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Outline

Chandra resolved X-ray line profile spectroscopy of O star winds

1. Resolved X-ray line profiles can provide diagnostically useful information about:
   A. plasma kinematics
   B. local absorption

2. Applications to massive star X-rays
   A. wind-shock physics
   B. wind absorption: wind mass-loss rate
   C. with H-alpha: wind clumping
Prior to 2000: only low-resolution X-ray data

zeta Pup (O4 If): runaway, single O supergiant

ROSAT (early 1990s): resolving power, $R \sim 3$

BBXRT (early 1990s): resolving power, $R \sim 10$

Overall X-ray luminosity; crude, model-dependent plasma temperature information

Hillier et al. (1993)

Corcoran et al. (1993)
Chandra and XMM-Newton launched ~2000

ROSAT (early 1990s): resolving power, $R \sim 3$

BBXRT (early 1990s): resolving power, $R \sim 10$

Chandra MEG: resolving power, $R$ up to 1000

XMM RGS: resolving power, $R \sim$ few 100
O star X-ray spectra have broad lines

$63 \text{ ks HETGS zeta Pup (O4 If)}$

$\nu_{\text{wind}} \sim 10^3 \text{ km/s}$

$\nu_{\text{resolution}} \sim 10^2 \text{ km/s}$

$\nu_{\text{therm}} \sim 10^1 \text{ km/s}$

$\sim 2000 \text{ km/s}$
O star X-ray spectra have broad lines

Doppler, \( v/c = \Delta\lambda/\lambda \)
resolving power, \( R = \lambda/\Delta\lambda \)

\( v_{\text{wind}} \sim 10^3 \text{ km/s} \)
\( v_{\text{resolution}} \sim 10^2 \text{ km/s} \)
\( v_{\text{therm}} \sim 10^1 \text{ km/s} \)
X-ray emission lines are well resolved

Typical O star line profile; here Fe XVII

*Chandra* resolution
dominated by Doppler broadening due to bulk motion of the emitting plasma

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

\[ v_{\text{wind}} = +2250 \text{ km/s} \]
Asymmetric line shape due to continuum absorption by the cool wind component

\[ \nu_{\text{wind}} = -2250 \text{ km/s} \]

\[ \nu_{\text{wind}} = +2250 \text{ km/s} \]

physically meaningful model fit

line center
Rich diagnostics provided by HRXS

shock physics: hot plasma kinematics and spatial distribution
and wind mass-loss rates and clumping properties
Soft-X-ray emission is ubiquitous in O stars

$L_X \sim 10^{-7} \ L_{\text{Bol}}$ ($L_X \sim 10^{31}$ to $10^{33}$ ergs s$^{-1}$)

soft thermal spectrum: $kT < 1$ keV

minimal time variability

HD 93129A (O2 If*)

Carina: ESO
optical/IR

Trumpler 14 in Carina: Chandra
High- and low-mass stars have different X-ray production mechanisms.

Massive stars show no correlation between rotation and X-ray emission.

No convective envelope; no dynamo; no corona.
High- and low-mass stars have different X-ray production mechanisms.

Massive stars produce X-rays via shock-heating of their winds.
OB star winds are (line) radiation driven
& though they’re very dense, they are not best seen via imaging.
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

Velocity (km/s)

Radiation-driven O star winds

variability in wind UV lines
Embedded Wind Shock (EWS) paradigm

Line Deshadowing Instability (LDI) - intrinsic to line-driven flows

numerous shocks distributed throughout the wind, generally above some onset radius

\[ r = 1.5R_* \]
1-D rad-hydro simulation

with J. Sundqvist, S. Owocki, Z. Li

movie available at http://astro.swarthmore.edu/~cohen/presentations/movies/ifrc3_1abbott0.65_xkoybc350_xmbko1.e-2_epsabs-1.e-20.gif
Physics of the Line Deshadowing Instability (LDI)

Milne (1926)

radiation force depends on changes in the local wind velocity (moving out of the Doppler shadow)

stability analysis: Owocki, Castor, Rybicki (1984, 1988)

overlap between line profile and local radiation field
Embedded Wind Shock (EWS) paradigm

Less than 1% of the mass of the wind is emitting X-rays.

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

$\frac{r}{R_*} = 1.5$
Open theoretical issues

clump-clump collisions vs. self-excited instability

Feldmeier, Puls, & Pauldrach (1997)
Lower boundary conditions

self-excited photospheric perturbations + limb darkening

Figure 4. Inner wind time evolutions of a simulation without limb darkening and photospheric perturbations (left) and one including both effects (right).

Sundqvist & Owocki (2013)
2-D radiation-hydro simulations
initial work; line transport is expensive
Simulations constrained by data?

In addition to explaining the overall X-ray emission levels, the LDI physics generating embedded wind shocks makes predictions that can be tested by high-resolution X-ray spectroscopy:

- Spatial distribution of X-ray emitting plasma
- Kinematics
- Degree of absorption by the wind in which it’s embedded
- ...clumping
Chandra grating spectra confirmed the EWS scenario.

\[ V_{\text{Doppler}} \approx V_{\text{wind}} \]

\( \text{Ne X} \quad \text{Ne IX} \quad \text{Fe XVII} \)

\( \zeta \text{ Pup (O4 If)} \quad \text{Capella (G5 III)} \)

\(~2000 \text{ km/s}\) (unresolved)

Chandra easily resolves the wind-broadened X-ray emission lines.
lines are asymmetric:
this is a signature of wind absorption, and enables us to measure the wind mass-loss rate.
Build a model
to fit data
that captures
the physics of
the EWS/LDI
\[ v = v_\infty (1 - r/R_*)^\beta \]

beta velocity law assumed

observer

star

color coding: Doppler shifted, emitting plasma

resulting emission line profile
Line Asymmetry

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

mass-loss rates $\sim 10^{-6}$: expect wind to be modestly optically thick

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

Increasing $\tau_*$
Line profile shapes

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

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

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

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

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

Owocki & Cohen 2001

custom model in XSPEC (windprofile)
Fit the model to data

ζ Pup: Chandra

\( \tau_\star = 2.0 \)

\( R_\odot = 1.5 R_\star \)

uncertainties < 10%
Spatial distribution and kinematics of shocked wind plasma
Look at all unblended lines in the Chandra HETGS spectrum of ζ Pup
Distribution of $R_o$ values for $\zeta$ Pup

consistent with a global value of $R_o \sim 1.5 R_*$
$v_\infty$ can be constrained by the line fitting too

$v_\infty = 2250$ km/s from UV

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

$v_\infty = 2250$ km/s from UV

68% confidence limit on mean from five lines
Absorption signatures in the X-ray line profiles
Fit the model to data

\[ \tau_\star = 2.0 \]

\[ R_\odot = 1.5 \, R_\star \]
Quantifying the wind optical depth of the cold wind component (due to photoionization of C, N, O, Ne, Fe)

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

- Wind mass-loss rate: \( \dot{M} = 4\pi r^2 v \rho \)
- Stellar radius
- Wind terminal velocity
**soft X-ray wind opacity**

note: absorption arises in the dominant, cool wind component

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

- opacity with CNO processed abundances
- opacity with solar abundances
ζ Pup Chandra: three emission lines

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

Recall:

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

![Graph showing the relationship between $\tau_*$ and Wavelength (Å). The graph displays three data points with error bars.](image)
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

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

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

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

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

6.4 \times 10^{-6} M_{\text{sun}}/\text{yr} Theory (Vink)
consistent with new UV&IR measurements that model the wind clumping (Bouret et al. 2012, Najarro et al. 2011)

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
X-ray line profile based mass-loss rate: implications for clumping

**Basic definition:**

\[ f_{\text{cl}} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \frac{\langle \rho^2 \rangle^{0.5}}{\langle \rho \rangle} \]

**Clumping factor**

Ignoring clumping will cause you to overestimate the mass-loss rate... for density-squared diagnostics.

**Optical:**

\[ F_{H\alpha} \sim f_{\text{cl}} \rho^2 \sim f_{\text{cl}} \dot{M}^2 \]

\[(f_{\text{cl}})^{0.5} \dot{M} \text{ is the invariant for } H\alpha\]
X-ray combined with Hα

optical: \( F_{\text{Hα}} \sim f_{\text{cl}} \rho^2 \sim f_{\text{cl}} \dot{M}^2 \)

X-ray: \( \tau_\star \sim \rho \sim \dot{M} \)

\((f_{\text{cl}})^{0.5} \dot{M}\) is the invariant for Hα

optical Hα: \((f_{\text{cl}})^{0.5} \dot{M} = 8.3 \times 10^{-6}\) for ζ Pup

X-ray: \( \dot{M} = 1.8 \times 10^{-6}\) for ζ Pup (this work)

\(f_{\text{cl}} \sim 20\) for ζ Pup

but see Puls et al. 2006, Najarro et al. 2011: radial variation of clumping factor
clumping factor \~10 to \~20 (Najarro et al. 2011)

Fig. 18. Radial stratification of the clumping factor, $f_{cl}$, for $\zeta$ Pup. Black solid: clumping law derived from our model fits. Red solid: Theoretical predictions by Runacres & Owocki (2002) from hydrodynamical models, with self-excited line driven instability. Dashed: Average clumping factors derived by Puls et al. (2006) assuming an outer wind matching the theoretical predictions. Magenta solid: run of the velocity field in units of 100 km s$^{-1}$. See also Sect. 4.
2-D radiation-hydro simulations
clumps break up to the grid scale; $f_{cl} \sim 10$

Dessart & Owocki 2003
HD 93129A (O2 If*)

Tr 14: Chandra

Carina: ESO
Strong stellar wind: traditional diagnostics

UV

\[ \dot{M} = 2 \times 10^{-5} \, M_{\text{sun}}/\text{yr} \]
\[ v_\infty = 3200 \, \text{km/s} \]

H\(\alpha\)

Fig. 13. Observed H\(\alpha\) profile (solid) compared with the calculation assuming a mass loss of \(18 \times 10^{-6} \, M_\odot/\text{yr}\) (dashed). Note that the blue narrow emission peak originates from the HII-region emission.
Chandra MEG spectrum of HD 93129A

$d = 2.2 \text{ kpc vs. } 0.4 \text{ kpc for } \zeta \text{ Pup}

HD 93129A

Mg XII Lyman-alpha

$\tau^* = 1.0$

$R_\odot = 1.4 \, R^*$
$R_0 = \text{onset radius of X-ray emission}$

$R_0 = 1.4 \, R^*$
HD 93129A

$\tau_*$ from five emission lines

$\dot{M} = 1.2 \times 10^{-5} M_{\text{sun}}/\text{yr}$

Theory (Vink)

$\dot{M} = 6.8 \times 10^{-6} M_{\text{sun}}/\text{yr}$
\[ \dot{M} = 7 \times 10^{-6} \, \text{M}_{\odot}/\text{yr} \]

- Clumping \( f_{\text{cl}} = 12 \), onset at \( R_{\text{cl}} = 1.05 \, R_\ast \)
- No clumping

![Graph showing relative flux vs. wavelength with labeled clumping and no clumping cases](image)
Extension of X-ray profile mass-loss rate diagnostic to other stars

lower mass-loss rates than theory predicts with clumping factors typically of ~ 20

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

Binary wind-wind interaction X-rays
Conclusions

0. HRXS provides useful diagnostic information about hot plasma physics and also can probe surrounding material via absorption

1. X-ray onset at $R_o \sim 1.5 R_\star$

2. Mass-loss rates are lowered by roughly a factor of three

3. Clumping factors of order 10 are consistent with optical and X-ray diagnostics

4. Clumping starts at the base of the wind, lower than the onset of X-ray emission