RevMexAA (Serie de Conferencias), **15**, 220–222 (2003)

HIGH RESOLUTION SPECTRA OF STELLAR WINDS IN VERY YOUNG MASSIVE STARS

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RESUMEN

Presentamos una serie de espectros de estrellas calientes obtenidas con el *Observatorio de Rayos X Chandra*, usando el espectrómetro HETGS. La mayoría de las estrellas seleccionadas se ubican en los centros, o cercano, de las regiones de formación estelar supuestamente jóvenes, las cuales incluyen IC 1396, NGC 2362 y Orión. Las edades medias de estos cúmulos varían desde 0.3 a 12 millones de años. Las propiedades de los espectros de rayos-X de estas estrellas calientes jóvenes son entonces comparadas al espectro de rayos-X altamente resuelto de la estrella de campo evolucionada, ζ Pup. Las estrellas del cúmulo con edades más grandes que 3 millones de años muestran temperaturas moderadas y líneas asimétricas anchas. Estas propiedades son bastante similares a las que se han observado en ζ Pup y son consistentes con los rayos-X producidos por las inestabilidades de choque en un viento impulsado por radiación. Las estrellas con edades apreciablemente menores que 1 millón de años, como las que se encuentran en el Trapecio de Orión, muestran características completamente distintas. Aquí, la mayoría del flujo de rayos-X muestra temperaturas muy altas y las líneas son muy delgadas y no resueltas. Esto indica fuertemente que las propiedades de los rayos-X están dominadas por los efectos de los campos magnéticos.

ABSTRACT

We present a series of spectra from hot stars obtained with the high energy transmission grating spectrometer (HETGS) onboard the *Chandra X-ray Observatory.* Most of the selected stars are located at or near the centers of young star-forming regions, which include IC 1396, NGC 2362, and Orion. The median ages of these clusters range from 0.3 to 12 Myr. The X-ray properties of these young, hot stars are then compared to a highly resolved X-ray spectrum of the more evolved field star ζ Pup. Cluster stars with ages larger than 3 Myr show moderate temperatures and broad asymmetric lines. These properties are quite similar to what has been observed in ζ Pup and are consistent with X-rays produced by shock instabilities in a radiation-driven wind. Stars with ages significantly less than 1 Myr, as found in the Orion Trapezium, show completely different characteristics. Here most of the X-ray flux shows very high temperatures and the X-ray lines are narrow and unresolved. This strongly indicates that the X-ray properties are dominated by magnetic field effects.

Key Words: **STARS: EARLY TYPE — STARS: CLUSTERS — STARS: FORMATION — TECHNIQUES: SPECTROSCOPIC — X-RAYS: STARS**

1. INTRODUCTION

The X-ray properties of very young massive stars are very difficult to study because their pre-main sequence evolution timescales are much faster than the ones for low-mass stars and because they spend most of their pre-main sequence lives deeply embedded in their natal cloud environments. Many are at the centers of very young stellar clusters in active star-forming regions and require sufficient spatial resolving power. *Einstein* and *ROSAT* established the fact that all O and B stars, in general, are strong X-ray emitters (see Berghöfer, Schmitt, & Cassinelli 1996, and references therein). Typical X-ray luminosities range from $\log(L_{\rm x}[{\rm erg/s}]) = 30.5$ to 32.5 and scale with bolometric luminosities with $\log(L_{\rm x}/L_{\rm bol}) = 10^{-5}$ to 10^{-7}. It is now very much accepted that X-rays are produced by shocks forming due to instabilities within a radiatively driven wind (see Owocki & Cohen 2001, and references therein).

However, even with *ROSAT* it was difficult to spatially resolve the cores of young clusters and to study the X-ray properties of very young massive stars. *ASCA* was spectroscopically a step forward as it offered medium spectral resolution over a bandpass up to 10 keV. Here the hard X-ray spectrum observed in a B0.2 V star (Cohen, Cassinelli, & Waldron 1997) indicated that there are massive stars with X-ray properties inconsistent with normal wind shock instabilities. *ASCA* also could not resolve cluster cores and thus the X-ray properties of young massive stars remained notoriously understudied.

This situation changed with the launch of the *Chandra X-ray Observatory.* Schulz et al. (2001) fully resolved the Orion Trapezium in X-rays and

TABLE 1

STELLAR PROPERTIES VS. X-RAY PROPERTIES[a]

Cluster	D (kpc)	Age (Myr)	Star	Spectral Type	$T_{\rm eff}$ (10^3 K)	$R_{\rm star}$ ($R_\odot$)	v_∞ (km s^{-1})	log $N_{\rm H}$ (cm^{-2})	X-ray line properties[b]
Field	0.43	···	ζ Pup	O4 I(f)	42	19	2250	20.00	Blue-shifted, B , A N VII FT, $T = 3$–8 MK
Orion	0.45	< 12	ζ Ori	O9.7 Ib	32	24	2350	20.48	B, S, $T = 2$–10 MK
Orion	0.45	< 12	ι Ori	O9 III	34	18	1850	20.30	B, A, FT, $T < 12$ MK
NGC 2362	1.38	5–7	τ CMa	O9 Ib	26	···	2350	20.74	B, S, FT, $T < 14$ MK
Tr 37	0.75	3	HD 206267	O6.5V	38	···	3225	21.45	B, A, $T = 6$–11 MK
Trapezium	0.45	0.3	θ^1 Ori C	O6.5Vp	38	8	1000	21.28	N, S, $T = 8$–74 MK
Trapezium	0.45	0.3	θ^1 Ori A	B0.5V	24	···	···	21.28	N, S, $T = 5$–41 MK
Trapezium	0.45	0.3	θ^1 Ori E	B0.5	24	···	···	21.28	N, S, $T = 4$–47 MK

[a]Data from Howarth & Prinja (1989); Puls et al. (1993); Hillenbrand (1997); Schulz et al. (2003).

[b]B: Broad. N: Narrow. A: Asymmetric. S: Symmetric. FT: Some lines flat-topped.

showed that four out of five of the brightest and most massive Trapezium stars showed hard X-ray spectra. θ^1 Ori C is the hottest star and a first preliminary analysis of its highly resolved X-ray spectra indicated temperatures of up to 6×10^7 K (Schulz et al. 2000). These findings are in strong contrast to expected properties from wind shocks. Highly resolved spectra of ζ Pup, which is considered to be archetypical for wind instabilities, on the other hand, impressively confirmed expected X-ray properties from winds (Kahn et al. 2001; Cassinelli et al. 2001). These characteristics include moderate temperatures of 5 to 10×10^6 K, blue-shifted and asymmetric lines. Other observations of hot stars so far show these characteristics as well, although sometimes not quite as explicitly (Waldon & Cassinelli 2001; Wojdowski et al. 2002).

2. X-RAY SPECTRA AND STELLAR PROPERTIES

For this investigation observations obtained with the high energy transmission grating spectrometer (HETGS) onboard *Chandra* are used to compare highly resolved X-ray spectra from young cluster stars with spectra from ζ Pup. The data reduction was performed using the standard *Chandra* data systems tools and some customized software. An update on these procedures is found in Schulz et al. (2003) and references therein.

Table 1 summarizes the stellar properties of all stars that are included in this analysis so far. ζ Pup is an evolved field star. ζ Ori and ι Ori belong to a somewhat older population in Orion with an age of up to 12 Myrs (Hillenbrand 1997). These three stars do not coincide with any young stellar cluster core. Two stars, τ CMa and HD 206267, are found at the center of young open clusters, NGC 2362 and Tr 37 respectively, with median ages of 3 to 7 Myr. The Orion Trapezium Cluster is one of the youngest and closest active star-forming regions with a median age of 0.3 Myr (Hillenbrand 1997). The ionization age of the Orion Nebula is less than a few hundred thousand years and thus θ^1 Ori C and the other Trapezium members are candidates for zero-age main sequence stars (ZAMS) in this sample. Here zero-age is defined as the time when energy generation by nuclear reactions first fully compensates the energy loss due to radiation from the stellar photosphere.

Figure 1 shows three examples of X-ray spectra. The spectrum of ζ Pup (top) shows broad, asymmetric and slightly blue shifted lines (Cassinelli et al. 2001) and can be described with a collisional equilibrium plasma of typical temperatures expected for wind shocks. HD 206267 (middle) is at the center of the about 3 Myr old cluster Tr 37. Its spectrum exhibits very similar characteristics to ζ Pup. Table 1 shows that all stars in the sample that are presumably older than about 3 Myr show similar characteristics to ζ Pup. Differences occur only in the line shapes, where symmetric lines indicate low wind opacities (Owocki & Cohen 2001). In θ^1 Ori C (bottom) the spectral properties are in stark contrast to these wind-shock characteristics. Schulz et al. (2003) report that the Orion Trapezium spectra are dominated by X-ray fluxes of very high temperatures and that the lines basically remain unresolved. These characteristics are more reminiscent of what is observed in cool systems like II Peg (Huenemoerder, Canizares, & Schulz 2001) and hint a magnetic origin. Recent model calculations of magnetic wind confinement by Ud-Doula & Owocki (2002) describe similar characteristics.

3. SUMMARY

A comparison of highly resolved X-ray spectra shows that for most very early-type stars observed so far the basic X-ray characteristics are quite consistent with wind-shock models. This includes massive stars in very young open clusters of median age of 3 Myr and older. For some of the very youngest stars, however, with a projected age of less than 0.5 Myr this does not seem to be the case. Here the emission process appears to be of magnetic origin. Since these magnetic characteristics are observed in at least three Trapezium stars, Schulz et al. (2003) also rule out that these properties are due to possible low-mass companions and raise the question as to whether massive stars generally arrive at the main sequence carrying significant magnetic fields at moderate mass outflow rates.

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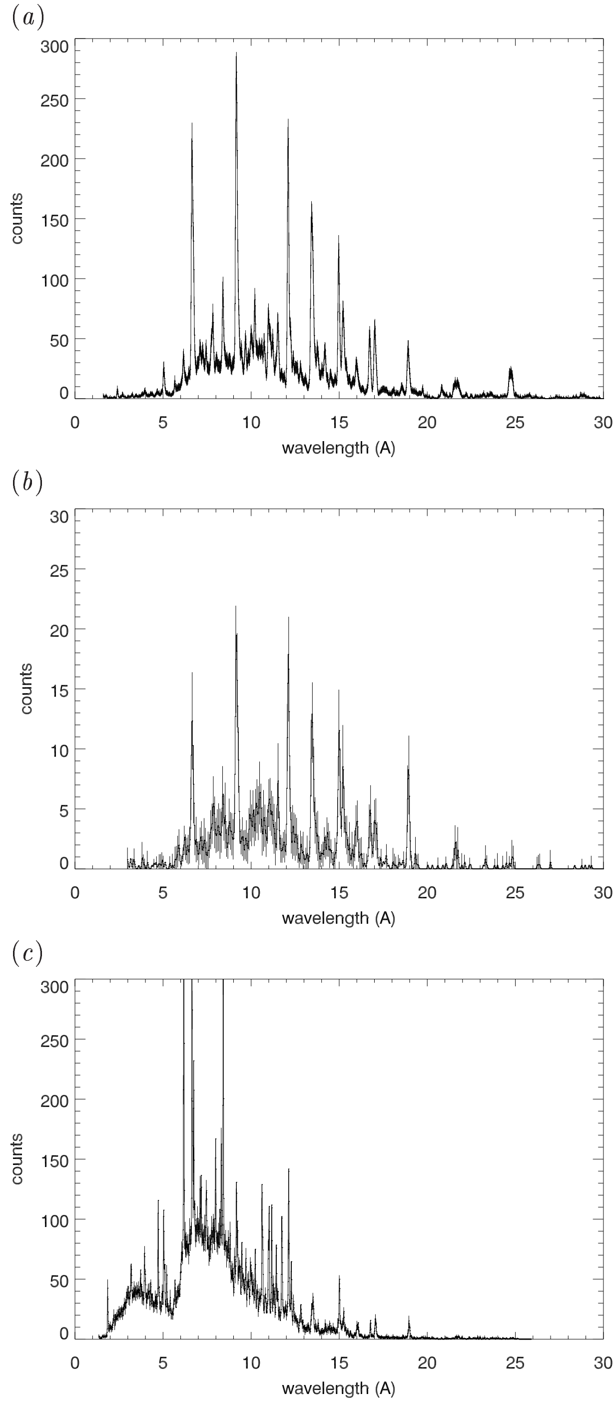

Fig. 1. X-ray spectra of three stars: (*a*) ζ Pup, (*b*) HD 206267, and (*c*) θ^1 Ori C.

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