Constraints on Hot Star X-Ray Source Characteristics from Combined Analysis of X-Ray and UV Observations

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CONSTRAINTS ON HOT STAR X-RAY SOURCE CHARACTERISTICS FROM COMBINED ANALYSIS OF X-RAY AND UV OBSERVATIONS

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Abstract. Results from wind ionization calculations are presented which show how the P-Cygni profiles of "superionized" species such as O VI can provide information about the X-ray source characteristics of early-type stars. Using detailed radiative and atomic physics models, we find that a significant source of X-ray emission from ζ Pup (O4 If) comes from a region in the wind located within roughly 1 to 2 stellar radii of the photosphere. Our results suggest that X-rays sources in which emission occurs exclusively at large radii ($r \gtrsim$ a few R_*) are inconsistent with UV P-Cygni profiles for O VI. Instead, we find that X-ray emission from shocks distributed throughout the lower regions of the wind ($r \simeq 1 - 2\ R_*$) is consistent with both X-ray and UV data, as well as mass loss rates deduced from radio and H_α observations.

1. Introduction

Ultraviolet observations of hot stars indicate that their winds contain anomalously high ionization species, such as O VI and N V (Snow and Morton 1976). These species are often referred to as "superionization" states because they are generally believed to be produced by a mechanism other than photoionization induced by stellar photospheric radiation. Cassinelli and Olson (1979) proposed that the ions are produced via Auger (K-shell) ionization from X-rays originating from a corona at the base of the wind. However, a coronal source appears to be at odds with X-ray spectral observations because of the lack of significant attenuation by the overlying wind. This attentuation problem does not exist if the X-rays originate in wind material that has been shock-heated (Lucy and White 1980; Lucy 1982) to temperatures $\sim 10^6$ to 10^7 K because there is less overlying cool wind between the source and the observer. Calculations of the stability of radiatively-driven winds (Owocki et al. 1988; Owocki 1991) predict that strong shocks should develop in the wind close to the star ($R_* < r < 2\,R_*$). An alternative hypothesis is that the X-rays form far from the star due to the interaction of the stellar wind with circumstellar matter (Chlebowski 1989).

If O VI (or other superionized species) in hot star winds is produced by X-rays, then its UV P-Cygni profile can be used as a diagnostic of the X-ray source properties. This is particularly true in the relatively dense winds of O stars and early-B supergiants. Below, we summarize results from wind ionization calculations which show how the O VI profile observed for ζ Pup can be used to deduce some of the characteristics of its X-ray source.

2. Models

In our model, the wind is assumed to be spherically symmetric, expanding at a rate given by a "β-velocity law". The radial dependence of the wind density is specified by assuming the mass flux is constant with radius. The temperature in the wind is assumed to decrease radially outward as predicted by Drew (1989). To determine atomic level populations, multilevel statistical equilibrium equations are solved self-consistently with the radiation field. Approximately 200 atomic levels were included in the multicomponent plasma model consisting of H, He, C, N, O, and Si. In addition to the usual collisional and radiative processes, we also include dielectronic recombination (Nussbaumer and Storey 1983) in our model.

The radiation field included contributions from the photosphere (Mihalas 1972), diffuse radiation from the wind, and X-rays from a high-temperature plasma source in which the frequency-dependence is computed using XSPEC (Raymond and Smith 1977). The X-rays were assumed to be emitted either from a thin region at the base of the wind (coronal model), or as a distributed source throughout the wind (shock model). Radiative transfer effects for the X-rays were computed assuming spherical symmetry using a multiray impact parameter model. P-Cygni profiles were calculated using the SEI code (Lamers et al. 1987) in conjunction with ionization distributions obtained from the wind ionization calculations. For additional details, see MacFarlane et al. (1993).

3. Results

For the calculations described below, we assume a mass loss rate for ζ Pup of 5×10^{-6} $M_\odot$/yr, a wind terminal velocity of $v_\infty = 2200$ km/s, and a distributed X-ray emission source with $T_X = 10^{6.8}$ K. Figure 1 shows the cumulative X-ray emission measure — integrated from the base of the wind out to a radius r — as a function of the scaled velocity ($\equiv v(r)/v_\infty$) for two cases. In one case (dotted curve), a significant source of X-ray emission is assumed to occur at low velocities ($v \sim 0.3 - 0.9\ v_\infty$), while in the second case, X-ray emission originates primarily from regions where $v \gtrsim 0.8\ v_\infty$. The magnitude of the emission measure was adjusted so that the resultant flux was consistent with Einstein IPC (Cassinelli et al. 1981) and BBXRT observations (Corcoran et al. 1993).

Using the O VI ionization distributions calculated for these two cases, P-Cygni profiles were computed using the SEI code. Results are shown in Figure 2, where the two cases are compared with the observed profile for ζ Pup (Morton 1976). It is seen that for the case in which X-rays originate closer to the star (dotted curve with circles) the P-Cygni profile is qualitatively consistent with observation as redward emission is clearly seen

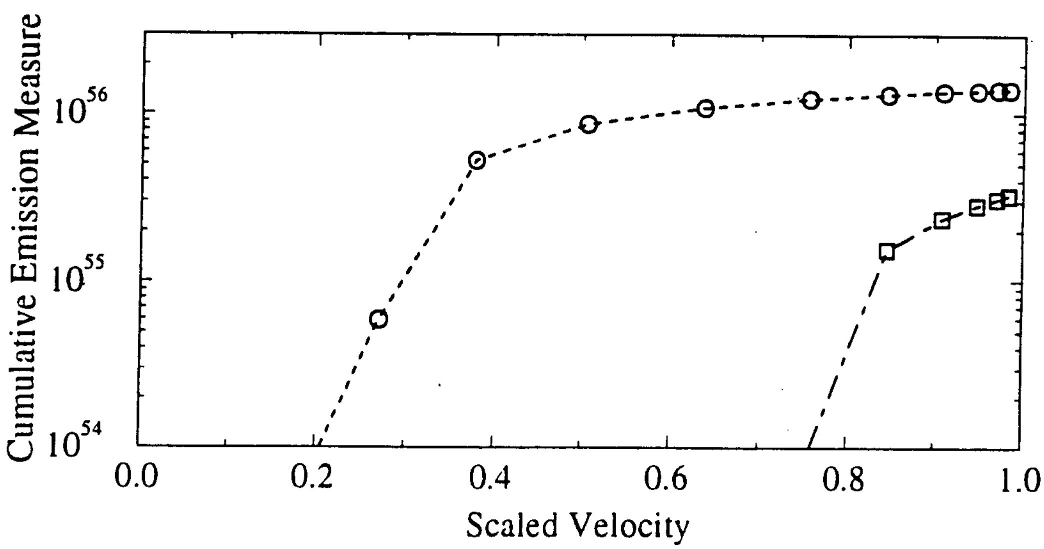

Fig. 1. Cumulative X-ray emission measure for two distributed emission (shock) models discussed in text.

($v/v_\infty \approx +1$). On the other hand, when the X-rays are assumed to originate in the "external" regions of the wind (dot-dashed curve) the emission peak is significantly reduced. This occurs because very little O VI is being produced in the low velocity regions of the wind due to the fact that X-rays are unable to penetrate back down through the cool wind to Auger ionize O VI, which is the dominant species.

The frequency dependence of the optical depth (measured from the base of the wind to infinity) is shown in Figure 3. Note that at the oxygen K-shell edge ($h\nu \approx 0.6$ keV) the optical depth reaches a peak of roughly 40. It is this photoabsorption mechanism which prevents O VI from being produced at low velocities. This is also the mechanism which causes problems for coronal models. At these wind densities, one expects that there be a significant attenuation of X-rays at the oxygen K-edge if the X-rays originate in a coronal region at the base of the wind. It is found that coronal model calculations agree well with X-ray spectra only if the mass loss rate for ζ Pup is reduced to $\lesssim 1 \times 10^{-6}$ $M_\odot$/yr (MacFarlane et al. 1993).

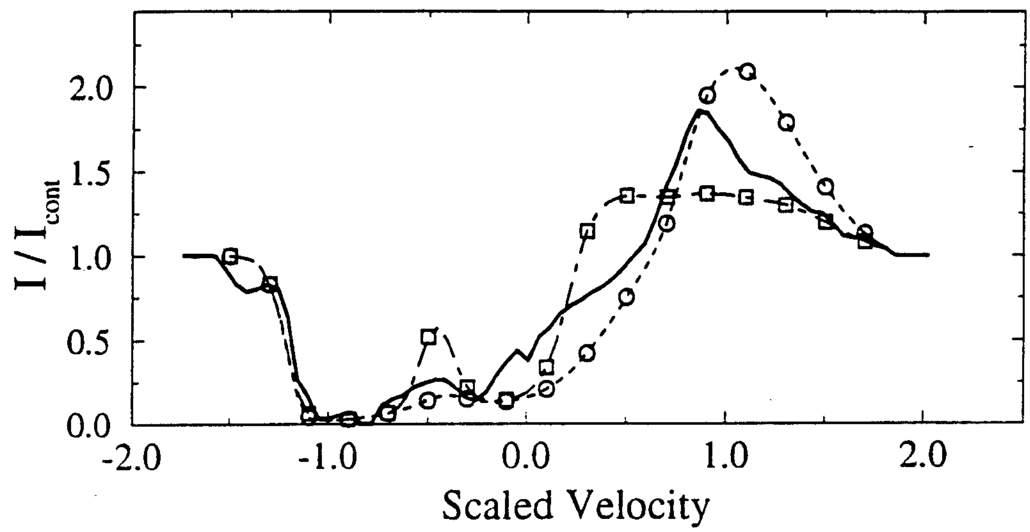

Fig. 2. Comparison of calculated O VI P-Cygni profiles with observation (solid curve). Note the poor agreement with data for the model in which the X-rays are primarily emitted at $r \gtrsim 4\ R_*$ (dot-dashed curve).

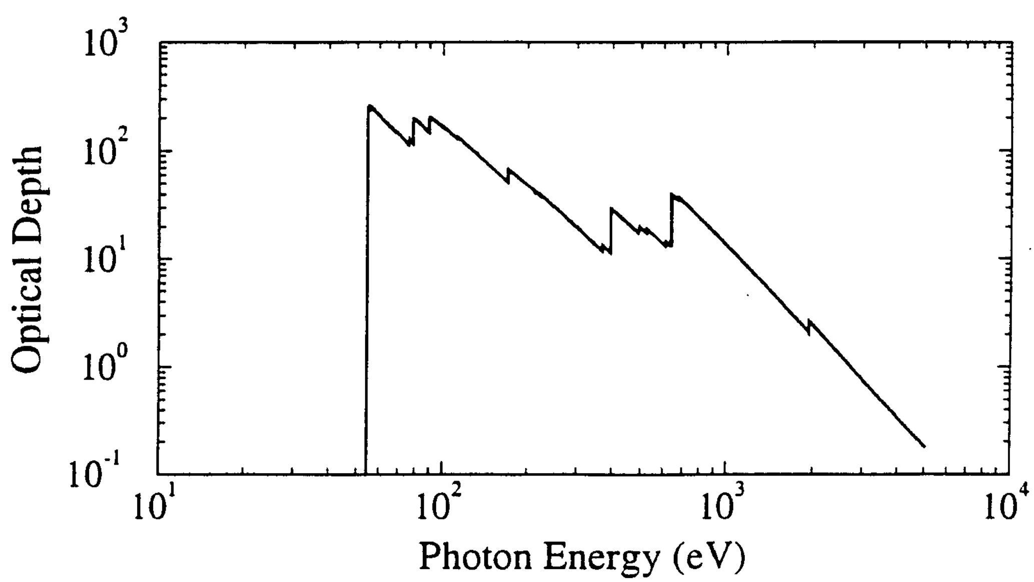

Fig. 3. Dependence of wind optical depth on photon energy.

4. Conclusions

Our results suggest that a distributed X-ray emission source near the base of the wind of ζ Pup ($R_* < r \lesssim 2\ R_*$) is consistent with both X-ray and UV observations. On the other hand, we find that a solely "external" source, in which all X-rays originate from beyond a few stellar radii, is inconsistent with the observed O VI P-Cygni profile. The reason is that X-rays cannot penetrate through the wind back toward the star to produce sufficient amounts of O VI at low velocities. A purely coronal X-ray source is not in agreement with X-ray observations unless the mass loss rate of ζ Pup is at least a factor of a few lower than the rates deduced from both radio and H_α observations. Instead, our calculations tend to support the work of Owocki et al. (1988), whose radiation-hydrodynamic simulations predict that strong shocks form due to instabilities in the lower regions of the wind ($r \lesssim 2\,R_*$).

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