X-ray spectroscopy of single O stars

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X-ray Universe 2008
All O stars emit X-rays

- $0.01 \text{MK}< T_{\text{eff}} < 0.06 \text{MK}$, $L_{\text{bol}} = 10^{4.6}L_{\text{sun}}$
- Clumped wind $\dot{M} = 10^{-6-8} M_{\text{sun}}/\text{yr}$, $v_{\text{wind}}>10^3\text{km/s}$
- Superionization (e.g. OVI) = X-rays (Cassinelli et al. '79, '83)
- Einstein, Rosat: $L_X \sim 10^{-7}L_{\text{bol}}$ (Seward et al. '79, Berghoever et al. '97)

Model + X-rays $\Rightarrow$ O VI superionisation
How X-rays are generated in O stars? Leading theories.

- Bow shocks around blobs (Lucy & White ’80, Cassinelli et al. ’08)
- Magnetically confined loops at the stellar base (Cassinelli & Swank ’83)
- Wind shocks from the instabilities of radiation driving (Owocki et al. ’83)
- Collisions of dense shells in deep wind regions (Feldmeier et al. ’97)
How X-rays are generated in O stars? Leading theories:

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Do These Models Exclude Each Other?
High-Resolution X-ray Spectra

* Overall spectral fitting → plasma model, abundances
* Line ratios → $T_x(r)$, spatial distribution
* Line profiles → velocity field, wind opacity
Line Ratios of He-Like Ions: Location and Temperature

- Strong UV field $\Rightarrow$ radiative de-population of metastable level $^3S$
- $f/i$ is diagnostic of UV field. UV field dilutes with radius

* Kahn + '01, Waldron & Cassinelli'01,'07, Wojdowski & Schulz'05, Oskinova '06, Leutenegger+’06, Raassen et al. ’08
* Similar trends for different stars (Waldron & Cassinelli ’07)
* Full UV RT needed: Mg XI $f \rightarrow i$ transition blended with O VI resonance line (cool wind) (Leutenegger et al. ’06)

from Oskinova+’06
Near-Star High-Ion Problem (Waldron & Cassinelli ’07)

O supergiants: strong photoabsorbing wind

- Observed f/i → radii of formation
- Ions with higher Z only close to the base
- Waldron’05: $T_x(r) \downarrow$
  20MK @ 1.5$R_*$ → 2.5MK @ 8$R_*$
- Contradiction to all shock models ??!
- Magnetically confined loops @ surface ! (?)
Near-Star High-Ion Problem (Waldron & Cassinelli '07)

O dwarfs: weak winds: low absorption of X-rays

Ions with high and low Z are at the same distance, close to the core

Comparison with the O supergiants: correlation with wind $\tau_E$ is expected
Wind opacity for X-rays

Using modern atmosphere model \( \zeta \) Pup \( \dot{M} = 8.7 \times 10^{-6} M_\odot/\text{yr}^{-1} \)

Agreement between wind \( \tau_E \) and radii of line formation from fir analysis
Why it matters: mass-loss from massive stars

\( \dot{M} \) - key feedback agent
\( \dot{M} \) - key parameter of stellar evolution

Empirical determinations are model dependant
Spectral analysis is hampered by unknown degree of wind clumping
Literature values differ by 100 times
X-rays measure wind opacity -> \( \dot{M} \)
**Observed X-ray emission line profiles**  
Waldron & Cassinelli’07  Analysis of spectra of 17 OB stars

- Shift (skewness) correlates with $\tau_E$
- Line shifts are small
- Lines are Doppler broadened  
  less than terminal wind velocity
Directions to explain observed X-ray line profiles

- New paradigm of X-ray emission
  Colissionless shocks, Pollock ’07

- Optically thick X-ray emission lines
  Ignace & Gayley ’02
  Cannot be true for lines of ALL ions

- Reducing wind opacity via
  * \( \dot{M} \) reduction
    Waldron & Cassinelli ’01, Kramer et al. ’03, Cohen et al. ’06, ...
  * Wind clumping
    Waldron & Cassinelli ’01, Feldmeier etal. ’03, Oskinova etal.’06, ...
Can X-ray line profiles be explained by reduction of $\dot{M}$? Hardly!

Spectral fits of UV and optical lines: $\dot{M}$ is reduced when wind is strongly clumped **ASSUMING** that clumps are optically thin

**Sole justification:** convenient to modify VERY complex stellar atmosphere codes
Line shift is a measure of wind opacity.

If clumps were optically thin X-ray lines would have different shape

CVI should be more significantly more shifted/skewed than NeIX
Observed lines imply GREY opacity

Observed emission line profiles are similar, opacity IS grey

Assumption of optically thin clumps is not physically justified!
Macroclumping

Clump are allowed not to be optically thin.

Formalism: Feldmeier et al. ’03, Owocki et al. 04, Oskinova et al. 07
Clumping Reduces Effective Opacity

Wind opacity for X-ray drastically reduced by clumping if clumps are NOT optically thin

Opacity becomes "grey" if clumps are optically thick

Similar line profiles across the spectrum

Symmetric lines due to anisotropic opacity

- Owocki & Cohen '06: warnings
Observed and model lines of ζ Puppis (no fitting!)
Conclusions: Intrinsic wind emission from O stars

- X-rays originate close to the stellar core. Hot plasma fills some space between clumps.
- High-ion near-star problem. New implications for X-ray formation
- "Hybrid" model? Loop-like structures at the surface, shocks around blobs due to the wind instability?
- Stellar wind is clumped until proven otherwise. Radiative transfer is affected by clumping
- Clumping explains shape of X-ray emission line profiles.
- Consistent $\dot{M}$ estimates based on analyses of spectra ranging from radio to X-ray