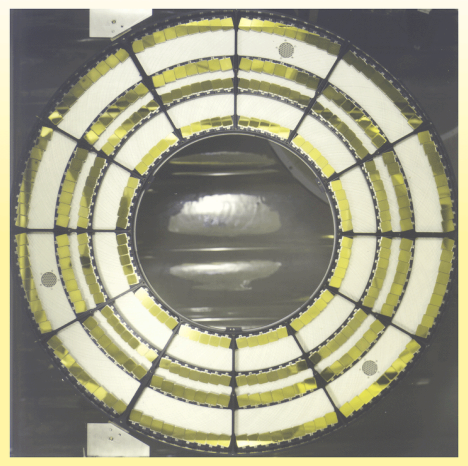

X-rays and Magnetic Fields on Young OB Stars

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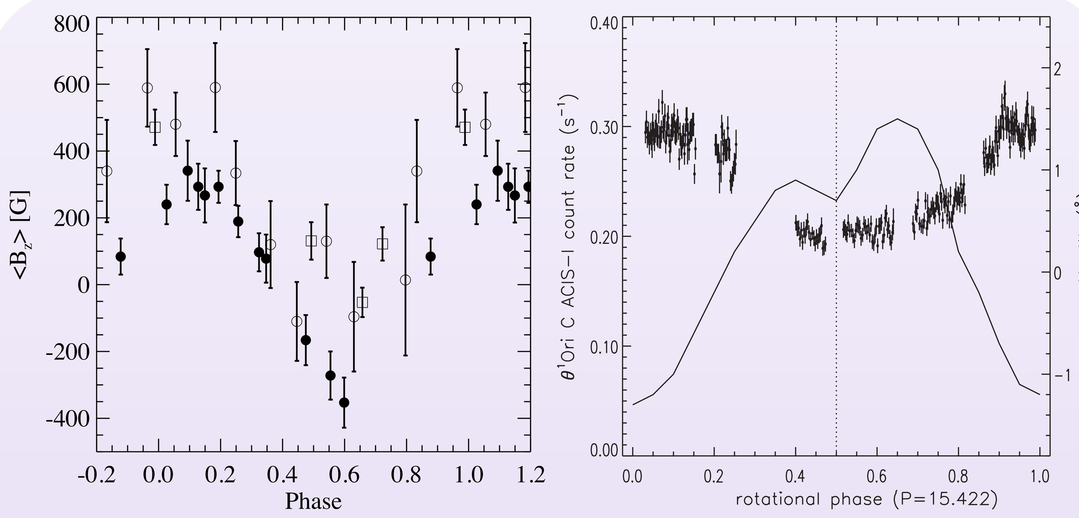
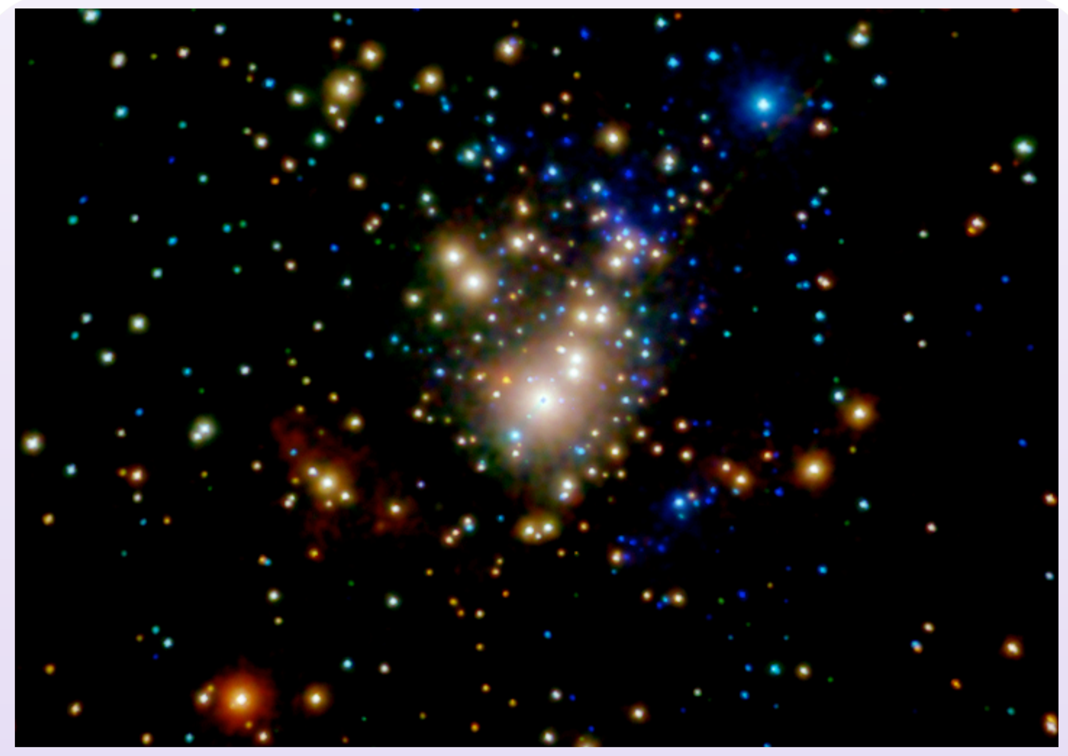
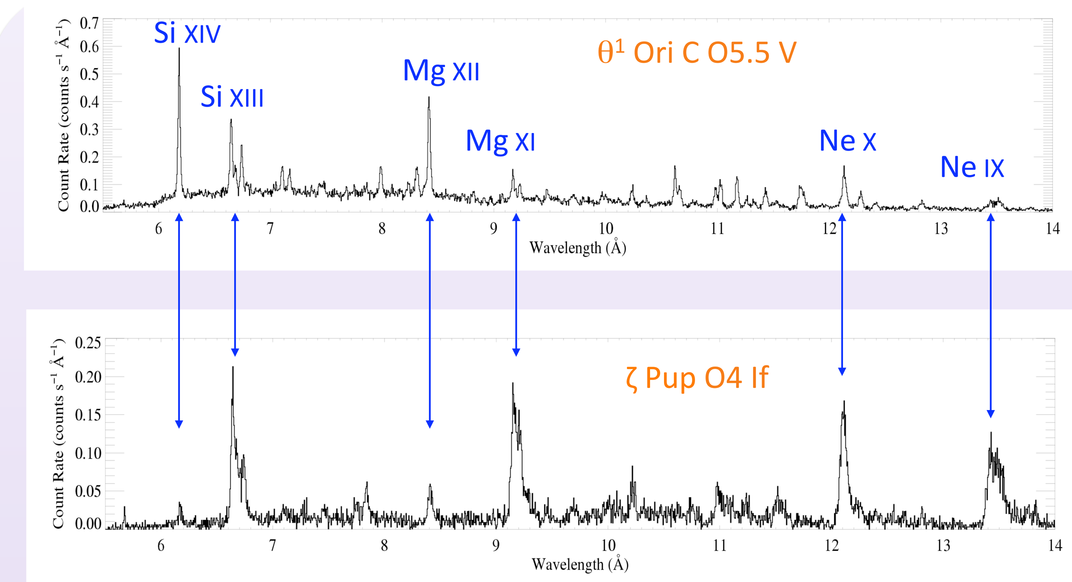


Peter Conti (1972) noted the variable spectral type of θ¹ Orionis C (O5.5 V), the central star of the Orion Nebula. Nolan Walborn (1972 , 1973) defined the Of?p stars and suggested in 1981 that θ¹ Ori C's spectral variations were magnetic in nature, like those of the magnetic star σ Ori E (B2 Vp). In addition to the He-strong Bp stars, a dozen or so O and very early B stars now have measured magnetic fields: τ Sco (B0.2 V), ζ Ori (O9.7 I), HD 191612 (O8 f?p), HD 36879 (O7 V), HD 148937 (O6.5 f?p), HD 152408 (O8 Iafpe), HD 155806 (O7.5 V[n]e) and the young O4 V ((f)) star 9 Sgr, though no fields are as strong as θ¹ Ori C's. *Left panel*: θ¹ Ori C's longitudinal field strength versus phase from Hubrig et al. (2008). *Right panel*: *Chandra* 0.3-8 keV count rate versus phase (data points with error bars). Also shown is its Hα equivalent width versus phase (solid line). Maximum field strength, Hα and x-ray emission are seen at phase 0.0 when the oblique magnetic rotator is seen pole-on. At phase 0.5, the magnetic equator is seen edge-on.



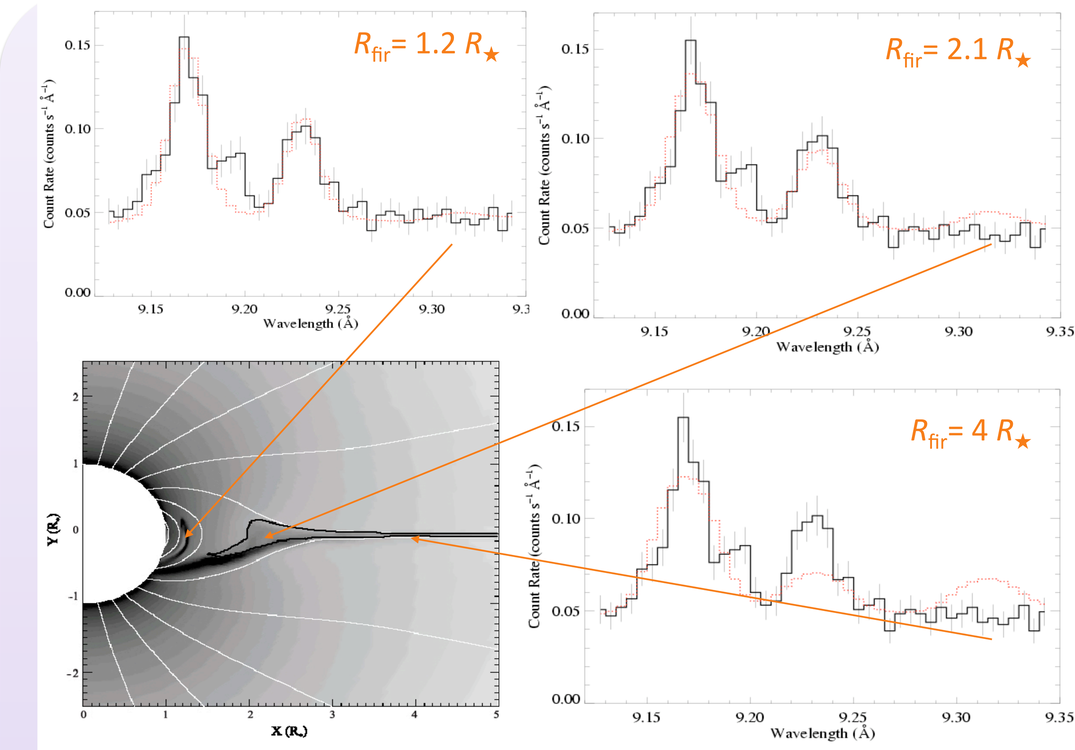
Chandra Orion Ultra-deep Project (COUP) image of the central 2′ of the 3×10⁵ year-old Orion Nebula cluster. North is up, east is to the left. θ¹ Ori C (O5.5 V) is the bright saturated source at center. θ² Ori A (O9.5 V) is the bright orange source near the southeast corner. In this false-color image, red represents soft 0.3-1.5 keV counts, green 1.5-2.5 keV counts, and blue hard 2.5-8 keV counts. The data, obtained over the course of 10 days in January, 2003, show strong x-ray flares from the blue low-mass T Tauri stars and lower-amplitude, periodic variations from the softer O stars.



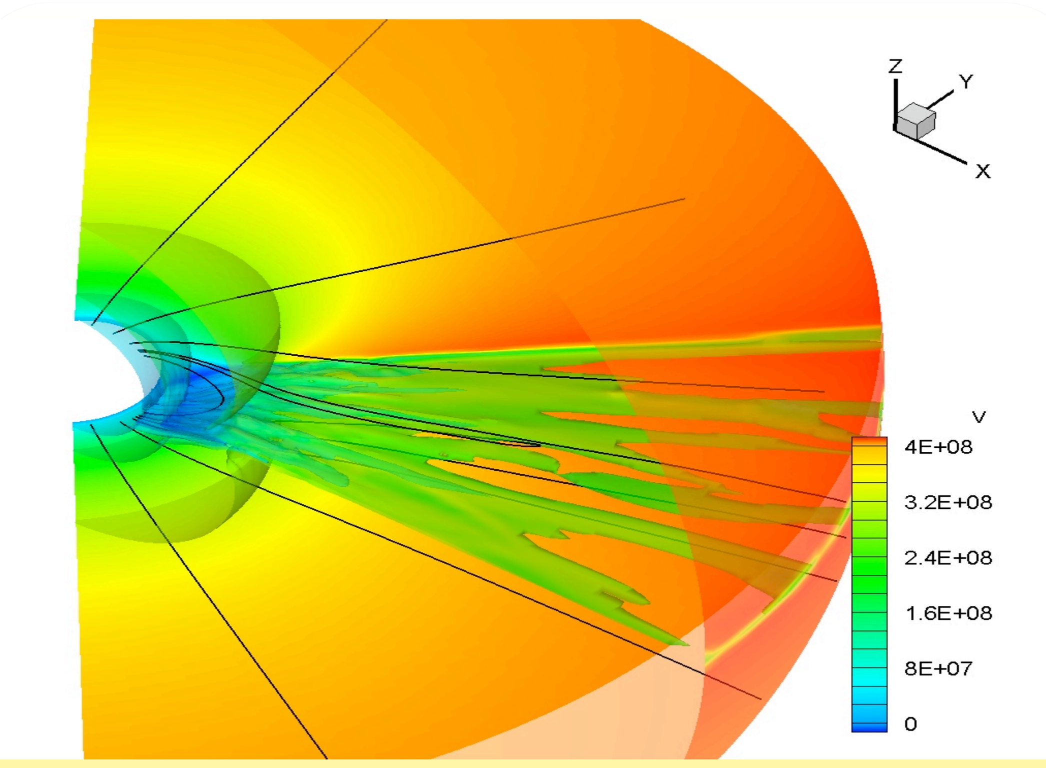
θ¹ Ori C: $T \approx 33$ MK, $R_{shock} \approx 2R_\star$, $v_{turb} \approx 350$ km s^{-1}

ζ Pup: $T \approx 4$ MK, $R_0 \approx 1.5R_\star$, $v_{HWHM} \approx 1000$ km s^{-1}

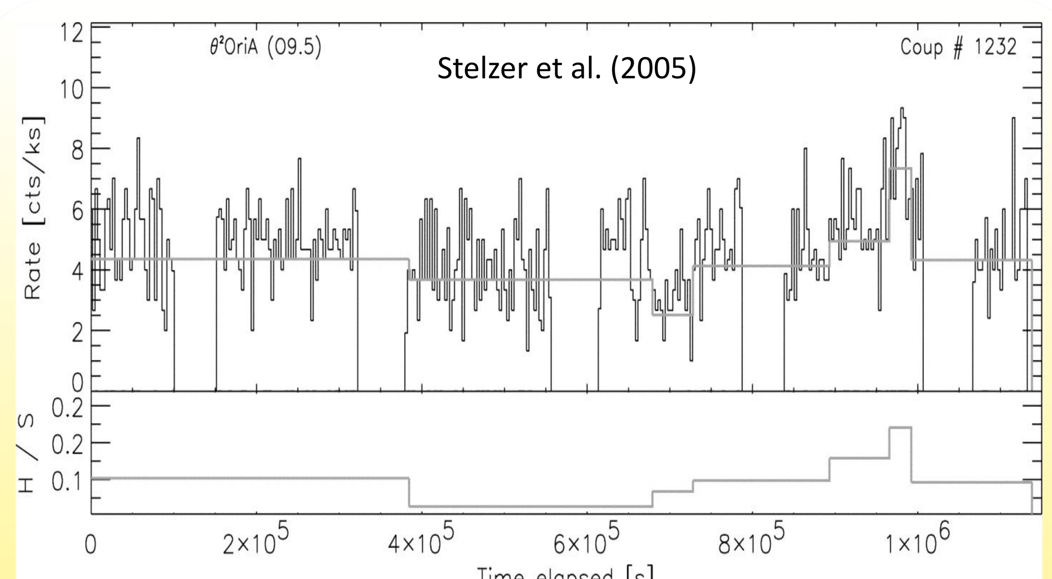
Chandra high-energy transmission grating spectra of the magnetic O dwarf θ¹ Ori C and the non-magnetic O supergiant ζ Puppis. The x-ray lines of ζ Pup are broad, asymmetric, and formed throughout the wind starting at a radius of just 1.5 R_*. ζ Pup's 4 MK shocks produce a relatively weak bremsstrahlung continuum. The forbidden lines of He-like Si, Mg and Ne are weak because electrons in the upper level of the forbidden line are photo-excited to the upper level of the intercombination line. θ¹ Ori C's lines are resolved but narrower and symmetric. The strong continuum emission, and strong lines of Fe XXV, S XVI and Si XIV indicate very high shock temperatures.



The Mg XI resonance, intercombination and forbidden of θ¹ Ori C (solid histogram and error bars). The three panels show the expected line strengths at three radii (red dotted lines). Note the forbidden line strength at 4 $R_\star$. *Lower left*: 2D non-isothermal MHD simulation of MCWS on θ¹ Ori C. These simulations include a detailed treatment of the wind energy balance, accounting for both shock heating and radiative cooling. The black contour contains 1-40 MK plasma. The MCWS model predicts the right amount, temperature and location of the x-ray emitting plasma.



Isothermal 3D MHD simulation of magnetically confined wind shocks on the central star of the Orion Nebula, θ¹ Ori C (O5.5 V). This snapshot of wind speed (in cm s⁻¹) shows that shocks near the magnetic equatorial plane are fast enough to produce hard x-rays. The 3D simulations provide the azimuthal extent of the shocks, needed to estimate the total x-ray emission measure. In the simulations the field is Initially dipolar with B_p = 1100 G. Mass loss distorts the field lines (in black), channeling plasma from high magnetic latitudes to the equatorial plane. Courtesy Asif ud-Doula.

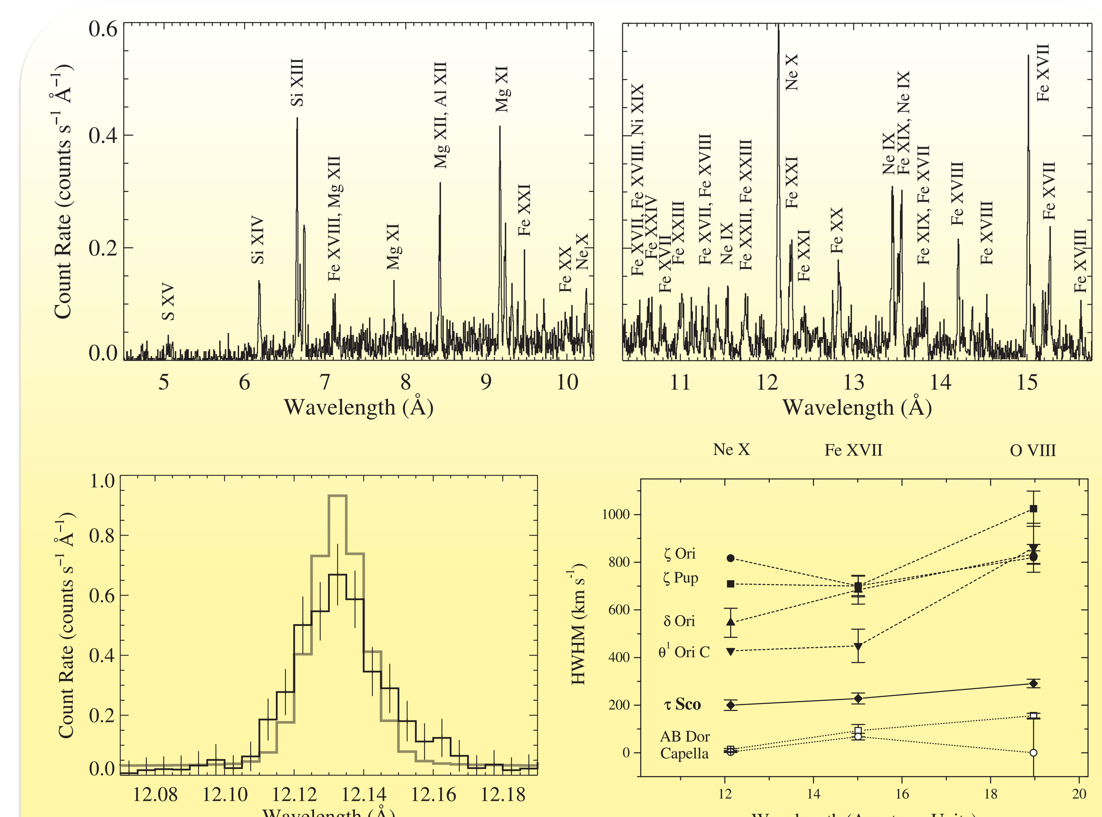


MCWS: θ² Ori A1 primary (O9.5, soft)

COUP flare: θ² Ori A3 (hard)

The third brightest x-ray source in Orion and the only other O star, θ² Ori A, is a hierarchical triple: a spectroscopic binary A1 (O9.5 V, 25 $M_\odot$) + A2 (8 $M_\odot$) in an elliptical orbit with a = 0.47 AU and A3 (5 $M_\odot$) at 0.4" (160 AU at a distance of 400 pc). Long- and short-term variability, including a strong, hard flare, were seen in the COUP light curve. Schulz et al. (2006) proposed that both A1 and A2 are magnetic stars (lower-mass analogs of θ¹ Ori C) and further suggested that the flares reported by Stelzer et al. (2005) and Feigelson et al. (2002) were manifestations of binary-induced reconnection wherein the magnetospheres of A1 and A2 interact at periastron.

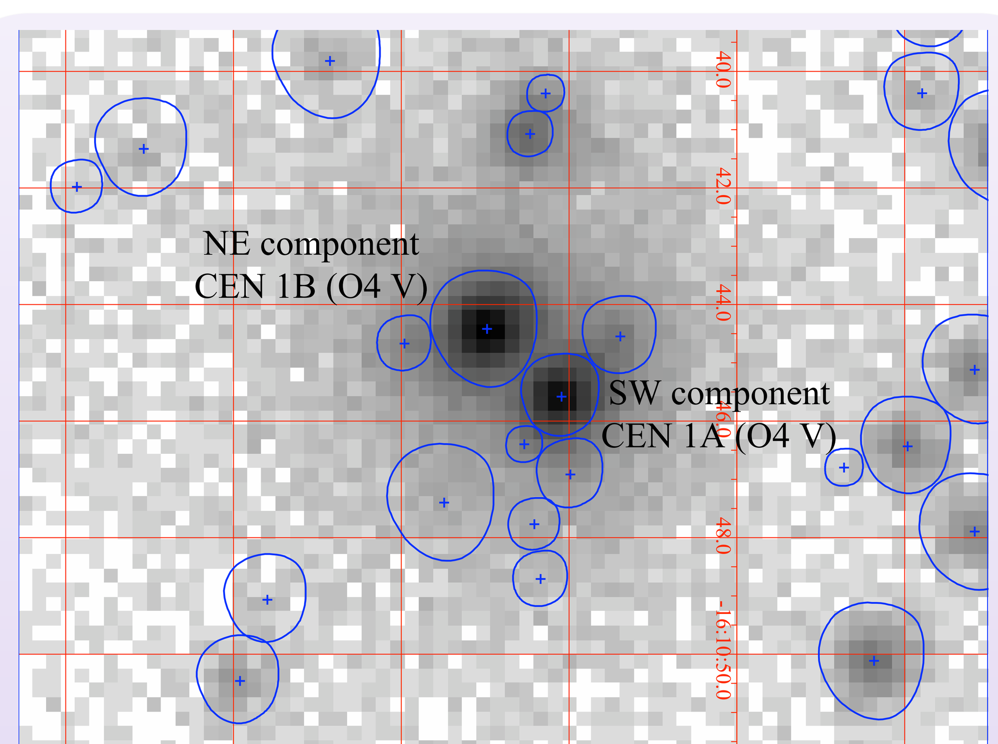
This is the same event data as box 2 but sampled at high spatial resolution. The cross-shaped *Chandra* PSF is elongated and bluer (harder) in the NW, unlike any other source in the COUP data. The positions of θ² Ori A1+A2 and θ² Ori A3 are superposed. Image reconstruction confirms this result: the hard x-rays are produced by the ~5 $M_\odot$ A3 companion, not the high-mass SB A1+A2. During the flare, A3 accounts for ⅔ of the total x-ray luminosity. Though high L_x is not typically seen in intermediate-mass stars, we note that the second brightest x-ray source in Orion, θ¹ Ori E, is a late-B + early G SB.



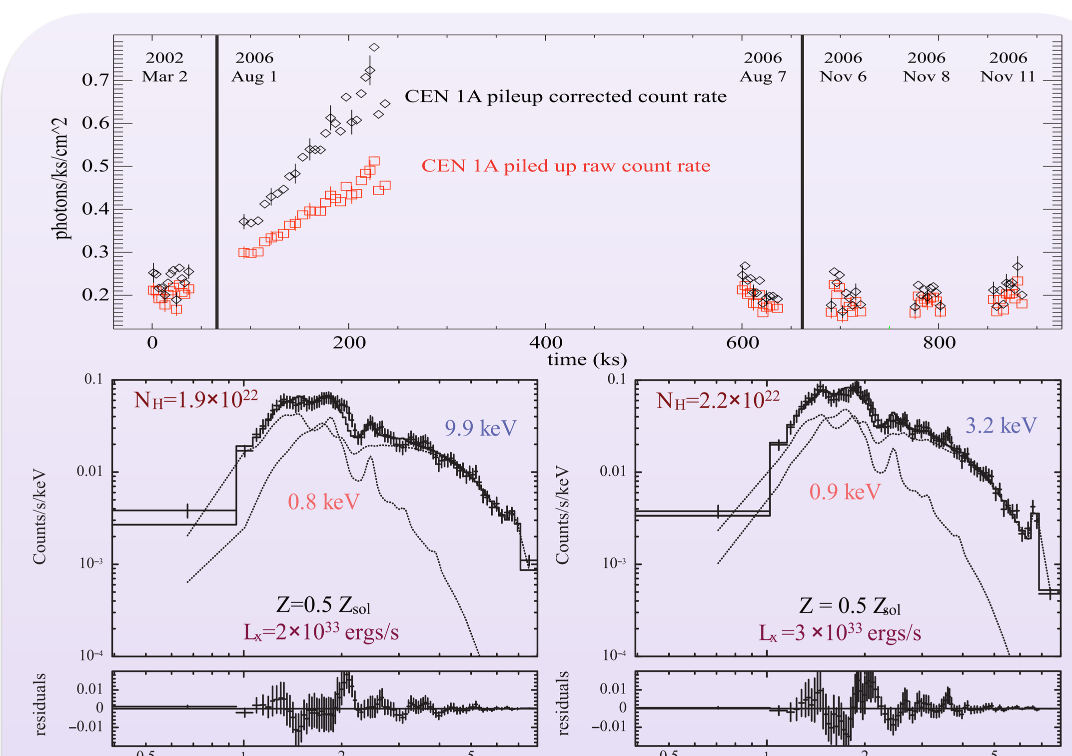
Chandra HETG spectrum of the magnetic B0.2 dwarf τ Scorpii, a member of the 5 Myr old Sco OB2 association. $B_p \approx 500$ G, its magnetic topology is complex and it's an ultra-slow rotator with P_{rot} = 41 days (Donati et al. 2006). τ Sco's x-ray lines (black line in lower left panel) are narrower than θ¹ Ori C's, but broader than coronal lines (gray line). τ Sco's rich X-ray spectrum arises from harder shocks than those in older B0 stars like β Crucis.

X-ray Properties of Magnetic O4-B0 Dwarfs

1. Polar field strengths of 50-1100 G, fossil fields
2. Young (less than 5 Myr)
3. Strong fields ➔ slow rotators
4. X-rays from magnetically confined wind shocks
5. Moderate-amplitude, periodic x-ray emission
6. Symmetric lines, small redshifts
7. Variability caused by rotation and occultation
8. 200-1000 km s⁻¹ x-ray line widths, depending on confinement
9. 8-40 MK shocks, depending on confinement
10. 1.5-3.0 $R_\star$ x-ray formation radius
11. No x-ray flares observed on magnetic OB stars, though flares seen on σ Ori E (B2 Vp)
12. Long-term, large-amplitude variability and very hard x-rays may indicate colliding wind shocks, not magnetic confinement



This *Chandra* 0.3-8 keV high-resolution image of the core of M17, reveals a pair of hard, variable x-ray sources separated by 1.8" (> 3000 AU at the distance of M17). The O4 pair CEN 1A and 1B (after Chini, Elsaesser & Neckel 1980) is the ionizing source of the Omega Nebula. Softer, diffuse x-rays pervade the cavity to the east. The cluster contains at least 2000 x-ray point sources (blue circles). All 14 O stars in M17 are detected with *Chandra*. Most like CEN 1A and 1B show anomalously hard x-rays. *Chandra* HETG spectra to be obtained in 2009 on CEN 1A+1B will measure f/i ratios and line widths.



Top panel: Raw (red) and pileup corrected (black) count rates of CEN 1A in 2002 and 2006. CEN 1B shows a similar range of count rates, but not the ramp seen on CEN 1A in 2006 August. *Lower panels*: the pileup corrected CCD spectra of CEN 1B (left) and CEN 1A (right) show very high temperatures of 100 MK and 35 MK. CEN 1A shows a 6.5 keV Fe Kα line as well. This type of hard variable emission is reminiscent of η Car and HR 5980. In LBV and WR binaries, the x-rays arise in the wind interaction zone between two very massive stars. Thus CEN 1 may be a hierarchical quadruple system.

Strategies for Finding Magnetic OB Stars

Though magnetic fields have been detected on OB dwarfs, He-strong Bp stars, He-weak Bp stars, slowly pulsating B stars, β Cephei stars, δ Scuti stars, and Herbig Be stars (e.g., Hubrig et al. 2006, Briquet et al. 2007, Bouret et al. 2007 and 2008, Alecian et al. 2008a and 2008b, Wade et al. 2006, Donati et al. 2006, Donati et al. 2002), fields on most OB stars are weak or absent.

Though hard and variable x-rays from θ¹ Ori C, θ² Ori A and τ Sco strongly suggest magnetic wind shocks, in broad-band surveys most other OB stars (magnetic **and** non-magnetic) have relatively soft, constant x-rays. High-resolution x-ray spectroscopy is needed.