3. X-RAY OBSERVATIONS

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ROSAT OBSERVATIONS OF B AND Be STARS

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Abstract. We present results from a survey of X-ray emission properties of near main-sequence B stars, including several Be and β Cephei stars. The main conclusions of our survey are: 1) The X-rays are soft, probably because the shock velocity jumps are small since the terminal wind speeds are small. 2) A major fraction of the wind emission measure is hot, assuming wind theory estimates for the density distribution. A large fraction of the wind is not expected to be hot in current wind shock models. 3) A hard component is found to be present in τ Sco; possible causes are discussed. 4) For the Be stars, the X-rays emission is from a normal B-star wind that is coming from the poles as in the WCD model of Be stars. 5) None of the stars, including the β Cep stars, show noticeable variability in their X-rays. For the normal B stars we conclude from the lack of variability that the shocks are in the form of fragments in the wind instead of spherical shells. 6) Our observations suggest that all B stars are X-ray sources and that there is a basal amount of X-ray luminosity of about $10^{-8.5} L_{bol}$. The hot component in τ Sco and the high X-ray luminosity of B stars detected in the all-sky survey suggests that there is a source of X-ray emission in addition to wind shocks in some B stars.

1. Introduction

This paper summarizes results of a four-year survey of "near main-sequence" B stars carried out using the *ROSAT* PSPC. By near main sequence we mean stars of luminosity classes V, IV and III, and we refer to these as "BV stars". Some of the material described here is presented in greater detail in Cassinelli *et al.* (1994), but we also describe some results obtained since that paper was submitted.

The B stars are of special interest for several reasons. 1) Relative to the O stars their winds are poorly understood. The terminal speeds of the winds are not known from the ultraviolet profiles because in most cases the wind lines are weak, and the wavelength of the maximum doppler displacement does not clearly correspond to the maximal wind speed. These stars do not have a strong radio free-free continuum like that of the O stars, so the mass-loss rates are not known. Perhaps X-ray observations will provide information regarding mass loss properties. For example, if the winds cease to be driven at some spectral type, the X-ray emission should also cease. 2) The winds should be optically thin to X-rays of most energies, so for BV stars we can study emission from all portions of the wind. We perform our analysis under the assumption that the radiation-instability wind shock model (Owocki, Castor & Rybicki 1988; Cooper 1994) is the correct explanation for O- and B-star X-ray emission. The X-ray emission properties of the BV stars will help us constrain the properties of the shock model as well as indicate whether other modes of X-ray production should be invoked. For example, the maximum X-ray temperature will be determined by the

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maximum velocity jump across shock fronts, so the X-ray spectral properties provide information about the strength of the shocks. 3) There is an interesting variety of stars in the B spectral class which may exhibit X-ray emission properties reflecting the underlying physical processes which define these classes of stars. The β Cep variables exist in the spectral range B1–B2. The radial pulsations of these stars could lead to periodic shocks as a fast wind from the star in its compressed state collides with a slower wind when the star is in a more extended state. The Be stars are rapidly-rotating stars of special interest to us: very little is known about their X-ray properties. At the conclusion of the Einstein satellite survey of hot stars, only one non-binary Be star had been observed in X-rays. Now there are observations of several others, and we can see if the presence of a disk around these stars gives rise to additional X-ray emission.

Even before our *ROSAT* observations were made, it could be assumed that the X-rays would be soft and of low luminosity, L_X. The softness is expected because of the relatively small shock-jump velocities likely for the slower winds of B stars. The total luminosity is expected to be small for two reasons. Firstly, if the $L_X/L_{bol} \sim 10^{-7}$ relationship known to hold for O stars continues into the B-star range, then the lower-luminosity B stars will have correspondingly lower X-ray emission. Secondly, as the winds get thinner with later spectral type, there is simply less material with which to produce X-rays. Beyond some spectral type we expect the level of X-ray emission to fall below our detection threshold.

With these characteristics in mind, we chose to observe B stars that are nearby and have low interstellar column densities. This latter attribute is crucial for soft X-ray sources because the opacity of interstellar matter varies roughly as ν^{-3}. Estimates of the column densities in stars with negligible extinction were, for the most part, taken from the Na I interstellar absorption studies of our collaborators: Welsh, Vedder & Vallerga (1990). The column densities are typically in the range $\log N_{\mathrm{H}} = 18.0$–$19.5$. The detection limit for our sample stars varies, but is typically 5×10^{27} erg s^{-1}. This detection limit is more than an order of magnitude below the limit of the *ROSAT* all-sky survey (RASS).

2. Results of the *ROSAT* Observations

Fig. 1a shows the energy distribution of the X-rays from a typical B star, α Vir. As expected, the X-rays are very soft, with the count distribution peaking at about 0.2 KeV. This is to be compared with a peak at 0.8–1.0 KeV in a typical O star and OB supergiant X-ray spectrum. The decrease in the count rate towards lower energies is due to the sensitivity of the *ROSAT* detectors, so these stars have spectra about as soft as is possibly observed. To determine the temperature of the emitting plasma and

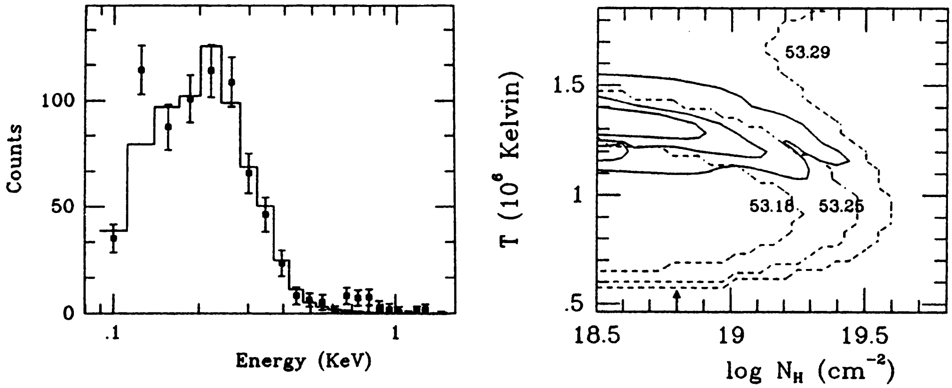

Fig. 1. The left panel shows the *ROSAT* spectrum of α Vir in PSPC counts versus energy. The right panel shows the results of a statistical analysis of the data, which provide information on the source temperature, source emission measure and the column density of the intervening interstellar material.

to assess the amount of absorption, we fit models of optically-thin thermal (line plus bremsstrahlung) emission (Raymond & Smith 1977). These models also include attenuation by neutral material (Morrison & McCammon 1983) with column densities equal to or greater than the known interstellar column densities. Fig. 1b illustrates the section of parameter space which is consistent with the data using χ^2 confidence limits defined for a joint probability distribution (Lampton, Margon & Bowyer 1976). The figure shows the results of calculations of a grid of models in $T - N_H$ space, with the emission measure of the best fit models at each point indicated by the dotted contours. The solid χ^2 contours correspond to confidence limits of 68, 95, and 99 per cent. As is typical for B stars in the sample, the column density we derive does not need to exceed the interstellar value (indicated by an arrow), although values somewhat higher than interstellar cannot be ruled out. Note that neutral gas with a column density of 10^{19} cm^{-2} has optical depth unity at the low energy end of the *ROSAT* PSPC detector. We are able to constrain the temperature to 1.3×10^6 within a factor of 25 per cent in either direction. The emission measure is a few times 10^{53}. The X-ray luminosity we derive for this source is 4×10^{30} erg s^{-1}.

Fig. 2 shows the emission measures and source temperatures of the stars in our sample to which we fit spectral models. The uncertainties correspond to the 68 per cent confidence limit as in Fig. 1b. With one exception, the temperatures are "low": about $1 - 4 \times 10^6$ K versus $5 - 8 \times 10^6$ K for typical early O-stars. The exception is the well studied "standard star" τ Sco. To fit its spectrum requires a two-component model with the high temperature being about 10^7 K as indicated in Fig. 2.

Fig. 3 shows the ratio of L_X/L_{bol} versus spectral type from O9.5–B7. For

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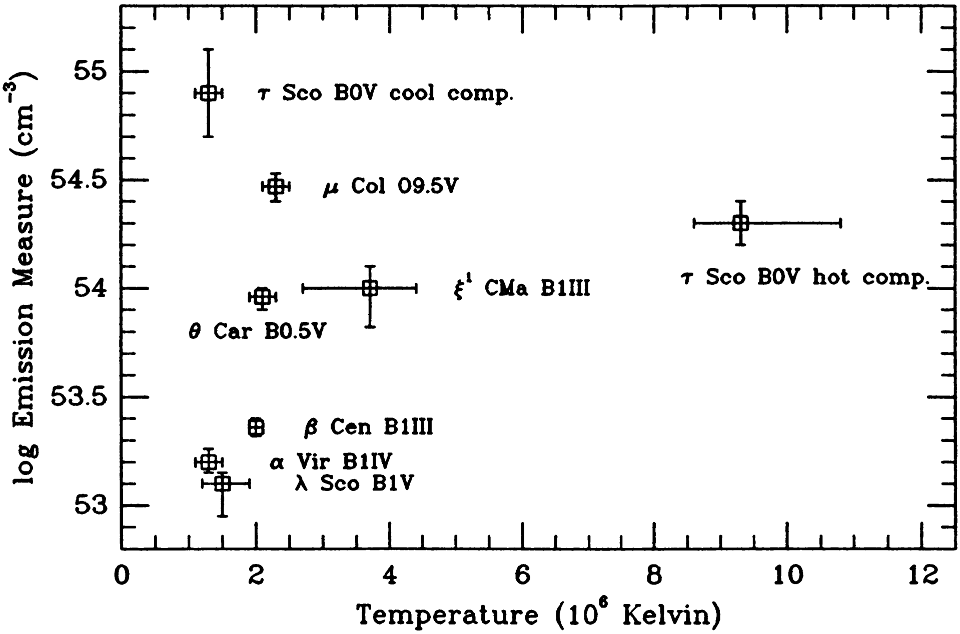

Fig. 2. The emission measures and source temperatures of the objects for which a spectral analysis could be made.

the earlier stars, the ratio is not much different from the value 10^{-7} in the O stars. However, in the B2–B3 spectral range there is a large decrease in the L_X/L_{bol} ratio to values near a few times 10^{-9}. Several classes of B stars are noted in the figure. The solid circles represent the β Cep variables. Also of special interest are observations of several Be stars. It is very interesting that there is essentially no difference between the X-ray luminosity of the Be stars and normal B stars of the same spectral class. The same can be said of the β Cep stars, but since there are no stars of the same spectral type which are not also variable, the comparison is more difficult.

These results for L_X/L_{bol} are quite different from those that have been reported from the RASS by Meurs *et al.* (1992) and Berghoeffer & Schmitt (1994). These authors find that there is a continuation of the 10^{-7} law throughout the B spectral range extending to late-B stars. However, the RASS observations were typically only about 400 s and only about 5 per cent of the B stars were detected. By contrast, we have a 2.5 σ level or higher detection in *all* our targets. Perhaps about 5 per cent of the stars are of a higher luminosity type similar to τ Sco. Alternatively, perhaps the ones that are seen in the RASS are just on the high X-ray luminosity tail of the distribution. It may be true that *all* B stars are X-ray sources at about

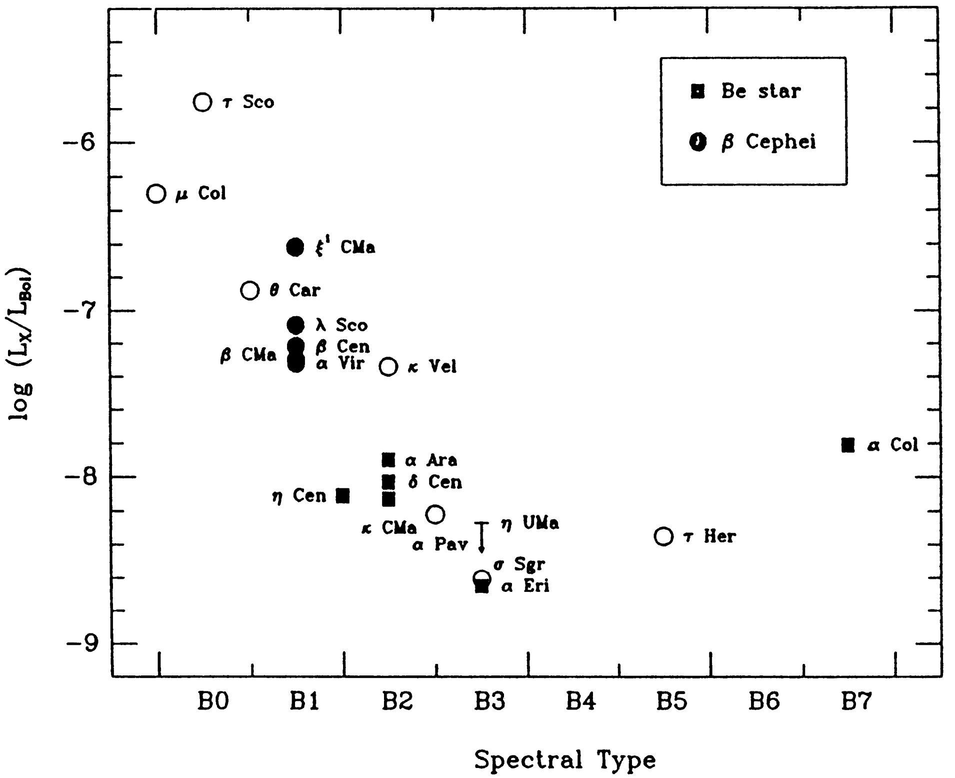

Fig. 3. The ratio of the X-ray luminosity to bolometric luminosity versus spectral type of our targets. All were detected at the 3 sigma level except for η UMa which was detected at the 2.5 sigma level.

the $L_X \sim 10^{-9} L_{bol}$ level or higher. This is probably the most surprising suggestion resulting from our survey thus far.

We also performed time variability analyses on those observations which had high enough count rates. This includes all those stars for which we fit spectral models. We observed most of these stars continuously for one or two kiloseconds. Several stars were observed two or more times, with the separate observations spread out over many hours or even months. The variability analysis was hampered by the presence of spacecraft wobble. This is employed to average obscuration by window support wires over a large area of the image plane (Downes *et al.* 1991). The wobble has a period of 400 s, making variability analysis on timescales of a few hundred seconds problematic. Variations of a *ROSAT* point source intensity up to about 25 per cent are known to occur (Dennerl & Kurster 1993). We found no evidence of variability above this level on timescales up to a few thousand seconds for any of the seven stars which we subjected to analysis, including the four β Cep variables. For two of the variable stars in the sample, α Vir and β Cen, and for τ Sco, we have several observations of each separated by days or months. For each object, the count rates of the different observations are consistent with a constant source at about 5–10 per cent. The hardness ratios of the different observation segments are also consistent with each other within the quoted uncertainties (of about 10 or 20 per cent). We caution that these results are for short segments of data or for poorly-sampled data. However, we can rule out large and rapid variability (say of a factor of one half over hundreds or thousands of seconds) in either the normal B stars or in the known variables. In a future paper, Finley, Cohen & Cassinelli (1994) will report on the final results of a *ROSAT* survey of β Cep variables which includes ten objects observed for up to 20 kiloseconds.

As mentioned above, we expected to find variability in the X-ray emission of the β Cep stars reflecting wind variability induced by photospheric pulsations. We thus far have no solid evidence for this. Furthermore, general variability is predicted in the hydrodynamical models of O- and B-star winds (Cooper 1994).

3. Interpretation of the L_X/L_{bol} behaviour

The softness of the spectra is not unexpected, but the fact that the X-rays persist through the full spectral range of our survey is surprising. The first question we should try to understand is: why is there a strong decrease in the L_X/L_{bol} relation at about B2–B3? Perhaps there is simply too little material in the wind to maintain the higher value of the ratio. To test this basic idea, we computed a plausible upper limit to the X-ray emitting emission measure in B stars. The upper limit represents the emission measure of the "entire wind". Our assumption is that the X-rays are produced by strong shocks which need a significant wind velocity to form. Thus we integrate the expected wind density structure from infinity down to the point in the wind where the velocity is 267 km s^{-1}, the jump speed required to produce gas at 10^6 K. We show three O stars for comparison and, due to their higher terminal velocities, we use 500 km s^{-1} for the integration limit. These upper limits are shown in Fig. 4.

To compute the emission measures, we need to know the density distribution in the wind. Unfortunately, observations provide almost no information about this, so we have chosen to follow Bjorkman & Cassinelli (1993) and use line-driven wind theory to provide the mass-loss rates and wind speeds that are expected for B stars. This requires that we specify the CAK line wind parameters k, α and δ—which we take from Abbott (1982)—and use the fitting formula of Kudritzki *et al.* (1989) to get the values for $\dot{M}$ and v_∞. We

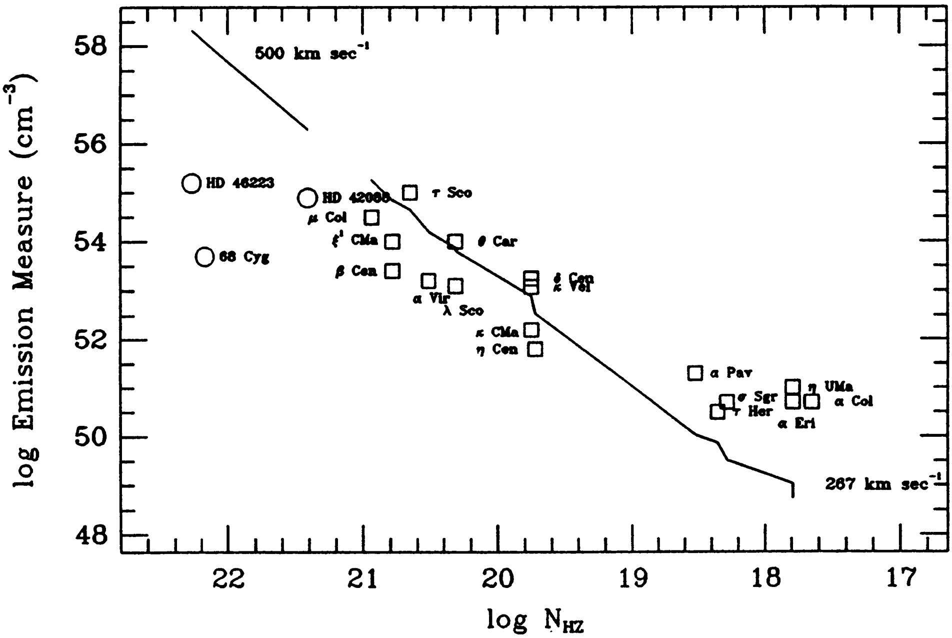

Fig. 4. X-ray emission measure versus a measure of the wind column density estimated from wind theory. Also shown is a line of the estimated "maximal emission measure" taken to be the emission measure of the entire wind.

assume a smooth distribution of material in the wind for the calculation of the emission measure. Any clumping will increase the emission measure, but since the winds are relatively thin, the cooling lengths will be long and the shocks can be considered to be adiabatic. Hence the density enhancement will not be excessive. Finally, we use the ratio $N_{HZ} = \dot{M}/(v_\infty R_\star 4\pi \mu_H m_H)$ as an indicator of wind column density. This is a better quantity to use for comparison of the results than spectral type or T_{eff}, because we have stars with a range of luminosity classes (V–III) and wind properties depend also on luminosity and surface gravity, and their effects are included in N_{HZ}.

The trend we see in Fig. 4 is that both the observed and predicted emission measures fall with N_{HZ}, but that the observed values do not fall as fast as predicted by standard wind theory. By about spectral type B2.5, the observed emission measures exceed those predicted for the entire wind. In this instance we are learning something about the properties of the winds from the X-ray observations. The inconsistency could be resolved if we postulate that the B stars are better than expected in driving a stellar wind. The early-type B stars exhibit emission measures which, while consistent with the upper limit shown in the figure, are high compared to the predictions of hydrodynamical simulations (Cooper & Owocki 1994). These high emission measures pose a real problem for radiation-instability shock models which indicate that most shocks are reverse shocks with rarefied, fast gas accelerating into the shock zones. Only a small fraction of the wind material is hot at any given time in these models. Note that our calculations show that the very high X-ray luminosities found in a small portion of the RASS sample cannot be supported by any reasonable stellar wind. The source of their X-ray emission is a real puzzle.

4. X-rays from Be Stars

Since some of our targets are Be stars, it is interesting to draw conclusions about the nature and origin of their X-rays. With the Wind Compressed Disk (WCD) picture of Be stars in mind (see the paper by Jon Bjorkman in these Proceedings), there are several possible source locations. a) There should be shocks in radiatively-driven winds that are coming from the poles of the WCD envelope model. These should be very much like the X-ray emitting regions of ordinary B stars which do not have disks. b) There are shocks at the upper and lower boundaries of the WCD disk which are responsible for the high compression of the material in the disk around the stars. c) There is an infall shock at the surface of the star in the equatorial region as deduced from 2-D modelling by Owocki, Cranmer & Blondin (1994). They found that there should be a stagnation point in the disk, inwards of which there should be an infall toward the star and beyond which there should be an outflow. d) There could be hot gas confined to magnetic structures on the star. Smith *et al.* (1993) deduced from their X-ray observation of the Be star λ Eri that a flare of X-ray emission occurred. During the flare the X-ray emission changed from the soft X-ray spectrum that is seen in the other B stars, to a two-component picture with a 10^7 K component. Recall that in τ Sco we found a hot component that might perhaps be indirect evidence for the presence of hot, magnetically-confined gas. This may be related to the possible status of τ Sco as a pole-on Be star (Waters *et al.* 1993).

Since our observations of Be stars indicate that their X-rays have the same properties as those from normal B stars, we conclude that their X-rays are coming primarily from the polar wind component. The WCD boundaries are basically too cool to provide X-ray emission, although they are warm enough to provide the enhanced superionization that is detected as discrete absorption components in the UV spectra of Be stars (Grady *et al.*1989). There is also no clear evidence for X-rays from the infall shock. Perhaps the infall loss of material in the disk is occurring at a reduced rate. This could potentially explain one of the major problems with the WCD model: that the disk is "too leaky". Material flows out from the disk in two directions (J. Bjorkman, these Proceedings) and causes the mass in the disk to be too small to explain the IR excess and polarization observations.

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Discussion

Smith: Why are your L_X/L_{bol} values at spectral classes B2–B4 so much lower than is shown in papers in the literature and in posters at this meeting?

Cassinelli: The results that have been presented elsewhere are for the *ROSAT* all-sky survey observations, which were for durations of only about 400 s. Only about 5 per cent of the later-B stars were detected, whereas we detected all of our targets, and one of our 20 stars (τ Sco) is anomalous. So perhaps, the all-sky survey is picking up a "τ Sco class" of hard

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and luminous X-ray emitters. Perhaps there is a continuous distribution of B-star X-ray emitters, with the luminous ones being well out in the tail of the X-ray luminosity distribution. In either case, there is an indication that another cause of X-ray emission is present other than the wind shocks that we investigated. Even the relatively low X-ray luminosities that we are detecting seriously strains the shock model. Possibly the extra cause of emission is related to the magnetic phenomena that you observe in λ Eri (Smith *et al.* 1993).

Sofia: There has been a recent proposal that "dynamical friction" might heat the winds of early-type stars. This interaction is strong when the relative velocity between fast ions and wind is not too large, and stops for larger velocities. Perhaps the emission for B stars may be due to this effect.

Cassinelli: A dynamical friction or driving ion runaway model has recently been studied by Springmann & Pauldrach (1992). The drift speed between ions that are driven by the stellar radiation field and the wind material increases in the outward direction. This could in principle lead to the heating of the outermost regions of the wind and to a terminal wind speed that is less than expected without the runaway. I do not think the mechanism would lead to the production of X-ray emitting temperatures, however.

Ghosh: You have suggested a wind-shock model for the production of X-rays in Be stars. However, we should expect to find a frequency dependence of optical polarization from the envelope of Be stars, and that is not seen.

Cassinelli: To affect the polarization, a blob or shock fragment or whatever would need to have an optical depth near unity in electron scattering opacity. I am quite sure that the optical depths associated with the wind shocks of near main-sequence B stars are small. There can be large optical depths in the disks around Be stars. Karen Bjorkman (these Proceedings) has discussed the wavelength dependence of polarization in Be stars observed at ultraviolet wavelengths.

Owocki: When speaking about the canonical relation $L_X \sim 10^{-7} L_{bol}$, I think it is important to bear in mind that the *observed* X-rays could be a small fraction of the *intrinsic* X-ray emission produced by wind shocks. Theory suggests that the latter should perhaps be proportional to the mass-loss rate, which for the CAK model scales something like L_{bol}^2. For O-stars, it may be that true absorption in the wind effectively reduces this to $L_X \propto L_{bol}$. In this context it is actually somewhat encouraging to see a steeper L_X decline for the B stars, for which the winds are optically thin enough to observe even the soft X-rays.

Cassinelli: Yes, optical thinness is one of the real advantages for the B stars. We calculated the X-ray emission associated with just a single shock to find a plausible lower limit to the X-ray emission of these stars. The X-ray luminosities of BV stars of spectral class B0–B2 lie within the two limits derived from a single shock, and from the entire wind. In the case of the O stars, we find that the observed X-ray luminosity is roughly consistent with the idea that we see just the outermost shock. Nearly all of the X-ray emission from the inner shocks is attenuated by the overlying wind. The 10^{-7} law has been known since 1979, but it has not been adequately explained yet.