Magnetic View of AGN-Driven Winds

Keigo Fukumura (James Madison University, USA)
fukumukx@jmu.edu

Demos Kazanas (NASA/GSFC)
Chris Shrader (NASA/GSFC)
Francesco Tombesi (NASA/UMD)
Ehud Behar (Technion, Israel)
Ioannis Contopoulos (Academy of Athens, Greece)
Outline

1) X-ray ionized winds in AGNs

2) What can motivate MHD-driven?

3) Observables

4) Implications

5) Summary
AGN-driven outflows

Ubiquitous across diverse Seyferts/QSOs populations can learn

1. column density: $N_H$
2. ionization parameter: $\xi = L_{\text{ion}}/(n r^2)$
3. wind velocity: $v_{\text{LoS}}$
4. geometry, global property, AGN feedback... etc.

General Review:
Blustin+(05), Reynolds+(97)
Laor&Brandt (02)
Crenshaw&Kraemer(12)
Crenshaw+(03)

Classical MHD Models: e.g.
Blandford+Payne82 (BP82), Contopoulos+Lovelace94 (CL94),
Konigl+Kartje94 (KK94)... etc.
Ionized X-ray Winds
(i.e. Warm Absorbers & Ultra-Fast Outflows)

- WAs in Soft X-ray
- UFOs* in Fe K band

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

- $v_{\text{out}}/c \sim 0.1 - 0.7$
- $\log \xi \sim 3-6$
- $N_H \sim 10^{23-24} \text{ cm}^{-2}$

* Also soft X-ray UFOs (?)

LoS $\log N_H$ [cm$^{-2}$] vs. LoS $v_{\text{outflow}}/c$ graph showing:
- WAs
- UV outflows
- UFOs
Outstanding Questions

✓ Flow Geometry?
✓ Continuous/Patchy flows?
✓ Defining quantities?
✓ How are they launched?

Some “good” indicators for MHD-driven winds...

- High \( \xi, v, N_H \) (UFOs)
- Flat (or slightly varying) AMD
- Insufficient Force Multiplier argument
- Process of elimination by “R” and “\( \xi \)”...

FKCB(10b)
Absorption Measure Distribution (AMD)

Increasing with increasing $\xi$
What does AMD tell us?

\[ n \propto r^{-p}, \quad \xi \equiv \frac{L}{nr^2} \propto r^{p-2} \Rightarrow r \propto \xi^{p-2} \quad \therefore \Delta N_H = n \cdot \Delta r \propto \xi^{p-2} \Delta \xi \]

\[
AMD \equiv \frac{\Delta N_H}{\Delta (\log \xi)} = \xi \frac{\Delta N_H}{\Delta \xi} \propto \xi^{-\frac{p-1}{p-2}}
\]

Hence, \( p \sim 1 \) wind

- shows \( AMD \sim \text{const} \) \( \Rightarrow n \sim r^{-1} \)
- is favored by minimization argument of B-energy \((B_\phi \sim r^{-1})\) in the disk. \( \text{e.g. CL94, KK94} \)

As toroidal rotation efficiently converted into poloidal motion,

- Plasma accelerated along a field line while \( V_{\text{LOS}} \sim V_{\text{esc}} \sim r^{-1/2} \)
- \( N_H \sim \text{const per decade in radius} \)
- \( \xi \sim r^{-1} \sim v^2 \)

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

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

Kazanas+(2012)

outflow rate \( \leftrightarrow \) exterior \hspace{1cm} kinetic power \( \leftrightarrow \) interior
Multi-λ campaign of Mrk 509

From 600ks RGS spectrum

$\nu_{out} \sim \xi^{0.64+/-0.10}$

$\nu_{out} \sim \xi^{0.5}$ (for $n \sim r^{-1}$ wind)

Indicating magnetic-origin?
What does AMD tell us?

\[ n \propto r^{-p}, \quad \xi \equiv \frac{L}{nr^2} \propto r^{p-2} \Rightarrow r \propto \xi^{p-2} \quad \therefore \Delta N_H = n \cdot \Delta r \propto \xi^{\frac{2p-3}{p-2}} \Delta \xi \]

\[ AMD \equiv \frac{\Delta N_H}{\Delta (\log \xi)} = \xi \frac{\Delta N_H}{\Delta \xi} \propto \xi^{\frac{p-1}{p-2}} \]

What about other slope?

- \( p=3/2 \) for BP82 MHD winds
  - \( \text{AMD} \sim \xi, \xi \sim r^{-1/2}, N_H \sim r^{-1/2} \) (slowly dropping)

- \( p=2 \) for spherical winds & asymptotically coasting radiative winds
  - As soon as wind reaches \( V \sim V_{\text{coast}} \), ionization freezes at \( \xi \sim \xi_o \)
  - singular blueshift, monochromatic \( \xi \)
  - \( N_H \sim r^{-1} \) (rapidly dropping)
  - AMD not a function of \( \xi \) or very narrow

Are we seeing MHD-driven winds???

YES!
WAs in NGC 4151

Couto+(16)
Crenshaw+(05)
Model Description

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

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

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

Disk treated as BC

MHD wind is 2D!

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

Toroidal (Keplerian) to poloidal motion transition.
Fe XXV UFO in PG 1211+143

Best-fit MHD wind model with $p = 1.1$:

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

Faster layer of MHD-winds (at smaller radii) can be "visible"

Outflow velocity depends on SED hardness
**QSO: Velocity vs. Ionizing SED**

Faster layer of MHD-winds (at smaller radii) can be “visible”

→ Outflow velocity depends on SED hardness
WAs in XRB GRO J1655-40

density slope: “p−1” \(\Rightarrow\) control global feature

Fukumura+(17), Kallman+(09), Miller+(06,08)
WAs in XRB GRO J1655-40

density slope: “$p - 1$” $\Rightarrow$ control global feature

$\bullet$ $n_o = 9.3 \times 10^{17}$ cm$^{-3}$
$\bullet$ $p = 1.2$
$\bullet$ $\theta_{\text{obs}} = 80^\circ$

WAs in NGC 3783

900 ks (stacked) Chandra/HETG/METG spectrum

SED (PL: $\Gamma_X \sim 1.8$)
$L_{ion} = 1.5 \times 10^{43}$ erg/s

Kaspi+(01)
WAs in NGC 3783

$\rho = 1.15$ wind

wind density at base: $1.7 \times 10^{11} - 1.1 \times 10^{13} \text{ [cm}^{-3}\text{]}$

Inclination: $30^\circ - 50^\circ$

- Ne X Lya
- Ne X Lyb
- Mg XII Lya
- Si XIV Lya
- S XV Heα
- S XVI Lya

preliminary
\[ n_0 = 6.8\text{e}11 \text{ cm}^{-3} \]
\[ p = 1.15 \]
\[ \theta_{\text{obs}} = 39^o \]
WAs in NGC 3783

\[ p = 1.5 \text{ wind (BP82 model)} \]

wind density at base: \(1.7 \times 10^{11} - 1.1 \times 10^{13} \text{ [cm}^{-3}\text{]}\)

Inclination: \(30^\circ - 50^\circ\)
\( p = 1.5 \) wind (BP82 model)
Summary

- Ability to launch H/He-like high-columns

- Global scaling (2D):
  - LoS dependence → AMD
  - $(\theta,\phi)$ dependence → Transverse motion?

- Correlations for a given source
  - AMD, $V_{\text{LOS}}(\xi)$, $FM=\sigma_{\text{abs}}/\sigma_{\text{Thomson}}$, SED-dependence...

- Asymmetric spectral shape due to $\nabla^2$

Potential AGNs for meaningful AMD diagnostics:
NGC 3516, Ark 564, NGC 4051, Mkn 509, Mkn 766, NGC 4151, NGC 3783, NGC 3227, NGC 4507, PG 1211+143, MCG 6-30-15, IRAS 13349+2438 ... etc.