The Universal Magnetic Structure of Black Hole Accretion Disk Winds

Demos Kazanas with
Keigo Fukumura
Ehud Behar (Technion)
Chris Shrader
Francesco Tombesi
and
John Contopoulos (Academy of Athens)

Acknowledgements to Tim Kallman

Credit: NASA/CXC
Radiation Emission from Accreting Black Holes

• Accretion onto Black Holes proceeds with the formation of accretion disks.
• Their structure, still not well understood, relies on comparison of models with observed features.
• The ubiquitous spectral features of these objects comprise:
  – A multicolor disk component consistent with thermal emission by an accretion disk that extends to $\sim 100 \ R_\text{S}$.
  – X-ray emission, presumably by a corona.
  – Broad (and Narrow) emission lines consistent with isotropic velocity of the emitting gas.
  – Blue-shifted absorption lines indicating OUTFLOWS (not accretion !!!).
Outflows are Ubiquitous in AGN (originally discovered in their UV spectra)

Fig. 1—Representative C iv line profiles of NGC 4151 obtained in a low state (SWP 21578, 120 minute exposure, day = 82051), and in a high state (SWP 18490, 45 minute exposure, day = 82310). The spectra are plotted on the same absolute intensity scale and are shown in velocity space corrected for redshift.
X-ray Absorbers

- *Chandra* and *XMM-Newton* discovered a host of absorption features in the X-ray band of wide ionization state and velocities, hinting of much richer wind structures than thought before.

(1) **Moderate Outflows** ~ various charge state
   (\(\sim 100\) - 1,000 km/sec; \(N_H \sim 10^{21-22}\) cm\(^{-2}\))
   - Many charge state from X-ray-bright AGNs
     e.g. *MCG-6-30-15*, *IRAS 13349+2438*

(2) **Fast Outflows** ~ K-shell resonance
   (\(v/c \sim 0.1 - 0.7\); \(N_H \sim 10^{23-24}\) cm\(^{-2}\))
   - H/He-like ions from hard-X-ray-weak AGNs
     e.g. *PDS 456*, *PG 1211+143*, *APM 08279+5255*
**X-ray-Bright AGNs**

QSO: **IRAS 13349+2438:**
(z = 0.10764)

- X-ray bright, IR-loud/radio-quiet QSO
- X-ray obs. with ROSAT, ASCA, Chandra, XMM-Newton
- Ions with various charge state
- Fe XVII ~ 300 km/sec
- Fe XXV ~ 3000 km/sec
- Integrated $N_H \sim 1.2 \times 10^{22}$ cm$^{-2}$
- Absorption lines are characterized by their ionization state ($\xi = L/nr^2$), velocity $v$ and column $N_H$.
- Importance of X-ray Spectroscopy:
  - In 1.5 decades of $E$ covers transitions that span 5 decades in $\xi$
  - *Chandra* data

Holczer+(07)
Narrow-Line Seyferts

- “Narrow” H$\beta$ line < 2,000 km/sec
- Weak O III/H$\beta$ ratio
- Strong “Soft X-ray Excess”
- Highly-blueshifted absorption lines

**PG 0844+349**

(v/c $\sim$ 0.2)

Chandra/XMM-Newton data

**PG 1211+143**

(v/c $\sim$ 0.1)

**PDS 456**

(v/c $\sim$ 0.25)
**Galactic Black Hole Candidates (GBHC)**

**GRO J1655-40:**
- High ionization: \( \log(\xi[\text{erg cm s}^{-1}]) \sim 4.5 - 5.4 \)
- Small radii: \( \log (r[\text{cm}]) \sim 9.0 - 9.4 \)
- High density: \( \log(n[\text{cm}^{-3}]) \sim 14 \)

- \( M(\text{BH}) \sim 7 M_{\odot} \)
- \( M(2^{\text{nd}}) \sim 2.3 M_{\odot} \)

*Chandra Data*  
Miller+(06)

---

*NASA/CXC/A.Hobart*

*Chandra Data*  
Miller+(08)
Can we make sense of all these diverse Observations?

Fundamental Questions:

- Geometry?
- Spatial location?
- Properties?
- Physical origin?
Absorption Measure Distribution (AMD)

\[ AMD(\xi) = \frac{dN_H}{d\log \xi} \sim (\log \xi)^p \]

where \( \xi = L/(n r^2) \)

column column ionization

presence of nearly equal \( N_H \) over \( \sim 4 \) decades in \( \xi \) (p~0.02)

Holczer+(07)
Behar(09)

(5 AGNs)

\( 0.02 < p < 0.29 \)
Schematic run of $v$, $\xi$, $N_H$, for radiation driven outflow
$V \sim r$, $n(r) \sim 1/r^3$, $N_H \sim 1/r^2$ then $V \sim \text{const}$, $n(r) \sim 1/r^2$, $N_H \sim 1/r$.

Low $V$, low $\xi$
High $V$, high $\xi$

$N$ decreases with $\xi$
$N$ decreases with $V$
$N$ independent of $V, \xi$
Some Simple Estimates/Conclusions

\[ \xi = \frac{L}{nr^2} \approx \frac{L}{rN_H} \Rightarrow N_H \approx \frac{L}{r \xi} \]

\[ \frac{dN_H}{d \log \xi} \approx \frac{L}{r \xi} \approx \text{const.} \Rightarrow \]

\[ r \xi \approx \text{const.} = \xi \approx \frac{1}{r} \approx \frac{L}{nr^2} \Rightarrow n \approx \frac{1}{r} \quad \text{Not } n \sim 1/r^2 \text{ !!} \]

\[ \dot{M} \approx nr^2 v \approx r^{-1} r^2 r^{-1/2} \approx r^{1/2} \quad \text{Mdot not constant! (ADIOS Blandford . Begelman 1999)} \]

The flow is 2 dimensional! (Blandford+Payne 82, Contopoulos and Lovelace 94 ∎ AGN Unification: Torus = MHD Wind)

\[ \text{Mdot} \sim r^{1/2}, \quad \text{Edot} \sim \text{Mdot} v^2 \sim r^{-1/2}, \quad \text{Pdot} \sim \text{Mdot} v \sim r^0 \]
Flow line geometry

From Konigl+Kartje (94), based on the models of Contopoulos + Lovelace (94)
With the above density scaling we get the following relation for $\xi$

$$m \approx \frac{M}{M_{Edd}} \cdot \dot{M}_{Edd} = \frac{L_{Edd}}{C^2} \propto M,$$

$$x = \frac{r}{R_s} \Rightarrow r = xM.$$

$$L \propto M \Rightarrow \frac{\dot{M}}{M_{Edd}} \propto mM,$$

$$n = \frac{m}{\frac{1}{M} \times x}.$$

$$\frac{L}{nr^2} \Rightarrow \frac{\xi}{x} = \text{const.}.$$

$\xi$ is independent of the mass $M$ of the BH!! The models are equally well applicable to AGN and galactic XRBs. Their difference lies in the fraction of the bolometric emission that comprise the X-rays.

The larger the X-ray content the more ionized the high $V$ segments of the wind and the lower the absorber velocities.

BAL QSOs: $V \sim 10,000 - 100,000$ km/s

GRO J1655-40: $V \sim 300-1200$ km/s
• **Basic Dogma:**

• All winds have the same velocity \((v \sim 1/r^{1/2})\) and density \((n \sim 1/r)\) all the way to \(\sim\) (a few) ISCO

• Their overall normalization is given by \(\dot{m}\) at \(r \sim 1\)

• The observed diversity is due to their ionization status and the observer’s inclination angle.

• The X-ray contribution to their spectra most important for the appearance of their spectral / kinematic structure (broad-narrow lines)}
The velocities and size of the winds measured in $v/c$ and $r/R_s$ scale directly from those of AGN to those of XRBs.
Magnetically-Driven Outflows
Magnetohydrodynamics (MHD)

(At least) 2 candidates:
- GRO J1655-40
  Miller+(06,08)
- NGC 4151
  Kraemer+(05)
  Crenshaw+Kraemer(07)
Simple Wind Solutions with $n \sim 1/r$

Assume:

- $M(BH) = 10^6$ Msun, $\Gamma \sim 2$ (single power-law), $L_x \sim 10^{42}$ erg/s,
- $\dot{m} \sim 0.5$, rad. eff. $\sim 10\%$, $n(in) \sim 10^{10}$ cm$^{-3}$

(Fukumura+10a)

![Graph](image)
Simple Wind Solutions with $n \sim 1/r$

Assume:

- $M(BH) = 10^6 \text{ M}_\odot$, $\Gamma \sim 2$ (single power-law), $L_x \sim 10^{42} \text{ erg/s}$,
- $\dot{m} \sim 0.5$, rad. eff. $\sim 10\%$, $n(\text{in}) \sim 10^{10} \text{ cm}^{-3}$

(Fukumura+10a)
Photoionization with XSTAR (e.g. Kallman+Bautista01)

Ionization Distribution

LoS Radiation Transfer

1D computational zones
Modeling Absorption Spectra

Wind optical depth
Line photo-absorption cross-section

\[ \tau(\nu) = \sigma(\nu)N_H(\nu) \]
\[ \sigma = 0.01495(\frac{f_{ij}}{\Delta \nu_D})H(a, u) \]

- \( f_{ij} \) = oscillator strength
- \( \Delta \nu_D \) = broadening factor
- \( H(a,u) \) = Voigt function (e.g. Mihalas78)

We need not use the Parameter vturb of XSTAR; we use the Velocity gradient of The wind.
Table 2. Summary of our best-fit mhdwind model parameters for PG 1211+143.

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>Model (A)</th>
<th>Model (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe XXV/Fe XXVI</td>
<td>Fe XXV/Fe XXVI</td>
</tr>
<tr>
<td>$\theta$ [degree]</td>
<td>40.0 $\Diamond$</td>
<td>49.4$^{+3.7}_{-4.5}$</td>
</tr>
<tr>
<td>$kT_{\text{bb}}$ [eV]</td>
<td>30.1$^{+0.01}_{-0.06}$</td>
<td>38.1$^{+0.59}_{-0.60}$</td>
</tr>
<tr>
<td>$E_{94}$ [keV]</td>
<td>6.54$^{+0.09}_{-0.04}$</td>
<td>6.52$^{+0.10}_{-0.11}$</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>0.096$^{+0.006}_{-0.005}$</td>
<td>0.235$^{+0.024}_{-0.023}$</td>
</tr>
<tr>
<td>$\log(r_{\circ}/R_{\circ})$</td>
<td>2.96$^{+0.10}_{-0.11}$</td>
<td>2.37$^{+0.14}_{-0.15}$</td>
</tr>
<tr>
<td>$\log\left[\xi \left(\text{cm s}^{-1}\right)\right]$</td>
<td>5.21$^{+0.06}_{-0.07}$</td>
<td>5.31$^{+0.07}_{-0.08}$</td>
</tr>
<tr>
<td>$v_{\circ}/\Delta$</td>
<td>0.15$^{+0.03}_{-0.02}$</td>
<td>0.11$^{+0.04}_{-0.03}$</td>
</tr>
<tr>
<td>$N_{\text{H}}$ [cm$^{-2}$]</td>
<td>$10^{22}$</td>
<td>$10^{20}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$ (with mhdwind)</td>
<td>200/44/129</td>
<td>198.54/128</td>
</tr>
<tr>
<td>$\Delta\chi^2$ (from phabs*(ps+zga))</td>
<td>-34.1</td>
<td>-36.4</td>
</tr>
</tbody>
</table>

$\Diamond$ The value is pegged.

$\circ$ The characteristic LoS radius $r_{\circ}$ where wind Fe XXV opacity $\tau_{\circ}$ (see eqn. (9)) is maximum along a given LoS angle.

$\Delta$ The characteristic value ("X") is evaluated at the LoS position $\tau = r_{\circ}$.

$\xi$ LoS-integrated total Fe XXV column density.

$\text{Model (B)}$

---

![Graph and diagram showing model parameters and disk temperature](image)
45ks Chandra/HETGS spectrum of GRO J1655–40

\[ \Gamma = 3.54 \]
\[ \text{Norm(PL)} = 4.77 \]
\[ \text{kT(diskbb)} = 1.34 \text{ keV} \]
\[ \text{Norm(diskbb)} = 515.4 \]

MHD-driven disk-wind model of n~1/r
\[ n \sim \frac{1}{r^{1.2}} \]

\[ \Theta = 80 \text{ deg} \]
Development of the Fe XXVI Lyα and Ne X Lyα profiles
MHD disk-winds provide a promising unified account of the entire absorber phenomenology. This can serve a basic benchmark for further development and refinement.

- Key ingredients: $\dot{m}_{\text{dot}}$ (overall column normalization), SED ($\Gamma$, mainly $\alpha_{\text{ox}}$), $\theta$ (Inclination angle)

(These are not all independent parameters – correlation of $L-\alpha_{\text{ox}}$)

- The model implies that AGN and XRB winds are multiscale objects, governed (basically) by magnetic forces.

- An instrument with higher throughput and resolution would be able to probe also the detailed velocity structure of these features and their variability to provide the density-velocity structure of the entire AGN flow. (Hitomi 2 ? Athena)
THE END

Thank you
The Astrophysics Science Division supports the GSFC astrophysics projects by providing scientific leadership and supports a research program to achieve NASA’s strategic science goals. The key questions addressed by the Division’s research programs include:

How do galaxies, stars, and planetary systems form and evolve?
What is the diversity of worlds beyond our solar system?
Which planets might harbor life?
What powered the big bang?
What is Dark Energy?

**Newborn Black Holes Boost Explosive Power of Supernovae**

An international team of scientists, including two astronomers from NASA’s Marshall Space Flight Center in Huntsville, Ala., have observed a supernova with peculiar radio emission. In the Jan. 28 issue of “The Astrophysical Journal,” they present the first evidence that newborn black holes are still п

*Image Credit: Z. Paragi, Joint Institute for VLBI in Europe (JIVE)*