Time-dependent behavior of cool-star winds

Peter Woitke

Institut für Astronomie und Astrophysik, TU Berlin, Sekr. PN 8–1,
Hardenbergstraße 36, 10623 Berlin, Germany

Abstract. The present status of time-dependent modeling of the circumstellar envelopes of cool pulsating stars on the AGB is reviewed. Such model calculations nowadays investigate the complex interplay between hydrodynamics, thermodynamics, chemistry, dust formation and radiative transfer. We report on the scientific insight provided by such models and show the physical mechanisms which control the dynamical behavior of these envelopes and drive the massive winds of these stars. The common results as well as the contrary aspects obtained by different groups are summarized and discussed. Observational and theoretical constraints on the temperature structure in these winds are outlined which allow for some important conclusions concerning the wind driving mechanism.

1 Introduction

Long-period variables (LPVs) and Miras on the Asymptotic Giant Branch (AGB) belong to the class of stellar objects which exhibit the largest mass loss rates known ($10^{-7} \ldots 10^{-4}\,M_\odot/yr$). Such massive outflows are certainly capable of returning a considerable fraction of the original stellar material back to the interstellar medium. Since the overwhelming part of the newly born stars[1] evolve along the AGB at the end of their lifetime, these winds provide the most important source of new fuel for star formation. Understanding the final stages of stellar evolution and the circuit of matter therefore requires detailed knowledge about the mass loss mechanisms of AGB stars.

Considerable progress has been achieved in the last decade concerning the dynamic modeling of the atmospheres and circumstellar envelopes (CSEs) of LPVs and Miras. This review intends to summarize the physical insight provided by time-dependent model calculations performed in *Iowa* (Bowen 1988, Willson et al. 1997), in *Berlin* (Fleischer et al. 1992, Winters et al. 1994, Fleischer et al. 1995) and in *Vienna* (Feuchtinger et al. 1993, Höfner et al. 1995, Höfner & Dorfi 1997). Despite this progress, the basic wind driving mechanism is still a matter of debate. The most promising processes which can generate the wind could be (i) stellar pulsations, (ii) radiation pressure on newly formed dust grains and — most probably (iii) a combination of both. Atmospheric levitation due to radiation pressure on molecules has been discussed (e. g. Jørgensen & Johnson 1992), but adequate dynamical model computations are still lacking. Magnetic fields and stellar rotation are usually considered to play a minor role for the wind generation from these late-type giant stars (Dorfi & Höfner 1996).

[1] More than 97% based on the assumptions $M_i \leq 8\,M_\odot$ (Reimers & Köster 1979), initial mass function $dN/d\log M_i \propto M_i^{-1.7}$ (Miller & Scalo 1979) and $M_i \geq 1\,M_\odot$.

2 The models: common aspects and distinct approaches

First we discuss the *common aspects of the model computations* performed in *Iowa, Berlin*, and *Vienna*. A typical model covers the region from about 0.9 to 30 R_*, containing the stellar atmosphere and the inner part of the CSE where the wind is generated. The interior driving zone of the stellar pulsation is *not* included in any of the models[2]. The set of hydrodynamic equations

$$\frac{d\rho}{dt} = -\rho \operatorname{div} u \tag{1}$$

$$\frac{du}{dt} = -g + a_{\rm dust} - \frac{1}{\rho} \operatorname{grad} p \tag{2}$$

$$\frac{de}{dt} = -p \frac{dV}{dt} + \frac{1}{\rho} Q_{\rm rad} \quad , \tag{3}$$

comprising the equation of continuity, the equation of motion and the energy equation, are simultaneously solved together with the radiative transfer problem. As acceleration terms in the equation of motion (2), all groups account for gravitation g, gas pressure gradient and radiation pressure on dust grains $a_{\rm dust}$. Only adiabatic and radiative ($Q_{\rm rad}$) heating/cooling rates are considered in the energy equation (3). Due to the large time consumption of the computer models, all groups so far rely on spherical symmetry and on the grey approximation of the radiative transfer problem. Its solution yields the local radiative equilibrium temperature $T_{\rm RE}$ which enters into the determination of $Q_{\rm rad}$. For the numerical treatment of the discontinuities caused by shock waves, an artificial viscosity is included. In order to simulate the interior pulsation of the star, the so-called piston approximation $u_1(t) = \Delta u \cdot \cos(2\pi t/P)$ is applied. It adopts a sinusoidal motion of the inner boundary with Δu being the amplitude and P the period of the stellar pulsation. All calculations start from an initially hydrostatic model given by the static solution of Eqs. (1–3) without piston motion and excluding the presence of dust.

The distinct model assumptions are summarized in Table 1. The main difference between the *Iowa* approach on one hand and the *Berlin* and *Vienna* approaches on the other hand concerns the treatment of the dust complex. In the pioneering work of Bowen (1988), a parameterized step-function for the dust opacity is used which solely depends on $T_{\rm RE}$, whereas in the *Berlin* and *Vienna* models, the dust formation process is modeled relying on chemical equilibrium, classical nucleation theory and a time-dependent moment method from which the dust properties (e. g. $a_{\rm dust}$) are consistently calculated. Up to now, the latter detailed description of the dust complex has been applied to carbon stars only, because the details of the nucleation and growth of inorganic grains in an oxygen-rich environment are still not fully understood.

[2] Therefore, an artificial approximation for the inner boundary is applied (the "piston" approximation), which introduces two additional parameters to the models.

Table 1. Summary of the different model approaches

<table>
<tr><th></th><th>Iowa</th><th>Berlin</th><th>Vienna</th></tr>
<tr><td>chemistry</td><td>–</td><td colspan="2">equilibrium</td></tr>
<tr><td>nucleation</td><td>–</td><td colspan="2">modified classical nucleation theory
(Gail et al. 1984)</td></tr>
<tr><td>dust</td><td>$f(T_{\mathrm{RE}})$
(Wood 1979)</td><td colspan="2">time-dependent moment method
(Gail & Sedlmayr 1988)</td></tr>
<tr><td>Q_{rad}</td><td>$Q_{\mathrm{rad}} \propto \rho^2$
(non-LTE)</td><td>– (1)</td><td>$Q_{\mathrm{rad}} \propto \rho$
(LTE)</td></tr>
<tr><td>radiative transfer</td><td>grey Eddington
(Chandrasekhar 1934)</td><td>grey Eddington
(Lucy 1976)
(Unno & Kondo 1976)</td><td>time-dependent grey variable Eddington
(Yorke 1980)</td></tr>
<tr><td>num. scheme</td><td colspan="2">explicit Lagrange
(Richtmyer & Morton 1967)</td><td>implicit adaptive grid
(Dorfi & Feuchtinger 1991)</td></tr>
</table>

(1) : Iowa's or the LTE approach may be considered optionally

Another difference concerns the treatment of the radiative heating/cooling function $Q_{\mathrm{rad}}[\mathrm{erg\,s^{-1}\,cm^{-3}}]$: The *Iowa* group uses an approximate formula adjusted to the non–LTE behavior of permitted line transitions which scales as $Q_{\mathrm{rad}} \propto \rho^2$. The *Vienna* group relies on the assumption of LTE resulting in a heating/cooling rate which roughly scales as $Q_{\mathrm{rad}} \propto \rho$. Most of the published *Berlin* models use the "isothermal" approximation based on the assumption that the gas relaxes instantaneously towards radiative equilibrium ($T = T_{\mathrm{RE}}$). In this case, the energy equation (3) becomes obsolete and the temperature structure is an immediate result of the solution of the radiative transfer equation. In all cases where efficient dust formation takes place, the different approaches for Q_{rad} adopted do not result in substantial deviations from the published Berlin models (Gauger et al. 1993, Fleischer & Gauger 1997).

3 Basic physical results

Shock waves: generation and propagation. A simple but very important implication from all the models is that propagating shock waves are almost inevitably present in the atmospheres of pulsating stars. According to the large density gradient present in the photosphere, even small scale (subsonic) waves steepen into strong shocks the propagation of which is demonstrated in Fig. 1. Inside the photosphere these shocks cause large time variations of the atmospheric structure which, nevertheless, can still be considered as a "disturbance" of the static stratification governed by gravitation and pressure gradients. However, in the outer atmosphere, the shock waves create a completely different dynamical behavior of the gas which no longer can be understood on the basis of static or even stationary models, but is only revealed by time-dependent models.

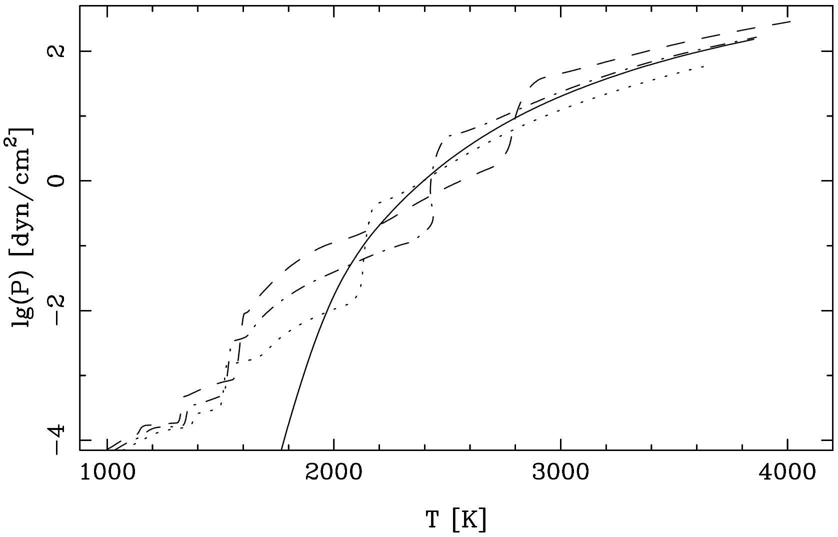

Fig. 1. The initial model (full line), the propagation of shock waves through the atmosphere (dashed: phase 0.5, dash-dotted: phase 0.75 and dotted: phase 1.0), and the levitation of the outer atmosphere (Höfner et al. 1997). Parameters: $T_* = 2880\,$K, $L_* = 7000\,\mathrm{L}_\odot$, $M_* = 1\,\mathrm{M}_\odot$, C/O$\,=\,$1.4, $P = 330\,$d and $\Delta u = 4\,\mathrm{km\,s^{-1}}$.

Levitation and dust formation: The shock waves introduce an outward directed, periodically acting, additional force on the gas which causes a levitation of the outer atmosphere resulting in densities being larger by orders of magnitude as compared to a hydrostatic model (cf. Fig. 1). Levitation alone, however, is not the primary cause of the mass loss. It only provides larger densities at distances where efficient mass loss mechanisms may set in and, therefore, helps to drive more *massive* outflows. For example, since effective dust formation from the gas phase requires large densities, the driving of stellar winds by radiation pressure on dust grains is strongly supported by matter levitation. The two-step process of levitation and dust (+ wind) formation is demonstrated by the emergence of two distinct radial zones as shown in Fig. 2 for a typical *Berlin* model.

1.) In the inner levitated regions ($r \lesssim 2\,R_*$), the gas elements are periodically hit by shock waves, which causes instantaneous outward accelerations. In the meantime, the fluid elements fall back towards the star following roughly ballistic trajectories.
2.) On top of these levitated layers, effective dust formation takes place, radiation pressure on dust accelerates the gas and causes the transition into the wind region ($r \gtrsim 2\,R_*$).

Further details of this model are shown in Fig. 3. An unexpected but typical feature being common to all models which include a time-dependent dust formation is that the emerging dust is not distributed uniformly. The step-like behavior of

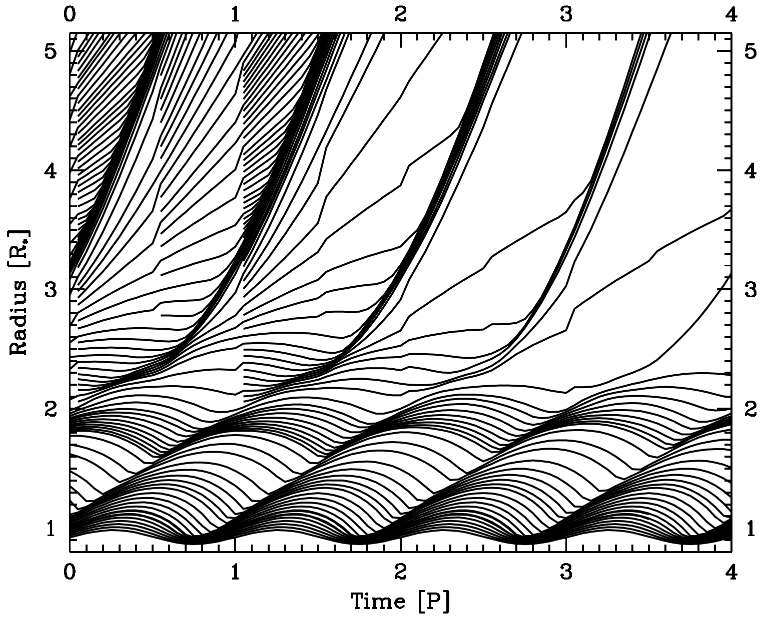

Fig. 2. A "Lagrange-plot" of a typical Berlin model indicating the radial positions of fixed fluid elements (in units of the initial stellar radius R_*) as function of time (in units of the pulsational period P). The sinusoidal variation at the bottom reflects the prescribed motion of the "piston". The CSE is clearly divided into two distinct zones: the levitated layers at the bottom and the wind region on top. Parameters: $T_* = 2600$ K, $L_* = 10000\,L_\odot$, $M_* = 1\,M_\odot$, C/O = 1.8, $P = 650$ d and $\Delta u = 2\,\mathrm{km\,s^{-1}}$.

the degree of condensation f_c (i.e. the amount of condensible material actually condensed into grains) indicates that the dust is present in discrete, onion-like layers. When new dust forms close to the star, an optically thick shell appears which blocks the radiation and re-radiates it towards the star. Consequently, the region inside of this layer heats up ("backwarming", see T-plateau at about 2000 K in Fig. 3) and further nucleation is temporarily inhibited. The optically thick layer is driven out by radiation pressure, radially dilutes and finally becomes transparent again. Accordingly, the inner region cools down and a new cycle of dust formation may start. This "exterior κ-mechanism", which acts in combination with pulsations in the depicted model, is thoroughly described in Fleischer et al. (1995) and in Höfner et al. (1995). In fact, the model described here belongs to the most simple class of *single periodic* models. The dust complex introduces an additional characteristic time scale to the system which is given by the time between the formation of two subsequent dust layers. Coupling with the pulsational period may cause a *multiperiodic* or even chaotic behavior of the CSE.

Wind driving mechanisms: pulsation and/or dust formation? Besides the dust-driven winds supported by pulsation (*Berlin, Vienna*), a quite different mass

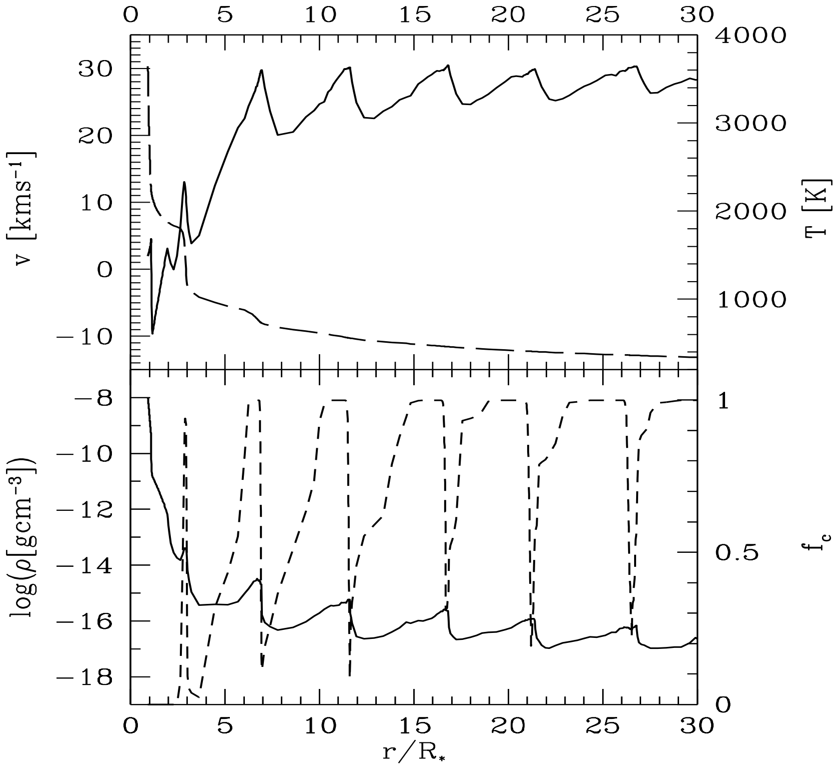

Fig. 3. Velocity v (upper diagram, full line), temperature T (upper diagram, dashed line), mass density ρ (lower diagram, full line) and degree of condensation f_c (lower diagram, dashed line) as function of radius at a fixed time. The remarkable steps in the f_c-curve reflect the onion-like, layered dust distribution. Parameters as in Fig. 2.

loss mechanism has been proposed by the *Iowa* group (Bowen 1988): According to the assumption $Q_{\rm rad} \propto \rho^2$, the efficiency of radiative cooling of the gas ($\propto Q_{\rm rad}/\rho$) decreases linearly with decreasing density in the CSE. Consequently, there exists some point in the envelope, beyond which the gas is too diluted to radiate away the excess internal energy dissipated by a shock wave and to re-establish radiative equilibrium (RE) within one period. Hence, the gas behaves almost adiabatically. In this case, the propagating shocks produce a so-called "calorisphere" (cf. Fig. 5b) having temperatures always much higher than in RE, and the large pressure gradients alone may cause substantial mass loss rates, *even without dust.* The mass loss rates of such *pulsation induced, thermally driven* winds critically depend upon the details of the evaluation of $Q_{\rm rad}$ (Willson 1997, this conference). If dust formation is included (in the approximate way described above), the dust may take over the driving of the wind and may increase the mass loss rate. In this case, the calorisphere disappears because of the additional adiabatic expansion in the enhanced dust-driven outflow and the *Iowa* results look similar to the corresponding *Berlin* and *Vienna* results.

4 Synthetic observations

A recent development concerning the research on AGB stars is to use the time-dependent models as a basis for the calculation of various synthetic observations. The common procedure is to perform a frequency-dependent radiative transfer calculation[3] on top of the model structures (density, temperature, velocity, dust). In spite of the inherent inconsistency of this treatment, important observational facts have been found to be directly related to the dynamical characteristics of the calculated models. Some examples for such results are listed below. This success in turn proves the quality and the capability of the time-dependent models compared to static or stationary approaches.

spectral energy distribution	Winters et al. (1997) Windsteig et al. (1997)
synthetic lightcurves	Winters et al. (1994)
brightness profiles	Winters et al. (1995)
synthetic photospheric spectra	Höfner et al. (1997) Aringer et al. (this conference)
synthetic line profiles: • CO lines	Gauger et al. (this conference) Windsteig et al. (this conference)
• atomic lines	Luttermoser & Bowen (1990)
molecular band strengths	Alvarez & Plez (1997)

5 Mass loss rate formula for C–rich AGB stars

Besides the studies of the physical processes in single models and their links to observations, the behavior of a sample of models yields important informations, for example the functional dependence of the resulting quantities on the input parameters. In particular, the value of the mass loss rate is a result of each consistent model calculation, which implies that the influence of the stellar parameters on $\dot{M}$ can be determined. Based on a statistical analysis of 48 *Berlin* models, Arndt et al. (1997, see also this conference) have recently extracted such a "model"-mass loss rate formula for C-rich AGB stars, which could serve e. g. as input for stellar evolutionary calculations, where the effect of mass loss has to be taken into account quantitatively. The mean error of this formula for $\log \dot{M}$ relative to the individual *Berlin* model values is less than 3%. As long as the same input physics is used, the *Vienna* results agree within about 6%.

A comparison between calculated and observed mass loss rates for C–stars is shown in Fig. 4. A clear correlation exists between $\dot{M}$ and the $\mathrm{K-L}$ color index, which is an approximate measure of the dust optical depth of the CSE. The *Berlin* models tend to predict mass loss rates which are, on average, too large by a factor of two. One should keep in mind, however, that these models have been

[3] In contrast to the grey approximation used during the time-dependent model computations.

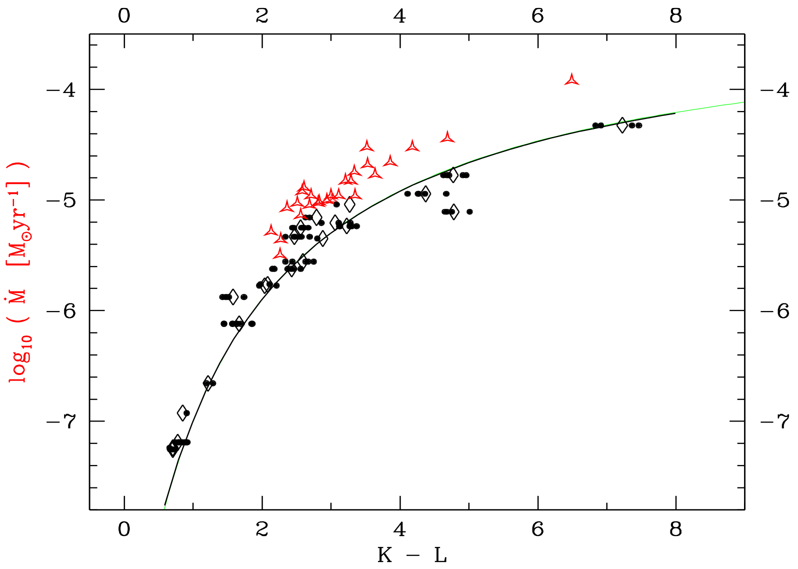

Fig. 4. The observed mass loss rates of C–stars (open diamonds and dots) as a function of the K − L color index compared with the results of the Berlin models (open triangles). The full line indicates the correlation obtained from the observations (Le Bertre 1997).

calculated *self-consistently*, i.e. from first principles. Accordingly, there are no additional parameters which could be tuned. The existence of such a correlation suggests that the winds of C–stars, in fact, are dust-driven or at least strongly determined by the emerging dust component. The consistency of the slope of the correlation between observations and models moreover indicates that the wind driving mechanism is modeled in an appropriate way.

6 Discussion: hot or cool envelopes?

The basic question whether the winds of LPV and Mira stars are driven by pulsation or by dust is closely related to the slope of the temperature profile in the envelope. The thermal driving by pulsation is causally connected with the formation of a "calorisphere" (cf. Fig. 5b) with temperatures several thousand degrees above $T_{\rm RE}$ in the wind driving zone. This requires a *low efficiency of radiative cooling*, because the energy dissipated by the shocks must not be radiated away, but is to be converted into work done on the gas via adiabatic expansion, thereby driving the wind. Thus, the debate on the driving mechanism may be decided by means of reliable information about $T(r)$ either obtained by observations or by theory.

Radio observations: Recently, Reid & Menten (1997) detected and partially resolved centimeter-wavelength emissions from a sample of nearby long-period (Mira and semi-regular) variables. They found an optically thick "radio photosphere" (caused by H^- and H_2^- free-free transitions) located at about $2\,R_*$ and

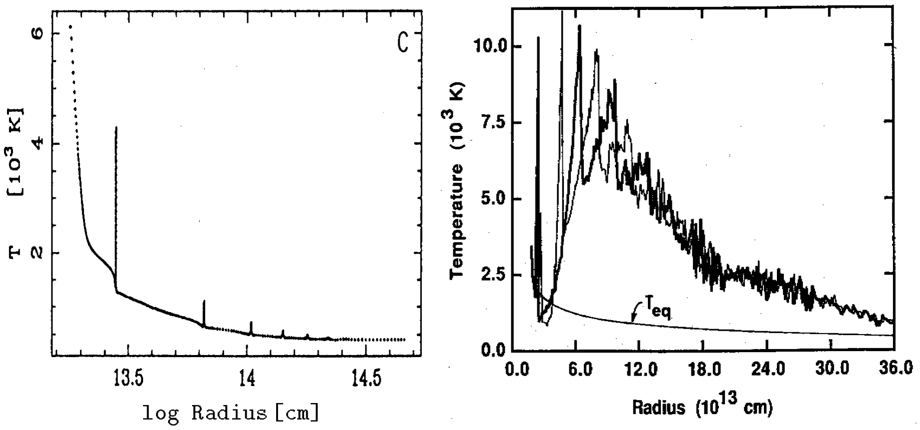

Fig. 5. Temperature structures of different model calculations: (a) dust-driven model (Feuchtinger et al. 1993) — (b) dust-free, pulsation-driven model (Bowen 1988).

derived brightness temperatures of 1500 ± 570 K. Furthermore, they argue for temperatures $\lesssim 1100$ K at radial distances $r \gtrsim 10^{14}$cm. Crosas & Menten (1997), analyzing CO rotational lines, come to similar conclusions concerning the LPV carbon star IRC+10216. These observations are compatible with the dust-driven models, but seem to contradict the purely pulsation-driven models.

Shock models: The efficiency of radiative cooling under conditions typical for CSEs has scarcely been investigated. Some models of radiative, plane-parallel, stationary shock waves are available nevertheless, which contain important information about the cooling time scale $\tau_{\rm cool}$, after which a shocked gas element returns to temperatures of the order of a few 1000 K. The corresponding hydrogen column density behind the shock $N_{\rm H} = \int n_{\rm H} v \, dt = n_{\rm H,1} v_1 \tau_{\rm cool}$ proves to be fairly independent of the pre-shock density $n_{\rm H,1}$ and the shock velocity v_1.

reference	$n_{\rm H,1}[\rm cm^{-3}]$	$v_1[\rm km\,s^{-1}]$	$N_{\rm H}[\rm cm^{-2}]$
Hollenbach & McKee (1989)	10^{5}	80	$10^{20.2}$
Neufeld & Hollenbach (1994)	10^{9}	50	10^{21}
Fadeyev & Gillet (1997)	$10^{13.6}$	25	$\approx 10^{19.6}$

Assuming $N_{\rm H} \approx 10^{21}\rm cm^{-2}$ (worst case) and considering $v_1 = 20\,\rm km\,s^{-1}$ and $P = 1\,\rm yr$ as typical values for Miras and LPVs, the critical pre-shock density $n_{\rm cr,1}$ where $\tau_{\rm cool}$ equals P is given by

$$n_{\rm cr,1} = \frac{N_{\rm H}}{v_1 P} \approx \frac{10^{21}\rm cm^{-2}}{20\,\rm km\,s^{-1} \cdot 1\,yr} = 10^{7.2}\rm cm^{-3} \quad . \tag{4}$$

Evaluating various radiative heating/cooling rates and relying on time scale arguments, Woitke et al. (1996) arrived at similar conclusions (critical post-shock density $10^{6\ldots8}\mathrm{cm}^{-3}$). The formation of a calorisphere requires $\tau_{\rm cool} > P$ or, equivalently, $n_{\rm H} < n_{\rm cr,1}$. Such small densities, however, are only present at radial distances as large as $\gtrsim 3 \cdot 10^{14}$cm (calculated for $\dot{M} = 4\pi r^2 \rho\, v_\infty = 10^{-6}\mathrm{M}_\odot/\mathrm{yr}$ and $v_\infty = 20\,\mathrm{km/s}$), i.e. at distances which are unlikely to be relevant for the wind generation and where the formation of dust is expected to be almost completed. Thus, theoretical constraints on the efficiency of radiative cooling do not favor high mass loss rates caused by pulsations alone.

Acknowledgments The author would like to thank E. Sedlmayr, J. M. Winters and P. Cottrell for valuable comments on the manuscript. This work has been supported by the Deutsche Forschungsgemeinschaft (grants Se 420/8–1, Se 420/15–1) and by the BMBF (grant 05 3BT13A 6).

Puls: One of the major ingredients in the hydro-description is the temporal behavior of the radiation pressure on the dust. What is the basic "trick" of calculating this quantity accounting for the NLTE-dust formation investigated by your group?

Woitke: The time-dependent treatment of the dust complex is based on the moment method developed by Gail & Sedlmayr (1988) and the way it is included into the hydro-description is shown in Fleischer et al. (1992). Four additional differential equations for the dust complex are solved together with the usual hydrodynamic equations. Applying the small particle limit of Mie theory, the radiation pressure on dust grains can be expressed in algebraic terms of the third moment of the dust distribution function.

Owocki: I was intrigued by your scaling formula, particularly by the -8 power dependence on temperature, and the $+1.5$ power on the luminosity, which is reminiscent of scaling in hot stars. But for stars of a given evolutionary status, must there not also be some relation among these parameters, and that this will be relevant when comparing predicted scaling to observations?

Arndt: Regarding the extreme -8 power for T_*, I think it is (mostly) due to the extreme temperature-dependence of dust formation and growth. Dependences between stellar parameters, arising from evolutionary considerations, are part of planned studies – but right now the shown $\dot{M}$-scaling formula is restricted to C-rich AGB stars. The observed stellar parameters of C-stars are somewhat a matter of debate, because their CSEs tend to be enshrouded by circumstellar dust, often causing them to be pure IR-objects. Therefore, I feel personally that "observed" relations may be misleading in the parameter range of "our" $\dot{M}$-formula.

Linsky: Tom Ayres, David Muchmore and others have called attention to the thermal instability that results from the strong cooling by CO and SiO that can lead to rapid formation of these molecules. Their model atmospheres are bistable in the sense that two solutions can result. In your models of carbon rich Mira variables do you see evidence for this bistability?

Woitke: The work of T. Ayres and D. Muchmore is mainly devoted to solar-type stars, where in addition to the warm atomic, almost molecule-free gas phases, cool molecule-rich phases may coexist which are thermally stable as well. According to my personal studies, C-star envelopes do not show much of these thermal bifurcations, because the gas is molecule-rich anyway, in particular CO-rich. Nevertheless, some minor instabilities may be present, e.g. due to SiS formation. This effect has to be further investigated and may be very important, if another heating mechanism is active, for example the heating by propagating shock waves.

References

Alvarez R., Plez B. (1997): A&A accepted
Arndt T. U., Fleischer A. J., Sedlmayr E. (1997): A&A 327, 614
Bowen G. H. (1988): ApJ 329, 299–317
Chandrasekhar S. (1934): MNRAS 94, 444
Crosas M., Menten K. M. (1997): ApJ 483, 913–924
Dorfi E. A., Feuchtinger M. U. (1991): A&A 249, 417–427
Dorfi E., Höfner S. (1996): A&A 313, 605–610
Fadeyev Y. A., Gillet D. (1997): A&A, submitted
Feuchtinger M. U., Dorfi E. A., Höfner S. (1993): A&A 273, 513–523
Fleischer A. J., Gauger A., Sedlmayr E. (1992): A&A 266, 321–339
Fleischer A. J., Gauger A., Sedlmayr E. (1995): A&A 297, 543–555
Fleischer A. J., Gauger A. (1997): private communications
Gail H.-P., Sedlmayr E. (1988): A&A 206, 153–168
Gail H.-P., Keller R., Sedlmayr E. (1984): A&A 133, 320–332
Gauger A., Fleischer A. J., Winters J. M., Sedlmayr E. (1993): AG Abstr. Ser. 9, 127
Höfner S., Feuchtinger M. U., Dorfi E. A. (1995): A&A 297, 815–827
Höfner S., Dorfi E. A. (1997): A&A 319, 648–654
Höfner S., Jørgensen U. G., Loidl R. (1997): In Waters R., Waelkens C., van der Hucht K., *ISO's view on Stellar Evolution*, in press. Kluwer Academic Publishers
Hollenbach D., McKee F. (1989): ApJ 342, 306–336
Jørgensen U. G., Johnson H. R. (1992): A&A 265, 168–176
Le Bertre T. (1997): A&A 324, 1059–1070
Lucy L. B. (1976): ApJ 205, 482–491
Luttermoser D. G., Bowen G. H. (1990): In Wallerstein G., *Sixth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, 491–493
Miller G. E., Scalo J. M. (1979): ApJS 41, 513–547
Neufeld D. A., Hollenbach D. J. (1994): ApJ 428, 170–185
Reid M. J., Menten K. M. (1997): ApJ 476, 327–346
Reimers D., Köster D. (1979): A&A 202, 77–80
Richtmyer R. D., Morton K. W. (1967): *Difference methods for initial-value problems*, John Wiley & Sons, New York, 2^{nd} edition
Unno W., Kondo M. (1976): PASJ 28, 347–354
Willson L. A., Struck–Marcell C., Bowen G. H. (1997): In *Cosmic Winds and the Heliosphere*, eds. Jokipii J. R. et al. , University of Arizona Press, in press
Windsteig W., Dorfi E., Höfner S., Hron J., Kerschbaum F. (1997): A&A 324, 617
Winters J. M., Fleischer A. J., Gauger A., Sedlmayr E. (1994): A&A 290, 623–633
Winters J. M., Fleischer A. J., Gauger A., Sedlmayr E. (1995): A&A 302, 483–496
Winters J. M., Fleischer A. J., Le Bertre T., Sedlmayr E. (1997): A&A 326, 305–317
Woitke P., Krüger D., Sedlmayr E. (1996): A&A 311, 927–944
Wood P. R. (1979): ApJ 227, 220–231
Yorke H. W. (1980): A&A 86, 286–294