X-ray Emission from the Winds of Massive Stars

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massive stars are usually hot & therefore blue
Orion Nebula, Hubble Space Telescope
“O-type star” is the hottest stellar spectral classification

$\theta^1$ Ori C: only O star here
Basic properties of O stars

mass $\sim 50 \, M_{\text{sun}}$

luminosity $\sim 10^6 \, L_{\text{sun}}$

surface temperature $\sim 45,000 \, \text{K}$
Basic properties of O stars

mass ~ 50 $M_{\text{sun}}$

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

surface temperature ~ 45,000 K
Sun and full Moon - factor of a million ($10^6$) in brightness
Blackbody spectra

above $T \sim 10,000$ K most of a star’s emission is in the UV

O stars are even more extreme: $T > 30,000$ K

even so, no X-ray emission from the photospheres (surfaces) of even the hottest stars
Basic properties of O stars

mass $\sim 50 \, M_{\text{sun}}$

luminosity $\sim 10^6 \, L_{\text{sun}}$

surface temperature $\sim 45,000 \, \text{K}$

significant momentum in the photospheric radiation field
Strong, *radiation-driven* stellar winds are a characteristic of massive stars.
O star - source of wind bubble:
~1 arc second instrumental resolution;
star’s angular size is $10^4$ times smaller
small spatial scales can be studied using spectroscopy
Ultraviolet spectrum showing wind feature from $C^{+3}$

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

UV spectrum: C IV 1548, 1551 Å

Spectral lines:

*absorption line* when translucent gas is between you and a hotter, opaque source of continuum photons

*emission line* when hot gas is seen against a cold background
$C^+{}^3$ is lithium-like.

Absorption and emission: atomic energy level diagrams.
Ultraviolet spectrum showing wind feature from $\text{C}^{+3}$

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

UV spectrum: C IV 1548, 1551 Å

Radiation Force on an Atom

\[ F_{\text{rad}} = \frac{L \sigma}{4 \pi r^2 C} \]

- \( h \nu \) (energy)
- \( \frac{h \nu}{c} \) (momentum, \( p \))

rate at which atom absorbs momentum \( \frac{dp}{dt} = F_{\text{rad}} \)

\( L \) - luminosity, star's power output (watts)
\( \sigma \) - absorption cross section of atom (m\(^2\))
Radiation driving of massive star winds

\[ \dot{M} \sim 10^{-6} \, M_{\text{sun/yr}} \quad (10^8 \text{ times the Sun's value}) \]

Kinetic power in the wind = \( \frac{1}{2} \dot{M} v_{\infty}^2 \) \( \sim 10^{-3} \, L_{\text{bol}} \)
Radiation driving of massive star winds

$\dot{M} \sim 10^{-6} \ M_{\text{sun/yr}}$ (10$^8$ times the Sun’s value)

kinetic power in the wind = $\frac{1}{2} \dot{M}v_\infty^2$ ($\sim 10^{-3} \ L_{\text{bol}}$)
Carina Nebula

massive, luminous stars drive the physics

winds, eruptive mass loss, and supernovae all contribute
~1000 year-old core-collapse supernova remnant

Crab Nebula, WIYN
Scale nearest massive stars are $\sim 1000$ parsecs* away

*1 parsec = 3.26 light years
Massive stars as drivers of Galactic physics
Key points so far:

Massive stars have strong winds

Spectroscopy allows us to study structures that we can’t see in images

Next: Stellar X-ray emission
The Sun - and other cool, low-mass stars - emit X-rays
The Sun’s X-ray emission is associated with its magnetic dynamo (rotation + convection are key ingredients)

rotation

convection
cool stars vs. hot stars

starfish, *in situ*, at the Monterey, California Aquarium (photo: D. Cohen)
cool stars vs. hot stars

no convection, no dynamo, no magnetic field, no corona, no X-rays?

starfish, *in situ*, at the Monterey, California Aquarium (photo: D. Cohen)
discovery of massive star X-ray emission in 1970s

**DISCOVERY OF AN X-RAY STAR ASSOCIATION IN VI CYGNI (CYG OB2)**


Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts

Received 1979 June 26; accepted 1979 July 26

**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 $T \sim 10^{6.8}$ 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.
Massive stars have some different X-ray production mechanism

Maybe due to their powerful winds?

No observed correlation between rotation and X-ray luminosity
X-ray properties of bright OB-type stars detected in the ROSAT all-sky survey

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Abstract. The ROSAT all-sky survey has been used to study the X-ray properties for all OB-type stars listed in the Yale Bright Star Catalogue. Here we present a detailed astrophysical discussion of our analysis of the X-ray properties of our complete sample of OB-type stars; a compilation of the X-ray data is provided in an accompanying paper (Berghöfer, Schmitt & Cassinelli 1996).

We demonstrate that the “canonical” relation between X-ray and total luminosity of \( \frac{L_x}{L_{\text{bol}}} \approx 10^{-7} \) valid for O-type stars extends among the early B-type stars down to a spectral type B1–B1.5; for stars of luminosity classes I and II the spectral type B1 defines a dividing line for early-type star X-ray emission. 1979, Pallavicini et al. 1981, Chlebowski et al. 1989, Sciortino et al. 1990). However, the scatter for values of individual stars, 2 orders of magnitude, around the mean value is quite large. The widely accepted model for the X-ray emission from O stars assumes that it is produced by shock-heated gas propagating in the strong winds of these stars. In a phenomenological model Lucy & White (1980) and Lucy (1982) postulate the existence of shocks in the radiation driven winds of hot stars which are formed as a consequence of a strong hydrodynamic instability (e.g., Lucy & Solomon 1980). Hydrodynamical calculations for hot star winds (e.g., Owocki, Castor & Rybicki 1988) provide strong support for such a model. The base corona source of X-
Fig. 4. X-ray luminosities $L_x$ plotted versus bolometric luminosities $L_{\text{bol}}$; solid lines represent regression lines for $L_{\text{bol}} < 10^{38}$ erg s$^{-1}$ and $L_{\text{bol}} > 10^{38}$ erg s$^{-1}$, whereas the dashed line shows $L_x = 10^{-7} \times L_{\text{bol}}$. Grey bars at the left side show typical ranges for the X-ray luminosity of Algol-type systems, pre-main sequence stars (PMS), and our Sun.
The wind kinetic power is typically $10^4$ times larger than the observed $L_X$

some process - which doesn’t have to be very efficient - converts a small fraction of this kinetic power to heat

the observed X-rays are the thermal radiation from this hot stellar wind plasma
The line-deshadowing instability (LDI)

causes fast, rarefied wind plasma to slam into slower, denser wind plasma

the resulting shocks heat the plasma

the X-rays we see are the thermal emission from this hot wind plasma

**general result from shock theory:**

\[ T \approx 10^6 \left( \frac{\Delta v_{\text{shock}}}{300 \text{ km/s}} \right)^2 \]
X-ray emitting plasma is embedded in the wind intrinsic instability of radiative driving, Line Deshadowing Instability (LDI), leads to shock-heating of the wind.

![Graph showing temperature, velocity, and density as functions of distance from the center of the star.](astro.swarthmore.edu/~cohen/presentations/ifrc3_xmbko1_e-2.gif)

- **Temperature**
- **Velocity**
- **Density**

Distance from the center of the star (in units of $R_\ast$, the radius of the star): 1.5, 5, 10.
snapshot from the hydro simulation

\[ r \sim 1.5 \, R_\star \quad \text{numerous shock structures above } 1.5 \, R_\star \]
shocked wind plasma is decelerated back down to the local steady-state wind velocity
X-ray emission lines should be Doppler broadened.
Less than 1% of the mass of the wind is emitting X-rays

>99% of the wind is cold and X-ray absorbing
Key points so far:

Massive stars emit X-rays

Their radiation-driven winds are the site of the X-ray emission (according to theory)

Next: X-ray spectroscopy of massive stars
X-ray spectroscopy confirms the general scenario embedded wind shocks (EWS)

Chandra launched in 1999 - first high-resolution X-ray spectrograph

response to photons with $h\nu \sim 0.5$ keV up to a few keV (corresp. $\sim 5\text{Å}$ to $24\text{Å}$)

X-ray imaging? $> 0.5$ arc sec, at best ($100s$ of AU)
spectroscopy ($\lambda/\Delta\lambda < 1000$ corresp. $v > 300$ km/s)
Spectral resolution and velocity

“spectral resolution” how close can two lines be in a spectrum and still be seen as two separate lines?

“spectral resolution” how broad does an intrinsically narrow spectral line looks in the spectrograph?

Spectral resolution, \( R = \frac{\lambda}{\Delta \lambda} \)

Doppler shift, \( \frac{\Delta \lambda}{\lambda} = \frac{v}{c} \)
now for some X-ray data... the same star (tau Sco) observed with three different X-ray telescopes

ROSAT 1991

ASCA 1994

Chandra 2001
X-ray emission process

thermal emission from collisional plasma

[Diagram showing the process of X-ray emission involving collisional excitation and spontaneous emission.]
Chandra grating spectroscopy

ζ Pup (O4 If)
Chandra grating (HETGS/MEG) spectra

ζ Pup (O4 If)

Capella (G5 III)
typical temperatures $T \sim \text{few } 10^6 \text{ K}$

(late-type stellar coronae tend to be hotter)

$\zeta$ Pup (O4 If)

Capella (G5 III)
Zoom in

ζ Pup (O4 If)

Ne X  Ne IX  Fe XVII

Capella (G5 III)
Zoom in

ζ Pup (O4 If)

Capella (G5 III)

Ne X  Ne IX  Fe XVII

~2000 km/s

(unresolved)
A careful look at the individual emission lines characteristic *asymmetry*

blue-shifted peak & skewness
A careful look at the individual emission lines characteristic *asymmetry*

How can this be explained in the context of embedded wind shocks (EWS)?
We need a model that...

captures the basic physical properties of
the hydro simulations of the LDI

but is simple enough to parameterize and
fit to data
Recall that most of the wind is cold.

>99% of the wind is cold and X-ray absorbing.
>99% of the wind is cold and X-ray absorbing
star observer

color coding: Doppler shifted, emitting plasma

resulting emission line profile
2 representative points in the wind that emit X-rays
2 representative points in the wind that emit X-rays

absorption along the ray
2 representative points in the wind that emit X-rays.

Absorption along the ray.

Extra absorption for redshifted photons from the rear hemisphere.
Wind Profile Model

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

Increasing \( \tau_\ast \)
**Line profile shapes**

**key parameters:** $R_0$ & $\tau_*$

\[ v = v_\infty (1-r/R_*)^\beta \]

\[ j \sim \rho^2 \text{ for } r/R_* > R_0, \]
\[ = 0 \text{ otherwise} \]

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

\[ \tau_* \equiv \frac{\kappa M}{4\pi R_* v_\infty} \]
Model is fit to data

\( \tau_\star = 2.0 \)

\( R_\odot = 1.5 \, R_\star \)
Hot plasma kinematics and location

$R_\odot$ controls the line width via $v(r)$

$R_\odot = 1.5 R_\star$

$R_\odot = 3 R_\star$

$R_\odot = 10 R_\star$
Distribution of $R_\circ$ values for ζ Pup

consistent with a global value of $R_\circ = 1.5 \, R_\star$
$v_\infty$ can be constrained by the line fitting too.

$v_\infty = 2250 \text{ km/s}$ from UV

68% confidence limit on mean from five lines.
X-ray plasma and mean wind have same kinematics

\[ v_\infty = 2250 \text{ km/s} \]

from UV

68% confidence limit on mean from five lines
The profiles also tell us about the level of wind absorption.
Wind Profile Model

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

Increasing \( \tau_\ast \)
Model is fit to data

\[ \tau_* = 2.0 \]
\[ R_\odot = 1.5 R_* \]

ζ Pup: Chandra

Fe XVII
Quantifying the wind optical depth

opacity of the cold wind component (due to bound-free transitions in C, N, O, Ne, Fe)

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

wind mass-loss rate

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

stellar radius

wind terminal velocity
soft X-ray wind opacity

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

note: emission comes from hot wind component, while absorption arises in cool wind component
ζ Pup Chandra: three emission lines

\[ \text{Mg Ly}\alpha: 8.42 \, \text{Å} \quad \text{Ne Ly}\alpha: 12.13 \, \text{Å} \quad \text{O Ly}\alpha: 18.97 \, \text{Å} \]

Recall:

\[ \tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty} \]
Results from the 3 line fits shown previously

\[ \tau_\ast \]

\[ \text{Wavelength (Å)} \]
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

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

\[
\tau_\star \equiv \frac{\kappa \dot{M}}{4\pi R_\star v_\infty}
\]
soft X-ray wind opacity

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

- Si V
- Mg IV
- Ne IV
- Fe L
- O IV

CNO processed
$\tau_\ast \equiv \frac{\kappa \dot{M}}{4\pi R_\ast \nu_\infty}$

$\dot{M}$ becomes the free parameter of the fit to the $\tau_\ast(\lambda)$ trend

$\tau_\ast(\lambda)$ trend consistent with $\kappa(\lambda)$
$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* \nu_\infty}$

\dot{M} becomes the free parameter of the fit to the $\tau_*(\lambda)$ trend
1.8 \times 10^{-6} \, M_{\text{sun}}/\text{yr} 

Theory (Vink)

6.4 \times 10^{-6} \, M_{\text{sun}}/\text{yr}

1.8 \times 10^{-6} \, M_{\text{sun}}/\text{yr}

from X-rays
Fe XVII
Preliminary Conclusions

1. Doppler-broadened line profiles tell us the kinematics of the shock-heated wind plasma

2. Line profile asymmetry tells us about the wind absorption; joint analysis of an ensemble of lines tells us the mass-loss rate of the wind
Preliminary Conclusions

1. Doppler-broadened line profiles tell us the kinematics of the shock-heated wind plasma consistent with hydro simulation predictions

2. Line profile asymmetry tells us about the wind absorption; joint analysis of an ensemble of lines tells us the mass-loss rate of the wind mass-loss rate factor \( \sim 3 \) lower than theoretically expected value
Survey of a dozen O stars

X-ray mass-loss rates: a few times less than theoretical predictions

binary wind-wind interaction X-rays
Recall the O star that ionizes the Orion Nebula

θ^1 Ori C: only O star here
Chandra X-ray image of the Orion Nebula Cluster

θ¹ Ori C: very X-ray bright
~10% of massive stars are magnetic!

unlike solar type magnetism, though: time-constant, not dynamo generated, often large-scale dipole
\( \theta^1 \) Ori C: prototype magnetic O star

temperature

emission measure

simulations by A. ud-Doula; Gagné et al. (2005)
The line-deshadowing instability (LDI) causes fast, rarefied wind plasma to slam into slower, denser wind plasma.

The resulting shocks heat the plasma.

The X-rays we see are the thermal emission from this hot wind plasma.

General result from shock theory:

\[ T \sim 10^6 \left( \frac{\Delta v_{\text{shock}}}{300 \text{ km/s}} \right)^2 \]
Magnetically Channeled Wind Shock model

magnetic channeling causes wind flows from opposite hemispheres to collide in the magnetic equator

the resulting shocks heat the plasma

the X-rays we see are the thermal emission from this hot wind plasma

general result from shock theory:

\[ T \sim 10^6 (\Delta v_{\text{shock}}/300 \text{ km/s})^2 \]
$\theta^1$ Ori C: prototype magnetic O star

temperature

magnetic channeling: strong shocks = hotter plasma

magnetic confinement: low post-shock velocity = narrower lines

simulations by A. ud-Doula; Gagné et al. (2005)
$\theta^1$ Ori C: hotter plasma, narrower lines

$\text{Mg}^{\text{XII}} / \text{Mg}^{\text{XI}}$ is proportional to temperature
recently discovered largest O star magnetosphere
(team includes Prof. V. Petit)

Chandra observations at two phases

more absorption when viewed edge-on

photon energy
Preliminary Conclusions

1. Magnetic massive stars produce X-rays via wind shocks in their magnetospheres

2. X-ray observations show that this process is more efficient than LDI-generated embedded wind shocks in non-magnetic O stars
Overall Conclusions

1. Shock heating extracts kinetic energy from radiation-driven winds, producing the X-rays

2. X-ray spectroscopy provides diagnostic information about plasma temperatures, velocities, and absorption
Extra Slides
Helium-like ions (e.g. O\textsuperscript{6+}, Ne\textsuperscript{8+}, Mg\textsuperscript{10+}, Si\textsuperscript{12+}, S\textsuperscript{14+}) – schematic energy level diagram

- 10-20 eV
  - 1s2s \textsuperscript{3}S
  - 1s2p \textsuperscript{3}P
- 1-2 keV
  - forbidden (f)
  - intercombination (i)
  - resonance (r)
- g.s. 1s\textsuperscript{2} \textsuperscript{1}S
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.
θ¹ Ori C: prototype magnetic O star

\[ R_{\text{fir}} = 1.2 \, R_\star \]

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

\[ R_{\text{fir}} = 4.0 \, R_\star \]

A. ud-Doula
\( \theta^1 \text{ Ori C: prototype magnetic O star} \)

- \( R_{\text{fir}} = 1.2 \, R_\star \)
- \( R_{\text{fir}} = 2.1 \, R_\star \)

MDH simulations are only marginally consistent with \( f/i \) constraints.

Data say hot plasma is closer to the photosphere.

A. ud-Doula
What produces the hot, X-ray emitting plasma in massive stars?

plasma with $T > 10^6$ K radiates X-rays ($h\nu > 100$ eV)

shocks heat plasma to $T \sim 10^6$ K
if $\Delta V_{\text{shock}} \sim 300$ km/s
and $T \sim (\Delta V_{\text{shock}})^2$

shocks are radiative in dense O star winds, but adiabatic in lower-density early B star winds
\[ \Delta v_{\text{shock}} = v_{\text{pre}} - v_{\text{post}} \]
β Cru (B0.5 III)
Fe XVII line in the *Chandra* grating spectrum of β Cru (B0.5 III)
X-ray filling factors of B stars

\[ \log \text{f.f.} = \log \frac{\text{EM}_{\text{obs}}}{\text{EM}_{\text{wind}}} \]

\[ \beta \text{ Cru} \]

Cohen et al. 1997
B star winds have low density, shocks are *adiabatic*.

Once the wind is shocked (at $\sim 1.5 \, R_\star$) it essentially never cools $\Rightarrow$ outer wind is (nearly completely) filled with hot (few $10^6 \, K$) plasma that is no longer radiatively driven.

Hence, narrow-ish X-ray lines.