HIGH-RESOLUTION X-RAY SPECTROSCOPY OF β CRUCIS: A NEARBY HOT STAR WITH A HIGH X-RAY COUNT RATE

1 Scientific Background

The origin of X-ray emission from early-type stars has been a mystery since its surprising discovery more than 25 years ago (Cassinelli & Olson 1979; Harnden et al. 1979). The advent of high-resolution astrophysical X-ray spectroscopy adds a new dimension by providing constraints on models of hot star X-ray production. Unfortunately, only a handful of non-interacting hot stars have X-ray fluxes high enough to yield an adequate signal-to-noise spectrum in a reasonable length exposure. Our proposed target, the B0.5 III star β Cru, has the highest ROSAT count rate (1.5 c s^{-1} in the PSPC) of any single early-type star not already observed by Chandra.[1] We propose to to use the Chandra HETG to observe β Cru, and to analyze these data in conjunction with other existing hot-star X-ray spectra to guide our ongoing efforts to develop theoretical models for the origin of hot-star X-rays.

Following the original discovery, initial models for hot-star X-ray emission centered on analogues to the heating and X-ray production of the solar corona (Cassinelli & Olson 1979). But such a solar analogy seems at odds with many basic properties of both hot-stars and their observed X-rays – lack of convective energy to heat a corona; clear presence of UV driven wind at moderate temperatures; lack of wind X-ray absorption edges expected for base corona; and the general scaling of L_x with L_{bol} instead of with rotation speed. Over the years, consensus has thus instead favored an *Intrinsic Wind Shock* (IWS) model, in which the X-ray emission comes from shocks distributed throughout the wind, most likely arising from the strong, intrinsic instabilities in the wind driving by line-scattering (Owocki, Castor, & Rybicki 1988). In addition, for those hot-stars showing evidence of rotational modulation of their wind and/or X-ray signatures (e.g. θ^1 Ori C), or showing anomolously hard X-ray spectra (e.g. τ Sco), there has developed in recent years a model based on *Magnetically Confined Wind Shocks* (MCWS) (Babel & Montmerle 1997). Though such models still must posit the presence of strong surface fields of several hundred Gauss (roughly the order of current observational upper limits), there is less need to invoke active field generation than in the coronal-type picture, wherein heating is envisioned to come from the ongoing reconnection. As such, the MCWS paradigm may apply to relatively young stars that retain a fossil field from their initial formation.

Recent spectroscopic observations have provided important new tests for each of these pictures. For ζ Puppis (O4Ife), Chandra HETG spectra (Cassinelli et al. 2001) show broad (HWHM $\sim$ 1000-1700 km s^{-1}), blue-shifted, and asymmetric emission lines that are generally quite consistent with the wind emission and absorption expected for the IWS model. However, the forbidden to intercombination (f/i) line ratios for the highest energy transitions (e.g. S XV) suggest formation very close to the stellar surface, a characteristic that may be difficult to reproduce in the IWS picture. Moreover, Chandra HETG spectra of ζ Ori (O9.7 Ib) show X-ray profiles that are still broad (HWHM $\sim$ 1000 km s^{-1}), but with little or none of the asymmetry or blue-shift expected from a wind models (Waldron & Cassinelli 2001). And the f/i line ratios in this star again suggest formation nearer to the surface than expected from IWS picture. On the other hand, a coronal-analogue model would require an extreme level of turbuent motion to explain the line-broadening. The other two hot-stars with HETG spectra reported thus far, are τ Sco and θ^1 Ori C. Both of these seem likely candidates for the MCWS model. For the latter star, published results suggest only modest line-broadening (HWHM $\sim$ 500 km s^{-1}, and little asymmetry or blue-shift) (Schulz et al. 2000). Our own preliminary analysis of our HETG spectra of τ Sco suggests similar results for the line profiles, perhaps with slightly lower characteristic velocity widths.

2 HETG Spectroscopy of β Cru

Within this context, β Cru is an attractive spectroscopic target for Chandra because of its X-ray brightness and its relative normality. Its brightness stems primarily from its proximity (D = 107 pc from Hipparcos), as its intrinsic X-ray luminosity is in line with the $L_X/L_{bol} \sim 10^{-7}$ scaling law that holds for most O and very early B stars. Compared to the very young hot stars θ^1 Ori C and τ Sco, β Cru appears to be slightly evolved off of the main sequence (Feigelson & Lawson 1997), and has a relatively soft ROSAT spectrum (Cohen et al. 2001). As such, it represents an excellent opportunity to study the base-line level of X-ray emission that may be due to wind shocks.

[1] Only seven stars in the ROSAT OB catalog have higher PSPC count rates than β Cru (Berghöfer, Schmitt, & Cassinelli 1996), and several of these are interacting binaries (e.g. Cyg X-1). Furthermore, the PSPC count rate of β Cru is misstated in this catalog, but is listed correctly in the ROSAT bright source catalog, and is confirmed by a long pointed ROSAT observation which is reported in Cohen, Finley, & Cassinelli (2001).

As a B star with a lower density wind than ζ Pup, however, it requires a higher X-ray volume filling factor and thus provides a stringent test of the IWS model (Cooper 1994; Cohen, Cassinelli, & MacFarlane 1997). If the Chandra spectrum indicates that instability-generated wind shocks cannot explain the X-ray emission, then it would suggest further exploration of magnetic models, either coronal or MCWS. As discussed further below, our group is especially well-qualified to explore and test both the IWS and MCWS models.

Thus, Chandra spectroscopy of β Cru will provide a high signal-to-noise data set of a normal early-type star that will facilitate direct comparisons with the other Chandra spectral data from the more unusual and extreme hot stars. The comparison with τ Sco will be especially illuminating, as this star has a very similar spectral subtype to β Cru, with a similar wind mass-loss rate and terminal velocity[2]. If the physical processes on τ Sco are unusual and definitely involve magnetic confinement, then β Cru could be the first normal B star observed spectroscopically in the X-ray at high-resolution. And therefore it might be the best test of wind shock models (whatever their physical origin) at low mass-loss rates.

Some of the diagnostics we will apply to the β Cru HETG dataset include:

- Line profiles – Are there any wind-induced asymmetries (Owocki & Cohen 2001)? If the profiles are instead symmetric, how much broadening is there compared to τ Sco and to the O stars, which have even higher HWHMs? If X-ray line formation is near the surface (see next item) are there any occultation-induced asymmetries?

- Intercombination-to-forbidden line ratios in helium-like O, Ne, Mg, and Si – These provide diagnostics of electron density and radiation flux (and thus line formation radius through the dilution-factor) (Kahn et al. 2001; Waldron & Cassinelli 2001). These line ratios can be used to discriminate between the MCWS model (high densities and proximity to the photosphere) and spatially distributed wind shocks (low densities and farther from the photosphere). Note that the UV fluxes in B stars are lower than in O stars, and thus this diagnostic is, to some extent, sensitive to electron density.

- H-like/He-like and (f+i)/r ratios – These provide information about the plasma temperature distribution (Porquet & Dubau 2000) (i.e. differential emission measure), and thus constrain the requirements of any physical model of the X-ray production.

Finally, we note that β Cru is a β Cephei variable, pulsating in several non-radial, relatively high-l modes. Cohen et al. (2001) have shown the ROSAT X-ray data are modulated on the 4 hour primary pulsation period at the 5% level. These low level photospheric pulsations are not likely to be the direct cause of the X-ray emission, but we can use any time-variability present in the Chandra spectrum to probe the photosphere-wind connection, which has been the subject of much debate recently (Massa et al. 1995). We will explore the time-dependence of each of the individual diagnostics outlined above to look, for example, at changes in the line profiles with pulsation phase.

3 Analysis and Modeling Capabilities

Our team has a wide range of modeling and analysis tools to extract the maximum amount of information from this data set.

We have been performing numerical simulations of the line-force instability in radiation-driven winds for over a decade (Owocki et al. 1988), developing progressively more sophisticated treatments of the non-local line transport (Owocki & Puls 1996). We are currently preparing manuscripts on the temperature distribution with radius in these numerical simulations as well as on line synthesis in quasi 3-D simulations. In Figure 1 we show time-dependent output from a typical wind instability simulation.

We have also recently begun to calculate self-consistent MHD simulations of the MCWS model. These models do not include the line-force instability, but go beyond the original work of Babel & Montmerle (1997) in that the magnetic field morphology is computed dynamically along with the wind flow. Our prelimary results indicate that copius hot plasma can be produced in the magnetic equator at the tops of closed loops where oppositely-directed wind streams collide. The level of shock heating seems to be governed by the relative strength of the field and the radiation-driven wind. The softer X-ray emission seen in β Cru may be explained in the context of MCWS by a weak field that can confine the wind only at low velocities. In Figure 2 we show an MHD simulation of the MCWS model.

[2] The mass-loss rates are calculated to differ by a factor of less than two ($\sim 3 \times 10^{-8} M_{\odot}$ yr^{-1} for τ Sco and $\sim 6 \times 10^{-8} M_{\odot}$ yr^{-1} for β Cru), and terminal velocities are nearly identical according to the line-force parameter tabulation of Abbott (1982).

We have a suite of codes that are used for non-LTE wind ionization/excitation calculations, and include associated codes for calculating atomic input data (*e.g.* MacFarlane, Cohen, & Wang 1994). We are currently using them to more fully explore the relative effects of photospheric radiation and electron collisions on the helium-like forbidden-to-intercombination line ratios (MacFarlane et al. 2000). These codes, more generally, can be used to supplement the standard coronal plasma codes (e.g. Raymond-Smith) as we can include an arbitrary amount of detail in the atomic models as well as including numerous atomic processes, some of which are not included in the coronal approximation used in the off-the-shelf codes, and optical depth effects.

We have also been calculating semi-analytic X-ray line profiles based on models of X-ray emission and absorption in an accelerating stellar wind (Owocki & Cohen 2001). This work demonstrates the different line-profile trends one would expect to see from a coronal model versus a wind-shock model.

Finally, several members of our team have extensive experience working with high-resolution EUV and X-ray spectra, not simply from Chandra (and soon XMM), but also from EUVE. In addition, our team has extensive experience analyzing and modeling data from high temperature plasma experiments in the laboratory (e.g. Bailey et al. 1997).

4 Technical Justification

Our target, β Cru has high visibility for nearly all of the AO3 observing season. While the ROSAT field around this star has a fair number of X-ray sources, only one is within 10 arc minutes, so a grating observation should be relatively straight-forward.

We are requesting a 90 ksec HETG observation based on simulations we have performed using XSPEC, the parameters of which are based on the ROSAT PSPC observation. In Figure 3 we show a simulated MEG first order spectrum assuming a two-temperature thermal model. We also show the helium-like magnesium FIR complex from this simulation and compare it to the HETG measurement of the same complex in the τ Sco spectrum. We are requesting the 90 ksec in order to build up sufficient signal to noise in as many lines as possible so that we can reliably measure the line profiles, and to have sufficient signal to noise in the forbidden and intercombination lines in the helium-like silicon to make a meaningful measurement of those line ratios. We find in our τ Sco HETG spectrum that over 100 counts per line are required to confidently measure the modest line broadening that is present in that source. The XSPEC simulation indicates that we can expect about 0.18 c s^{-1} in the combined +1 and -1 order MEG spectra. We verified this number using PIMMS.

We are requesting an HETG (as opposed to LETG) observation to facilitate comparison with the extant Chandra spectra of hot stars, especially τ Sco. The HEG/MEG spectra will also provide the best possible resolution (compared to either Chandra LETG or XMM RGS) for the analysis of line profiles and line shifts and to separate the different components of the fir line complexes and other closely spaced lines.

5 References

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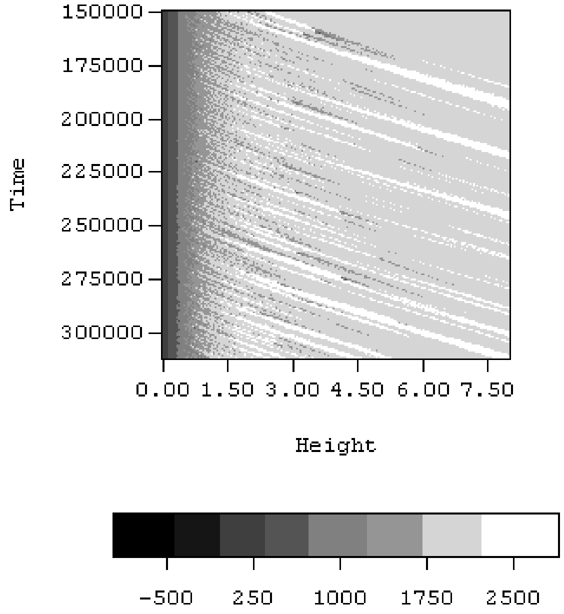

Figure 1: Velocity structure in a hydrodynamics simulation of a radiation-driven hot-star wind subject to the line-force instability. Note the onset of structure below 1 stellar radius, and the multiple interactions of different wind streams above this height, leading to shock-heated gas.

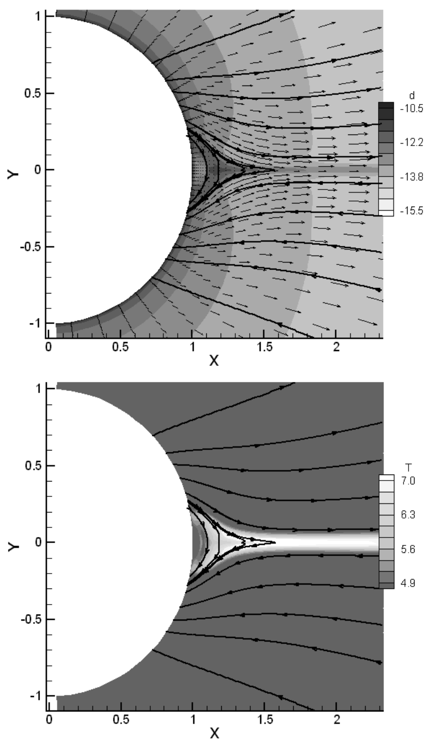

Figure 2: Log of density (top) and temperature (bottom) structure in an MHD simulation of the MCWS model. Note that the shock-heated plasma in the equatorial plane arises from the focusing of high-latitude wind material by the magnetic field (velocity vectors superimposed on the top plot and field lines shown as contours on both plots).

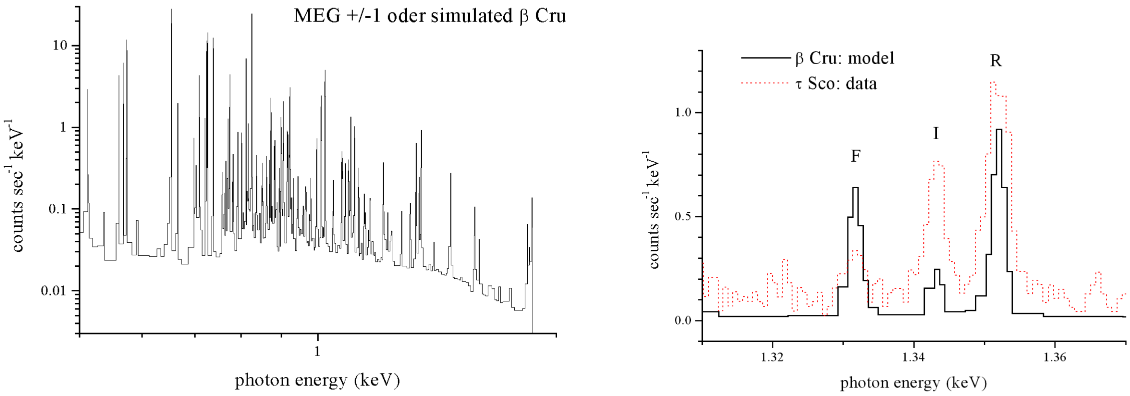

Figure 3: 90 ksec simulated MEG (sum of + and - first orders) spectrum of β Cru. This simulation assumes a two-temperature (2.5 and 5 MK) coronal equilibrium model with 60 % of the emission measure in the cooler component. These model assumptions are consistent with the ROSAT PSPC data, and are relatively conservative in the sense that the temperature distribution is on the cooler side of the models that fit the ROSAT data. On the right, we compare the *observed* Mg XI FIR lines from τ Sco with those from the β Cru model. Note that the f/i ratio in τ Sco is about 0.3, as some combination of the photospheric radiation field and electron collisions are quenching the forbidden line. In the β Cru model we show the case of low density and low flux, so that f/i > 1.