

On flow phenomena that emit X-rays in hot star winds

A. Feldmeier¹, J. Puls¹, R.P. Kudritzki^{1,2}, A.W.A. Pauldrach¹, S.P. Owocki³, C. Reile¹, and R. Palsa¹

¹ Institut für Astronomie und Astrophysik der Universität, Scheinerstr. 1, 81679 München, Germany

² Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching, Germany

³ Bartol Research Institute, Newark, Delaware 19716, USA

Abstract. The X-ray emission from O stars may originate from instability-generated shocks in their stellar winds. Previous numerical simulations that assumed the wind to be isothermal could only draw limited conclusions concerning this emission. We present new calculations including the energy transfer in the wind. They confirm that up to a few stellar radii, radiative cooling is efficient, i.e., shock cooling zones are short compared with dynamical lengths. At larger radii, however, the wind structure changes drastically because all shocks are destroyed quickly due to a broadening of their cooling zones. We discuss the following flow phenomena as possible sources of X-rays: (1) inner radiative shocks; (2) shock merging; (3) outer adiabatic shocks; (4) leftover hot gas from shock destruction; and (5) an outer corona.

Introduction. With the recent progress in the stationary theory of radiatively driven stellar winds it is possible to predict mean flow properties like mass-loss rates and terminal velocities (Castor et al. 1975; Abbott 1982; Pauldrach et al. 1986, 1994). However, the observed X-ray emission from OB stars (ROSAT: Hillier et al. 1993) gives evidence for vigorous flow disruptions, i.e., shocks, which heat the wind gas locally to $T > 10^6$ K. The shocks may stem from a hydrodynamic instability due to the radiative driving (Lucy & Solomon 1970; Owocki & Rybicki 1984; Lucy 1984).

Flow features emitting X-rays. For details on the calculation of the nonlinear growth of unstable perturbations we refer to Owocki et al. (1988), Owocki (1991), and Feldmeier (1995). Fig. 1 shows the evolution of the radial wind (assuming spherical symmetry) of a typical O supergiant. A base perturbation of period 5,000 s and amplitude 25% was applied. Guided by this figure, we discuss some flow features which may contribute to the X-ray emission.

1. Radiative shocks. Due to the radiative instability, very narrow and dense shells which are separated by nearly void regions propagate through the wind. The shells are enclosed by a strong reverse shock at the inner side and a

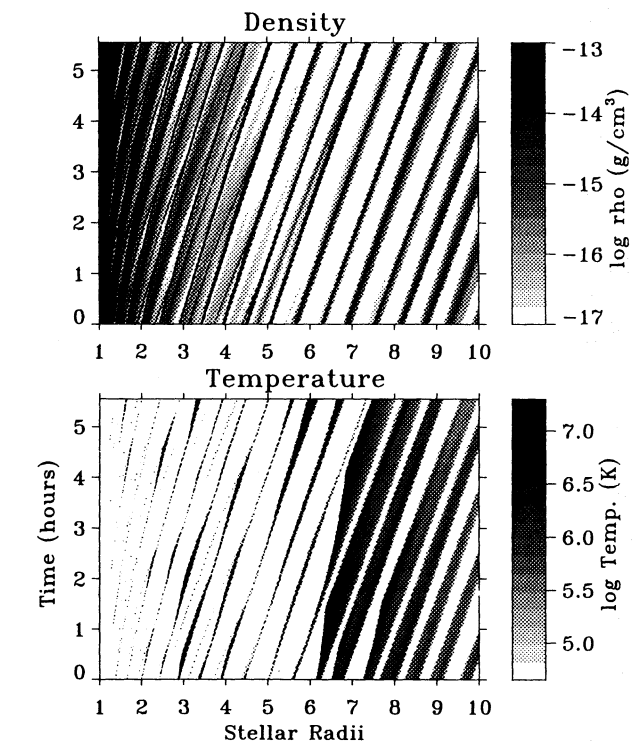


Fig. 1. Evolution of a typical O supergiant wind being subject to the radiative instability.

weak forward shock at the outer side. Since radiative cooling is efficient at small radii, the shock cooling zones are short compared with the shell distances. Radiative shocks above some 10^5 K are subject to the thermal instability of Langer et al. (1981), which leads to a periodic contraction and expansion of the cooling zones. In our present models, the forward shocks do not contribute significantly to X-ray emission since their temperatures are some 10^5 K only.

2. Shell collisions with shock merging. In Fig. 1, shell-shell collisions occur quite frequently up to $6 R_*$. During the merging of a reverse with a forward shock the total velocity jump becomes larger than the single shock jumps.

This leads temporally to (i) higher temperatures (the hot cusps in the temperature diagram), and (ii) a broadening of the cooling zone. Shock merging has therefore immediate significance for the hard component of the X-ray emission. Fig. 1 shows a rather periodic wind structure due to the regular, strictly periodic seed perturbation. In models with a more chaotic perturbation spectrum many more shell collisions can occur, and the total X-ray emission from the wind might not show an observable variability due to individual shell collisions.

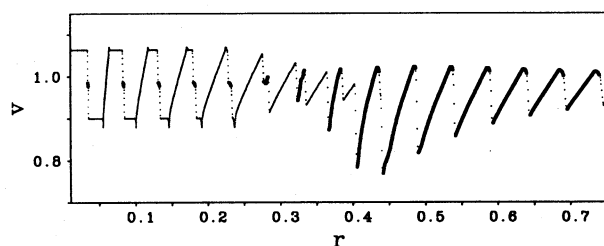


Fig. 2. Velocity versus radius (in arbitrary units) for a test calculation with an interior sequence of adiabatic shells. A forward shock catches up and merges with a reverse shock at $r \approx 0.4$. This leads to an outer, sawtooth-like sequence of forward shocks. The full circles mark post-shock material.

Furthermore, shell collisions can possibly influence the global wind dynamics. Fig. 2 shows a test calculation with a sequence of adiabatic shells enclosed by equally strong reverse and forward shocks in a spherical wind with $v = \text{const.}$, $\rho \sim r^{-2}$. Only pressure forces are included here. The adiabatic shells expand, and a forward shock catches up with a reverse shock at $r \approx 0.4$ (arbitrary units). This collision transforms the inner shell sequence into an outer sawtooth-like sequence of forward shocks. For the inner shell sequence only the material within the shells passed through a shock, whereas for the outer forward shock sequence every gas particle undergoes repeated shock transitions. However, it is not clear yet how this test simulation translates into the wind simulations including line driving, radiative cooling, shock destruction (see section below), etc.

3. Adiabatic shocks. When radiative cooling becomes inefficient at low densities, the cooling is by expansion only, either laterally due to spherical divergence, or radially by acceleration of the gas. However, such adiabatic shocks are not found in Fig. 1. The reason is that the reverse shocks are abruptly destroyed at intermediate radii, instead of being progressively transformed into adiabatic shocks at large radii:

4. Hot material leftover from shock destruction. Fig. 1 shows a major change in the wind structure around 6 to

$7 R_*$. The following sequence of events occurs (Feldmeier 1995). (1) Radiative cooling behind shocks ceases to be efficient after the main mass of gas has been compressed into shells. (2) Therefore the cooling zones broaden. Since the gas at the end of the cooling layer is very dense and inert, this takes place by driving the shock front into the pre-shock gas. (3) Since the material ahead of the shock is accelerating, the front encounters always slower material. The shock jump becomes ever smaller until it finally vanishes. (4) Leftover from this is gas which was heated in the front at former times, and which had not yet time enough to cool. The main cooling of this very rarefied gas should be by expansion.

5. Outer corona. Beyond this shock-destruction site, the volume filling factor of leftover hot, rarefied gas is quite high (0.5 to 0.8). This region resembles therefore an outer corona. However, (i) the mass fraction and therefore the emission measure of hot gas is still very small, and (ii) the large filling factor in Fig. 1 results mainly from the large perturbation at the wind base, whereas small perturbations give small filling factors. It therefore remains an open question whether an outer corona surrounds O supergiants. On the other hand, for B near main sequence stars with thin winds and inefficient radiative cooling the accumulation of hot gas seems quite probable.

Conclusions. In an initial attempt to fit the ROSAT spectra of hot stars, we assume radiative shocks to be distributed stochastically in the inner wind regions, and adiabatic shocks in outer regions (cf. Kudritzki et al. and Palsa et al., this volume). A more detailed picture of the X-ray emission including the flow features discussed in the present paper is currently being developed.

Acknowledgements. This project was supported by the DFG (Pa 477/1-2 and Pu 117/2-1), BMFT (50 OR 9304 0 and 05-2MU114(7)), NSF (AST 91-15136), and NASA (NAGW-2624).

References

- Abbott D.C., 1982, ApJ 259, 282
- Castor J.I., Abbott D.C., Klein R.I., 1975, ApJ 195, 157
- Feldmeier A., 1995, A&A 299, 523
- Hillier D.J., Kudritzki R.P., Pauldrach A., et al., 1993, A&A 276, 117
- Langer S.H., Chanmugam G., Shaviv G., 1981, ApJ 245, L23
- Lucy L.B., 1984, ApJ 284, 351
- Lucy L.B., Solomon P.M., 1970, ApJ 159, 879
- Owocki S.P., 1991, in: Crivellari L., Hubeny I., Hummer D.G. (eds.) Stellar atmospheres: beyond classical models. Kluwer, Dordrecht, p. 235
- Owocki S.P., Rybicki G.B., 1984, ApJ 284, 337
- Owocki S.P., Castor J.I., Rybicki G.B., 1988, ApJ 335, 914
- Pauldrach A., Puls J., Kudritzki R.P., 1986, A&A 164, 86
- Pauldrach A., Kudritzki R.P., Puls J., Butler K., Hunsinger J., 1994, A&A 283, 525