MHD Accretion-Disk Winds as the Unifying AGN Structure

Demos Kazanas  Keigo Fukumura
Astrophysics Science Division  Code 663, NASA/GSFC

Ehud Behar (Technion, Israel)
John Contopoulos (Academy of Athens, Greece)
Markos Georganopoulos (UMBC)
Sean Scully (JMU)

Dust reprocessing, \( n(r) \sim 1/r \) (Rowan-Robinson 1995)
The Scientific Method

It is a capital mistake to theorize before one has the data. Insensibly, one begins to twist facts to suit theories, instead of theories to suit facts.

Sir Arthur Conan Doyle

It is also a good rule not to put too much confidence in experimental results, until they have been confirmed by theory.

Sir Arthur Eddington

First you get your facts; then you can distort them at your leisure.

Mark Twain
Some Facts

- AGN are multiscale, multifrequency objects. Need to understand their structure over large number of decades in $r$.

- Use Unification arguments to obtain their structure from objects at high inclination angle (IR - Torii).

- Structure along LOS can be probed efficiently by X-ray spectroscopy! X-ray absorption features are ubiquitous in the spectra of AGN, GBHC (50% of all AGN exhibit UV and X-ray absorption). They span a factor of $\sim 10^5$ in ionization parameter indicating the presence of ions ranging from highly ionized (H-He - like Fe) to neutral, all in 1.5 decades in X-ray energy!

- These “live” in very different regions of ionization parameter space and likely in different regions of real space.
Use X-ray spectroscopy to probe the molecular torii and the intervening region.

Molecular torii are impossible objects: They have $H/R \sim 1$ implying random velocities comparable to their Keplerian ones (300 - 500 km/s).

However, with temperatures $T \sim 10-100$ K, $V_{th} \ll 1$ km/s!!

They cannot be static objects $\rightarrow$ Winds.
At their distances ($\sim$ pc) the radiation field has very little momentum; Therefore

Magnetically-Driven Accretion-Disk Winds! (Konigl-Kartje 1994).
**BAL QSO: X-ray Absorptions**

- High-velocity outflows: $v/c \sim 0.1 - 0.7$ in Fe XXV/XXVI

X-ray Absorption line (Fe XXV)  
Spectral index vs. wind velocity

Fe resonance transitions  
X-ray absorber

Effect of ionizing spectrum(!?)

Brandt+(09); Chartas+(09)

Chandra/XMM/Suzaku
**Galactic Black Hole (GBH) Binaries**

**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: $\log(n [\text{cm}^{-3}]) \sim 14$

$M(\text{BH}) \sim 7\text{M}_{\odot}$

$M(2^{\text{nd}}) \sim 2.3\text{M}_{\odot}$

Miller+(06)

Chandra Data

Miller+(08)

NASA/CXC/A.Hobart
Seyfert and Radio Galaxies

**MCG-6-30-15:**

(z = 0.007749)

- **Photoelectric Absorption:**
  - Lines
  - Edges

"Warm Absorber"

- Slow ~ 100 km/sec @ low-\(\xi\)
- High ~ 1,900 km/sec @ high-\(\xi\)
- Integrated \(N_H \sim 5.3 \times 10^{21} \text{ cm}^{-2}\)

(see also Otani+96, Reynolds+97, Sako+03, Miller+08)

10/28/2010 SEAL@GSFC
Our thesis (and hope) is that these diverse data (including those of galactic X-ray sources) can be systematized to include the blazar phenomenology with a small number of parameters (2)

Boroson 2002
Flows (accretion or winds) and their ionization structure are invariant (independent of the mass of gravitating object; ADAF) if:

1. Mass flux is expressed in terms of Eddington mass flux

\[ \dot{m} = \frac{\dot{M}}{M_E}, \quad \dot{M}_E = \frac{L_E}{c^2}, \quad L_E \propto \frac{M}{\sigma T / \sigma} \approx 1.3 \times 10^{38} \left( \frac{M}{M_\odot} \right) \text{ erg/sec} \]

2. The radius in terms of the Schwarzschild radius

\[ x = \frac{r}{R_S}, \quad R_S = \frac{2GM}{c^2} \approx 3 \times 10^5 M, \quad M = \left( \frac{M}{M_\odot} \right) \]

3. The velocities are Keplerian

\[ v^2 \propto \frac{1}{x} \]
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
- Potential velocity scatter
- Integrated $N_H \sim 1.2 \times 10^{22}$ cm$^{-2}$

Chandra data
Holczer+(07)
Narrow-Line Seyferts (PG QSOs)

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

PG 0844+349
(v/c ~ 0.2)

PG 1211+143
(v/c ~ 0.1)

Pounds+(03)

Chandra/XMM-Newton data

Pounds+Reeves(09)

PDS 456
(v/c ~ 0.25)

Reeves+(09)
Broad Absorption Line (BAL) QSOs: APM 08279+5255

- ~10% of optically-selected QSOs
- Faint X-ray relative to O/(F)UV continua
- Broad C IV line ~ 2,000-30,000 km/sec
- Highly-blueshifted ~ 10,000-30,000 km/sec

Credit: NASA/CXC/PSU/M.Weiss/G.Chartas

10/28/2010 SEAL@GSFC

NRAO/AUI/NSF,STScI
**BAL QSO: UV Absorptions**

APM 08279+5255:  
(z = 3.91)

- Lensed QSO (x100)  
- Optically-bright  
- IR-loud, radio-quiet  

High-velocity outflows  
\( v/c \sim 0.04-0.1 \) in C IV  
(UV: Keck/HIRES)
Absorption Measure Distribution (AMD)

$\text{AMD}(\xi) = \frac{dN_H}{d\log\xi} \sim (\log\xi)^p$ where $\xi = L/(n r^2)$

- Holczer+(07) 
- Behar(09)

$\Rightarrow$ presence of nearly equal $N_H$ over $\sim 4$ decades in $\xi$ ($p \sim 0.02$)
For radiatively driven winds one obtains

\[ \xi(r) \sim \frac{L}{n(r)r^2} \sim \frac{L}{N_H r} \rightarrow N_H \sim \frac{L}{\xi(r)r} \]

\[ \frac{dN_H}{d\log \xi} \sim \frac{L}{\xi(r)r} \simeq \text{const.} \rightarrow \xi(r) \sim \frac{1}{r} \]

\[ n(r) \propto \frac{1}{r} \]

\[ u(r) = u_\infty (1 - r_*/r) \]

\[ AMD = \frac{dN_H}{d\log \xi} \propto \frac{\xi_\infty}{\xi} \]

\[ \xi_\infty \] is the ionization parameter at the distance where the asymptotic wind velocity is attained.
Fundamental Questions:

- Geometry?
- Spatial location?
- Properties?
- Physical origin?
Accretion disks necessarily produce outflows/winds (launched initially with Keplerian rotation)

- Driven by some acceleration mechanism(s)
- Local X-rays heat up and photoionize plasma along the way

Need to consider mutual interactions between ions & radiation
Magnetohydrodynamics (MHD)

(At least) 2 candidates:

- GRO J1655-40
  Miller+(06,08)
- NGC 4151
  Kraemer+(05)
  Crenshaw+Kraemer(07)
MHD Disk-Wind Solutions
(Blandford+Payne82; Contopoulos+Lovelace94)

- Steady-state, axisymmetric MHD solutions (2.5D):

\[
\begin{align*}
\nabla \cdot (\rho \mathbf{v}) &= 0 \quad \text{(mass conservation, } P_{\text{rad}}=0) \\
\nabla \times \mathbf{B} &= \frac{4\pi}{c} \mathbf{J} \quad \text{(Ampere’s law)} , \\
\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} &= 0 \quad \text{(ideal MHD)} , \\
\nabla \times \mathbf{E} &= 0 \quad \text{(Faraday’s law)} , \\
\rho(\mathbf{v} \cdot \nabla)\mathbf{v} &= -\nabla p - \rho \nabla \Phi_g + \frac{1}{c}(\mathbf{J} \times \mathbf{B}) \quad \text{(momentum conservation)} ,
\end{align*}
\]


- Look for solutions that the variables separate
Assume Power Law radial dependence for all variables

\[
B(r, \theta) \equiv (r/r_o)^{-(s+1)/2} \tilde{B}(\theta) B_o,
\]
\[
v(r, \theta) \equiv (r/r_o)^{-1/2} \tilde{v}(\theta) v_o,
\]
\[
p(r, \theta) \equiv (r/r_o)^{-(s+1)} \mathcal{P}(\theta) B_o^2,
\]
\[
n(r, \theta) \equiv (r/r_o)^{-s} \mathcal{N}(\theta) n_o,
\]
\[
n_o = \frac{f \bar{m}_o}{2\sigma_T r_s},
\]

- Solve for their angular dependence using the force balance equation in the \(\theta\)-direction (Grad-Safranov equation).
- This is a wind-type equation that has to pass through the appropriate critical points.
- BP82 solution: \(s = 3/2\); CL94 solution: \(s = 1\)
• With the above scalings

\[ \dot{m}(x) = \dot{m}_0 x^{-s + 3/2} \]

• In order that \( n(r) \sim 1/r \), \( s = 1 \) and

\[ \dot{m} \propto x^{1/2} \]

• The mass flux in the wind increases with distance!! Or rather, most of the accreting gas “peels-off” to allow only a small fraction to accrete onto the black hole (Blandford & Begelman 1999).

• There is mounting observational evidence that the mass flux in the wind is much higher than that needed to power the AGN/LMXRB.

• Feedback! \( E_{\text{dot}} \sim \dot{m} \dot{v}^2 \sim r^{-1/2} \); Momentum input: \( P_{\text{dot}} \sim \dot{m} \dot{v} \sim \log r \) \( \rightarrow \) Equal momentum per decade of radius!
• By expressing BH luminosity in terms of dimensionless variables \( \left( L \propto \eta \dot{m}_a M \right) \) or \( L \propto \eta \dot{m}_a^2 M \) the ionization parameter can now be expressed in the dimensionless variables

\[
\xi(x) \sim \frac{L}{n(r)r^2} \sim \frac{\eta \dot{m}_a}{N_H(x)x} \sim \left\{ \begin{array}{ll}
10^8 \frac{\eta}{f_W} \frac{1}{x^{-s+2}} & \text{for } \dot{m}_a > \alpha^2 \text{ (non-ADAF)} \\
10^8 \frac{\eta}{f_W} \frac{\dot{m}_a}{x^{-s+2}} & \text{for } \dot{m}_a < \alpha^2 \text{ (ADAF)}
\end{array} \right.
\]

• For \( s=1 \), \( \xi(r) \sim 1/r \); species “living” in lower \( \xi \)-space should come from larger distances.
• The radiation seen by gas at larger distances requires radiative transfer thru the wind.
**MHD Disk-Wind Solutions**

(Contopoulos+Lovelace94)

We seek “q=1” self-similar wind:

- $B(r, \theta) \sim B(\theta)/r$
- $n(r, \theta) \sim F(\theta)/r$ (i.e. equal column per decade in radius)
- LoS velocity $\sim 1/r^{1/2}$ (Keplerian profile)
- $\xi(r, \theta) \sim G(\theta)/r$ (w/o attenuation)

**Density**

$$n(r, \theta) = \frac{\rho(r, \theta)}{\mu m_p} = n_0 x^{2q-3} N(\theta)$$

$$n_0 = \frac{\eta_w m}{2\sigma T r_s}$$

$x = r/rs$

**LoS column density**

$$N_H(\Delta r, \theta) = \int_{\Delta r} n(r, \theta) dr$$

**Ionization parameter**

$$\xi(r, \theta) \equiv \frac{L}{n(r, \theta)r^2} \sim \frac{\epsilon}{N(\theta)\eta_W} \left( \frac{3 \times 10^8 m}{x^{2q-1}} \right)$$

(c.f. Ueda+03; Tueller+08)
The density has a very steep $\theta$-dependence with the polar column being $10^3 - 10^4$ smaller than the equatorial. The wind IS the unification torus (Konigl & Kartje 1994).
**Simple Wind Solutions with n~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. $\sim 10\%$, \( n(\text{in}) \sim 10^{10} \text{ cm}^{-3} \)

---

**Equation:**
- Toroidal velocity $V_\phi$
- Poloidal velocity $V_p$

---

![Graph showing wind velocity and density distribution](image-url)
The photon density at the gamma-ray blob can be calculated by integrating the source function along rays.
\[ r = \frac{D}{1 - \cos \theta} \]

\[ \epsilon(r) = \frac{L}{4\pi r^2} f(\theta) \tau(r), \quad f(\theta) = e^{(\theta - \pi/2)/0.2} \]

\[ \tau(r) \approx n_0 \left( \frac{r_0}{r} \right) \sigma_T r = n_0 r_0 \sigma_T \approx \dot{m} \]
For sufficiently small values of $\dot{m}$ the magnetic energy dominates over the photon energy, depending on the bulk acceleration of the jet relative to the size of the disk.

This simple MHD-wind based model provides a direct account of the BL Lac - FSRQ phenomenology.
Line emission reflects also on the accretion / wind mass flux rate and should relate to the character of the objects (P. Padovani’s talk)
**Dust reprocessing**: For \( n(r) \sim 1/r \), equal energy per decade of radius is absorbed and emitted as dust IR emission at progressively decreasing temperature. This leads to a flat \( n u F_nu \) IR spectrum.
What about the particle acceleration?

IMHD pulsar solution: BC force a parallel electric field and Creation of charges while none is assumed in the outset.

\[ \text{Color: } \frac{J}{\rho c}, \quad \text{Streamlines: } B_p \]

(Kalapotharakos, Kazanas, Harding, Contopoulos, 1108.2138)
Conclusions

• AGN Unification models that can accommodate their X-ray absorber properties provide novel insights concerning the Fermi blazar observations:

• The $\sim 1/r$ density profiles implied by the AMD provide the possibility of external photons along the jet axis either through scattering or reprocessing into lines. Both can be calculated once we fix on a specific MHD model.

• The model suggests that low values of $\dot{m}$ are associated with non-thermal emission dominated by SSC rather than EC.

• The model relates the wind characteristics (e.g. outer radius) to the IR properties of AGN, which in turn are related to the Compton dominance of the object.
\[ \alpha_{ox} = 0.384 \log \left( \frac{f_{2 \text{ keV}}}{f_{2500 \text{ Å}}} \right) \]

\[ \Rightarrow \text{tells you X-ray weakness} \]
Apply the model to BAL QSOs by changing only $\alpha_{OX}$: The decrease in ionizing X-rays allow for FeXXV very close to the BH $\rightarrow$ hi FeXXV velocity, absorption of CIV forming photons $\rightarrow$ CIV forms also at small distances leading to hi CIV velocity (but smaller than that of FeXXV).

$\log(\text{density})$

Injected SED ($F_\nu$)

- $\dot{m} = 0.5$
- $kT(\text{in}) = 5\text{eV}$
- $\Gamma_X = 2$
- $\alpha_{OX} = -2$

Fukumura+(10b)
Production of CIV and FeXXV/XXVI

- \( \dot{m} = 0.5 \)
- \( kT(\text{in}) = 5 \text{eV} \)
- \( \Gamma_x = 2 \)
- \( \alpha_{\text{OX}} = -2 \)
Correlations with Outflow Velocity

Velocity Dependence on SED (X-ray)

- X-ray data of APM 08279+5255 from Chartas+(09)
- Model from Fukumura+(10b)

(a) $\theta = 50^\circ$

- Fe XXV
- C IV

LoS Velocity $v/c$

Photon Index $\Gamma$

$Q_{ox}$
**Issues (Future Work)**

*Wind Solutions (Plasma Field)*:

- (Special) Relativistic wind
- Radiative pressure (e.g. Proga+00; Everett05; Proga+Kallman04)

*Radiation (Photon Field)*:

- Realistic SED (particularly for BAL quasars)
- Different LoS between UV and X-ray (i.e. $R_{UV} > R_X$ by x10...)
- Including scattering/reflection (need 2D radiative transfer)

*(Ultimate) Goals*:

- Comprehensive understanding of ionized absorbers within a single framework (i.e. disk-wind)
- AGNs/Seyferts/BAL/non-BAL QSO with high-velocity outflows (e.g. PG 1115+080, H 1413+117, PDS 456 and more...)
- Energy budget between radiation and kinetic energy...
Broad Absorption Line (BAL) QSOs

- Became known with ROSAT/ASCA survey
- Large $C\ IV\ EW(\text{absorb}) \sim 20-50\ \AA\ \sim 30,000\ \text{km/sec}$
- $\sim 10\%$ of optically-selected QSOs
- Faint (soft) X-ray relative to O/UV continua
- High-velocity/near-relativistic outflows:
  - $v/c \sim 0.04 - 0.1$ (e.g. UV $C\ IV$)
  - $v/c \sim 0.1 - 0.8$ (e.g. X-ray $\text{Fe XXV}$)
- High intrinsic column of $\sim 10^{22}\ \text{cm}^{-2}$ (UV)
- $\sim 10^{23}\ \text{cm}^{-2}$ (X-ray)
10. Normal galaxies vs. BAL quasars

- Normal galaxies show typical absorption lines such as Lyα, C IV, Mg II, Hβ, and Hα.
- BAL quasars exhibit broad absorption lines (P Cygni profiles) in addition to the above lines.

**Diagram:**
- Left panel: Normal galaxy spectrum with labels for Lyα, C IV, Mg II, Hβ, and Hα.
- Right panel: BAL quasar spectrum with labels for Lyα, NV, Si IV, C IV, and a note on broad absorption lines (P Cygni profiles).
Ramirez(08)
12. Quasars - SED (UV/X-ray property)

**Table 3**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>1eV</th>
<th>10eV</th>
<th>0.1keV</th>
<th>1keV</th>
<th>10keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10cm</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>1cm</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>1mm</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>100µ</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>1µ</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>1000Å</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
<tr>
<td>1Å</td>
<td>-24</td>
<td>-26</td>
<td>-28</td>
<td>-30</td>
<td>-32</td>
</tr>
</tbody>
</table>

α\_ox = 0.384 log (f\_2 keV / f\_2500 Å)

UV-bright, X-ray-faint!

Gallagher+(06)

UV tells you X-ray weakness

Chandra BAL QSO survey

Richards+(06)

Elvis+(94)

α\_x = 0.5
α\_x = -0.5
α\_x = -1.0
α\_x = -1.5

2500 Å
2 keV
MCG 6-30-15

X-ray spectrum of NGC 3783

Holczer+10

Netzer+(03)
UV Luminosity vs. $\alpha_{\text{ox}}$

**Define:**

$$\Delta \alpha_{\text{ox}} = \alpha_{\text{ox}} - \alpha_{\text{ox1.6 UV}}(L_{\text{uv}})$$

- Brighter in X-rays
- Fainter in X-rays

228 SDSS Quasars with ROSAT (Strateva et al. 2005)
(ii) Velocity dependence on LoS

Optimal view (e.g. ~50deg)
\[ \text{high } N_H, \text{high } v/c \]

Face-down view (e.g. ~30deg)
\[ \text{low } N_H, \text{low } v/c \]
APM 08279+5255
z=3.911 Quasar
V=15.1 mag