A NEW GENERATION OF MODEL ATMOSPHERES FOR AGB STARS INSPIRED BY ISO

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ABSTRACT

We present a new generation of dynamical model atmospheres for AGB stars based on a combined solution of time-dependent hydrodynamics and frequency-dependent radiative transfer. We discuss the variable structure of the atmosphere and the resulting synthetic spectra, as well as the dependence of these properties on fundamental stellar parameters.

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

1. INTRODUCTION

The atmospheres of AGB stars are strongly influenced by the effects of stellar pulsation. The shock waves developing in the outer layers of the star due to the pulsation affect the atmospheric structure in two ways: local temporal variations caused by passing shock waves and a levitation of the outer atmosphere where the formation of molecules and dust takes place. Therefore a reliable interpretation of high-quality observational data like ISO-SWS spectra requires a consistent time-dependent modelling of the stellar atmosphere and circumstellar envelope.

Early attempts to calculate synthetic spectra in the ISO-SWS range showed that the state-of-the-art dynamical models – mainly constructed to investigate dust formation, mass loss and the observational properties of dust-enshrouded AGB stars – were not sophisticated enough to study molecular spectra in the IR. Therefore we started a project to improve the dynamical models, especially with regard to the treatment of molecular opacities and radiative transfer.

Recently, we have succeeded to construct a new generation of models which combine time-dependent dynamics and frequency-dependent radiative transfer (Höfner 1999). The resulting synthetic spectra show a dramatic improvement compared to the existing dynamical models which are based on grey radiative transfer. The models cover a region which starts below the stellar photosphere and reaches out into the circumstellar envelope, giving a consistent description of the transition zone between the atmosphere and the stellar wind. This region of the outer atmosphere and inner circumstellar envelope can be probed by analysing molecular features in the ISO-SWS spectra that we have obtained.

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, describing the momentum and energy balance of the radiation field.

The frequency-integrated opacities and the Eddington factor which are 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 models presented here are based on opacity sampling data of molecular opacities (SCAN data base, Jørgensen 1997) at 51 randomly chosen frequency points. For a more detailed description of the modelling method see Höfner (1999).

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 $R_{\rm in}(t)$ below the photosphere, moving sinusoidally with a velocity amplitude $\Delta u_{\rm p}$ and a period P. Since the total flux is kept constant there the luminosity at this boundary varies proportional to $R_{\rm in}^2$ (see Höfner & Dorfi 1997).

The dynamical calculation gives the structure (density, temperature, velocity, etc.) of the atmosphere as a function of time. Snapshots of the structure at selected phases are used as input for a detailed radiative transfer code to obtain synthetic spectra (see Loidl et al., this volume; Aringer et al., this volume).

3. ATMOSPHERIC STRUCTURE AND SPECTRA

We are currently working on a small grid of such non-grey time-dependent model atmospheres to study the influence of stellar parameters and pulsation properties on the IR molecular spectra. In this contribution we restrict the discussion to C-rich models. Results for the O-rich case are presented by Aringer et al. (this volume). Furthermore, we concentrate on relatively hot stars with a low C/O

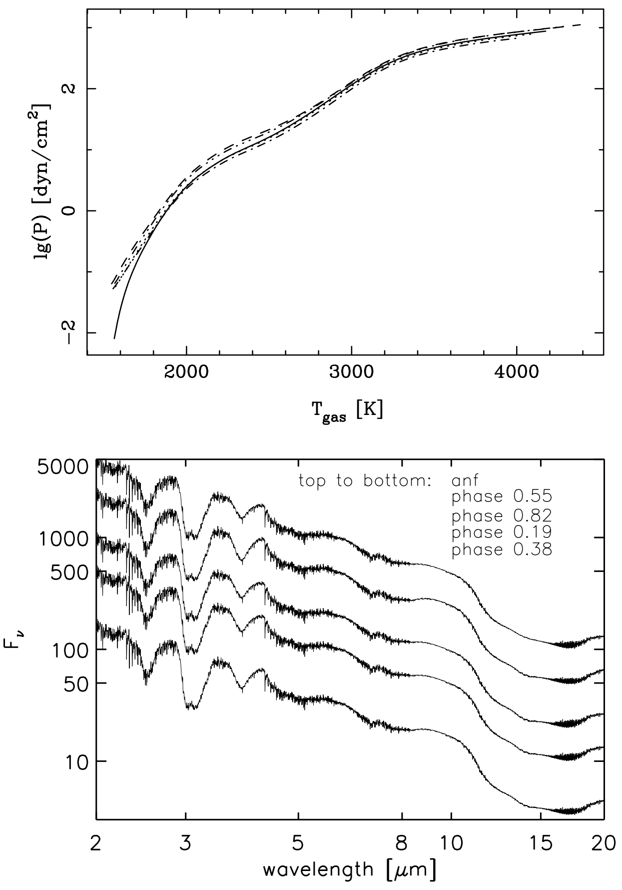

Figure 1. Model A: pressure–temperature structure (upper panel) and synthetic spectra (lower panel); the full line in the upper plot corresponds to the structure of the hydrostatic initial model, the other lines (dashed, dash-dotted, dotted and dash-triple-dotted) represent selected phases of the dynamical computation; the fluxes in the lower panel are in arbitrary units, the individual spectra have been shifted with respect to each other so that the lines can be distinguished in the plot; the top-most line is the spectrum of the hydrostatic initial model.

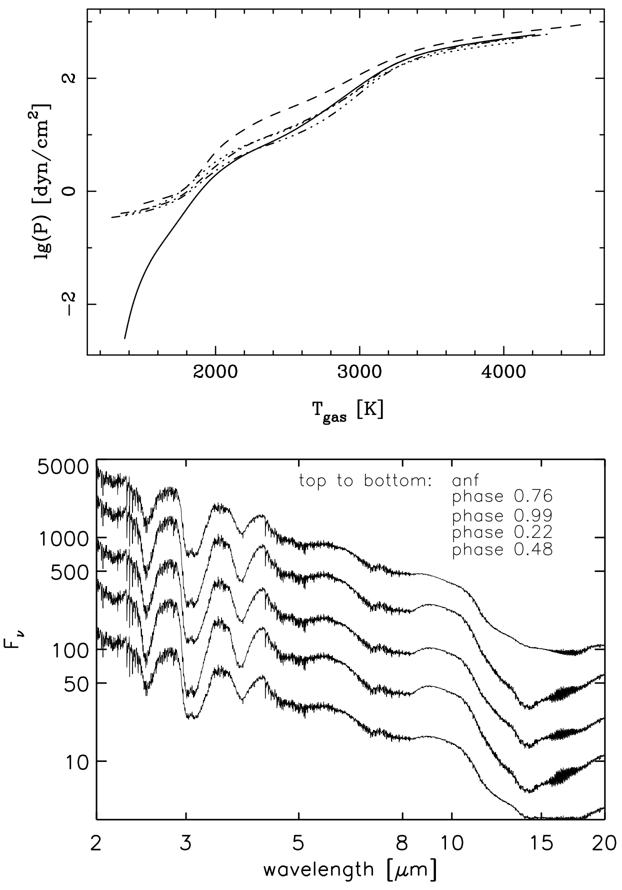

Figure 2. Model B: pressure–temperature structure (upper panel) and synthetic spectra (lower panel); the full line in the upper panel and the top-most line in the lower panel correspond to the hydrostatic initial model, the other lines represent selected phases of the dynamical computation (for further comments see the caption of Fig.1).

ratio and weak pulsation which form practically no dust and no wind. We have chosen this regime to compare our dynamic models with state-of-the-art hydrostatic model atmospheres and to investigate molecular features without too much influence of dust. A detailed comparison of the resulting synthetic spectra with both observations and hydrostatic model atmospheres can be found in the contribution of Loidl et al. (this volume).

The parameters of the models which we discuss here are given in Tab. 1. We describe the models in order of decreasing $\lg g_\star$, increasing $L_\star$ and decreasing $T_\star$. In this sequence, the effects of pulsation on the structure and on the resulting molecular spectra become more and more pronounced (see Figs. 1 – 4).

Model A is relatively strongly bound by gravitation. The motions and luminosity variations caused by the weak stellar pulsation have very little effect on the structure of the atmosphere. At all phases the pressure–temperature structure (Fig. 1, upper panel) closely resembles the structure of the hydrostatic initial model (full line). Consequently, the resulting spectra (Fig. 1, lower panel) show little variation and are similar to the spectrum of the corresponding hydrostatic model (top-most line).

Model B has similar parameters as model A except for the mass which is $1\,M_\odot$ instead of $2\,M_\odot$. Therefore the model is much less bound than model A, a fact which is also expressed by the lower value of $\lg g_\star$. The inner parts of model B still resemble the corresponding hydrostatic initial model quite well but in the outer layers the effects of pulsation become visible: at all phases the gas pressure at a given temperature is much higher than in the hydro-

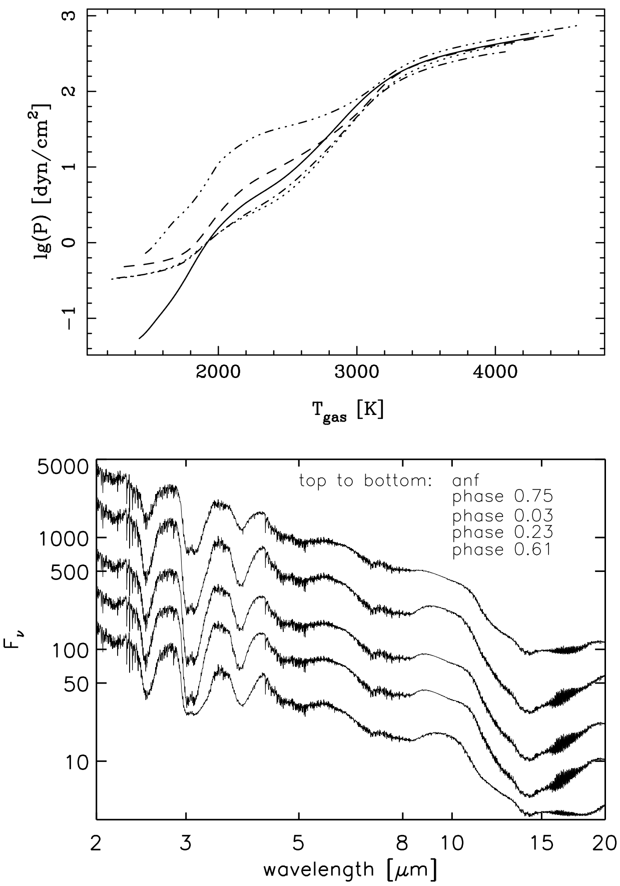

Figure 3. Model C: pressure–temperature structure (upper panel) and synthetic spectra (lower panel); the full line in the upper panel and the top-most line in the lower panel correspond to the hydrostatic initial model, the other lines represent selected phases of the dynamical computation (for further comments see the caption of Fig.1).

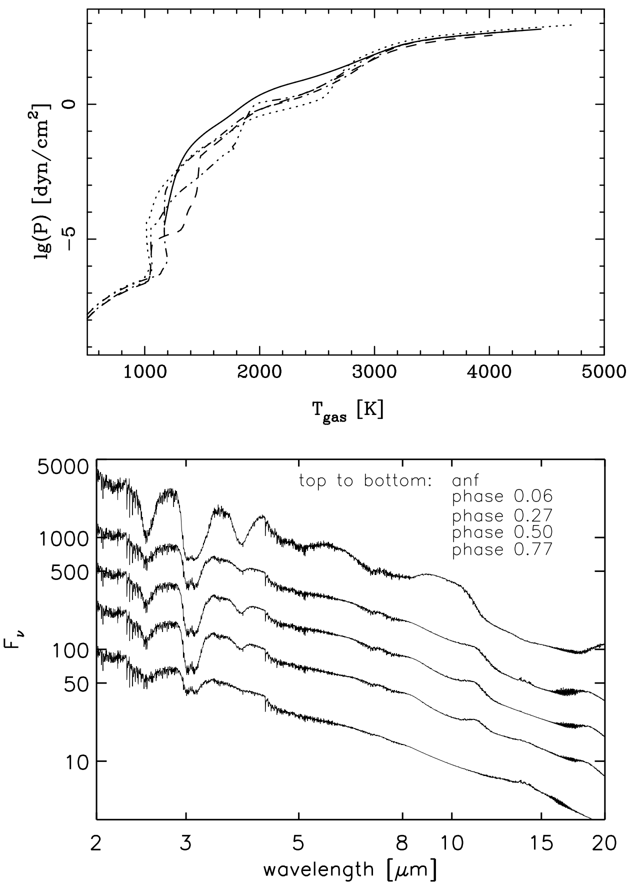

Figure 4. Model D: pressure–temperature structure (upper panel) and synthetic spectra (lower panel); the full line in the upper panel and the top-most line in the lower panel correspond to the hydrostatic initial model, the other lines represent selected phases of the dynamical computation (for further comments see the caption of Fig.1).

static case (Fig. 2, upper panel). The corresponding spectra show a pronounced variation with time and the molecular features formed in the outer atmosphere are stronger than in the hydrostatic initial model (Fig. 2, lower panel). The increased strength of the features is a consequence of higher densities in the outer layers at a given temperature, and, consequently, a more efficient formation of molecules like C_2H_2 and HCN.

Model C differs from model B by a higher luminosity, only. The resulting difference in lg $g_\star$ is much less than between models A and B. The effects of pulsation on the atmospheric structure are somewhat stronger in model C than in model B but the qualitative picture is quite similar (Fig. 3). As for model B the spectra show a considerable variation with time and the molecular features tend to get stronger compared to the hydrostatic case.

Model D differs from model C by a lower effective temperature (the difference in P has no severe consequences for the effects discussed here). Furthermore, the dynamical structures are far more spatially extended, reaching down to much lower gas temperatures than models A to C. This has an interesting effect on the resulting spectra: the cool extended outer layers contribute in emission to the total spectrum, partly filling in features seen in the hotter models, or even causing net emission in the longer wavelength regions. Therefore, in this case the molecular features of the dynamical model become weaker than the features of the hydrostatic initial model, in contrast to the other models discussed here (Fig. 4).

In particular, using dynamical models it seems possible to fill in the broad feature around 14 μm (due to C_2H_2 and HCN) without making the features around 3 μm vanish. This might help to resolve the problems of fitting the

Table 1. Model parameters: luminosity $L_\star$, mass $M_\star$ and effective temperature $T_\star$ of the hydrostatic initial models; all models discussed here have C/O = 1.1 and a piston velocity amplitude $\Delta u_{\rm p}$ = 2 km/s. The period P is 295 d except for model D (390 d); we also list lg $g_\star$ *and the stellar radius $R_\star$ (computed from $L_\star$, $M_\star$ and $T_\star$).*

model	$L_\star$ $[L_\odot]$	$M_\star$ $[M_\odot]$	$T_\star$ [K]	lg $g_\star$	$R_\star$ $[R_\odot]$
A	5200	2	3000	−0.11	267
B	5200	1	3000	−0.41	267
C	7000	1	3000	−0.54	310
D	7000	1	2900	−0.60	331

whole ISO-SWS spectral range of carbon stars with hydrostatic model atmospheres (see Loidl et al., this volume for details). Similar effects for O-rich stars are discussed by Aringer et al. (this volume).

4. CONCLUSIONS

Summing up our results, we state that dynamical models are essential to understand the complex phenomena observed in AGB star atmospheres. The strength and variability of molecular features in the ISO-SWS range depends on the stellar parameters and on the extended atmospheric structure in a non-trivial way which can not be simulated by series of hydrostatic models. Synthetic spectra based on dynamical models show new phenomena compared to hydrostatic model atmospheres.

Regarding the dynamical models, a frequency-dependent treatment of radiative transfer is necessary to obtain realistic atmospheric structures. The model structures and spectra presented here show a considerable improvement compared to earlier models based on grey radiative transfer. Presently, a transition from qualitative to quantitative modelling is taking place.

In this context, we want to stress the importance of monitoring spectral variations in individual stars to constrain the models.

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