X-raying the wind of the B0 supergiant QV Nor


The Universe in High Resolution X-ray Spectra, August 2015, Cambridge MA
• The clumpy wind paradigm in massive stars well established (Lucy & Solomon 1980, Owocki et al. 1988, Feldmeir et al. 1997)

• There is, however, considerable uncertainty on the physical properties of these clumps (size, density, distribution).

• Of particular interest is the radial onset of clumping in the wind of the massive star. Feldmeier et al. 1997 predicted a smooth wind up to 1.5R\textsubscript{*} after which the instabilities develop and fragment the wind.

• Observations suggest that the innermost wind regions could be already clumped (Puls et al. 2006, Waldron & Cassinelli 2007).

• Some theoretical models predict subsurface convection cells in OB stars (Cantiello & Braithwaite 2011)
Intro.

• In HMXBs a compact object is deeply embedded into the massive star wind providing a source of intense X-ray illumination.

• The X-rays excite transitions in the wind governed by the ionization parameter

\[ \xi = \frac{L_x}{n(r_x) r_x^2} \]

• The Fe Kα line is regularly observed in virtually all HMXBs (Torrejón et al. 2010, Gimenez-García et al. 2015).

• In order to have strong lines from near-neutral Fe, \( \xi \leq 10^2 \). For typical luminosities of \( L_x \sim 10^{36} \text{ erg s}^{-1} \) and distances \( r_x \sim 10^{11-12} \text{ cm} \) the required \( n \sim 10^{10-12} \text{ cm}^{-3} \) which is a factor between 1 and 100 the average wind densities predicted by the smooth wind scenario.

• The Fe Kα line is a tracer of the wind “overdensities”, i.e., the clumps.
QV Nor

B0 I (supergiant) donor of the X-ray pulsar 4U1538-52. The NS orbits QV Nor every 3.7d

Two orbital solutions individually \textbf{precisally determined} (Clark 2000). The NS at $r=[1.2, 1.5]R_*$ probing the \textit{innermost wind region}.

Wind radial density profile well established (Clark+ 1994=CWN94)

\begin{center}
\begin{tabular}{llll}
\hline
ObsID  & Date         & $t_{\exp}$ & \phi (start)
\hline
15704  & 2014-02-03 10:27:14 & 25.63       & 0.97 \\
16581  & 2014-02-06 10:21:40 & 52.27       & 0.77 \\
\hline
\end{tabular}
\end{center}

Eclipsing

Periastron passage close to eclipse allowing maximum constrast
\[ P_{\text{spin}} = 526.69 \pm 1.31 \text{ s} \]

NS Spin pulse

Pulsed fraction 54%
**HETG Lightcurve**

- **Observed** light curve re binned to $P_{\text{spin}} = 526.69$ s
- Strong variability
- HR anticorrelated with flux

Synthetic light curve:
- Constant X-ray source
- X-rays propagate towards the observed and suffer from absorption in the wind
- Mass-absorption coefficients from NLTE models
  - $\kappa=20 \text{ cm}^2 \text{ g}^{-1}$ at $\lambda=10 \text{ Å}$ and $\kappa=3 \text{ cm}^2 \text{ g}^{-1}$ at $\lambda=3 \text{ Å}$
- A **smooth wind** and **stationary accretion rate** can be excluded

- The variability observed in the **hard** band can not be explained solely by clump absorption (the wind is transparent for $\lambda < 4$ Å). There must be a **non-stationary accretion rate**.

- The absorption may help to explain the variability of the **soft** band provided that the wind is **significantly clumped**.
$F(E) = \text{Abs}(E') \times C_{po} \times E^{-\Gamma}$
$Abs(E) = (1 - f) \times TB_{new_1}(E) + f \times TB_{new_2}(E)$

$f$ is the X-ray source covering fraction a proxy for the degree of wind clumping. 
$Tbnew$ photoelectric absorption (Wilms+ 2010)
Spectrum: continuum model

Model parameters for the continuum.

<table>
<thead>
<tr>
<th></th>
<th>$N_H^1$ (a)</th>
<th>$N_H^2$</th>
<th>$f$</th>
<th>$C_{po}$</th>
<th>$\Gamma$</th>
<th>$N_H^3$</th>
<th>$C_{bb}$</th>
<th>$kT_{bb}$</th>
<th>Flux (c)</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>5.1$^{+1.1}_{-1.2}$</td>
<td>12.8$^{+1.9}_{-1.4}$</td>
<td>0.77$^{+0.15}_{-0.04}$</td>
<td>4.5$^{+1.3}_{-0.8}$</td>
<td>1.33$^{+0.17}_{-0.15}$</td>
<td>2.45$^{+0.9}_{-0.8}$</td>
<td>0.3$^{+0.1}_{-0.1}$</td>
<td>0.10$^{+0.03}_{-0.02}$</td>
<td>5.86$^{+0.43}_{-0.27}$</td>
<td>0.92 (412)</td>
</tr>
<tr>
<td>I</td>
<td>2.5$^{+0.5}_{-0.5}$</td>
<td>26.1$^{+4.4}_{-4.2}$</td>
<td>0.95$^{+0.01}_{-0.06}$</td>
<td>0.79$^{+0.22}_{-0.14}$</td>
<td>1.33 (fixed)</td>
<td>1.4$^{+0.8}_{-0.7}$</td>
<td>0.2$^{+0.1}_{-0.1}$</td>
<td>0.10 (fixed)</td>
<td>2.51$^{+0.23}_{-0.15}$</td>
<td>0.95 (340)</td>
</tr>
<tr>
<td>E</td>
<td>1.6$^{+0.9}_{-0.8}$</td>
<td>58$^{+10}_{-8}$</td>
<td>0.89$^{+0.08}_{-0.09}$</td>
<td>0.120$^{+0.020}_{-0.018}$</td>
<td>1.33 (fixed)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.12$^{+0.02}_{-0.02}$</td>
<td>0.95 (343)</td>
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</tbody>
</table>

(a) All $N_H$ in units of $\times 10^{22}$ cm$^{-2}$.
(b) All $C$ in units of $\times 10^{-2}$
(c) Unabsorbed 1-10 keV model flux in units of $\times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$

\[
Abs(E) = (1 - f) \times TB_{new_1}(E) + f \times TB_{new_2}(E)
\]

\[
N_H^1 = N_H^{\text{inter-clump}} + N_H^{\text{ISM}}
\]

\[
N_H^2 = N_H^{\text{clumps}} + N_H^{\text{ISM}}
\]
Spectrum: continuum model

Model parameters for the continuum.

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<th>( \phi )</th>
<th>( N_H^1 ) (^{(a)} )</th>
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<th>( f )</th>
<th>( C_{po}^{(b)} )</th>
<th>( \Gamma )</th>
<th>( N_H^3 )</th>
<th>( C_{bb} )</th>
<th>( kT_{bb} )</th>
<th>Flux (^{(c)} )</th>
<th>( \chi^2 ) (dof)</th>
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<td>0.77 (O)</td>
<td>5.1(^{+1.1}_{-1.2} )</td>
<td>12.8(^{+1.9}_{-1.4} )</td>
<td>0.77(^{+0.15}_{-0.04} )</td>
<td>4.5(^{+1.3}_{-0.8} )</td>
<td>1.33(^{+0.17}_{-0.15} )</td>
<td>2.45(^{+0.9}_{-0.8} )</td>
<td>0.3(^{+0.1}_{-0.1} )</td>
<td>0.16(^{+0.03}_{-0.02} )</td>
<td>5.86(^{+0.43}_{-0.27} )</td>
<td>0.92 (412)</td>
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<td>0.88 (I)</td>
<td>2.5(^{+0.5}_{-0.8} )</td>
<td>26.1(^{+4.4}_{-4.2} )</td>
<td>0.95(^{+0.01}_{-0.06} )</td>
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\(^{(a)} \) All \( N_H \) in units of \( \times 10^{22} \) cm\(^{-2} \).
\(^{(b)} \) All \( C \) in units of \( \times 10^{-3} \).
\(^{(c)} \) Unabsorbed 1-10 keV model flux in units of \( \times 10^{-10} \) erg s\(^{-1} \) cm\(^{-2} \).

\( E(B-V) = 2.2 \) (Crampton+ 1978) \( \rightarrow N_{\text{ISM}}^1 H\approx 1.5 \times 10^{22} \) cm\(^{-2} \)

\( N_{H}^1 = N_{\text{inter-clump}}^{\text{inter-clump}} + N_{\text{ISM}}^1 \)

At \( \phi = 0.97 \) (E) \( \rightarrow N_{\text{inter-clump}}^{\text{inter-clump}} H\approx 0 \)

The interclump medium contributes very little to the continuum absorption

We have an “extra” \( N_{H} (5.1-1.5 \approx 3.6 \times 10^{22} \) cm\(^{-2} \) at \( \phi = 0.77 \)
Spectrum: continuum model

MAXI 5 years lightcurve
(Rodes-Roca+ 2015)

Chandra HETG spectrum consistent with increased absorption in the second half of the orbit.
### Spectrum: He-like triplets

Emission lines identified in the *Chandra* phase average spectrum of QV Nor

<table>
<thead>
<tr>
<th>Ion</th>
<th>λ (Å)</th>
<th>Flux × 10^−4 (ph s^−1 cm^−2)</th>
<th>σ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si XIV Lyα</td>
<td>6.1880±0.0019</td>
<td>2.2±0.08</td>
<td>0.005</td>
</tr>
<tr>
<td>Si XIII r</td>
<td>6.6396</td>
<td>1.8±1.0</td>
<td>0.005</td>
</tr>
<tr>
<td>Si XIII i</td>
<td>6.6850</td>
<td>&lt;0.75</td>
<td>0.005</td>
</tr>
<tr>
<td>Si XIII f</td>
<td>6.7377</td>
<td>1.8±1.0</td>
<td>0.005</td>
</tr>
<tr>
<td>Si Kα</td>
<td>7.1186±0.0005</td>
<td>1.0±1.8</td>
<td>0.005</td>
</tr>
<tr>
<td>Mg XII Lyα</td>
<td>8.4236±0.0032</td>
<td>10±13</td>
<td>0.009±0.009</td>
</tr>
<tr>
<td>Mg XI r</td>
<td>9.1688</td>
<td>1.2±0.7</td>
<td>0.005</td>
</tr>
<tr>
<td>Mg XI i</td>
<td>9.2300</td>
<td>&lt;0.6</td>
<td>0.005</td>
</tr>
<tr>
<td>Mg XI f</td>
<td>9.3136</td>
<td>1.5±0.7</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Note. — Numbers without errors are fixed to the quoted value.
Si XIII He-like triplet

$\approx f$ not expected from a photoinozed plasma
significant (AD test) but very weak
$R = f/i$ the formation region cannot be constrained with the available data
The Fe lines

\[
\phi = 0.77 \text{ (O)} \quad \phi = 0.97 \text{ (E)}
\]

Fe emission lines identified in the *Chandra* spectrum of QV Nor at several orbital phases.

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda ) (Å)</th>
<th>Flux ( \times 10^{-4} ) (ph s(^{-1}) cm(^{-2}))</th>
<th>( \sigma ) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out of eclipse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe K(\beta)</td>
<td>1.7551(^{+0.0035}_{-0.0021})</td>
<td>0.5(^{+0.1}_{-0.4})</td>
<td>(\leq 0.005)</td>
</tr>
<tr>
<td>Fe xxv</td>
<td>1.8588(^{+0.0025}_{-0.0025})</td>
<td>0.5(^{+0.4}_{-0.4})</td>
<td>(\leq 0.005)</td>
</tr>
<tr>
<td>Fe K(\alpha)</td>
<td>1.9368(^{+0.0032}_{-0.0018})</td>
<td>1.4(^{+0.3}_{-0.1})</td>
<td>(\leq 0.005)</td>
</tr>
<tr>
<td>Eclipse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe K(\beta)</td>
<td>1.7551(^{+0.0036}_{-0.0021})</td>
<td>0.22(^{+0.6}_{-0.15})</td>
<td>0.005</td>
</tr>
<tr>
<td>Fe xxv</td>
<td>1.8574(^{+0.0025}_{-0.0025})</td>
<td>0.3(^{+0.7}_{-0.2})</td>
<td>0.005</td>
</tr>
<tr>
<td>Fe K(\alpha)</td>
<td>1.9368(^{+0.0035}_{-0.0019})</td>
<td>0.38(^{+0.16}_{-0.03})</td>
<td>0.005</td>
</tr>
</tbody>
</table>

*Note.* — Numbers without errors are fixed to the quoted value.
The Fe lines

- The Fe Kα λ range is compatible with Fe II-X and the λ centroid with Fe III-VIII \( \rightarrow \log \xi = [-1, 2] \) (Kallman+ 2004, Fig.5) with a most likely predominance of \( \log \xi < 0 \)

- The line is narrow, not resolved by Chandra HEG gratings, implying that the bulk of the reprocessing material has \( \nu_w \leq 800 \) km/s

- \( F_{\text{line}}^E = 0.3 \ F_{\text{line}}^O \) (while \( F_{\text{cont}}^E = 0.03 \ F_{\text{cont}}^O \))
Fe Kα photons (λ=1.9368 Å) can **not** be resonantly scattered in the wind. Only photons shortward of the Kα edge (λ <1.75 Å) have enough energy to effectively excite fluorescence. The observed **Fe Kα emission must come from regions** in the wind directly in the line of sight to the observer and the neutron star simultaneously.

70% of the **Fe Kα photons must be produced at distances from the NS rₓ < 1R**
Fe Kα photons must come from the wind region that meet the conditions:

\[ v_w \leq 800 \text{ km/s} \]
\[ \log \xi \leq 2 \]

The vast majority of Fe Kα emission must be produced at radial distances from QV Nor \( \leq 1.25 R^* \) in the direction facing the NS.
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\[ v_w \leq 800 \text{ km/s} \]
\[ \log \xi \leq 2 \]

The vast majority of Fe Kα emission must be produced at radial distances from QV Nor \( \leq 1.25 \, R^* \) in the direction facing the NS.
If this scenario is correct we should observe:

a) A *minimum* Fe Kα emission during ingress

b) A *maximum* Fe Kα at orbital phase $\phi = 0.5$
Ingress (φ=0.88)

No FeK lines are seen

Clark+94
Other sites for Fe Kα

Two other places can meet the conditions above:

- **Accretion wake**: the contribution must be minor because it should still be visible in phase bin I when no Fe line is observed.
- **Ionization wake**: the contribution must be minor, as well, because the Fe is near to neutral.
Conclusions

• The Fe Kα emission is mostly confined to the stellar wind region that meets the conditions $v_w < 800$ km and $\log \xi < 2$, in the direction facing the NS.

• The stellar wind of the B0I star QV Nor must be significantly clumped at $r < 1.25R_*$ (probably an upper limit)

• At such small radial distances, the wind instabilities may not be fully developed and a triggering mechanism should be invoked.

• Subsurface convection can be at work in OB stars (Cantiello & Braithwaite 2011) giving rise to localized surface magnetic fields. These could trigger such instabilities.

• Our Chadra observation provides firm empirical evidence of strong inhomogeneity in a B-type star supergiant wind close to stellar photosphere.