Probing the clumpy winds of giant stars with high mass X-ray binaries

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December 10, 2015
1. Clumpy winds of O/B stars

2. Three challenges of HMXBs as probes of clumpy winds

3. Probing the clumpy winds of giant stars
   - Cygnus X-1: orbital variability of absorption
   - Cygnus X-1: X-raying the clumps
   - Vela X-1: deciphering accretion structure

4. Outlook: Astro-H and Athena
Winds of O/B stars

- line-driven (scattering of the star’s UV radiation; CAK-winds after Castor, Abbott & Klein, 1975)
- mass loss \( \gtrsim 10^{-7} M_\odot/\text{yr} \)
- terminal velocities \( > 2000 \text{ km/s} \)
- trigger or inhibit star formation
- impact chemical evolution of galaxies through enrichment

LH 72 in LMC; ESA/Hubble, NASA and D. A. Gouliermis
Dessart & Owocki, 2005; 2D simulations

Multiple observational lines of evidence structure of optical emission lines (Hillier 1991, Eversberg et al. 1998, Markova et al. 2005); wind-shocks as explanation for strong X-ray emission from single O-stars (Feldmeier 1997), etc.

but: clump properties inferred indirectly, probes only clump ensemble
High mass X-ray binaries:
Material flows from O/B star onto neutron star or black hole

- accretion and ejection processes
- bulk of radiation in X-ray range
High mass X-ray binaries: Material flows from O/B star onto neutron star or black hole

▶ accretion and ejection processes
▶ bulk of radiation in X-ray range

winds influence the accretion rate and thus X-ray production

▶ flares
▶ long-term variability?
▶ superfast X-ray transients

 radiation from close to BH/NS effectively X-rays the wind

▶ in situ probes close to stellar surface
▶ different parts of the wind at different orbital phases
Challenge I: intrinsic variability

X-ray binary intrinsic variability on timescales from seconds to years:

solution: talk to X-ray binary experts!
Challenge I: intrinsic variability

X-ray binary intrinsic variability on timescales from seconds to years:

solution: talk to X-ray binary experts!
Challenge II: accretion structure

NS/BH disturbs the wind, resulting in accretion & photoionization wakes and focused winds

analytical and numerical models of compact object/wind interaction so far for smooth winds only
Chance: accretion structure

NS/BH disturbs the wind, resulting in accretion & photoionization wakes and focused winds

analytical and numerical models of compact object/wind interaction so far for smooth winds only

solution: learn more about accretion structure of HMXBs
cold(er) clumps ⇒ low ionization lines

\[ E_{\text{obs}} \neq E_{\text{lit}} \]

Doppler shifts or lack of knowledge of atomic physics?

solution: lab measurements!

crucial for microcalorimeters! *(Astro-H, Athena)*

EBIT: Electron Beam Ion Trap

https://ebit.llnl.gov/overviewEBIT.html
Challenge III: reference line energies

Use EBIT-I @ LLNL

N. Hell, G. Brown; Si, S, Mg, Al, Cl, Ar, and Mn data exist, publications in prep.
Cyg X-1 / HDE 226868 system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Companion</td>
<td>O-type supergiant</td>
</tr>
<tr>
<td>Mass loss rate</td>
<td>$\sim 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$</td>
</tr>
<tr>
<td>Orbital period</td>
<td>5.6 days</td>
</tr>
<tr>
<td>Inclination</td>
<td>$i \approx 27^\circ$ (Orosz et al., 2011)</td>
</tr>
<tr>
<td>ISM equivalent hydrogen density</td>
<td>$\sim 0.5 \times 10^{22} \text{ cm}^{-2}$ (Xiang et al., 2011)</td>
</tr>
</tbody>
</table>

Hanke 2011

- orbital variability of overall absorption $\Rightarrow$ focussed wind
- orbital variability of ‘dip’-occurrence $\Rightarrow$ individual clumps in the wind
RXTE campaign

Grinberg et al., 2013, 2014

typical exposure: $\sim2\text{ ks}$
Outlook: Astro-H and Athena

X-ray states

distinct radiation regimes
\( \hat{=} \) states

only hard state useable for absorption studies

Cygnus X-1; Nowak et al., 2011

Chandra • Suzaku-XIS • Suzaku-GSO • RXTE-PCA • RXTE-HEXTE • INTEGRAL
RXTE campaign

Grinberg et al., 2013, 2014

typical exposure: \(\sim 2\) ks
Orbital variability of absorption: soft and intermediate states

disk component $\Rightarrow$ large uncertainties in $N_H$

wind strongly ionized $\Rightarrow$ mainly transparent to X-rays
Orbital variability of absorption: soft and intermediate states

ionized material $\Rightarrow$ line-driving mechanism breaks down $\Rightarrow$ changes in the geometry of the system

Čechura & Hadrava, 2015
Orbital variability of absorption: hard state

all hard state data

one long, stable hard state

Grinberg et al., 2015
Hard state: a focussed wind model

- toy model for a focussed CAK wind (Gies & Bolton, 1986; Friend & Castor, 1982)

Grinberg et al., 2015

- fails to describe the variability due to lack of clumps
Hard state: a clumpy wind model

(Owocki&Cohen 2006, Sundqvist et al. 2012, but see also Oskinova et al. 2012)

- discrete, spherical clumps
- $\beta$ velocity law
- no focussed wind component (yet)

- known: stellar parameters, terminal velocity, mass loss rate
- variable: number of clumps $N$ and terminal porosity length $h_\infty$

(Fig. from Sundqvist et al. 2012)
Hard state: a clumpy wind model

terminal porosity length $h_\infty = 0.1 R_*$ stellar radii

Grinberg et al., 2015
Hard state: a clumpy wind model

terminal porosity length $h_\infty = 10 R_*$ stellar radii

Grinberg et al., 2015
Hard state: a clumpy wind model

terminal porosity length $h_\infty = R_*$ stellar radius

$N_{H} [10^{22} \text{ cm}^{-2}]$
**Hard state: a clumpy wind model**

**model**

\[ h_\infty = R_* \]

<table>
<thead>
<tr>
<th>( \phi_{\text{orb}} )</th>
<th>Fractional Number of Observations</th>
<th>Cumulative Fractional Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–0.1</td>
<td>50</td>
<td>0.3</td>
</tr>
<tr>
<td>0.1–0.2</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>0.2–0.3</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>0.3–0.4</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>0.4–0.5</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>0.5–0.6</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>0.6–0.7</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>0.7–0.8</td>
<td>50</td>
<td>0.3</td>
</tr>
<tr>
<td>0.8–0.9</td>
<td>50</td>
<td>0.4</td>
</tr>
<tr>
<td>0.9–1.0</td>
<td>50</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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Hard state: a clumpy wind model

Grinberg et al., 2015

agreement between data (black) and model (red)

$h_\infty \approx R_*$ agrees with values for single O stars

non-Gaussian tail for $\phi_{\text{orb}} \approx 0$ in data

$\Rightarrow$ structure in wind $\Rightarrow$ fo-cussed wind? non-spherical clumps?

average values (circles) and standard deviations (error bars on the average values)
four observations in hard state:
ObsIDs 3814, 8525, 9847, 11044

three observations show dipping:
ObsIDs 3814, 8525, 9847

Miškovičová et al., A&A subm.
Dipping states

Hirsch et al., in prep.

divide each observation in four dipping stages with similar SNR

<table>
<thead>
<tr>
<th>Orbital phase φ</th>
<th>(0.5–1.5 keV) / (3–10 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.95</td>
</tr>
<tr>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>0.10</td>
<td>0.2</td>
</tr>
<tr>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>0.30</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Observed time [ks]
0.5–10 keV count rate (c/s)
3814
50
20
100
10
500

Energy [keV]
Photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$

Wavelength [Å]

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Clump structure

lower ionization stages of Si and S appear when absorption stronger
same Doppler-shift for lines in the same ObsID
⇒ onion-like clump structure

Hirsch et al., in prep.
Clump structure

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Hirsch et al., in prep.
Vela X-1

- B0.5 Iab supergiant
- 283 s pulsar
- eclipsing 9 d orbit

- binary separation: $53.4 \ R_\odot$
  $\Rightarrow$ neutron star embedded in companion wind
Variability along the orbit

changing **baseline absorption** best accessed with all sky monitors, e.g., MAXI, averaging over many orbits:

Doroshenko et al. 2013
Wind and accretion structure

accretion wake focussing of the wind through gravity

photoionization wake shocks on interface between CAK-wind and ionized plasma around neutron star

⇒ absorption highly variable with orbital phase $\phi_{\text{orb}}$
High resolution spectra along the orbit

Watanabe et al. 2006

high & low ionization stages seen at $\phi_{\text{orb}} \approx 0.5 \Rightarrow$ simultaneous presence of hot and cold gas
Suzaku at $\phi_{\text{orb}} = 0.17-36$:

- Odaka et al. 2013

$\Rightarrow$ highly variable absorption atop orbital variability at $\phi_{\text{orb}} \lesssim 0.5$
- time scales as short as 1–2 ks
- also seen in XMM (Martinez-Nunez et al. 2014) and EXOSAT (Haberl et al. 1990)

BUT: Chandra-HETG observations always been analyzed as a whole!
Short term variability in *Chandra* observations

![Graph showing variability in count rate and hardness](image)

ObsID 1928, Feb 11 2001

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Short term variability in *Chandra* observations

ObsID 1928, Feb 11 2001

⇒ clearly defined periods of enhanced hardness
the 2.5–10 keV continuum:

- **cannot** be described with same $N_h$, but different power laws
- **can** be described with same power law, but different $N_h$
Hardness-resolved spectra

Marked: detection in composite spectrum (Goldstein et al. 2004)
Hardness-resolved spectra

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Hardness-resolved spectra

Marked: detection in composite spectrum (Goldstein et al. 2004)
Marked: detection in composite spectrum (Goldstein et al. 2004)
no Si lines except of Si XIII triplet have been previously detected in the composite spectra (Goldstein et al. 2004)

lines in the high hardness/high absorption spectrum

complex structure in low absorption spectrum
Si region during dips

- use newest lab reference values for line energies
- tie lines with similar blueshifts

**Vela X-1 with Chandra-HETG**

**Ratio**

<table>
<thead>
<tr>
<th>Wavelength [Å]</th>
<th>ECS [counts/eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si VIII</td>
<td>7.4</td>
</tr>
<tr>
<td>Si VII</td>
<td>7.2</td>
</tr>
<tr>
<td>Si II–VI</td>
<td>7</td>
</tr>
<tr>
<td>Si I</td>
<td>6.8</td>
</tr>
<tr>
<td>Si XII</td>
<td>6.6</td>
</tr>
<tr>
<td>Si XI</td>
<td>6.4</td>
</tr>
<tr>
<td>Si X</td>
<td>6.2</td>
</tr>
<tr>
<td>Si IX</td>
<td>6</td>
</tr>
</tbody>
</table>

Lab measurements with Electron Beam Ion Trap (EBIT) @ LLNL

**High ionization lines**: ionized part of the wind
\[ \nu \approx -300 \text{ km/s} \]

**Low ionization lines**: reflection from clumps
\[ \nu \approx -1000 \text{ km/s} \]
low hardness/absorption
Outlook: Astro-H and Athena

Toy geometry

- clumps coming into the line of sight
- reduced continuum, makes fluorescent lines visible
- different velocities for hot (ionized) and cold (not yet ionized) medium

⇒ wind clumps or a patchy accretion wake?

high hardness/absorption ⇒ dips
Even shorter timescales?

⇒ shorter-term variability not yet accessible, but possibly crucial, also to test simulations (e.g., Blondin et al. 1990)
Chandra-HETGS

~180 ks at

$\phi_{\text{orb}} = 0.15$–0.45

forthcoming

Astro-H

higher effective area,

but lower energy resolu-

tion in Si-region

Kitamoto et al. 2014; plot by M. Kühnel & N. Hell
SWG3.3: End Points of Stellar Evolution

science goal R-SCIOBJ-332

Athena shall determine the geometry, porosity and mass loss-rate of stellar wind structures of isolated massive stars, especially in the presence of magnetic fields, through phase spectroscopy for a sample of objects. *Time resolved spectral analysis of X-ray emission from a sample of high mass X-ray binaries hosting supergiant and hypergiant companions shall be carried out to seek independent estimates of massive star wind properties.*

Outlook: *Athena*

- potential to resolve down to timescales of $\sim 10$–$100$ s, but unclear whether bright sources ($10$–$100$ mCrab) can be observed
- fainter analogues can be observed $\Rightarrow$ increase in sample!

![Diagram showing energy spectrum and velocity accuracy](image-url)
O/B star wind are structures and high mass X-ray binaries offer a chance to probe this structure

- intrinsic variability
- line energies
- wind vs. HMXB experts