DYNAMICAL MODELS OF CIRCUMSTELLAR DUST SHELLS AROUND LONG–PERIOD VARIABLES

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Abstract. We present dynamical models of circumstellar dust shells around Long-period variables which include time-dependent hydrodynamics and a detailed treatment of dust formation, growth and evaporation. Important effects due to the complex interaction between the dynamics of the pulsating atmosphere and the dust complex are demonstrated.

1. Introduction

We present results of our model calculations for circumstellar dust shells (CDS) of Long–period variables (LPVs). In particular, we will summarize the method and some results of the hydrodynamical calculations.
What is our main aim and what can we learn from these models?

First, as we treat in detail the dynamics and physical processes of the CDS we can study its intrinsic structure, the distribution of the dust, the velocity field, the density structure etc. which all are a result of the calculation.

Second, it turns out that it is absolutely necessary to take into account the relevant interactions among the physical processes. By doing so, we are able to study which processes contribute to the resulting structure and the dynamics of the model.

Third, as a result of the model we get the final outflow velocity, the mass loss rate, the dust–to–gas ratio, and the grain size distribution function. These values are a very result of the calculation, they are *not* prescribed parameters, and therefore, they can be directly compared with respective observations.

Finally, and perhaps most important, we can calculate the optical appearance of the model, the spectral energy distribution, light curves, brightness profiles etc. and can as well compare these quantities with observations. If this approach is applied to a particular source and the theoretical spectral energy distribution, the synthetic light curves etc. match with the respective observations we are able to determine the fundamental stellar parameter: stellar luminosity, stellar mass and temperature, and the elemental abundances. In this contribution we concentrate on the first three points and show typical results of the dynamics and the intrinsic structure of the CDS.

The second part, the optical appearance, can be found elsewhere (Winters et al. 1994, 1995, 1996 this volume).

2. The Non–linear Problem

In order to reach our aim described above we have to solve the following coupled problem:

Time–dependent hydrodynamics The hydrodynamical description has to be time–dependent, to describe the variations of the velocity field, and the occurrence of shock waves caused by the pulsation of the underlying star.

Dust complex Since the formation of dust is a central phenomenon in these objects, a respective theory has to be used which describes the formation of solid particles depending on the physical conditions, and which does not prescribe essential quantities such as for example the site where the dust forms.

Chemistry Furthermore, we have to describe the chemistry of the gas phase in order to know at each instant of time and at each radial position how much condensable material is available.

Radiative transfer Finally, we have to treat the radiative transfer problem in order to describe the influence of the radiation of the central object.

In contrast to the classical atmosphere problem the dust complex now introduces a number of non–linear couplings and interactions which are of essential importance for the whole problem. A reliable theoretical modelling requires on the one hand a *physical* description of the various ingredients, and on the other hand, at least equally important, it requires to take into account all interactions among the different physical components.

It is evident from the list, that the problem is non–linear and strongly coupled. Consider for instance the coupling between hydrodynamics and the dust complex:

only if the density is high enough, effective dust formation is possible, but vice versa, since radiation pressure on dust enters into the equation of motion, dust formation immediately influences the velocity structure, which in turn alters the density stratification. The basic equations and the numerical method are described in detail in Fleischer et al. (1992) and Fleischer (1994).

3. A typical model structure

A typical radial structure of such a dynamical model is shown in Fig. 1. From the figure it is evident that the dust is not distributed homogeneously across the CDS but is concentrated in distinct layers such that the CDS exhibits an onion–like structure. Furthermore it can be seen that the dust quantities, e.g. the degree of condensation (2^{nd} row, dashed line), are intimately correlated to the hydrodynamical quantities, e.g. the velocity (1^{st} row, crosses).

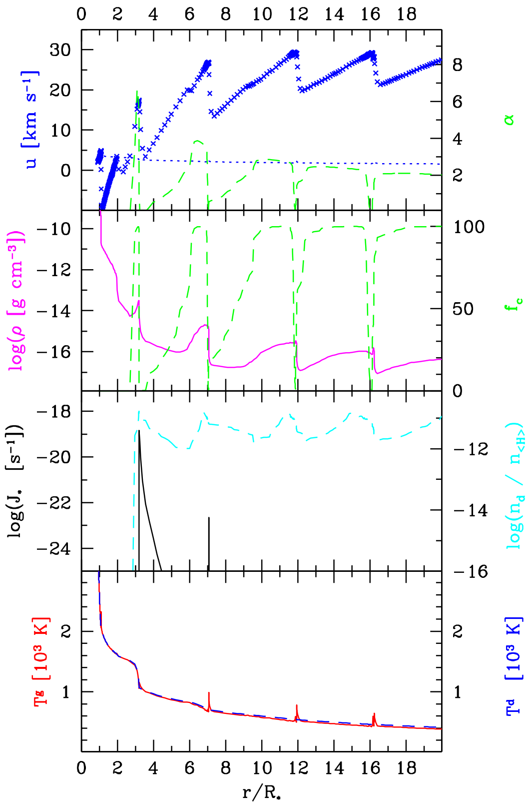

Figure 1. Typical radial structure of a dynamical model. The parameter of the model are $T_* = 2600$K, $L_* = 10^4 L_\odot$, $M_* = 1.0 M_\odot$, $\epsilon_C/\epsilon_O = 1.80$, P= 650d, $\Delta u = 2$km s^{-1}

This suggests that there is a common mechanism which produces this structure. A more detailed analysis shows that the strong shocks propagating through the atmosphere are not produced by the interior pulsation alone but that they are a product of the re–amplification of the pulsational shocks caused by the radiative acceleration on dust grains α in the discrete dust layers ($1^{st} row$, dashed line). Since α exceeds unity close to the star, the material is accelerated to velocities above the escape velocity $v_{\rm esc}$ already at radii around 4 R_*. Due to its opacity, the dust also leads to a pronounced heating of the material inside the dust layers (backwarming) as is evident from the steps present in the temperature stratification around 3 $R_\star$ and

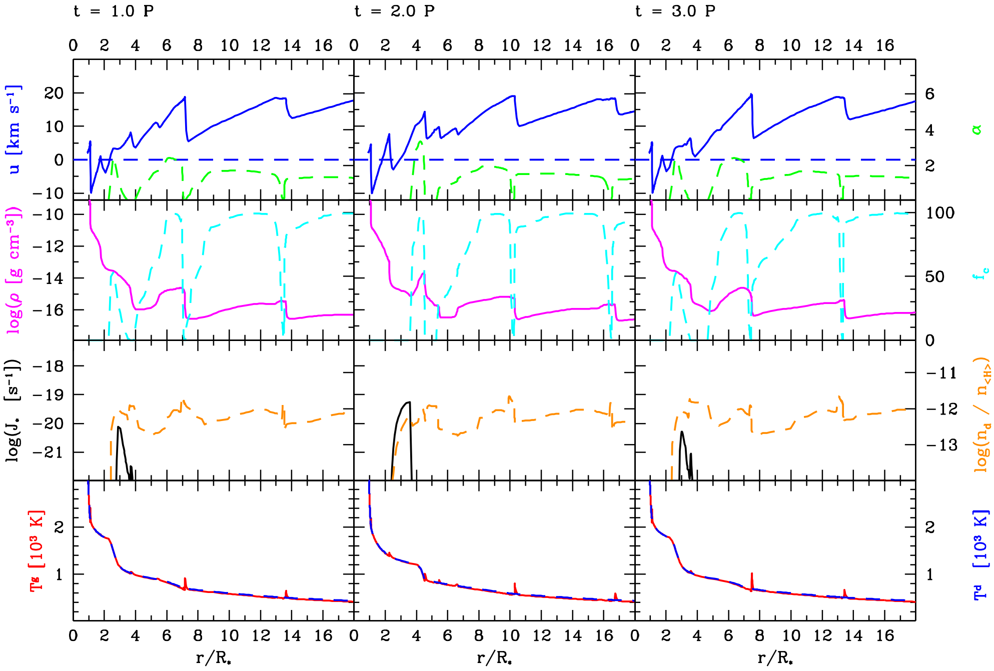

Figure 2. Same model as in Fig.1 but with a reduced carbon to oxygen ratio of $\epsilon_C/\epsilon_O = 1.50$

6 R_* (lower row). In summary we find, that the dust completely determines the internal structure of the circumstellar shell, a result that is only revealed by the consistent treatment of the involved physical processes.

4. Multiperiodicity

An important property of the model shown in the preceeding section is that its radial structure repeats after *one* pulsational cycle. Figure 2 shows three successive starting points of the hydrodynamical cycle of a model with a reduced overabundance of carbon to oxygen. All other parameter are the same as in Fig. 1. From Fig. 2 one can see that the radial structure of the model with a reduced carbon overabundance repeats only after *two* pulsational cycles. Even tiny details of the radial structure, e.g. the multiple shocks present below 4 R_*, are reproduced after this period of time. Around 2.5 R_* at $t = 1.0P$ and $t = 3.0P$, respectively, it can be seen that the radiative acceleration α causes a pertubation in the velocity structure which later on turns into a dominant shock wave that sweeps up the preceding pulsational shock, cf. $t = 2.0P$ between 4 and 5 R_*. Due to the reduced amount of condensable material it takes two pulsational cycles to

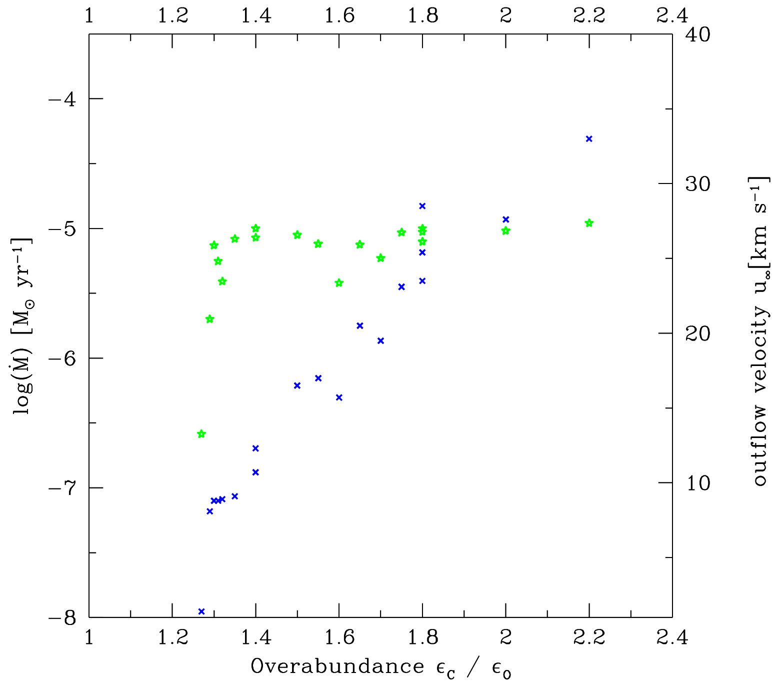

Figure 3. Dependence of the mass loss rate $\dot{M}$ (asterisks, l.h.s. axis) and the final outflow velocity u_∞ (crosses, r.h.s. axis) on the overabundance of carbon to oxygen ϵ_C/ϵ_O

form a new dust layer. The effect of *multiperiodicity* strongly depends on the ϵ_C/ϵ_O–ratio. Lowering this number causes longer intervals between the formation of two dust layers, an increase causes the opposite effect. The time interval between the formation of two dust layers is of course not necessarily an integer number, e.g. models with ϵ_C/ϵ_O–values between 1.8 and 1.5 form a new dust layer on time scales lager than 1 and smaller than 2 pulsational periods. Depending on the remaining model parameter it is also possible that a dust layer forms on time scales 3, 4 ...times the pulsational period or even twice a pulsational cycle.

5. Dependence of $\dot{M}$ and u_∞ on ϵ_C/ϵ_O

We have calculated a grid of models with the parameter given in the caption of Fig. 1 except for the overabundance of carbon to oxygen which is varied over a larger parameter range. The influence of this variation on the mass loss rate and the final outflow velocity is shown in Fig. 3. Keeping all parameter except the ϵ_C/ϵ_O–ratio fixed results in a fairly constant mass loss rate of $\approx 10^{-5}\mathrm{M}_\odot\mathrm{yr}^{-1}$ for all models with $\epsilon_C/\epsilon_O > 1.30$. In contrast, u_∞ is proportional to ϵ_C/ϵ_O. Below the value of $\approx$ 1.30 for ϵ_C/ϵ_O there is just enough dust formed to drive a wind which is, however, very slow and less massive. Going to even lower values of ϵ_C/ϵ_O, pulsation and radiative acceleration on dust grains alone no longer can support an outflow. A fit equation which relates a given set of the six model parameter to the resulting mass loss rate is derived in Arndt et al. (1996).

6. Shortcomings of the models

The models suffer from two major shortcomings: the usage of an equilibrium chemistry and the treatment of the cooling of the gas behind the shock fronts. As strong velocity changes and short–term variations in the radiation field are usually encountered in LPV atmospheres the standard situation of the gas phase is chemical non–equilibrium (cf. Sedlmayr & Winters, this volume). To consider these effects in the models would require to solve a time–dependent reaction network which is extremely CPU–time consuming. However, calculations of rate networks show that in the inner shell region, where the dust forms, the situation can be approximated by the equilibrium case if one is only interested in the densities of the dustforming species (cf. Beck et al. (1992)). In future work, also the treatment of the post–shock cooling processes in the models has to be improved. Calculations in the isothermal as well as adiabatic limit case show that the structure of the CDS appears in the way described above. Using LTE-cooling laws, as done in the models described in this paper and in Höfner et al. (1996) yields models very close to the isothermal limit case. Incorporating the laws proposed by Bowen (1988) results in models with an unrealistic temperature structure as the re–heating behind the shocks proceeds much too slow. A solution to the post–shock cooling problem could be the incorporation of the scheme developed in Woitke et al. (1996).

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