatic model atmospheres, even as few as 50 points can be sufficient to obtain relatively realistic structures in contrast to grey models. The results presented in this paper indicate that a similar conclusion can be drawn for dynamical model atmospheres.

2. Modelling method

The variable structure of the atmosphere is obtained by solving the equations of hydrodynamics (equation of continuity, equation of motion and energy equation) together with the frequency-integrated zeroth and first moment equations of the radiative transfer equation. The grey ver-

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sion of these equations is described in previous papers (see Höfner et al. 1995 and references therein).

For the non-grey models presented here, the terms describing the exchange of energy and momentum between matter and radiation (eqs. (2)-(5) in Höfner et al. 1995) have to be reformulated as

$$\kappa\,\rho\,(J-S) \;\longrightarrow\; \rho\,(\kappa_{\mathrm{J}} J - \kappa_{\mathrm{S}} S) \tag{1}$$

$$\kappa\,\rho\,H \;\longrightarrow\; \rho\,\kappa_{\mathrm{H}} H. \tag{2}$$

Here ρ denotes the density, J and H are the zeroth and first moment of the radiation field (corresponding to energy density and flux), S denotes the source function and the frequency-integrated opacities are defined by

$$\kappa_{\mathrm{X}} = \frac{\int_\nu \kappa_\nu X_\nu d\nu}{\int_\nu X_\nu d\nu} = \frac{\int_\nu \kappa_\nu X_\nu d\nu}{X} \tag{3}$$

where X corresponds to one of the quantities J, H or S, and variables without the subscript ν denote the frequency-integrated values $X = \int_\nu X_\nu d\nu$.

These integrated quantities and the Eddington factor $f_{\mathrm{edd}} = K/J$ (K = second moment of the radiation field) which is required to close the system of moment equations are obtained by solving the frequency-dependent equation of radiative transfer for a given density-temperature structure at each time-step. The model presented here is based on opacity sampling data of molecular opacities (SCAN data base, Jørgensen 1997) at 51 randomly chosen frequency points between 0.25 and 12.5 μm. Details of the modelling method will be discussed in a forthcoming paper.

The dynamical computation starts with a hydrostatic initial model which is characterized by the following parameters: luminosity $L_\star$, mass $M_\star$, effective temperature $T_\star$ and the elemental abundances. The stellar pulsation is simulated by applying a variable inner boundary $R_{\mathrm{in}}(t)$ below the photosphere, moving sinusoidally with a velocity amplitude Δu_{p} and a period P. Since the total flux is kept constant there the luminosity at this boundary varies proportional to R_{in}^2 (see Höfner & Dorfi 1997).

3. A prototype model

The effects of frequency-dependent radiative transfer on the atmospheric structure are discussed for a model with the following stellar parameters: $L_\star = 7000\,L_\odot$, $M_\star = 1\,M_\odot$, $T_\star = 2880\,\mathrm{K}$ and a carbon-to-oxygen ratio of 1.4 (all elemental abundances except carbon are assumed to be solar), as well as a piston amplitude $\Delta u_{\mathrm{p}} = 4\,\mathrm{km/s}$ and a period $P = 390\,\mathrm{d}$. This set of parameters corresponds to model P7C14U4 in Höfner et al. (1998) which is based on Planck mean opacities and will be used for comparison with the grey approach. Note however that for reasons of simplicity dust formation is not considered in the frequency-dependent model presented here. Models including dust formation as well as calculations with

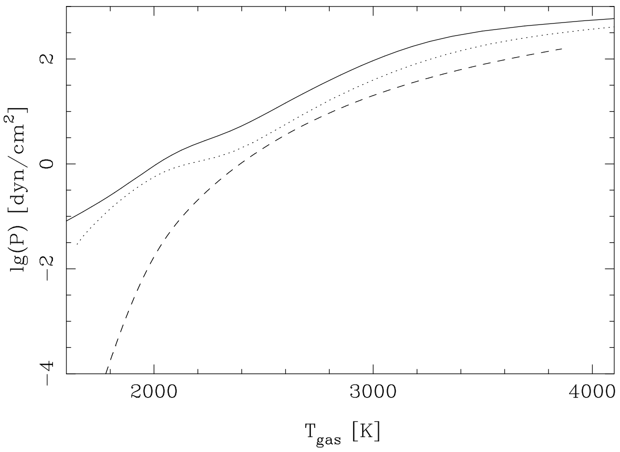

Fig. 1. Atmospheric structure (gas pressure vs. temperature) of hydrostatic models: the frequency-dependent initial model for the dynamical calculation (full line), a grey initial model based on Planck mean opacities (dashed) and a MARCS model atmosphere (dotted). All three models are based on the same molecular opacity data and have similar parameters.

different sets of stellar parameters will be discussed in a forthcoming paper.

3.1. Hydrostatic limit case

As discussed in Höfner et al. (1998) the structure of the inner parts of the atmosphere can be reproduced quite well with grey models by choosing an appropriate mean opacity (e.g. a Planck mean). However, in the outer regions the density at a given temperature will be severely underestimated. Frequency-dependent effects like line blanketing by molecules which cannot be simulated with a grey model result in much higher densities at a given temperature.

Figure 1 shows the pressure-temperature structure of two hydrostatic initial models with the same parameters but calculated with different treatments of radiative transfer: the frequency-dependent model used here (full line) and a grey model (dashed) based on Planck mean opacities (i.e. dependent on temperature and density, but not on frequency; cf. Höfner et al. 1998 for details). In addition, a structure obtained with the MARCS stellar atmosphere code (Gustafsson et al. 1975, in the version of Jørgensen et al. 1992) is shown (dotted). Note in this context that all three models are based on the same molecular opacity data.

While the structure of the frequency-dependent initial model (full line) is in qualitative agreement with the MARCS model (dotted) the grey model (dashed) diverges drastically from the other two in the outer layers. The offset between the two non-grey models may result from the fact that the MARCS model was calculated with approximately 5000 frequency points while the initial model for the dynamical calculation is based on the very limited number of 51 points. This reduction to a small number

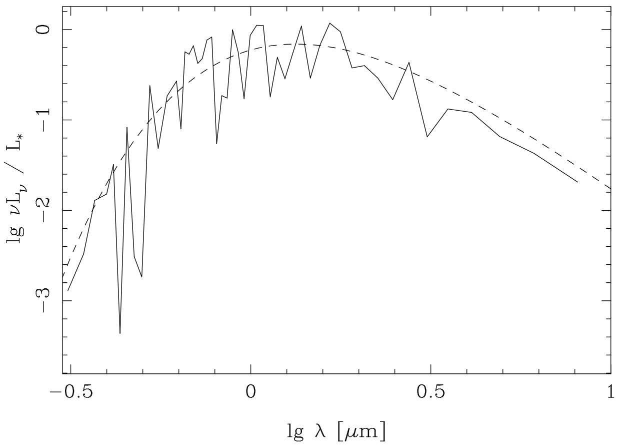

Fig. 2. Spectral energy distributions of hydrostatic models calculated with the same gas opacities as used in the construction of the model structure: the full line shows the spectrum of the frequency-dependent initial model (same frequency points used as in the dynamical model); the dashed line corresponds to the grey model based on Planck mean opacities.

of frequencies is necessary for reasons of computing time in the dynamical calculation. However, the improvement compared to a grey model is obvious. [1]

Figure 2 shows the spectral energy distributions of the frequency-dependent hydrostatic initial model (full line; calculated at the same frequency points as used in the dynamical computation) and of the grey Planck-mean model (dashed; obtained by using the frequency-independent Planck mean opacities). This plot clearly illustrates the fact that a grey treatment of radiative transfer in a line-blanketed cool stellar atmosphere is inadequate, even for the calculation of the model structure, and therefore leads to the discrepancies described above.

3.2. Dynamical calculation

To keep physics more simple and computing times on a reasonable level during this first test phase of the frequency-dependent dynamical models no dust formation is included in the calculation and the number of spatial grid points is reduced to 100 in contrast to the usual 500.

Figure 3a shows the pressure-temperature structure of the dynamical model at different phases (minimum light: dotted; maximum: dashed) and of the corresponding hydrostatic initial model (full line). As in the grey models (e.g. Höfner et al. 1998, Fig.4), shock waves can be seen as 'steps' in the pressure, moving outwards with increasing phase. Apart from this modulation the global structure stays close to the hydrostatic one, except in the outermost regions. This may however change if dust is included.

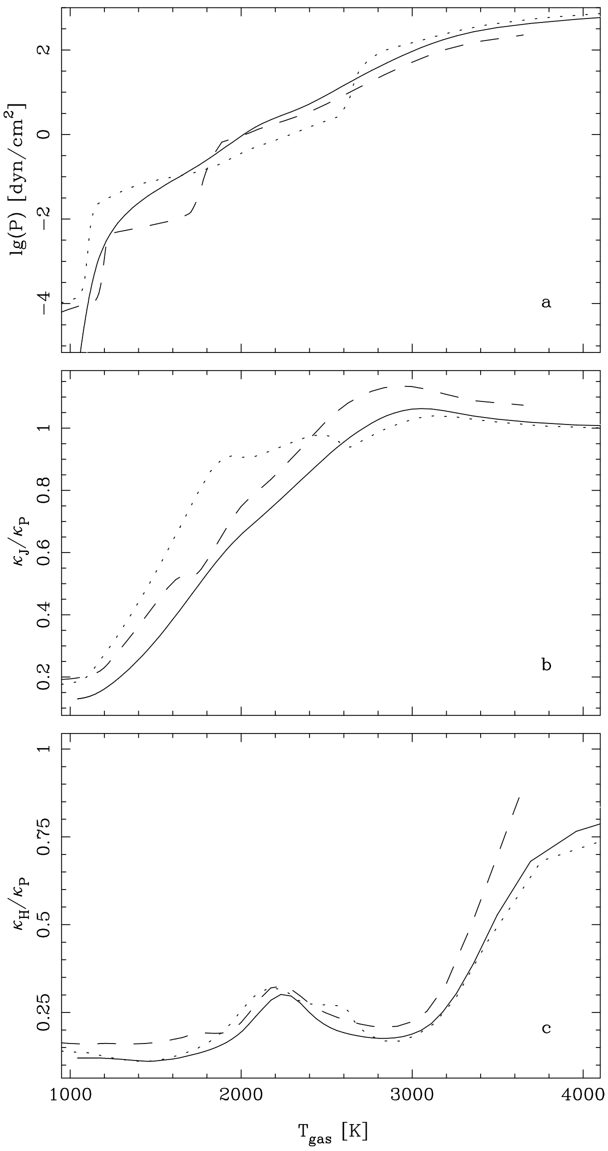

Fig. 3. Different phases of the frequency-dependent dynamical model (minimum light: dotted; maximum: dashed) and the corresponding hydrostatic initial model (full line). a) gas pressure vs. temperature structure, b) ratio of κ_J to the Planck mean, c) ratio of κ_H to the Planck mean; for details see text.

The higher densities in the outer regions of the atmosphere compared to a grey model are also visible in the dynamic structure. This has a considerable influence on molecular features formed there (e.g. the feature of C_2H_2 and HCN at 3 μm in C-stars) as well as on mass loss rates which are largely determined by the density in this region where the outflow starts. Preliminary results concerning detailed NIR molecular spectra look promising and will be presented in a separate paper (Loidl et al., in prep.).

Panels b and c in Fig. 3 show the ratio of the integrated opacities used in the energy and momentum equations, κ_J

[1] A second reason for the discrepancies between the frequency dependent models could be a different way of defining one of the key parameters, i.e. $T_\star$. Both aspects will be investigated further and discussed in a forthcoming paper.

and $\kappa_{\rm H}$, to the Planck mean opacity $\kappa_{\rm P}$. Both quantities are smaller than the Planck mean almost everywhere in the model, and in particular in the outer layers where the radiation field deviates strongly from a Planckian distribution due to molecular absorption. This illustrates how the use of Planck mean opacities leads to an overestimation of the integrated opacity and therefore to much lower densities in the upper atmospheric layers as discussed before.

4. Conclusions

The frequency-dependent dynamical model presented here has to be regarded as a first step in constructing a new generation of model atmospheres for pulsating AGB stars. It bridges the gap between classical hydrostatic models based on detailed microphysics and radiative transfer and time-dependent dynamic models for the atmosphere and circumstellar envelope. In spite of the small number of frequency points which can be used due to computational limitations, the qualitative and quantitative improvement compared to grey models is obvious. Furthermore, the present restrictions are just a consequence of lacking computing power, not an inherent problem of the chosen method.

The next steps are the inclusion of dust formation, as in the grey models, and an investigation of how the details of the frequency-dependent radiative transfer (e.g. number of frequencies, distribution of frequency points, etc.) influence the models. These results and several models with different sets of stellar parameters will be presented in a forthcoming paper.

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