Chandra X-ray Imaging and Spectroscopy of the Young Sigma Orionis Cluster and its Massive Central OB Stars

Steve Skinner[1], David Cohen[2] Marc Gagné[3], Stan Owocki[4], Rich Townsend[4]

[1] Univ. of Colorado (USA)
[2] Swarthmore College (USA)
[3] West Chester Univ. (USA)
[4] Bartol Research Inst./Univ. of Delaware (USA)

Abstract

We present an overview of a recent *Chandra* X-ray observation of the young σ Orionis cluster (d $\sim$ 350 pc; age $\sim$ 2 - 5 Myr), including high-resolution grating spectra of the massive central O-type star σ Ori A. *Chandra* detected soft emission from σ Ori A that is likely of wind origin, but much harder emission indicative of magnetic processes was detected in the unusual B2Vp star σ Ori E. We use these results to place constraints on the origin of X-ray emission in hot stars, which is currently not well-understood.

1 The σ Orionis Cluster

ROSAT observations near the belt of Orion led to the discovery of a remarkable X-ray cluster centered on the multiple star σ Orionis (Walter et al. 1997). This massive stellar system is a quintuplet dominated by the visual binary σ Ori AB, consisting of a O9.5V star with a B-type companion at an offset of 0.25$''$. The *Hipparcos* distance of σ Ori A is 352 pc. The σ Ori AB system is a luminous X-ray source but the close pair cannot be resolved with existing X-ray telescopes (Fig. 1). The B-type stars σ Ori C and D lie 11.2$''$ and 12.9$''$ away from Ori AB, but they emit little or no X-ray emission. In contrast, the unusual magnetic B star σ Ori E lying 42$''$ away is a hard variable X-ray source (Fig 1.). Its distance is uncertain and it may lie in the background at d = 640 pc (Hunger et al. 1989). Surrounding this massive quintuplet is a large population of X-ray emitting low-mass pre-main sequence stars and several brown dwarf candidates (Adams-Wolk et al. 2003).

The σ Orionis cluster provides an excellent target for studying X-ray properties of a diverse population of young stars with ages of a few million years across the entire stellar mass spectrum. Most importantly, the dust extinction toward the region is quite low ($A_V \approx$ 0.2 mag; Lee 1968), providing access to softer X-rays which may originate in the shocked stellar winds of massive O stars.

2 Chandra Observation

Chandra observed the σ Orionis cluster for 91 ksec on 12-13 August 2003 using the ACIS-S detector and the High Energy Transmission Grating (HETG). Pointing was centered on σ Ori AB. Data were analyzed using standard CIAO threads. Our primary objective was to obtain high quality spectra of the massive stars in the σ Ori AB region needed to test hot star X-ray emission models. We obtained a grating spectrum of the brightest X-ray source σ Ori AB, and 0th order spectra of several other nearby sources including the magnetic B star σ Ori E and low-mass pre-main sequence stars in the surrounding cluster. Figure 1 shows the inner portion of the *Chandra* image.

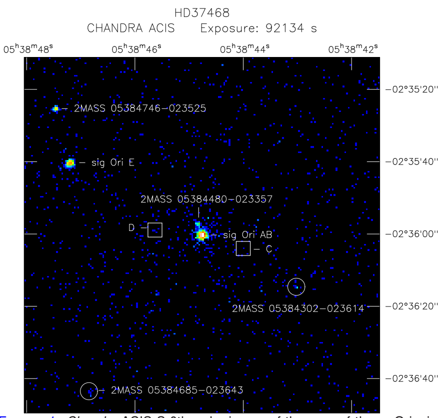

FIGURE 1: *Chandra* ACIS-S 0th order image of the core of the σ Orionis cluster. Boxes enclose the optical positions of the B stars σ Ori C, D.

	σ Ori AB	σ Ori E
Sp. Type	O9.5V	B2Vp
V (mag)	3.80	6.66
Dist. (pc)	352	370 - 640 (uncertain)
v_∞ (km/s)	$\sim$1100	$\sim$420
Binary	yes (0.25$''$)	?
log L_X (ergs/s)	31.6	30.7 - 31.2

3 X-ray Variability

Figure 2 shows the 0th order *Chandra* light curves of σ Ori AB and σ Ori E. X-ray flares have previously been detected in σ Ori E (Groote & Schmitt 2004; Sanz-Forcada et al. 2004), but no large-amplitude variability was detected by *Chandra*. However, low-level variability is likely and a Kolmogorov-Smirnov test gives a variability probability P(var) = 0.995 for σ Ori E. Interestingly, the minimum in the σ Ori E light curve (arrow in Fig. 2) occurs at phase ϕ = 0.75 (Reiners et al. 2000 ephemeris), close to ϕ = 0.8 where the HeIλ4713 line reaches maximum equivalent width.

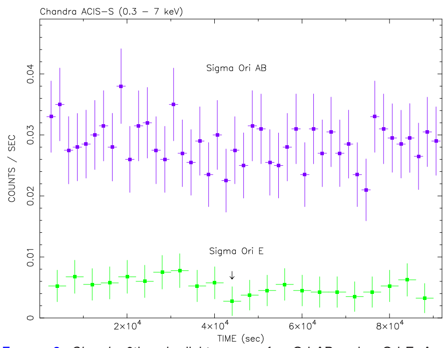

FIGURE 2: *Chandra* 0th order light curves of σ Ori AB and σ Ori E. Arrow marks the minimum at phase = 0.75 in σ Ori E, which occurs near the phase where HeI equivalent width is maximum.

4 Spectra of σ Ori AB and σ Ori E

Figure 3 compares the 0th order X-ray spectra of σ Ori AB and σ Ori E. Although σ Ori AB is brighter in X-rays, its spectrum is much softer with little or no emission seen above $\sim$2 keV. Spectral fits with thermal plasma models give characteristic temperatures of kT $\approx$ 0.2 - 0.3 keV. In contrast, the emission of σ Ori E is fainter, but much harder. Acceptable spectral fits require two temperature components at $kT_{cool} \approx$ 0.7 keV and $kT_{hot} \approx$ 2.2 - 3.8 keV.

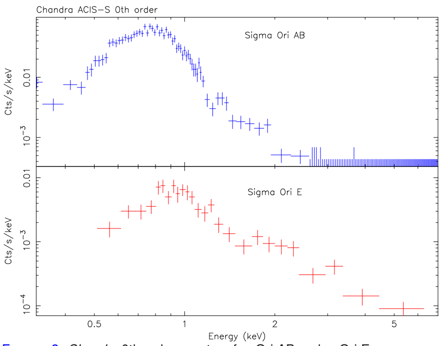

FIGURE 3: *Chandra* 0th order spectra of σ Ori AB and σ Ori E.

The grating spectrum of σ Ori AB (Fig. 4) shows very little absorption and is dominated by low-temperature lines with maximum power temperatures log $T_{max} \leq$ 7.0. The Mg XII (Lyα) line is absent, confirming that the plasma is cool. The weaker lines are narrow, but excess broadening is detected in some stronger lines such as O VIII Lyα (Fig. 5). We find no significant line Doppler shifts in the MEG spectrum. Forbidden lines in He-like triplets are weak, which is most likely due to the strong UV radiation field of the O star.

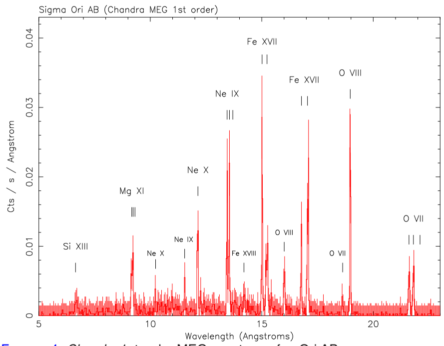

FIGURE 4: *Chandra* 1st order MEG spectrum of σ Ori AB.

5 Constraints on Wind Shock Models

Traditionally, the X-ray emission from hot stars has been attributed to shocks that form as a result of instabilities in their powerful winds. This standard model predicts soft X-rays (kT $<<$ 1 keV) and wind-broadened emission lines, which should be asymmetric if the wind is optically thick (Owocki & Cohen 2001). However, these predictions have generally not been confirmed, with the O4 supergiant ζ Pup being a notable exception. Specifically, we detect narrow emission lines in σ Ori AB, with only slight broadening seen in the brightest lines (Fig. 5), and no strong asymmetries or significant centroid shifts. The weak broadening and suppressed forbidden lines suggest that the lines of σ Ori AB are formed in the wind acceleration zone within a few radii of the photosphere where the wind speed is well below v_∞ and the stellar UV field is strong.

Although σ Ori E was not bright enough for a grating spectrum to be obtained, the hot plasma in its 0th order spectrum is clearly incompatible with the standard wind shock model. Its emission could be intrinsic to the B-star itself, or due to an as yet undetected late-type companion. Collaborators S. Owocki, R. Townsend, and A. ud-Doula are actively developing rigidly rotating magnetosphere models for σ Ori E and are investigating the hypothesis that centrifugal breakout of a magnetically confined wind may be responsible for the X-ray flares detected previously (see http://www.star.ucl.ac.uk/~rhdt/research/magnetic).

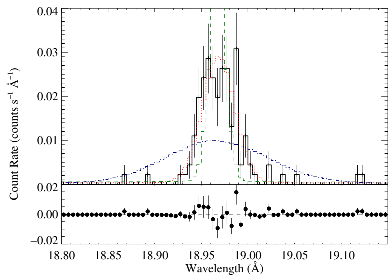

FIGURE 5: *Chandra* MEG1 profile of the O VIII line. Overlays are a best-fit Gaussian of half-width (HW) 250 km/s (red dotted) - which is $\approx v_\infty$/4, a line with no excess broadening (green dashed), and a line with HW = 1000 km/s (blue dash-dot) as might be expected from a wind-shock source such as the O4 supergiant ζ Pup. Bottom: best-fit residuals.

References & Acknowledgment

Adams-Wolk, N. et al. 2003, BAAS, 35(5), 1324
Groote, D. & Schmitt, J. 2004, A&A, 418, 235
Hunger, K., Heber, U., & Groote, D. 1989, A&A, 224, 57
Lee, T.A. 1968, ApJ, 152, 1968
Owocki, S. & Cohen, D. 2001, ApJ, 559, 1108
Reiners, A. et al. 2000, A&A, 363, 585
Sanz-Forcada, J., Franciosini, E., & Pallavicini, R. 2004, A&A, in press
Walter, F et al. 1997, Mem. S.A. It., 68, 1081

This work was supported by SAO grant GO3-4007A.