X-rays from Young Massive Stars

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O Stars are the brightest X-ray sources in young clusters

In addition to the X-ray and UV radiation from O stars

Prodigious matter, momentum, and kinetic energy input into the cluster environment via their winds

The winds are the site and energy source of the X-rays
Chandra Carina Complex Project (Townsley)
Radiation-driven O star winds

ζ Pup (O4 supergiant): \( \dot{M} \sim \text{few } 10^{-6} \, M_{\odot}/\text{yr} \)

UV spectrum: C IV 1548, 1551 Å

Three mechanisms for massive star x-ray emission

1. Instability driven shocks

2. Wind-wind interaction in close binaries

3. Magnetically channeled wind shocks
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Radiation-driven winds are inherently unstable: shocks, X-rays

Self-excited instability

Excited by turbulence imposed at the wind base

Owocki, Cooper, Cohen 1999

Feldmeier, Puls, Pauldrach 1997

numerical simulations of the line-driving instability
Numerous shock structures, distributed above \( \sim 1.5 \ R_\odot \).
Shocked plasma is moving ~few 1000 km/s

Emission lines should be Doppler broadened
Only ~1% of the wind is shock heated at any given time

Bound-free absorption in the other ~99% of the wind
ζ Pup – as prototypical (and nearby at ~400 pc) – O star X-ray source
Chandra HETGS

ζ Pup (O4 If)

Capella (G5 III)
- coronal source
- for comparison
Morphology – line widths

Ne X  Ne IX  Fe XVII

Count Rate (counts s$^{-1}$ Å$^{-1}$)

12  13  14  15
Wavelength (Å)

Capella (G5 III)
– coronal source
– for comparison
Morphology – line widths

\( \zeta \) Pup (O4 If)

\( \sim 2000 \text{ km/s} \sim v_{\text{inf}} \)

Ne X  Ne IX  Fe XVII

Capella (G5 III)
– coronal source
– for comparison
\[ \xi \text{ Pup (O4 If)} \]

Capella (G5 III) – *unresolved*
Kinematics conclusions: consistent with X-rays arising in the stellar wind
What about the distinctive profile shape?
blue shift
asymmetry
continuum absorption in the bulk wind preferentially absorbs red shifted photons from the far side of the wind
Wind Profile Model

\[ \tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty} \]

Increasing \( \tau_* \)
Wind opacity due to bound-free transitions
Opacity from partially ionized metals

![Graph showing wind opacity due to bound-free transitions.](image)
We fit these x-ray line profile models to each line in the *Chandra* data.
And find a best-fit $\tau_*$
**ζ Pup: three emission lines**

Mg Lyα: 8.42 Å  
Ne Lyα: 12.13 Å  
O Lyα: 18.97 Å

\[ \tau_\star = 1 \]  \quad \tau_\star = 2  \quad \tau_\star = 3

Recall:

\[ \tau_\star \equiv \frac{\kappa M}{4\pi R_\star v_\infty} \]
Results from the 3 line fits shown previously
Fits to 16 lines in the *Chandra* spectrum of ζ Pup
Fits to 16 lines in the *Chandra* spectrum of ζ Pup
$\tau_*(\lambda)$ trend consistent with $\kappa(\lambda)$

$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$
Fits to 16 lines in the *Chandra* spectrum of ζ Pup

\[ \tau_*(\lambda) \text{ trend consistent with } \kappa(\lambda) \]

\[ \tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty} \]
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\( \dot{M} \) becomes the free parameter of the fit to the \( \tau_*(\lambda) \) trend

\( \tau_*(\lambda) \) trend consistent with \( \kappa(\lambda) \)
\[ \tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty} \]

\( \dot{M} \) becomes the free parameter of the fit to the \( \tau_*(\lambda) \) trend.
Traditional mass-loss rate:
8.3 \times 10^{-6} \text{ M}_{\odot}/\text{yr}

From H_{\alpha}, ignoring clumping

Our best fit:
3.5 \times 10^{-6} \text{ M}_{\odot}/\text{yr}
Fe XVII

Traditional mass-loss rate:
$8.3 \times 10^{-6} \, M_{\text{sun}}/\text{yr}$

Our best fit:
$3.5 \times 10^{-6} \, M_{\text{sun}}/\text{yr}$

Count Rate (counts s$^{-1}$ Å$^{-1}$)

Wavelength (Å)

14.90 14.95 15.00 15.05 15.10 15.15
Mass-loss rate conclusions

The trend of $\tau_*$ value with $\lambda$ is consistent with:

- Mass-loss rate of $3.5 \times 10^{-6} \, M_{\text{sun}}/\text{yr}$
- Factor of $\sim 3$ reduction w.r.t. unclumped H-alpha mass-loss rate diagnostics
Pup mass-loss rate < $4.2 \times 10^{-6}$ M$_{\odot}$/yr

Bright OB stars in the Galaxy

III. Constraints on the radial stratification of the **clumping** factor in hot star winds from a combined H$_\alpha$, IR and radio analysis


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Abstract. Recent results strongly challenge the canonical picture of massive star winds: various evidence indicates that currently accepted mass-loss rates, $\dot{M}$, may need to be revised downwards, by factors extending to one magnitude or even more. This is because the most commonly used mass-loss diagnostics are affected by "clumping" (small-scale density inhomogeneities), influencing our interpretation of observed spectra and fluxes. Such downward revisions would have dramatic consequences for the evolution of, and feedback from, massive stars, and thus robust determinations of the clumping properties and mass-loss rates are urgently needed. We present a first attempt concerning this objective, by means of constraining the radial stratification of the so-called clumping factor.

To this end, we have analyzed a sample of 19 Galactic O-type supergiants/giants, by combining our own and archival data for H$_\alpha$, IR, mm and radio fluxes, and using approximate methods, calibrated to more sophisticated models. Clumping has been included in our analysis in the "conventional" way, by assuming the inter-clump matter to be void. Because (almost) all our diagnostics depends on the square of density, we cannot derive absolute clumping factors, but only factors normalized to a certain minimum.

This minimum was usually found to be located in the outermost, radio-emitting region, i.e., the radio mass-loss rates are the lowest ones, compared to $\dot{M}$ derived from H$_\alpha$ and the IR. The radio rates agree well with those predicted by theory, but are only upper limits, due to unknown clumping in the outer wind. H$_\alpha$ turned out to be a useful tool to derive the clumping properties inside $r < 3 \ldots 5$ R$_\odot$. Our most important result concerns a (physical) difference between denser and thinner winds: for denser winds, the innermost region is more strongly clumped than the outermost one (with a normalized clumping factor of $4.1 \pm 1.4$), whereas thinner winds have similar clumping properties in the inner and outer regions.

Our findings are compared with theoretical predictions, and the implications are discussed in detail, by assuming different scenarios regarding the still unknown clumping properties of the outer wind.
Three mechanisms for massive star x-ray emission

1. Instability driven shocks

2. Wind-wind interaction in close binaries

3. Magnetically channeled wind shocks
The embedded wind shock (EWS) mechanism should occur in all O stars.

But other mechanisms can dominate, especially in young clusters/SFRs.

Like colliding wind shocks (CWS) in η Car.
η Car RXTE X-ray light curve

Corcoran et al. 2005
Hydrodynamics simulations of the colliding wind shock mechanism explain much of the observed X-ray properties:

- **hard emission (≈ 5 keV)**
- **$L_x \sim 10^{35}$ erg/s**
- **orbital modulation of X-rays**
HD 93129A (O2If*) is the 2\textsuperscript{nd} brightest X-ray source in Tr 14.
HD93129A – O2 If*

Extremely massive (120 $M_{\text{sun}}$), luminous O star ($10^{6.1} L_{\text{sun}}$)

Strongest wind of any Galactic O star
($2 \times 10^{-5} M_{\text{sun}}$/yr; $v_{\text{inf}} = 3200$ km/s)

From H-alpha, assuming a smooth wind
There is an O3.5 companion with a separation of \( \sim 100 \text{ AU} \)

Non-thermal radio measurements indicate wind-wind interactions

But the vast majority of the X-rays come from embedded wind shocks in the O2If* primary
Typical of O stars like ζ Pup

$kT = 0.6 \text{ keV} \times \text{wind}_\text{abs} \times \text{ism}$

add 5% $kT = 2.0 \text{ keV} \times \text{ism}$

small contribution from colliding wind shocks
Its X-ray spectrum is hard
Its X-ray spectrum is hard

HD 93129A
Its X-ray spectrum is hard

Si       Mg       HD 93129A

low H/He

But the plasma temperature is low: little plasma with kT > 8 million K
Its X-ray spectrum is hard

Si
Mg

low H/He

Bound-free absorption in the wind is the cause of the observed X-ray hardness
X-ray line profiles show same characteristic shape

M-dot $\sim 8 \times 10^{-6} M_{\text{sun}}/\text{yr}$

$R_o = 1.8 R_*$

$\tau_* = 1.4$
M-dot ~ $2 \times 10^{-5} \, M_{\text{sun}}/\text{yr}$ from unclumped Hα

**HD 93129A (O2 If*)**: Mg XII Lyα 8.42 Å

$V_{\text{inf}} \sim 3200 \, \text{km/s}$

M-dot ~ $8 \times 10^{-6} \, M_{\text{sun}}/\text{yr}$

$R_o = 1.8 \, R_*$  
$\tau_* = 1.4$
Low-resolution *Chandra* CCD spectrum of HD93129A

Fit: thermal emission with wind + ISM absorption *plus* a second thermal component with just ISM

\[ kT = 0.6 \text{ keV} \times \text{wind\_abs\_ism} \]

add 5% \[ kT = 2.0 \text{ keV} \times \text{ism} \]
\[ kT = 0.6 \text{ keV} \times \text{wind}_\text{abs} \times \text{ism} \]

add 5% \[ kT = 2.0 \text{ keV} \times \text{ism} \]

\[ \tau_*/\kappa = 0.03 \text{ (corresp. } \sim 8 \times 10^{-6} \text{ } M_{\odot}/\text{yr}) \]

Typical of O stars like ζ Pup

\[ \tau_*/\kappa = 0.03 \text{ (corresp. } \sim 8 \times 10^{-6} \text{ } M_{\odot}/\text{yr}) \]

small contribution from colliding wind shocks
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Orion Nebula Cluster: age ~ 1Myr; 
d ~ 450pc
Chandra ~10^6 seconds, COUP (Penn. St.)

Color coding of x-ray energy: <1keV, 1keV < E < 2.5keV, >2.5keV
**Chandra HETGS**

**$\theta^1$ Ori C**: hotter plasma, narrower emission lines

**$\zeta$ Pup**: cooler plasma, broad emission lines
**H-like/He-like** ratio is temperature sensitive

\[ \text{Si XIV} \quad \text{Mg XII} \quad \text{Mg XI} \]

\[ \text{Si XIII} \quad \zeta \text{ Pup} \]

\[ \theta^1 \text{ Ori C} \]
Differential emission measure
(temperature distribution)

$\theta^1$ Ori C:
peak near 30 million K

Non-magnetic O stars,
peak at a few million K

Wojdowski & Schulz (2005)
Dipole magnetic field (> 1 kG) measured on \( \theta^1 \) Ori C

Zeeman magnetic field measurements

Magnetic field obliquity, \( \beta \sim 45^\circ \)

R. Townsend

Wade et al. (2006)
MHD simulations of magnetically channeled wind

simulations by A. ud-Doula; Gagné et al. (2005)

Chaanneled collision is close to head-on – at 1000+ km s$^{-1}$: $T = 10^7$+ K
Emission measure

contour encloses $T > 10^6$ K
MHD simulations show multi-$10^6$ K plasma, moving slowly, $\sim 1R_*$ above photosphere.

Contour encloses $T > 10^6$ K.
Differential emission measure
(temperature distribution)

MHD simulation of θ¹ Ori C reproduces the observed differential emission measure
Chandra broadband count rate vs. rotational phase

Model from MHD simulation
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

\begin{align*}
1s2s \, ^3S & \rightarrow 1s2p \, ^1P \\
1s2p \, ^3P & \rightarrow \text{resonance (r)} \\
& \rightarrow \text{intercombination (i)} \\
g.s. \, 1s^2 \, ^1S
\end{align*}
The $f/i$ ratio is thus a diagnostic of the strength of the local UV radiation field.
If you know the UV intensity emitted from the star’s surface, it thus becomes a diagnostic of the distance that the x-ray emitting plasma is from the star’s surface.
\( R_{\text{fir}} = 1.2 \, R_* \)

\( R_{\text{fir}} = 2.1 \, R_* \)

\( R_{\text{fir}} = 4.0 \, R_* \)
Conclusions

• **Shock processes in O star winds** convert kinetic energy to heat and X-rays

• Three different mechanisms can operate

• Harder and stronger emission from CWS and MCWS

• But significant and sometimes moderately hard X-ray emission from EWS too

• Wind absorption effects are significant and can be used as a clumping-independent mass-loss rate diagnostic: **mass loss rates are lower** (factors of 3 to 5) than previously thought