Fast Ionized X-ray Absorbers in AGNs

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Outline

(1) WAs (~sub-pc) vs. UFOs (<1000R_☉) in X-ray

(2) MHD-driven Wind Model

(3) Outlook
Ionized X-ray Winds
(i.e. Warm Absorbers & Ultra-Fast Outflows)

- (Soft) X-ray-bright Seyfert AGNs
- Distant QSOs
- Soft X-ray & Fe K band

- $v_{\text{out}} \sim 100 - 1,000$ km/s
- $\log \xi \sim -1$ to 4
- $N_H \sim 10^{20-22}$ cm$^{-2}$

- $v_{\text{out}}/c \sim 0.1 - 0.8$
- $\log \xi \sim 3-6$
- $N_H \sim 10^{23-24}$ cm$^{-2}$
Outstanding Questions

- Spatial location?
- Geometry?
- Continuous/Patchy flows?
- Defining quantities?
Absorption Measure Distribution (AMD)

IRAS 13349+2438

\[ \text{Equivalent } N_H \text{ [cm}^{-2} \text{]} \]

\[ \sim \log(T) \text{ [K]} \]

Mrk 509

Detmers+ (11)

NGC 5548

Steenbrugge+ (05)

Behar (09)

Detmers+ (11)

Holczer+ (10)
AMD ~ constant...So what?

\[ \xi \equiv \frac{L}{nr^2} = L \Delta r \quad \Rightarrow \quad N_H = \frac{\Delta (\log \xi)}{\Delta \xi} \frac{\Delta r}{r^2} L, \]

\[ AMD \equiv \frac{N_H}{\Delta (\log \xi)} = \frac{\Delta (1/r)}{\Delta \xi} L, \]

\[ \therefore \frac{\Delta (1/r)}{\Delta \xi} \approx \text{const.} \Rightarrow \xi \propto \frac{1}{r} \quad \Rightarrow \quad n \propto \frac{1}{r} \]

Then

\[ \dot{M} \approx nr^2 v \approx r^{-1} r^2 r^{-1/2} \approx r^{1/2} \]

\[ E_k = \dot{M} v^2 \propto r^{-1/2}, \quad P = \dot{M} v = \text{const.} \]

Therefore, the flow is 2D (e.g. Blandford+Payne82, Contopoulos+Lovelace94, Konigl+Kartje94...etc.)

outflow mass \(\leftarrow\) exterior
kinetic power \(\leftarrow\) interior
Absorbers as Disk-Wind

- Outflows necessary for accretion process
- Driven by “some” acceleration process(es)
- AGN X-ray photoionizing wind materials

\[ \text{Matter (gas) + photon (AGN SED) fields} \rightarrow \text{Absorption features} \]

(1) Thermal-driven models:
Begelman, McKee & Shields (83)
Proga & Kallman (02)

(2) Radiation-driven models:
Castor + (75), Murray + (95; 98)
Proga & Kallman (04)
Higginbottom + (14)

(3) MHD-driven models:
Blandford & Payne (82)
Konigl & Kartje (94)
Contopoulos (95), Everett (05)
Takeuchi + (13), Ohsuga + (11)
Fukumura + (10a; b, 14, 15)

Others (Phenomenological):
Blandford & Begelman (99)
Schurch & Done (07, 08)
Sim + (08; 10)

& more…
MHD-Driven Disk-Wind Model with $n \sim 1/r$

(e.g. Fukumura+10a,b,14,15)

(1) Steady-state, axisymmetric ideal MHD eqns. \hspace{1cm} (P_{rad}=0)

\[ \nabla \cdot (\rho \mathbf{v}) = 0 \]  
\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} \]  
\[ \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} = 0 \]  
\[ \nabla \times \mathbf{E} = 0 \]  
\[ \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p - \rho \nabla \Phi_g + \frac{1}{c} (\mathbf{J} \times \mathbf{B}) \]

(mass conservation) ,
(Ampere’s law) ,
(ideal MHD) ,
(Faraday’s law) ,
(momentum conservation) ,

\[ n(r, \theta) \equiv \frac{\rho(r, \theta)}{\mu m_p} = n_o x^{2q-3} N(\theta) \]

\[ N_H(\Delta r, \theta) \equiv \int_{\Delta r} n(r, \theta) dr \]

\[ \Psi(r, \theta) = (r/r_o)^q \psi(\theta) \Psi_o \]

Disk treated as BC

MHD wind is 2D!

Solving Grad-Shafranov eqns. with self-similar radial profiles in MHD framework.

acceleration done within Alfvén point

Toroidal (Keplerian) to poloidal motion transition.
(2) Solve radiative transfer along LoS with xstar photoionization code by discretizing wind in radius

\[ L_{i+1}^{(tr)} = L_i e^{-\tau_{i+1}} \]

Solve ionization balance under heating-cooling equilibrium in each cell:

\[ \rightarrow \text{Initial SED assumed} \]
\[ \rightarrow \text{Solve ionization balance in } i^{\text{th}} \text{ cell} \]
\[ \rightarrow \text{Obtain transmitted SED from } i^{\text{th}} \text{ cell} \]
\[ \rightarrow \text{Inject it to } (i+1)^{\text{th}} \text{ cell} \]
\[ \rightarrow \text{Repeat this process} \]

while also keeping track of columns for ions in each cell.

Then, calculate a global ionization structure.

\[ \xi(r, \theta) \equiv \frac{L}{n(r, \theta)r^2} \]
MHD-Driven Disk-Wind Model with $n \sim 1/r$
(e.g. Fukumura+10a,b,14,15)

RQ Seyfert 1:
Single PL: $\Gamma = 2$
$L_{\text{ion}} = 3 \times 10^{42}$ erg/sec
$M = 10^6$ Msun

calculating AMD for Seyfert WAs

- Constant AMD for 4 decades in $\xi$
  (all ions)
- Velocity profile
  (c.f. $v \sim \xi^{0.65}$ for WAs+UFOs)

Test 1:
Iron Column
Fe
\[ \Delta N_{Fe} \left[ \text{cm}^{-2} \right] \]
\[ (b) \ 30 \ (\text{deg}) \]
\[ v_{\text{out}} \sim \xi^{0.5} \ (\text{model}) \]

Tombesi+13
MHD-Driven Disk-Wind Model with $n \sim 1/r$

(e.g. Fukumura+10a,b,14,15)

Applying to the UFO in PG 1211+143

### PG 1211+143:

- $\Gamma = 2$ and $\alpha_{OX} = -1.5$
- $L_{\text{ion}} = 1.3 \times 10^{44}$ erg/sec
- $M = 10^8$ Msun

A grid of wind model parameters

<table>
<thead>
<tr>
<th>Primary Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing Angle $\theta$ (degrees)</td>
<td>$30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ$</td>
</tr>
<tr>
<td>$kT_{\text{bb}}$ (eV)</td>
<td>10, 30, 50, 70</td>
</tr>
<tr>
<td>Disk Truncation Radius $\log r_t \equiv \log (R_t/R_0)$</td>
<td>0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8</td>
</tr>
</tbody>
</table>

1D radiative transfer along LoS for various elements

Calculated Fe XXV columns

6/6/15 xmm-wrkshp
From radiative transfer calculations one finds columns.

With atomic/plasma physics one computes cross section

\[ \sigma_{\text{photo},\nu} \equiv 0.001495 \frac{f_{ij}H(a,u)}{\Delta \nu_D} \text{ cm}^2 \]

which yields optical depth of wind.

\[ \tau_{\nu}(r, \theta) = \sigma_{\text{photo},\nu}(r, \theta)N_{\text{ion}}(r, \theta) \]

Spectral shape is computed with Voigt profile \( H(a,u) \)

**MHD Wind Characteristics**

- There is always near-relativistic fast wind components at smaller radii
- SED will determine whether “spectroscopically” visible or not to us
MHD-Driven Disk-Wind Model with $n \sim 1/r$

(e.g. Fukumura+10a,b,14,15)

Best-fit model:

- $kT_{in} = 38$ eV and $\theta_{obs} = 49^\circ$
- $N_H(\text{FeXXV}) = 1.2 \times 10^{23}$ cm$^{-2}$, $\log \xi_c = 5.3$, $v/c = 0.115$
- $R(\text{FeXXV}) = 235$ $R_S$, $R_{\text{trunc}} = 29.3$ $R_S$
- $M_{out}(\text{FeXXV}) = 2.56$ $M_{\odot}$/yr
- $\chi^2/\nu = 198.54/128$

$\log(n/n_{max})$
Brief Outlook

- X-ray absorbers can tell us outflow physics phenomenology (micro) ➔ many progress! global perspective (macro) ➔ ???

- Launching mechanism(s)
  Thermal? Radiation? MHD?
  ➔ need some “smoking gun” evidence…
  (e.g. high-ξ & high-N_H wind ➔ MHD?)

- Contribution to AGN feedback process
  How much power can be delivered?
Thanks!

NASA's Goddard Space Flight Center