Substantial winds from the accreting supermassive black hole in M87 revealed by Faraday rotation observations

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Hot accretion flows prevalent in low luminosity AGNs (LLAGNs) are very important because they might govern the evolution of most of the galaxies in the universe.

Netzer 2013

Galaxies

- Fast-accreting SMBHs (2%)
- Slow-accreting SMBHs (30%)
- Quiescent SMBHs (68%)

Cold, thin disk

Hot, thick flows

Understanding hot accretion flows is very important because it might govern the evolution of most of the galaxies in the universe.
Winds in hot accretion flows

\[ \dot{M} \propto r^s \]

\[ \rho \propto r^{-p}, \quad p = 1.5 - s \]

**s = 0, p = 1.5**

ADAFs: pure inflows

Narayan & Yi (1994)

**0 < s < 1, 0.5 < p < 1.5**

ADIOS: inflows/outflows

Blandford & Begelman (1999)

**s = 1, p = 0.5**

CDAFs: convection

Igumenshchev & Abramowicz (1999)
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  - ADAFs: pure inflows
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Inflows

Net flows

Outflows

Numerical Simulations
Winds in hot accretion flows

GRMHD simulations Sadowski+ (2013)

Winds: (i) un-collimated, (ii) moderately magnetized, and (iii) non-relativistic gas outflows launched from the accretion flows.

Jets: (i) collimated, (ii) highly magnetized, and (iii) relativistic gas outflows.
Jets collimated by winds?

- AGN jets cannot be self confined → must be confined by an external medium.
  
  \[ p_{\text{ext}} = p_{\text{ext,1c}} (z/z_{1c})^{-\alpha} \quad z \propto r^a \]
  
  Begelman & Li (1994)

(i) \( \alpha < 2 \iff a = 4/\alpha > 2 \),  
(ii) \( \alpha = 2 \iff 1 < a \leq 2 \),  
(iii) \( \alpha > 2 \iff a = 1 \).

\[ \text{Parabolic jet shape (collimation)} \]
\[ \text{Conical jet shape (free expansion)} \]

- To have a parabolic jet shape, \( \alpha \leq 2 \) is needed (external-confinement).

Komissarov+ (2009)
Jets collimated by winds?

Strongly magnetized winds

Weakly magnetized winds
The collimation – acceleration paradigm

component of the momentum equation

\[ \gamma \rho_0 (V \cdot \nabla) (\gamma v V) = -\nabla p + J^0 E + J \times B \]

along the flow (wind equation):

where \( F \propto \omega^2 B_p \)

since \( B_p \delta S = \text{const} \),

\( F \propto \omega^2 / \delta S \propto \omega / \delta l \)

acceleration requires the separation between streamlines to increase faster than the cylindrical radius

the **collimation-acceleration** paradigm:

\( F \downarrow \) through stronger collimation of the inner streamlines relative to the outer ones (differential collimation)

Jet collimation and acceleration are intimately related.
The fundamental questions we want to answer are:

1. **Winds exist in hot accretion flows?**
   → Not all the hot gas captured by the black hole’s gravity is actually accreted.

2. **AGN jets are collimated by winds?**
   → This collimation can result in gradual acceleration of the jets to relativistic speeds (by converting EM energy into kinetic energy).
How to probe hot accretion flows and winds?
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- Emission or absorption lines
- Fully ionized
How to probe hot accretion flows and winds?

- Emission or absorption lines
- Measuring density profiles with X-ray observations

- Fully ionized
- Limited resolution
How to probe hot accretion flows and winds?

- Emission or absorption lines
- Measuring density profiles with X-ray observations
- Faraday rotation with VLBI

- Fully ionized
- Limited resolution

the medium between the jet and the observer
M87: a good laboratory for studying jets and winds

M87 has
(i) Hot accretion flows
(ii) Polarized Jets
(iii) Evidence for gradual collimation inside the Bondi radius

Kovalev+ (2007)

Nakamura & Asada (2013)
VLBA archive data analysis

- We analyzed the VLBA archive data at 1.7, 5, 8.3 GHz.
- We obtained EVPA rotation as a function of $\lambda^2$ ‘within the bands’ (across different baseband channels).

<table>
<thead>
<tr>
<th>Project Code</th>
<th>Epoch</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJ020A</td>
<td>1995 Nov 22</td>
<td>8.11, 8.20, 8.42, 8.59 GHz</td>
</tr>
<tr>
<td>BJ020B</td>
<td>1995 Dec 09</td>
<td>4.71, 4.76, 4.89, 4.99 GHz</td>
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<td>BC210B</td>
<td>2013 Mar 09</td>
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<td>BC210C</td>
<td>2014 Jan 29</td>
<td>4.85, 4.88, 4.92, 4.95, 4.98, 5.01, 5.04, 5.08 GHz</td>
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<td>BC210D</td>
<td>2014 Jul 14</td>
<td>4.85, 4.88, 4.92, 4.95, 4.98, 5.01, 5.04, 5.08 GHz</td>
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<td>BH135F</td>
<td>2006 Jun 30</td>
<td>1.65, 1.66, 1.67, 1.68 GHz</td>
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<tr>
<td>BC167C</td>
<td>2007 May 28</td>
<td>1.65, 1.66, 1.67, 1.68 GHz</td>
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<td>BC167E</td>
<td>2007 Aug 20</td>
<td>1.65, 1.66, 1.67, 1.68 GHz</td>
</tr>
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</table>
Internal Faraday rotation: no EVPA rotation larger than 45 degrees (Burn 1966)

→ The Faraday screen is external to the jet.

(Hot accretion flows)
RM distribution as a function of distance

Projected distance from the BH [mas]

|RM| [rad/m²]

RM < 0
RM > 0

De-projected distance from the BH [rₛ]

2 GHz
5 GHz
8 GHz

Bondi radius
HST-1
Applying the hot accretion flows model to the data

\[ RM = 8.1 \times 10^5 \int n_e B dl \]

\[ n_e = n_{\text{out}} \left( \frac{r}{r_{\text{out}}} \right)^{-p} \]

\[ B(r) = B_{\text{out}} \left( \frac{r}{r_{\text{out}}} \right)^{-1} \]

\[ RM = 8.1 \times 10^5 n_{\text{out}} B_{\text{out}} r_{\text{out}}^{(p+1)} \int_{r_{\text{in}}}^{r_{\text{out}}} r^{-(p+1)} dl \]
Applying the hot accretion flows model to the data

\[
RM = 8.1 \times 10^5 \int n_e B dl
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\[
RM = 8.1 \times 10^5 n_{out} B_{out} r_{out}^{(p+1)} \int_{r_{in}}^{r_{out}} r^{-(p+1)} dl
\]

from the model of hot accretion flows

\[
\rho(r) \propto r^{-p} \quad \dot{M}(r) \propto r^s \quad p = 1.5 - s
\]

Yuan & Narayan (2014)
Applying the hot accretion flows model to the data

\[
RM = 8.1 \times 10^5 \int n_e B \, dl
\]

\[
n_e = n_{out} \left( \frac{r}{r_{out}} \right)^{-p}
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B(r) = B_{out} \left( \frac{r}{r_{out}} \right)^{-1}
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RM = 8.1 \times 10^5 n_{out} B_{out} r_{out}^{p+1} \int_{r_{in}}^{r_{out}} r^{-(p+1)} \, dl
\]
Applying the hot accretion flows model to the data

Hirose+ (2004)
We obtained $p \sim 1$. 

- $p = 1.5$: classical ADAF
- $0.5 < p < 1.5$: ADAF with mass outflows, ADIOS
- $p = 0.5$: convection dominated accretion flows, CDAF

$\rho \propto r^{-1}$: Support ADIOS ($p \sim 1$)

$$n_e = n_{out} \left(\frac{r}{r_{out}}\right)^{-p}$$

\[ \rightarrow \text{Winds do exist in M87!} \]
Jet collimation

- AGN jets cannot be self confined $\rightarrow$ must be confined by an external medium.

\[ p_{\text{ext}} = p_{\text{ext,lc}} \left( \frac{z}{z_{\text{lc}}} \right)^{-\alpha} \quad \text{\( z \propto r^a \)} \]

Komissarov+ (2009)

(i) $\alpha < 2 \iff a = \frac{4}{\alpha} > 2$,  \hspace{1cm} \rightarrow \text{Parabolic jet shape (collimation)}

(ii) $\alpha = 2 \iff 1 < a \leq 2$,  \hspace{1cm} \rightarrow \text{Conical jet shape (free expansion)}

(iii) $\alpha > 2 \iff a = 1$.

- To have a parabolic jet shape, $\alpha \leq 2$ is needed (external-confinement).
Jet collimation

- GRMHD simulations found that winds are surrounding the highly magnetized jets.

"It is clear that the strong energy flux region is surrounded by the region where the mass-loss is most efficient." (Sadowski+ 2013)
Jet collimation

- GRMHD simulations found that winds are surrounding the highly magnetized jets.

- Winds are likely the source of Faraday rotation, given the small jet viewing angle (~17 deg, Mertens et al. 2016).
Jet collimation

- AGN jets cannot be self confined → must be confined by an external medium.

\[ p_{\text{ext}} = p_{\text{ext}, lc} \left( \frac{z}{z_{lc}} \right)^{-\alpha} \quad z \propto r^a \]

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- To have a parabolic jet shape, \( \alpha \leq 2 \) is needed (external-confinement).

\[ \rho \propto r^{-1} \quad P_{\text{gas}} \propto \rho^\gamma \propto r^{-1.67} \]
\[ \gamma = \frac{5}{3} \]

\[ P_{\text{gas}} \propto r^{-1.67} \]
Jet collimation & acceleration

Nakamura & Asada (2013)  
Jet collimation

Mertens+ (2016)  
Jet acceleration

Confinement of the jet by the winds  \(\rightarrow\) collimation  \(\rightarrow\) acceleration
Jet collimation & acceleration

Nakamura & Asada (2013)
Jet collimation

Hada+ (2017)
Jet acceleration

Confinement of the jet by the winds → collimation → acceleration
Mass accretion rate

- We obtained $\rho \propto r^{-1}$
- If the radial self-similarity holds, then
  \[ \dot{M}(r) \propto r^{0.5}, \]
  \[ \dot{M}_{\text{BH}} = 1.58 \times 10^{-4} M_\odot \text{ yr}^{-1} \]
  \[ \dot{M}_{\text{Bondi}} = 0.1 M_\odot \text{yr}^{-1} \]
  from X-ray observations
  (with a few assumptions…)

\[ \epsilon \equiv \frac{L_{\text{disk}}}{\dot{M}_{\text{BH}} c^2} \approx 3.8\% \]

The radiative efficiency of hot accretion flows might not be as small as usually assumed. The faintness of LLAGNs is due to the reduced mass accretion rate via winds.

\[ \eta \equiv \frac{P_{\text{jet}}}{\dot{M}_{\text{BH}} c^2} \gtrsim 110\%, \quad P_{\text{jet}} \gtrsim 10^{43} \text{ erg s}^{-1} \]

Blandford-Znajek process operating in a MAD state (Tchekhovskoy et al. 2011).
Mis-alignment between the jet axis and the wind axis

- RM sign is negative in almost all distance ranges.
If the Faraday screen is very close to the jet, e.g., a jet sheath, then
→ Different RM signs on different jet sides with respect to the axis.
Mis-alignment between the jet axis and the wind axis

The background light source exposes only one side of the toroidal magnetic loops. → **Mis-alignment** between the jet axis and the accretion axis.
We studied Faraday rotation in the jet of M87 inside the Bondi radius. The data are consistent with:

1. the presence of substantial winds from hot accretion flows
2. collimation of the jet by the winds with relatively flat pressure profile
3. mis-alignment between the jet and the wind axis.