Chandra X-ray Spectroscopy of Winds in AGN

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Based partly on work in
“A Soft X-ray Study of Type I AGN Observed with the Chandra HETGS”,
by McKernan, Yaqoob, & Reynolds (2006, submitted), and
“Iron K Features in the Quasar E1821+643: Evidence for Gravitationally Redshifted Absorption?”
The HETGS (MEG) spectra and XSTAR fits (red). Grey tick marks are angstroms. NGC 3783 is not shown (you've seen it many times). See McKernan, Yaqoob & Reynolds for references to previous work.
Correlations with Outflow Velocity & $L_{\text{ION}}/L_{\text{EDD}}$

- $V$ bimodal? Anti-correlated with $L_{\text{ION}}/L_{\text{EDD}}$?
- Correlation of $N_H$ with outflow velocity, $V$?
- $N_H$ and $\xi$ (high) not correlated with $L_{\text{ION}}/L_{\text{EDD}}$?
- As noticed by others, the photoionized gas does not occupy intermediate values of $\xi$.

Some of the AGN have more than one warm absorber component. These plots show parameters of each component. See McKernan, Yaqoob, & Reynolds (2006) for details.
The different warm absorber components in a given AGN appear to be in approximate pressure equilibrium with each other.

There appears to be no correlation between mass outflow rate and black-hole mass.

Possible correlation of mass outflow rate with $L_{\text{ION}}/L_{\text{edd}}$?

Total mass outflow rate is critically dependent on the covering factor and the volume filling factor, $C_V$. 
Three additional AGN from Blustin et al. (2005) included (MR 2251-178, IRAS 13349+2438, NGC 7469). These are NOT correlation plots (look at the formulae).

Left: $n_e$ unknown. High/Low ionization density ratio of $\sim$100-10000 makes the different components co-spatial, consistent with conclusion about pressure equilibrium.

Right: Volume filling factor ($C_V$) and $\Delta R/R$ unknown. Gives “maximum” radius if $\Delta R/R<1$ enforced. If the high & low ionization components are co-spatial, they must have different filling factors.
Some Implications & Considerations

- The filling factor \( (C_v) \) is HIGHLY UNCERTAIN (in most cases unconstrained) but the mass outflow rate critically depends on it.

- Blustin et al. (2005) derive filling factors \(~(0.03-8)\%\), (much less in a few cases), derived assuming momentum in outflow \~ momentum in radiation intercepted. This is an assumption which is not necessarily true. Indeed, using these derived filling factors Blustin et al. (2005) calculate a maximum distance of the warm absorber which is LESS than the minimum distance in FOUR sources!

- Independently of this, the Blustin et al. (2005) maximum warm absorber distances are in error: they should be larger by a factor \( C_v^{-2/3} \) (an error of a factor \(~5-218\)).

- Blustin et al. (2005) minimum distance of warm absorber calculated assuming outflow exceeds escape velocity - this is not necessarily true either.
Ratio of Mass Outflow Rate to the Accretion Rate

The ratio of the mass outflow rate to the accretion rate does not depend on the absolute luminosity or black-hole mass. It depends only on

- The covering factor, $\Delta \Omega/4\pi$
- The volume filling factor, $C_v$
- The outflow velocity, $v_{500}$ (units of 500 km/s)
- The ionization parameter, $\xi_{1000}$ (units of 1000 erg cm s$^{-1}$)
- The accretion efficiency, $\eta_{0.1}$ (units of 0.1)
- The ratio of the bolometric luminosity to the ionizing luminosity, $X = L_{bol}/L_{ion}$
  (we will use $X_{10} = X/10$)

$$\frac{\dot{M}_{outflow}}{\dot{M}_{accretion}} \sim 94 \left( \frac{\Delta \Omega}{4\pi} \right) \left( \frac{xy}{X_{10}} \right) \left( \frac{v_{500}}{\xi_{1000}} \right) \eta_{0.1} C_v$$

where $x$ is the mean number of Hydrogen atoms per electron and $y$ is the mean atomic mass per Hydrogen atom. For a gas consisting of only H and He, in which He is 10% abundant by number, $y = 1.3$ and $x = 9/11$, so $xy = 1.0636$.

Observationally, for the 30 warm absorber components for 13 AGN, $v_{500}/\xi_{1000}$ lies in the range $\sim 0.04–840$. Including only the high ionization components ($\xi > 90$), the range in $v_{500}/\xi_{1000}$ is $\sim 0.04–13$. The mass outflow rate may be much larger than the accretion rate, BUT if the volume-filling factor remains unconstrained we cannot conclude that $\Delta \Omega/4\pi$ is probably $\sim (2/3)(N_{Sv1}/N_{Sv2}) \sim 0.1$. 
Constraints from Gravitational Broadening Limits on the Absorption Lines

At a given radius from the central BH, an absorption line observed at “infinity” will be gravitationally broadened. This broadening has to be LESS than the observed line width because other broadening mechanisms will affect the line (e.g. dynamics). This EITHER means \((R/R_g) > (c/\text{FWHM})\) OR a lower limit on the volume filling factor \((C_V)\) is imposed as a function of radius (see figure).
Gravitational Line Broadening Limits: Observations

\[ k = \frac{1.48 \times 10^{-7} N_{21} \xi_{1000} M_8}{x L_{\text{ion,44}} f} \]

where \( f = C \sqrt[1/3]{r} \); for \( kr = k(R/R_g) \ll 1 \),

\[ \frac{\Delta E}{E_0} \sim k \left(1 - \frac{2}{r} \right)^{-\frac{1}{2}} \]

For \( r \gg 1 \),

\[ \frac{\Delta E}{E_0} \sim \frac{k}{1 + kr} \]

For all \( r \), the lower limit on the filling factor, for an observed line width, FWHM, is

\[ C_v = \left[ \frac{1.48 \times 10^{-7} N_{21} \xi_{1000}}{x L_{\text{ion,44}}} \right]^3 \left[ 2 \left( 1 - \left( \frac{\text{FWHM}}{c} \right) + \left( 1 - \frac{2}{r} \right)^{1/2} \right)^2 \right]^{-1} r^6 \]

The factor \( N_{21} \xi_{1000} M_8/L_{\text{ion,44}} \), which determines the importance of gravitational broadening, ranges between \( \sim 10^{-6} \) to \( \sim 10^3 \) for the 30 warm absorber components. In 8/13 sources, the factor is greater than unity. In two sources (NGC 4051 and NGC 5548) it is greater than 500.

The largest value is for NGC 5548 and in this case, using the fact that some of the absorption lines are not resolved with the Chandra MEG at a resolution of 300 km/s FWHM, we get a lower limit on the volume filling factor of 0.013 (1.3%). This then gives an absolute lower limit on the mass outflow rate of 0.057(\( \Delta \Omega/4\pi \)) \( M_\odot \text{ yr}^{-1} \). The lower limit on the ratio of the mass outflow rate to the accretion rate is then \( \dot{M}_{\text{outflow}}/\dot{M}_{\text{accretion}} > 8.4(\Delta \Omega/4\pi)(\eta_{0.1}/X_{10}) \).
E1821+643 (z=0.297)

Evidence for a gravitationally redshifted absorption line, the highest redshift, highest luminosity broad Fe-K emission line.

Significance of absorption line (from Monte Carlo simulations) is 2-3σ, depending on assumptions.

**Reality of the Absorption Feature**

Absorption feature is present in BOTH plus and minus arms of the Chandra High Energy Grating (HEG).

**Black: Combined plus & minus orders**

**Red: −1 Order**  **Green: +1 Order**

**Disk Emission Line Plus Gaussian Absorption Line Fit.**
Absorption Line Parameters

- All spectral fitting parameters are in the quasar frame.
- Absorption line is only marginally resolved (i.e. unresolved by the HEG at 99% confidence).
- Redshift corresponds to effective velocities ~21000 km/s (Fe XXV) or 32000 km/s (Fe XXVI).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-statistic</td>
<td>1014.5</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>966</td>
</tr>
<tr>
<td>Disk-line rest energy (keV)</td>
<td>$6.57^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>(6.51–6.68)</td>
<td></td>
</tr>
<tr>
<td>Disk-line emissivity index, $q$</td>
<td>2.69^{+0.19}_{-0.19}</td>
</tr>
<tr>
<td>(2.36–3.08)</td>
<td></td>
</tr>
<tr>
<td>Outer disk radius, $R_{\text{out}}$</td>
<td>&gt;930</td>
</tr>
<tr>
<td>(~18)</td>
<td></td>
</tr>
<tr>
<td>Disk inclination, $\theta_{\text{obs}}$ (deg)</td>
<td>0.0^{+0.4}_{-0.0}</td>
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<tr>
<td>(0–27)</td>
<td></td>
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<tr>
<td>Disk-line intensity ($10^{-5}$ photons cm^{-2} s^{-1})</td>
<td>7.0^{+1.9}_{-1.7}</td>
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<tr>
<td>(3.6–10.2)</td>
<td></td>
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<tr>
<td>Disk-line EW (eV)</td>
<td>209^{+51}_{-57}</td>
</tr>
<tr>
<td>(107–305)</td>
<td></td>
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<tr>
<td>Absorption line center energy (keV)</td>
<td>6.220^{+0.013}_{-0.012}</td>
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<tr>
<td>Absorption line Gaussian width, $\sigma$ (keV)</td>
<td>0.021^{+0.008}_{-0.008}</td>
</tr>
<tr>
<td>Absorption line velocity width, FWHM (km s^{-1})</td>
<td>2385^{+1440}_{-959}</td>
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<tr>
<td>Absorption line EW (eV)</td>
<td>34^{+13}_{-13}</td>
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<tr>
<td>Power-law photon index, $\Gamma$</td>
<td>1.84^{+0.03}_{-0.05}</td>
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<td>2–10 keV Observed flux ($10^{-11}$ ergs cm^{-2} s^{-1})</td>
<td>1.2</td>
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<tr>
<td>2–10 keV Luminosity, quasar frame ($10^{45}$ ergs s^{-1})</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Redshifted Absorption Lines in other Quasars

- **PG1211+143** (Reeves et al. 2005): Chandra LEG data. Two absorption lines, $V \sim 0.23c$ and $0.35c$ (if Fe XXVI Lya, $0.20c$ & $0.32c$ Fe XXV). Line widths poorly constrained, upper limit 7800 km/s FWHM.

- **Mkn 509** (Dadina et al. 2005): XMM-Newton EPIC data. $V \sim 0.21c$ (if Fe XXVI Lya, $0.18c$ if Fe XXV).

- **Q0056-363** (Matt et al. 2005): XMM-Newton EPIC data. $V \sim 0.23c$ (if Fe XXVI Lya, $0.20c$ if Fe XXV).

  - Compare with $V \sim 0.11c$ (Fe XXVI) or $\sim 0.07c$ (Fe XXV) for **E1821+643**.

  - In all cases, the EWs range from tens to $\sim 100$ eV.

  - Curve of growth analysis for **E1821+643** gives a lower limit on the optical depth at the center of the resonance line, and a lower limit on the column density of the ion responsible for the absorption. We get $N > 9 \times 10^{16}$ cm$^{-2}$ and $
\tau > \tau_0(1000/$FWHM [$km/s$])$ where $\tau_0 = 0.174$ or 0.321 for Fe XXV or Fe XXVI respectively.

  - Column density and optical depth limits for **PG 1211+143**, **Mkn 509**, and **Q0056-363** are similar to those obtained for **E1821+643** because of the similar EWs and the fact that the absorption lines are not clearly resolved.

  - Note: identification with lines other than from Fe creates a problem with predicted Fe lines (for “regular” abundances), which are not observed.
Inflow or Outflow?

Could the absorption line in E1821+643 be due to gravitationally redshifted outflow?

Photoionized outflows with $v \sim$ hundreds of km/s have been found to be common in type 1 AGN by Chandra gratings.

High velocity outflows found by XMM in two quasars:

PG 1211+143: $v \sim 25,000$ km/s; $R \sim 260$ Rg  
PG 0804+349: $v \sim 60,000$ km/s; $R \sim 25$Rg  
(Lower $v \sim 3000$ km/s claimed by Kaspi et al. 2005 for PG 1211+143).

Both outflows are optically thick.  
Thick photosphere near BH in $\sim$Eddington accretors may be common.

If absorption line in E1821+643 is gravitationally redshifted outflow (due to H–like Fe absorption) then

$R \sim 9.7$ Rg for $v \sim 1000$ km/s
$R \sim 4.3$ Rg for $v \sim 25,000$ km/s
$R \sim 6.2$ Rg for $v \sim 60,000$ km/s

Mass flow rate depends on the (unknown) filling factor.
Summary

- Photoionized wind found in 2/3 of HETGS Sy 1 sample.
- Wide range in \( N_H \) and \( \xi \) but gas with \( \xi \sim 10-100 \) is “missing”.
- Some sources have multiple components in approximate pressure eqm.
- Outflow velocities typically ~0-1000 km/s: bimodel distribution?
- Distance of absorber requires knowledge of \( n_e \) or the volume filling factor & NOT the covering factor. (Variability studies by Krongold et al. imply a “compact” absorber in NGC 3783 and NGC 4051, fractions of a pc).
- Mass outflow rate also depends critically on the unknown filling factor.
- Limits from gravitational absorption-line broadening give a lower limit on the volume filling factor, which may be interesting limits in a few cases (e.g. NGC 5548, NGC 4051). The method gives limits which are independent of the dynamics of the wind & can also be used for the UV absorption lines, which will give tighter limits. Otherwise, only limits on emission lines can give information on the volume filling factor.
- Ratio of mass outflow rate to accretion rate again critically depends on the unknown volume filling factor.
- Redshifted \( (1+z \sim 0.07-0.11c) \) absorption line, probably due to Fe XXV or Fe XXVI, found in the RQ high-luminosity \( (L[2-10 \text{ keV}] \sim 3 \times 10^{45} \text{ erg/s}) \), high \( z \) (0.297) quasar E1821+643. May be redshifted outflow, not infall. The broad Fe K emission line in this quasar kills the “X-ray Baldwin Effect”.

May
References


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