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Massive stars dominate their environments
massive stars:

20 to 100 $M_{\text{sun}}$

$10^6 L_{\text{sun}}$

$T \sim 50,000 \text{ K}$

The Orion Nebula (Messier 42)
(MPG/ESO 2.2-m + WFI)
The Orion Nebula and Trapezium Cluster
(VLT ANU + ISAAC)
Chandra X-ray Telescope image of the Orion Nebula Cluster

young, massive star: \( \theta^1 \) Ori C

Color coded according to photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)
Chandra X-ray Telescope image of the Orion Nebula Cluster

young, massive star: $	heta^1$ Ori C

young, massive star: $	heta^2$ Ori A

Color coded according to photon energy (red: $<$1 keV; green 1 to 2 keV; blue $>$ 2 keV)
Two different paradigms for (1) non-magnetic OB stars and for (2) magnetic OB stars

magnetic: 
$\theta^1$ Ori C

non-magnetic: 
$\theta^2$ Ori A

Color coded according to photon energy (red: $<1$ keV; green 1 to 2 keV; blue $>2$ keV)
Massive star X-rays are *not* Solar-type X-rays
The Sun at different wavelengths

Optical
5800 K

SOHO
EUV
few \(10^5\) K

YOKOH
x-ray
few \(10^6\) K
massive stars are not supposed to have a dynamo – no corona...no x-rays?
DISCOVERY OF AN X-RAY STAR ASSOCIATION IN VI CYGNI (CYG OB2)


Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts

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ABSTRACT

A group of six X-ray sources located within 0.4 of Cygnus X-3 has been discovered with the Einstein Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous O stars within the field of view and a B5 supergiant. These sources are found to have typical X-ray luminosities $L_x$ (0.2-4.0 keV) $\sim 5 \times 10^{33}$ ergs s$^{-1}$, with temperatures $T \sim 10^{6.3}$ K and hydrogen column densities $N_H \sim 10^{22}$ cm$^{-2}$, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.
Stellar rotation vs. X-ray luminosity

low-mass stars

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

RS CVn's

high-mass stars

Empty symbols: Sp O3–B5
Filled symbols: Sp B8–A5

Algos
Stellar rotation vs. X-ray luminosity

low-mass stars

high-mass stars

Activity-rotation correlation = dynamo, corona

NO correlation = some other x-ray production mechanism
radiation-driven winds of massive stars
wind-blown bubble: stellar wind impact on its environment
Radiation-driven massive star winds

$M \sim 10^{-6} \, M_{\text{sun}}/\text{yr}$

UV spectrum: C IV 1548, 1551 Å

$v_\infty = 2350 \, \text{km/s}$

Winds of massive stars are driven by radiation force

\[ F_{rad} = \frac{\sigma L}{4\pi R^2 c} \]

- cross-section (cm^2)
- Luminosity (ergs/s)
- radius
Winds of massive stars are driven by radiation force.

\[ a_{\text{rad}} = \frac{\kappa L}{4\pi R^2 c} \]

- opacity (cm²/g)
- Luminosity (ergs/s)
- radius
Eddington factor, $\Gamma_{\text{edd}}$: ratio of radiation force to gravity

\[ \Gamma_{\text{edd}} \equiv \frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{\kappa L}{4\pi c G M} \]

Assuming electron scattering (Thompson) opacity only

For the Sun, $\Gamma_{\text{edd}} \sim 10^{-5}$

For massive stars, $\Gamma_{\text{edd}}$ approaches unity
Mechanical power in these winds:

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

\[
\approx 0.001 L_*
\]

\[
L_{\text{sun}} = 4 \times 10^{33} \text{ erg s}^{-1}
\]

\[
L_{\text{massive}} \approx 4 \times 10^{39}
\]
Mechanical **power** in these winds:

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

\[ \approx 0.001 L_* \]

\[ L_{\text{sun}} = 4 \times 10^{33} \text{ erg s}^{-1} \]

\[ L_{\text{massive}} \approx 4 \times 10^{39} \]
The connection between X-rays and stellar winds in massive stars
Power in massive star winds:

\[ \frac{1}{2} \dot{M} v_\infty^2 \approx 3 \times 10^{36} \text{ erg s}^{-1} \]
\[ \approx 0.001 L_* \]

while the x-ray luminosity

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

\( L_{\text{sun}} = 4 \times 10^{33} \text{ erg s}^{-1} \)

\( L_{\text{massive}} \approx 4 \times 10^{39} \)

To account for the x-rays, only one part in \(10^{-4}\) of the wind’s mechanical power is needed to heat the wind.
Hydrodynamic shocks extract kinetic energy from a supersonic flow and convert it to thermal energy

\[ \Delta v_{\text{shock}} = 300 \text{ km/s} \text{ gives } \]
\[ T \sim 10^6 \text{ K} \]
\[ (\text{and } T \sim v^2) \]
Three models for massive star x-ray emission

1. Instability driven shocks

2. Magnetically channeled wind shocks

3. Wind-wind interaction in close binaries
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1. Instability driven shocks

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1-D rad-hydro simulation of a massive star wind

Radiation line driving is inherently unstable: shock-heating and X-ray emission
Predictions of the rad-hydro wind simulations:

1. Significant Doppler broadening of x-ray emission lines due to bulk motion of the wind flow (1a. Shock onset several tenths R. above the surface)

2. Bulk of the wind is cold and unshocked – source of attenuation of the X-rays.
ζ Puppis: $50 \ M_{\text{Sun}}, \ 10^6 \ L_{\text{Sun}}$
In front of the Gum Nebula, it is one of the very closest O stars to the Earth.
Chandra – launched in 1999
Energy Considerations and Scalings

\[ 1 \text{ keV} \sim 12 \times 10^6 \text{ K} \sim 12 \text{ Å} \]

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

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

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

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

*Chandra, XMM* 350 eV to 10 keV
Chandra HETGS/MEG spectrum
($R \sim 1000$ corresponding to $300$ km s$^{-1}$)

\[ \begin{array}{cccccc}
\text{Si} & \text{Mg} & \text{Ne} & \text{Fe} & \text{O} \\
\text{H-like} & \text{He-like} \\
\end{array} \]
Low-mass star (Capella) for comparison
The x-ray emission lines are broad: agreement with rad- hydro simulations
The x-ray emission lines are broad: agreement with radi-hydro simulations.

But... they’re also blue shifted and asymmetric.

*Is this predicted by the wind shock scenario?*
Line Asymmetry
Line Asymmetry
Wind Profile Model

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

Increasing \( \tau_* \)
Opacity of the cold wind component

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

Wind mass-loss rate

\[ \dot{M} = 4\pi r^2 \nu \rho \]

Radius of the star

Wind terminal velocity
\[\tau = 1, 2, 8\]

\[R_o = 1.5\]

\[R_o = 3\]

\[R_o = 10\]

key parameters: \(R_o & \tau_*\)

\[j \sim \rho^2 \text{ for } r/R_* > R_o,\]
\[= 0 \text{ otherwise}\]

\[\tau = \tau_* \int_{z_*}^{\infty} \frac{R_* dz'}{r^{1/2} (1 - R_* / r')^{1/2}}\]

\[\tau_* \equiv \frac{\kappa M}{4\pi R_* v_{\infty}}\]
We fit these x-ray line profile models to each line in the *Chandra* data.

And find a best-fit $\tau_*$ and $R_o$ & place confidence limits on these fitted parameter values.

**Fe XVII**

68, 90, 95% confidence limits
Wind opacity: photoelectric absorption

Abundances; ionization balance; atomic cross sections

Verner & Yakovlev 1996
$\zeta$ Pup: three emission lines

Mg Ly\(\alpha\): 8.42 Å  \hspace{1cm} \text{Ne Ly}\(\alpha\): 12.13 Å  \hspace{1cm} \text{O Ly}\(\alpha\): 18.97 Å

\[\tau_* = 1 \hspace{2cm} \tau_* = 2 \hspace{2cm} \tau_* = 3\]

\[\tau_* \equiv \frac{\kappa M}{4\pi R_* \nu_\infty}\]

Recall:
Fits to 16 lines in the *Chandra* spectrum of ζ Pup
Fits to 16 lines in the *Chandra* spectrum of ζ Pup
Fits to 16 lines in the *Chandra* spectrum of ζ Pup

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

\[ \tau_\star \equiv \frac{\kappa \dot{M}}{4\pi R_\star \nu_\infty} \]
Traditional mass-loss rate: $8.3 \times 10^{-6}$ Msun/yr

Our best fit: $3.5 \times 10^{-6}$ Msun/yr
Terminal velocity of the x-ray plasma – from line fitting
onset radius of x-ray emission, $R_o$
Onset of instability-induced shock structure: $R_o \sim 1.5$

$1.5 \, R_* = \text{height of } 0.5 \, R_*$
ζ Ori (09.7 I): O Lyα 18.97 Å

- $R_o = 1.6 R_*$
- $\tau_* = 0.3$
ε Ori (B0 Ia): Ne Lyα 12.13 Å

\[ R_o = 1.5 \, R_* \]

\[ \tau_* = 0.6 \]
Mass-loss Rate Results
THE DISCORDANCE OF MASS-LOSS ESTIMATES FOR GALACTIC O-TYPE STARS

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ABSTRACT

We have determined accurate values of the product of the mass-loss rate and the ion fraction of P\textsuperscript{+4}, \(\dot{M}_q(P^{+4})\), for a sample of 40 Galactic O-type stars by fitting stellar wind profiles to observations of the P\textsc{v} resonance doublet obtained with FUSE, ORFEUS BEFS, and \textit{Copernicus}. When P\textsuperscript{+4} is the dominant ion in the wind [i.e., \(0.5 \leq q(P^{+4}) \leq 1\)], \(\dot{M}_q(P^{+4})\) approximates the mass-loss rate to within a factor of \(\approx 2\). Theory predicts that P\textsuperscript{+4} is the dominant ion in the winds of O7–O9.7 stars, although an empirical estimator suggests that the range O4–O7 may be more appropriate. However, we find that the mass-loss rates obtained from P\textsc{v} wind profiles are systematically smaller than those obtained from fits to H\alpha emission profiles or radio free-free emission by median factors of \(\sim 130\) (if P\textsuperscript{+4} is dominant between O7 and O9.7) or \(\sim 20\) (if P\textsuperscript{+4} is dominant between O4 and O7). These discordant measurements can be reconciled if the winds of O stars in the relevant temperature range are strongly clumped on small spatial scales. We use a simplified two-component model to investigate the volume filling factors of the denser regions. This clumping implies that mass-loss rates determined from \(\rho_2\) diagnostics have been systematically overestimated by factors of 10 or more, at least for a subset of O stars. Reductions in the mass-loss rates of this size have important implications for the evolution of massive stars and quantitative estimates of the feedback that hot-star winds provide to their interstellar environments.

Subject headings: stars: early-type — stars: mass loss — stars: winds, outflows
Bright OB stars in the Galaxy

III. Constraints on the radial stratification of the clumping factor in hot star winds from a combined Hα, IR and radio analysis*,**


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ABSTRACT

Context. Recent results strongly challenge the canonical picture of massive star winds: various evidence indicates that currently accepted mass-loss rates, \( M \), 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.

Aims. 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.

Methods. To this end, we have analyzed a sample of 19 Galactic O-type supergiants/giants, by combining our own and archival data for Hα, IR, mm and radio fluxes, and using approximate methods, calibrated to more sophisticated models. Clumping has been included into our analysis in the “canonical” 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.

Results. 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 \( M \) derived from Hα 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. Hα turned out to be a useful tool to derive the clumping properties inside \( r < 3 \ldots 5 R_\star \). 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.

Conclusions. 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.

Key words. infrared: stars – radio continuum: stars – stars: early-type – stars: winds, outflows – stars: mass-loss
Part 2: Magnetically Channeled Winds
\( \theta^1 \) Ori C:

- \( 50 \, M_{\text{sun}} \)
- \( 10^6 \, L_{\text{sun}} \)
- \( T \sim 45,000 \, \text{K} \)

The Orion Nebula (Messier 42)
(MPG/ESO 2.2-m + WFI)
The central star in the Orion Nebula Cluster - $\theta^1$ Ori C - is a source of strong and relatively hard x-rays

*Chandra* image: color coded by photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)
Recently discovered dipole magnetic field of $\sim 1.5$ kG

Magnetic field obliquity, $\beta \sim 45^\circ$

Wade et al. (2006)

http://astro.swarthmore.edu/~cohen/movies/rrm-o25-i75-b60-retd.avi (R. Townsend)
This field confines and channels the stellar wind out to several stellar radii –

what is the effect?

…MHD simulations (ZEUS, 2-D)
X-ray emission from Ap-Bp stars: a magnetically confined wind-shock model for IQ Aur

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Fig. 7. Schematic view of the model proposed for the X-ray emission from IQ Aur (see text).
Predictions:

1. Shocks are strong – head-on – and so plasma is hotter;

2. Hot plasma is moving much slower (confinement);

3. Rotational modulation of X-ray flux;

4. Hot plasma is ~1 R. above the surface.
Chandra grating spectra

θ¹ Ori C

θ¹ Ori C: hotter plasma, narrower emission lines

ζ Pup

ζ Pup: cooler plasma, broad emission lines
H-like/He-like ratio is temperature sensitive

θ1 Ori C

Si XIV

Mg XII

Si XIII

Mg XI

ζ Pup
The magnetic O star – $\theta^1$ Ori C – is hotter

$\theta^1$ Ori C

Si XIV

Mg XII

Si XIII

Mg XI

$\zeta$ Pup
Differential emission measure
(temporary temperature distribution)

$\theta^1$ Ori C has bulk of its shock-heated plasma at 30 X $10^6$ K and above
Differential emission measure
(temperature distribution)

$\theta^1$ Ori C has bulk of its shock-heated plasma at $30 \times 10^6$ K and above

six normal, non-magnetic O stars have much cooler DEMs, peaking at $\sim 10^6$ K

Wojdowski & Schulz (2005)
Differential emission measure
(temperature distribution)

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

Wojdowski & Schulz (2005)
Emission lines are significantly narrower in the magnetic massive star’s x-ray spectrum.
The MHD simulations: different temperature intervals

http://astro.swarthmore.edu/~cohen/movies/zeus-movie.avi (Asif ud-Doula & Richard Townsend)
Chandra broadband count rate vs. rotational phase

Points (Chandra data); Line (model from MHD simulation)
$Chandra$ broadband count rate vs. rotational phase

Points (Chandra data); Line (model from MHD simulation)
The star itself occults the hot plasma torus

The closer the hot plasma is to the star, the deeper the dip in the x-ray light curve
Emission measure (gray scale)

contour encloses $T > 10^6$ K
Helium-like species’ forbidden-to-intercombination line ratios – $z/(x+y)$ – provide information about the location of the hot plasma.

...not the density, as is usually the case.
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

1s2s $^3S$

1s2p $^3P$

1s2p $^1P$

resonance (w)

intercombination (x+y)

g.s. 1s$^2$ $^1S$
Ultraviolet light from the star’s photosphere drives photoexcitation out of the $^3S$ level.
The f/i ratio is thus a diagnostic of the local UV mean intensity...
...and therefore also of the **distance** of the x-ray emitting plasma is from the photosphere.

**Diagram:**
- Ground state (g.s.) $1s^2\ 1S$
- $1s^2s\ 3S$
- $1s2p\ 3P$
- $1s2p\ 1P$
- UV

Forbidden (z)

Intercombination (x+y)

Resonance (w)
Model of f/i ratio dependence on dilution factor (distance)

\[ f/i = 0.08 \pm 0.08 \]

\[ 1.0 \, R_* < R_{\text{fir}} < 2.1 \, R_* \]
For $R_{\text{flare}} = 1.2 R_*$, $R_{\text{flare}} = 2.1 R_*$, and $R_{\text{flare}} = 4.0 R_*$, the count rate (counts s$^{-1}$ Å$^{-1}$) is shown for different wavelengths (Å).
He-like f/i ratios and the x-ray light curve both indicate that the hot plasma is *somewhat closer* to the photosphere than the MHD models predict.
Conclusions

Normal massive stars have x-ray line profiles consistent with the predictions of the wind instability model.
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Photoelectric absorption’s effect on the profile shapes can be used as a mass-loss rate diagnostic: 
*mass-loss rates are lower than previously thought.*
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Magnetic massive stars have harder spectra with narrower lines and rotationally modulated variability, in general agreement with MHD simulations.
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