TIME-DEPENDENT MODELS OF X-RAY EMISSION FROM SHOCKS IN RADIATIVELY DRIVEN STELLAR WINDS

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ABSTRACT. We report initial results of simulations of X-ray emission from shocks formed in a hot star wind. Simple models show that typical shock spectra are broadly consistent with observed X-ray spectra. A more complete model that includes the line-driven instability indicates general agreement, but also shows some differences with observed spectra.

INTRODUCTION

The X-rays observed from O and B stars probably come from shocks that form in the stellar wind. We are developing a numerical model of the emission from such shocks. We have expanded the radiation hydrodynamics code described in Owocki, Castor, and Rybicki (1988, hereafter OCR) to include energy balance, an improved force calculation (Owocki 1991a,b), and a more careful treatment of shock regions. We use the current version of the thermal emission code described in Raymond and Smith (1977) to calculate X-ray spectra. The results described here are for the B0 V star τ Sco, chosen because it was observed by the Einstein Solid State Spectrometer and because it has a relatively thin wind, so that absorption effects are less important.

The most important limitations of the present model are that (a) we have not yet included the self-absorption of the wind, and (b) because of technical problems involving a coupling between radiative cooling and numerical diffusion, we have turned off radiative cooling in the current set of models. This produces an excess of hot material, so that these results show upper limits for the amount of hot material present. (Note, however, that at the relatively low densities found in the wind of τ Sco, very hot material cools very slowly: for example, the cooling time for $10^7$ K material is on the order of $10^5$ seconds, or 60($R_{\infty}/v_{\infty}$).)

A SIMPLE MODEL

To begin, we set up an initial condition designed to create a strong shock: the steady-state velocity law was truncated at a chosen velocity, so that the wind is at constant velocity from that point outward. (Initial states for density, velocity, and temperature are shown by the dotted lines in Fig. 1.) This approach is similar to that of MacFarlane and Cassinelli (1989, hereafter MC).
The most important differences are that our model uses the Castor, Abbott, and Klein (1975) radiation force, rather than the phenomenological form used by MC; ours is an Eulerian calculation; and we have shut off radiative cooling, as discussed above.

**FIG. 1** Density, velocity, and temperature structure of a single strong shock. Dotted lines: initial condition. Solid lines: state after 5.6 hours.

**FIG. 2** X-ray spectrum of the wind structure shown in Fig. 1. Solid line: calculated spectrum. Dotted line: observed spectrum of τ Sco.
The result, shown by the solid lines in Fig. 1, is a forward-reverse shock pair, as discussed by OCR, MC, and others. The region behind each shock contains material with a distribution of temperatures and densities, since some material went through the shock when it had a smaller amplitude. (In general, of course, temperatures and densities also vary because material cools after passing through the shock.) As shown by Fig. 2, the X-ray spectrum emitted by the shocked material is in good agreement at higher energies with the observed spectrum of τ Sco (taken from MC). The apparent excess of soft X-rays will be reduced by absorption in the wind, so a strong shock or shocks apparently can explain the observed spectrum, at least in principle.

A LINE-DRIVEN INSTABILITY MODEL

The question is then, will wind instabilities in fact form shocks with the right strengths to match the observed X-rays? Fig. 3 shows the wind as calculated using the full, nonlocal radiation force (Owocki 1991a, b). This model used a steady-state initial condition, with a 10% density perturbation with period 1000 seconds introduced at the base. Many shocks with amplitudes $\Delta v \sim 300-400 \text{ km s}^{-1}$ are present, but none with the much larger amplitude ($\Delta v \sim 1000 \text{ km s}^{-1}$) required to produce the observed spectral slope at high energies.

These points are confirmed by the spectrum (Fig. 4), which shows approximate agreement with observation at low energies, but is softer than the observed spectrum at higher energies. It is difficult to tell at this point just how significant this disagreement with observations is. As noted above, the spectrum will be steepened by absorption in the wind, especially at lower energies. (Note also that this model includes only the inner 4 stellar radii of the wind, so that the total emitted flux of the entire wind will be higher.) In addition, higher-energy photons can be made by inverse Compton scattering of the stellar radiation off particles accelerated by shocks, thus steepening the spectrum at energies above 2 keV (Chen and White 1991).

We hope to have results from improved models, with the limitations discussed in the Introduction removed, in the near future.

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REFERENCES


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FIG. 3  Density, velocity, and temperature structure of the wind calculated using the full radiation force and driven by perturbations at the base.

FIG. 4  X-ray spectrum of the wind structure shown in Fig. 3. Solid line: calculated spectrum. Dotted line: observed spectrum of r Sco.
SECTION 3

LARGE-SCALE PHENOMENA