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AN X-RAY ANALYSIS OF α CRU

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ABSTRACT

The star α Cru is an early B type subgiant star recently observed by the *Chandra X-ray Observatory*. This star is of particular interest due to the observed X-ray emission produced by shocks that form in the stellar wind. We observe hydrogen-like Oviii and helium-like Ovii spectral lines in the Low Energy Transmission Grating spectrum. The Ovii produces a characteristic triplet line. We provide an analysis of the helium-like triplet that explains the conditions in the stellar wind where that line emission is formed. α Cru is also an ultraviolet bright star, so an International Ultraviolet Explorer observation is used to explain the effect of ultraviolet pumping on the forbidden component of the Ovii triplet line. The data appear basically consistent with theoretical models of shocks in stellar winds by Owocki, Castor,& Rybicki (1988) and Feldmeier et al. (1997).

Subject headings: X-rays stars: early-type—stars: α Cru—stars: winds, outflows

1. INTRODUCTION

B stars have relatively short lifetimes on the order of 10^8 yr, after which they terminate in a supernova. X-ray emission is observed from B type stars throughout their lifetime. As massive stars are not expected to have coronae, X-rays must be produced by some other mechanism. X-rays can be formed in hot gas created as a result of wind shocks as modeled by Owocki et al. (1988).

The star α Cru is a relatively unstudied early B subgiant star. It was observed 2008, August 5 with the *Chandra X-ray Observatory*. Specifications about the observation session and instrument are presented in § 2.1. From the X-ray spectrum obtained from *Chandra* we can deduce the conditions that produce the emitted X-rays.

In the spectrum, hydrogen-like and helium-like species of metallic elements in the wind are detected. These ions indicate that there are regions of extreme temperature in the wind. In particular we detect Oviii Lyman α and β lines and Ovii which are crucial to our analysis of the star. The helium-like Ovii ion produces triplet lines. The line transitions are referred to as resonance (r), intercombination (i), and forbidden (f) (see Gabriel & Jordan 1969). In § 3.1 and § 3.2 we discuss how to determine plasma temperature and where shocks start forming relative to the stellar photosphere, based on fluxes of the triplet line components.

2. OBSERVATION AND DATA REDUCTION

2.1. *The* Chandra *LETG HRC-S Spectrum*

The α Cru spectrum was obtained with the Chandra Low Energy Transmission Grating Spectrometer and High Resolution Camera Spectrometer. The star was observed for 30 ksec. The default bin size on the LETG HRC-S is 0.0125 Å over the spectral range 1.2 – 175 Å. For the α Cru observation, we used pipeline data for our spectral analysis. Observation specific response and bad pixel files were generated for use during the reduction. No grouping of bins was performed on the data and instrumental background was not subtracted. All analysis and reduction was done with the Chandra Interactive Analysis and Observations software 4.1.2 and Chandra Calibration Database 4.1.2, henceforth CIAO and CALDB respectively. Only the negative first order spectrum was used for this initial analysis. Figure 1 shows the entire spectrum. There is a detector gap at 50 Å as can be seen in Figure 1. This portion of the spectrum is ignored in our analysis.

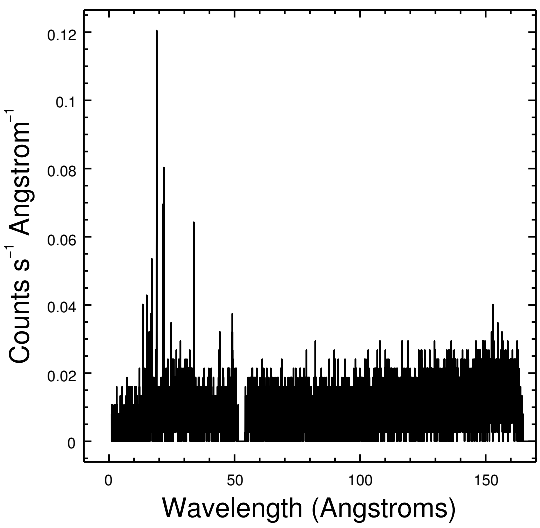

Fig. 1.— The LETG-S spectrum of α Cru. There is a detector gap at 50 Å.

2.2. *Line Identifications*

We searched for strong emission lines in the spectrum. We identified Lyman α and β lines of Oviii, the Ovii

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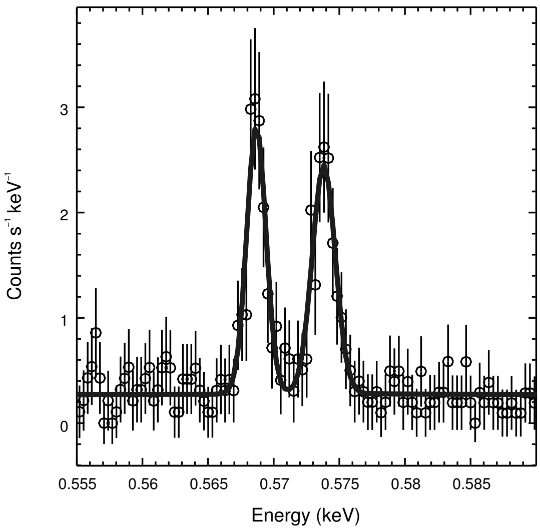

FIG. 2.— The OVII triplet line is fitted with two Gaussians and a constant to determine line fluxes. Only r and i components are detected.

triplet, NeIX, and FeXVII. The NeIX is helium-like, and thus should display emission similar to that of OVII; however, the lines are weak and unresolved. The identification of the spectral lines was done by referencing the atomic database and comparing values of their position on the spectrum .

2.3. *Spectral Modeling*

Each spectral line was fitted with a Gaussian model in the CIAO modeling package SHERPA. To assess the quality of a fit the SHERPA statistical method used was CSTAT. CSTAT uses Poission statistics to assess the quality of a fit. A constant was added to the Gaussian models to account for the continuum emission. In the case of the undetected forbidden component to the OVII triplet, we used the continuum noise level as an upper limit to the peak line flux. The reduced χ^2 for each fit is approximately 1.2, indicating a good fit. The results can be seen in Table 1. The OVII resonance and intercombination lines were fitted simultaneously. This was done using the sum of two Gaussian models and a constant. The same process was performed on the OVIII β and FeXVII lines due to their proximity in the spectrum.

The star α Cru is an ultraviolet bright star, and ultraviolet light can excite electrons from the forbidden state to the intercombination state, diminishing the forbidden line. There are two contributing wavelengths at 1623.9 Å and 1634.0 Å. We used an archival International Ultraviolet Explorer observation of α Cru to determine the ultraviolet flux of the star. Table 2 lists the wavelengths and fluxes from the IUE observation that were used for our analysis.

3. RESULTS

3.1. *Plasma Temperature Determination*

Line fluxes from Helium-like triplet components allow the temperature of the hot gas in which the lines formed to be determined. The plasma temperature is related to the ratio, denoted by G, of the sum of forbidden and intercombination line fluxes to that of the resonance line.

$$G(T_e) = \frac{f+i}{r}. \tag{1}$$

Measurements of the forbidden, intercombination, and resonance line fluxes taken from the fits shown in Figure 2 were used along with tables from Porquet et al. (2001). The measured value of G $\approx$ 1 for OVII gives a plasma temperature of 1.5×10^6 K.

3.2. *Location of Shocked Plasma*

Another way in which the Helium triplet line components is used to understand the hot gas component of the stellar wind comes from Gabriel & Jordan (1969). They show how the ratio $R \approx f/i$ relates to density. This relation was revised by Blumenthal et al. (1972) for ultraviolet pumping. The ratio is defined by three values: R_o , ϕ/ϕ_c, and N/N_c:

$$R = \frac{R_o}{1 + \frac{\phi}{\phi_c} + \frac{N}{N_c}}. \tag{2}$$

The expected ratio f/i is defined by atomic parameters. For OVII $R_o = 3.8$ (Blumenthal et al. 1972). In the case of α Cru, the ratio of electron density to critical electron density (N/N_c) is negligible and can be ignored, thus the equation 2 can be written as:

$$R = \frac{R_o}{1 + \frac{\phi}{\phi_c}} \tag{3}$$

The ratio of stellar flux to critical flux (ϕ/ϕ_c) is given by:

$$\frac{\phi}{\phi_c} = \frac{3c^3}{8\pi h\nu^3}\left(\frac{A_u}{A_f}\right)U_\nu, \tag{4}$$

where c is the speed of light, h is the Planck constant, ν is the ultraviolet frequency at which pumping occurs, U_ν is the energy density of radiation at the shock, and A_u/A_f is the ratio of transition probabilities for the ultraviolet and forbidden transitions. Due to the two ultraviolet wavelengths that contribute to pumping, A_u is the sum of the two A values:

$$U_\nu(r_{sh}) = \frac{W(r_{sh})}{c}\left(\frac{D}{R_\star}\right)^2 F_\nu\ , \tag{5}$$

where D is the distance to the α Cru. The radiation at the shock is diluted by a factor $W(r_{sh})$ as compared to a location at the stellar photosphere. This factor is given by:

$$W(r_{sh}) = \frac{1}{2}\left[1 - \sqrt{1 - \frac{R_\star^2}{r_{sh}^2}}\right]. \tag{6}$$

Figure 2 shows the OVII triplet. The resonance and intercombination lines are observed, but the forbidden line is undetected. An upper limit to the specific flux for the forbidden line is obtained from the fit at $\sim$ 0.575 keV where the forbidden line is expected. We adopt the continuum noise amplitude as the amplitude limit for the forbidden line. Only an upper limit is possible as

TABLE 1
Model Parameters and Fluxes

Species	FWHM (keV)	Pos. (keV)	Amp. cts s^{-1} keV^{-1}	C cts s^{-1} keV^{-1}	Red. Stat.
OVIII α	1.34×10^{-3}	0.653	3.79×10^{-1}	1.98×10^{-2}	1.22
OVIII β	5.72×10^{-3}	0.774	2.01×10^{-2}	1.03×10^{-2}	1.43
OVII r	0.88×10^{-3}	0.574	6.81×10^{-1}	3.68×10^{-2}	1.17
OVII i	1.41×10^{-3}	0.569	4.31×10^{-1}	3.68×10^{-2}	1.17
OVII f[1]	1.41×10^{-3}	0.561	$<3.68 \times 10^{-2}$	—	1.17
NeIX	7.42×10^{-3}	0.920	2.66×10^{-2}	0.61×10^{-2}	1.27
FeXVII	1.89×10^{-3}	0.825	7.67×10^{-2}	1.03×10^{-2}	1.43

TABLE 2
IUE Data of α Cru

λ (Å)	Flux (erg cm^{-2} s^{-1} $Å^{-1}$)
1623.9	7.52×10^{-9}
1634.0	8.49×10^{-9}

the flux of the forbidden line cannot be greater than the noise of the observation or the line would be observed. We measure the amplitude of f to be $\leq 3.68 \times 10^{-2}$ counts s^{-1} keV^{-1}.

To find the location of OVII emission in the wind, we can use equations (2) and (4), in addition to the expressions for the dilution factor and U_ν which are found in equations (6) and (5) respectively. Our calculations give $r_{sh} < 5.7R_\star$. This limit appears to be consistent with expectations from model simulations of wind shocks that indicate shocks develop at about $1.5R_\star$ and beyond (Owocki, Castor & Rybicki 1988 and Feldmeier et al. 1997).

4. CONCLUSION

We used the Chandra LETG HRC-S to observe α Cru, an early type B star. The ObsID of the spectral data is 8937. All data reduction was done using the CIAO 4.1.2 software and CALDB 4.1.2. The spectrum is particularly soft compared to the star τ Sco which has a similar spectral type (Cohen et al. 2003).

The OVII line is the most imperative for our analysis. The triplet line ratio forbidden and intercombination to resonance yields a temperature of 1.5×10^6 K, and the lack of an observed forbidden line limits the formation of shocks to within $5.7R_\star$. As previouisly mentioned these results appear consistent with model simulations of wind shocks

The results of our data were from the -1^{st} order spectrum. In the future it would be ideal to add the -1^{st} and $+1^{st}$ order spectra to increase the signal to noise of the data. In addition the entire spectrum should be fit with a broad spectral model to assess the differential emission measure of the hot gas in the stellar wind of α Cru.

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