X-ray Diagnostics and Their Relationship to Magnetic Fields

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If we understand the physical connection between magnetic fields in massive stars and X-rays, we could use X-ray observations to identify magnetic massive stars.

e.g. Which of the stars in this Chandra X-ray image of the Orion Nebula Cluster are massive magnetic stars?
But we’re *not* there yet…

X-ray behavior of known magnetic massive stars is diverse.

We don’t understand enough about the physical mechanisms of X-ray production in them.
The **Sun**: X-rays $\leftrightarrow$ Magnetic Fields

*TRACE*
Stellar rotation vs. X-ray luminosity

low-mass stars

High-mass stars

\[ L_x = 10^{27} (V \sin i)^2 \]

No trend
Massive star X-rays are not coronal
X-rays in massive stars are associated with their radiation-driven winds.
Power in these winds:

\[
\frac{1}{2} \dot{M} v_\infty^2 \approx 3 \times 10^{36} \text{ erg s}^{-1}
\]

\approx .001L_*

while the x-ray luminosity

\[
L_X \approx 10^{-7} L_*
\]

To account for the x-rays, only one part in $10^{-4}$ of the wind’s mechanical power is needed to heat the wind
Three models for massive star x-ray emission

1. Instability driven shocks

2. Magnetically channeled wind shocks

3. Wind-wind interaction in close binaries
Three models for massive star x-ray emission

1. Instability driven shocks

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What are these “X-rays” anyway?

...and what’s the available data like?
Launched 2000: superior sensitivity, spatial resolution, and spectral resolution

Chandra

sub-arcsecond resolution
Both have CCD detectors for imaging spectroscopy:

low spectral resolution: $R \sim 20$ to 50

And both have grating spectrometers: $R \sim$ few 100 to 1000

300 km/s
The gratings have poor sensitivity…
We’ll never get spectra for more than two dozen hot stars
The Future:

*Astro-H* (Japan) – high spectral resolution at high photon energies
...few years from now

*International X-ray Observatory (IXO)*
... 2020+
First, imaging (+ low resolution) spectroscopy with *Chandra*
Chandra ACIS
Orion Nebula Cluster (COUP)

Color coded according to photon energy (red: <1 keV; green 1 to 2 keV; blue > 2 keV)
X-ray: Chandra/ACIS/Feigelson et al. (COUP)
Infrared: VLT/ISAAC/McCaughrean et al.

Movie from the COUP team: astro.swarthmore.edu/~cohen/presentations/MiMeS2/COUP_optical_xray_m3.mov
Movie from the COUP team: astro.swarthmore.edu/~cohen/presentations/MiMeS2/COUP_variability_m2.mpg
σ Ori E: XMM light curve: flare-like variability

Counts/s

Time (hrs since JD 2452357)

Sanz-Forcada et al. 2004


...or low-mass binary companion?
**XMM EPIC** spectrum of σ Ori E

Fig. 9. PN spectra of σ Ori E during quiescence and at the peak of the flare. The best-fit model is also shown.

Sanz-Forcada et al. 2004
Chandra grating spectra: $\theta^1$ Ori C and a non-magnetic O star

$\theta^1$ Ori C

$\zeta$ Pup
thermal emission

“coronal approximation” valid: electrons in ground state, collisions up, spontaneous emission down

optically thin

lines from highly stripped metals, weak bremsstrahlung continuum (continuum stronger for higher temperatures)
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*Chandra* grating spectra: $\theta^1$ Ori C and a non-magnetic O star

$\theta^1$ Ori C

$\zeta$ Pup
Energy Considerations and Scalings

1 keV $\sim 12 \times 10^6$ K $\sim 12$ Å

Shock heating: $\Delta v = 300$ km/s gives $T \sim 10^6$ K (and $T \sim v^2$)

*ROSAT* 150 eV to 2 keV  
*Chandra, XMM* 350 eV to 10 keV
Energy Considerations and Scalings

1 keV ~ $12 \times 10^6$ K ~ 12 Å

Shock heating: $\Delta v = 1000$ km/s gives $T \sim 10^7$ K (and $T \sim v^2$)

*ROSAT* 150 eV to 2 keV
*Chandra, XMM* 350 eV to 10 keV
H-like/He-like ratio is temperature sensitive

θ¹ Ori C

Si XIV  Mg XII  Mg XI

ζ Pup
$\theta^1$ Ori C – is hotter

$\theta^1$ Ori C

Si XIV  Mg XII  Si XIII  Mg XI

H/He > 1 in $\theta^1$ Ori C
Differential Emission Measure (temperature distribution)

$\theta^1$ Ori C is much hotter
Emission lines are significantly narrower, too.

\( \theta^1 \) Ori C

\((O7 \, V)\)

\( \zeta \) Pup

\((O4 \, If)\)
Mg XII Ly-α in θ¹ Ori C compared to instrumental profile
Ne X Ly-α in θ¹ Ori C: cooler plasma, broader – some contribution from “standard” instability wind shocks
The X-ray properties of θ¹ Ori C can be understood in the context of its magnetic field and the magnetically channeled wind shock (MCWS) mechanism.
Dipole magnetic field

\( \chi^2 = 1.0 \)

Wade et al. 2008
Fig. 11b
Fig. 1.—Temperature map for the postshock region in the approximation of a steady-state shock. The shock front is indicated by a heavy solid line and wind trajectories (or magnetic field lines) by dashed lines. **Upper panel:** closed magnetosphere, $L_A = 1.49$ ($B_z \approx 370$ G). **Lower panel:** closed and open magnetosphere, $L_A = 1.39$ ($B_z \approx 300$ G).
Dynamical models (ud-Doula; Townsend): color scale shows emission measure in different temperature regimes

Optical / UV

Soft X-ray

Medium X-ray

Hard X-ray

astro.swarthmore.edu/~cohen/presentations/MiMeS2/zeus-movie.avi
Looking at individual physical variables:

Note that the hot, post-shock plasma:

- has relatively low density,
- is concentrated near the tops of the largest closed-loop regions ($\sim 2R_{\text{star}}$),
- and is very slow moving (due to confinement)
MHD simulation summary

temperature

emission measure

Channeled collision is close to head-on:
\( \Delta v > 1000 \text{ km s}^{-1} : T > 10^7 \text{ K} \)

Gagné et al. (2005)
Differential emission measure
(temperature distribution)

MHD simulation of $\theta^1$ Ori C reproduces the observed differential emission measure

Wojdowski & Schulz (2005)
There are *Chandra* observations at many different phases
$\theta^1$ Ori C ACIS-I count rate (s$^{-1}$) vs. rotational phase (P=15.422 days)

Model from MHD simulation
The star itself occults the hot plasma in the magnetosphere.

The closer the hot plasma is to the star, the deeper the dip in the x-ray light curve.
The star itself occults the hot plasma in the magnetosphere

hot plasma is too far from the star in the simulation – the dip is not deep enough
$\theta^1$ Ori C column density (from x-ray absorption) vs. phase

- **Column Density:**
  - Linear increase with viewing angle $\alpha$ (degrees)
  - Pole-on: Constant at column density $N_H = 4 \times 10^{21} \text{ cm}^{-2}$
  - Equator-on: Increase from $N_H = 0.1 \times 10^{21} \text{ cm}^{-2}$

- **Radial Velocity $v_r$ (km s$^{-1}$):**
  - Pole-on: Constant $v_r = 0$
  - Equator-on: $v_r$ increases with viewing angle $\alpha$

**Graph Details:**
- **Y-axis:**
  - Column density $N_H$ (10$^{21}$ cm$^{-2}$)
  - Radial velocity $v_r$ (km s$^{-1}$)

**Axes:**
- **X-axis:** View angle $\alpha$ (degrees)
- **Title:** $\theta^1$ Ori C column density (from x-ray absorption) vs. phase

- **Legend:**
  - Pole-on
  - Equator-on
Emission measure

contour encloses $T > 10^6$ K
Helium-like species’ forbidden-to-intercombination line ratios – $f/i$ or $z/(x+y)$ – provide information about the *location* of the hot plasma.
Helium-like ions (e.g. O$^{+6}$, Ne$^{+8}$, Mg$^{+10}$, Si$^{+12}$, S$^{+14}$) – schematic energy level diagram

10-20 eV

1-2 keV

1s$^2$ 1S

1s2s $^3$S

1s2p $^3$P

1s2p $^1$P

resonance (w)

intercombination (x+y)

forbidden (z)
Ultraviolet light from the star’s photosphere drives photoexcitation out of the $^3\text{S}$ level
Weakening the forbidden line and strengthening the intercombination line

- UV
- forbidden (z)
- intercombination (x+y)
- resonance (w)
- g.s. 1s² 1S
- 1s2p 3P
- 1s2s 3S
- 1s2p 1P
The f/i ratio is thus a diagnostic of the local UV mean intensity...
...and thus the distance of the x-ray emitting plasma from the photosphere
\[ R_{\text{fir}} = 1.2 \, R_* \]

\[ R_{\text{fir}} = 2.1 \, R_* \]

\[ R_{\text{fir}} = 4.0 \, R_* \]
He-like f/i ratios and the x-ray light curve both indicate that the hot plasma is somewhat closer to the photosphere of $\theta^1$ Ori C than the MHD models predict.
So, in θ¹ Ori C, the X-rays tell us about the magnetospheric conditions in several ways:

- High X-ray luminosity
- X-ray hardness (high plasma temperatures)
- Periodic variability (rotation and occultation)
- Narrow emission lines (confinement)
- f/i ratios quantify location
What about other massive stars?
What about confinement?

Recall:

\[ \eta_* \equiv \frac{B^2 R_*^2}{M v_\infty} \]

\[ \theta^1 \text{ Ori C: } \eta_* \sim 20 \quad : \text{decent confinement} \]
What about \textit{confinement}?

Recall: \[ \eta_* \equiv \frac{B^2 R^2_*}{M v_\infty} \]

\[ \zeta \text{ Ori: } \eta_* \sim 0.1 \quad : \text{poor confinement} \]
\[ \theta^1 \text{ Ori C: } \eta_* \sim 20 \quad : \text{decent confinement} \]
\[ \sigma \text{ Ori E: } \eta_* \sim 10^7 \quad : \text{excellent confinement} \]
\( \theta^1 \) Ori C has a hard X-ray spectrum with narrow lines

...HD191612 and \( \zeta \) Ori have soft X-ray spectra with broad lines

Fe XVII in \( \zeta \) Ori
\( \tau \) Sco *does* have a hard spectrum and narrow lines.

Ne Ly\( \alpha \) compared to instrumental response: narrow
τ Sco: closed loop region is near the star...
τ Sco: closed loop region is near the star…

…f/i ratios tell us X-rays are far from the star (∼3R_{star})
Do He-like f/i ratios provide evidence of hot plasma near the photospheres of O stars?
Do He-like f/i ratios provide evidence of hot plasma near the photospheres of O stars?

No, I’m afraid they do not.
Features are very blended in most O stars: here, the three models are statistically indistinguishable.
σ Ori E ($\eta_* \sim 10^7$: RRM+RFHD)
Chandra ACIS (low-resolution, CCD) spectrum
DEM derived from *Chandra* ACIS spectrum
DEM from RFHD modeling
Observed & theoretical DEMs agree well

Optical / UV

Soft X-ray

Hard X-ray

boom.to/swarthmore/astro/~cohen/presentations/MiMeS2/hav-rfhd-4p.avi
Conclusions

MCWS dynamical scenario explains $\theta^1$ Ori C well… but, in detail, MHD models do not reproduce all the observational properties

Most other magnetic massive stars have X-ray emission that is different from $\theta^1$ Ori C

Some have soft X-ray spectra with broad lines

Closed field regions may not always be associated with the X-rays ($\tau$ Sco)

$f/i$ ratios, hard X-rays, variability in massive stars… not unique to magnetic field wind interaction