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massive stars:

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

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

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

The Orion Nebula (Messier 42)
(MPG/ESO 2.2-m + WFI)
1000 yr old supernova remnant

Crab Nebula (WIYN)
wind-blown bubble: stellar wind impact on its environment

NGC 6888 Crescent Nebula  (Tony Hallas)
Radiation-driven massive star winds

\( \dot{M} \sim 10^{-6} M_{\text{sun}}/\text{yr} \)

UV spectrum: C IV 1548, 1551 Å

**STELLAR WIND OF ζ PUPPIS**

**UV telescope**

- **Front**
- **Emission**
- **Absorption**
- **Occulted**
- **Back**
- **Emission**
- **Side**

**P-Cygni Line Profile**

- Symmetric Emission = Blue-Shifted Absorption

**Flux**

- Velocity; Wavelength
Winds of massive stars are driven by radiation force

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

- cross-section (cm²)
- Luminosity (ergs/s)
- radius
Winds of massive stars are driven by radiation force.

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

- opacity (cm\(^2\)/g)
- Luminosity (ergs/s)
- radius
Winds of massive stars are driven by **radiation force**

\[
a_{rad} = \frac{\kappa L}{4\pi R^2 c}
\]
Eddington factor, $\Gamma_{edd}$: ratio of radiation force to gravity

$$\Gamma_{edd} \equiv \frac{F_{rad}}{F_{grav}} = \frac{\kappa L}{4\pi cGM}$$

For the Sun, $\Gamma_{edd} \sim 10^{-5}$
For massive stars, $\Gamma_{edd}$ approaches unity
Mechanical **power** in these winds:

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

\[ \approx 0.001 L_* \]

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

\[ L_{\text{massive}} \approx 4 \times 10^{39} \]
Massive star X-rays
vs.
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
Stellar rotation vs. X-ray luminosity

low-mass stars

graph showing the relationship between log of X-ray luminosity (erg s⁻¹) and log of V sin i (km s⁻¹)

RS CVn's

high-mass stars

graph showing the relationship between log of X-ray luminosity (erg s⁻¹) and log of V sin i (km s⁻¹)

Empty circles: Sp G0-M5
Filled circles: Sp F7-F8

IV+V
III+II

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

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

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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 $T \sim 10^6.8$ 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.
Chandra X-ray Telescope image of the Orion Nebula Cluster

young, massive star: $\theta^1$ Ori C

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

young, massive star: $\theta^1$ Ori C

young, massive star: $\theta^2$ Ori A

Color coded according to photon energy (red: <1 keV; green 1 to 2 keV; blue > 2 keV)
The connection between X-rays and stellar winds in massive stars
Power in massive star winds:

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

\[ L_{\text{sun}} = 4 \times 10^{33} \text{ erg s}^{-1} \]
\[ L_{\text{massive}} \approx 4 \times 10^{39} \]

while the x-ray luminosity

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

To account for the x-rays, only one part in $10^{-4}$ of the wind’s mechanical power is needed to heat the wind
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 $T \sim v^2$)

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

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

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

*Chandra, XMM* 350 eV to 10 keV
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 in the Gum Nebula
ζ Puppis: $50 \, M_{\text{Sun}}$, $10^6 \, L_{\text{Sun}}$
Chandra HETGS/MEG spectrum
(R ~ 1000 ~ 300 km s⁻¹)

ζ Pup

Si  Mg  Ne  Fe  O

H-like  He-like
Low-mass star (Capella) for comparison
The x-ray emission lines are broad: agreement with rad hydro simulations

But... they're also blue shifted and asymmetric. Is this predicted by the wind shock scenario?
Wind Profile Model
\[ \tau_\ast = \frac{\kappa \dot{M}}{4\pi R_\ast v_\infty} \]

Wind Profile Model

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

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

**opacity** of the cold wind component

wind mass-loss rate

radius of the star

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

\[ R_o = 1.5 \]

\[ R_o = 3 \]

\[ R_o = 10 \]

\[ \tau \equiv \frac{\kappa M}{4\pi R_\ast \nu} \]

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

\[ \tau = \tau_* \int_{z_*}^{\infty} \frac{R_* dz'}{r^2 (1 - R_*/r')^\beta} \]
We fit these x-ray line profile models to each line in the *Chandra* data

And find a best-fit $\tau_\star$ 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
ζ Pup: three emission lines

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

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

Recall:

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

![Graph showing terminal velocity of x-ray plasma](image)
onset radius of x-ray emission, $R_o$
Onset of instability-induced shock structure: $R_o \sim 1.5$

$1.5 \, R_\star = \text{height of } 0.5 \, R_\star$
\( \zeta \) Ori: O9.5

\( \epsilon \) Ori: B0
ζ Ori (09.7 I): O Lyα 18.97 Å

![Graph showing the count rate versus wavelength (Å) with peaks and valleys indicating the presence of O Lyα at 18.97 Å.]
ε Ori (B0 Ia): Ne Lyα 12.13 Å
Conclusions

Normal massive stars have x-ray line profiles consistent with the predictions of the wind instability model:

- Line widths are consistent with the wind velocity inferred from UV absorption lines;
- Onset radius of X-rays is $r \sim 1.5 \, R_{\text{star}}$

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.*