Atmospheric Dynamics and Stellar Winds of Long-Period Variables

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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 heavy mass loss by slow stellar winds. To allow a physical interpretation of various observations we have constructed improved dynamic models of atmospheres and circumstellar dust shells of long-period variables. We investigate the dependence of the wind characteristics on stellar pulsation, molecular opacities and dust formation and discuss the time-dependent behaviour of the circumstellar envelopes and its influence on observational properties.

1 Introduction

Large-amplitude pulsations with periods of about 100 to 1000 days are a characteristic feature of stars on the asymptotic giant branch (AGB). The stellar pulsation induces shock waves in the atmosphere of such long-period variables (LPVs) which play a crucial role for the atmospheric structure and the mass loss by a stellar wind. The strong non-linear interaction of dynamics, formation of molecules and dust grains and the stellar radiation field presents a challenge for the self-consistent modelling of such objects and makes the interpretation of observational results difficult. However, in recent years some progress has been achieved in modelling various time-dependent phenomena and understanding the wind mechanism of LPVs (see related reviews in this volume).

We present improved dynamic models for atmospheres and stellar winds of pulsating AGB stars which are based on a more realistic treatment of the gas opacity than most earlier time-dependent models in the literature. As discussed by Höfner et al. (1997) this has a dramatic influence on the atmospheric structure and the resulting observable properties. Our models show a good qualitative agreement with various observational results. In this contribution we investigate the wind characteristics of our new models and compare them to the results of Höfner & Dorfi (1997).

2 Atmospheric structure and dynamics

We obtain the variable spatial structure of the atmosphere and circumstellar envelope (density, temperature, degree of condensation, etc.) by solving the equations of grey radiation hydrodynamics together with a time-dependent descrip-

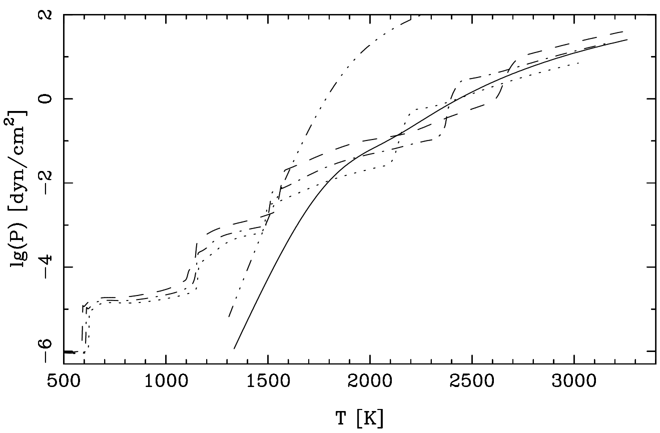

Fig. 1. Atmospheric structure (gas pressure vs. temperature) of the model with $L_\star = 13000\ L_\odot$ and $\varDelta u_p = 4$ km/s at different phases (0.50: dashed; 0.75: dash-dotted; 1.00: dotted) and of the corresponding hydrostatic initial model (full line); phase 0.5 corresponds to minimum light, 1.0 to maximum light. The "steps" in the pressure indicate 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). To demonstrate the influence of the gas opacity on the atmospheric structure we plot a hydrostatic initial model calculated with the same stellar parameters but a constant gas opacity ($-\cdots-$; see text) for comparison with the new inital model (full line).

tion of the dust formation (cf. Höfner & Dorfi 1997 and references therein for details of the modelling method).

The dynamic calculations start with an initial model which represents the full hydrostatic limit case of the grey radiation hydrodynamics equations (including a variable Eddington factor) and which is determined by the follwing parameters: luminosity $L_\star$, mass $M_\star$, effective temperature $T_\star$ and the carbon-to-oxygen ratio $\varepsilon_C/\varepsilon_O$ (all elemental abundances except carbon are assumed to be solar). The structure of this hydrostatic initial model can be directly compared to standard model atmospheres. We find that using Planck mean absorption coefficients based on detailed molecular line data (SCAN, Jørgensen 1997) yields reasonably realistic atmospheric structures which are largely comparable to standard MARCS model atmospheres based on the corresponding frequency-dependent opacities (cf. Höfner et al. 1997). On the other hand, models calculated with a constant gas absorption coefficient of $2 \cdot 10^{-4}\,\mathrm{cm}^2/\mathrm{g}$ (as introduced by Bowen 1988 and used by many time-dependent calculations in the literature, e.g. Fleischer et al. 1992, Höfner & Dorfi 1997) have a much higher overall density since they tend to underestimate the gas opacity in most zones (cf. Fig. 1). The resulting synthetic spectra exhibit far too strong molecular features.

The stellar pulsation of the LPV (which is simulated by a variable boundary

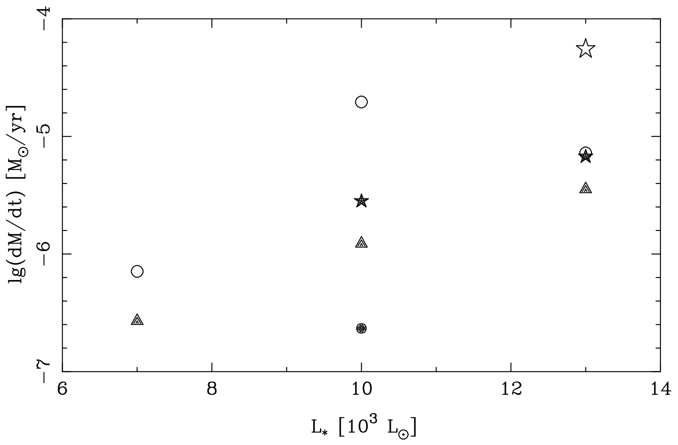

Fig. 2. Comparison of mass loss rates: selected models of Höfner & Dorfi (1997; open symbols) and this work (full symbols). The shape of the symbol indicates the piston velocity amplitude of the model (Δu_p: $\circ$ = 2 km/s, $\triangle$ = 4 km/s, $\star$ = 6 km/s), the other stellar parameters (which are correlated to $L_\star$) are given in the text.

located beneath the stellar photosphere, moving with a velocity amplitude Δu_p and a period P) creates shock waves in the atmosphere which basically influence the structure in two ways (see Fig. 1): In the inner part of the model the passing shocks cause a periodic modulation of the pressure-temperature structure which varies around that of the corresponding hydrostatic initial model. Further out (below $\approx$ 2000 K in Fig. 1) the shocks induce a levitation of the atmosphere, providing at all phases and temperatures much higher densities than in the hydrostatic model, hereby favouring the formation of molecules and dust grains, and eventually leading to the onset of a dust-driven wind.

These dynamic phenomena have a strong impact on the resulting synthetic spectra (Loidl et al. 1997). The variations of optical and near-infrared molecular features show a qualitative agreement with observations (Hron et al. 1997, Aringer et al., this volume). In particular, our dynamic models are able to reproduce observed out-of-phase variations of different features (causing e.g. loops in colour-colour diagrams) which reflect the effects of shock waves running through the atmospheres and cannot be simulated with hydrostatic model atmospheres (e.g. Aringer et al. 1997, Alvarez & Plez 1997). We have also started to investigate line profile variations of synthetic CO lines which probe the velocity structure of the atmosphere and circumstellar envelope (cf. Windsteig et al., this volume).

3 Wind properties

We have calculated new dynamic models based on mean molecular opacities using the same combinations of stellar parameters as in Höfner & Dorfi (1997), i.e.

$L_\star$ [$L_\odot$]	$M_\star$ [$M_\odot$]	$T_\star$ [K]	$\varepsilon_C/\varepsilon_O$	P [d]
7000	1.0	2880	1.80	390
10000	1.0	2790	1.80	525
13000	1.0	2700	1.40	650

Figure 2 shows a comparison of the resulting mass loss rates. As expected from the lower overall density of the new models (cf. Sect. 2) the mass loss rates are considerably lower for similar model parameters. This effect can partly be compensated by increasing the piston velocity amplitude Δu_p (cf. Fig. 2), which affects the density in the wind acceleration zone (levitation). All new models show significantly lower final degrees of condensation (< 0.3) than those of Höfner & Dorfi (1997), reflecting reduced grain growth rates due to the lower gas density. The wind velocities, however, are approximately the same as before (or at least not reduced by the same amount as the degree of condensation). Since, in a dust driven wind, the outflow velocity should be closely correlated to the degree of condensation (cf. Höfner & Dorfi 1997) this seems to indicate that in our present models radiation pressure on molecules contributes to driving the stellar winds.

Acknowledgments

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Linsky: In your models does the mass loss rate measured far from the star vary with pulsation phase?

Höfner: Close to the star (on spatial scales of several stellar radii) the variations with phase are more or less pronounced, depending on the stellar parameters. However, as the material moves away from the star the shocks are damped and the variations become smaller and smaller.

Mullan: You have examined different models with various amplitudes of piston motion. Do you calculate the velocity widths of spectral lines which are formed in these pulsating atmospheres?

Höfner: We have recently started to do detailed radiative transfer calculations (including velocity fields) for our dynamic models. One example is shown in the poster of Windsteig et al. where we discuss the variability of CO line profiles. The first overtone lines presented there show dramatic variations due to the dynamics of the stellar atmosphere.