A Look Through the Rotation Measure in M87

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M87 Workshop, Towards the 100th Anniversary of the Discovery of Cosmic Jets
May 24th, 2016 - ASIAA, Taipei
Contents

- Introduction
- Core Rotation Measure
  - Hints for Accretion Flows in M87
- Kiloparsec Scales Rotation Measure
  - Probing MHD jet properties
- Conclusions
A Brief Introduction

Helical B-fields thought to exist in AGN

Origin (sub-parsec scales):
- Combined action of the rotation of the SMBH and its accretion disk and relativistic jet outflow
- Alfvén waves downstream the jet

Meier, Koide & Uchida (2001)
A Brief Introduction

- The big I/O question of AGN
  - How are central SMBH fed?
  - What is the behavior of the outcome?
  - How much of the outcome is actual feedback? (i.e, BZ vs BP)

- Rotation measure, a way to measure both inflow and outflow properties...
  ...if you know where and how to look at!

- M87, the “Rosetta Stone” for AGN
  - Relativistic jet
  - Typical LLAGN with RIAF
  - High energy activity
  - Ideal source to probe properties on AGN
Hints of Accretion Flow Physics in M87
Accretion Flows in LLAGN

- Three types of RIAF

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<tbody>
<tr>
<td>$\dot{M}$</td>
<td>$\sim (r/r_B)^0$</td>
<td>$\sim (r/r_B)^{0-1}$</td>
<td>$\sim (r/r_B)^1$</td>
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$r_B =$ Bondi radius ($10^4 - 10^6 r_s$)

- Substantial decrease of mass accretion rate in ADIOS and ADAF
- What kind of accretion is crucial to understand energy balance between

$$L_{\text{acc}} \leftrightarrow L_{\text{rad}} \leftrightarrow L_{\text{jet}}$$
Accretion Flows

- How to investigate the RIAF?
  - Method 1: Fitting the SED
    (e.g., Narayan+95, Manmoto+97, Yuan+03)
Accretion Flows

- How to investigate the RIAF?
  - Method 1: Fitting the SED (e.g., Narayan+95, Manmoto+97, Yuan+03)
  - Method 2: Rotation Measure caused by accretion flow (e.g., Agol+2000, Bower+2003, Marrone+2006, Macquart+2006)

\[
\begin{align*}
RM &= (8.1 \times 10^5) \int n_e B \cdot dl \\
\beta &= 1/2 \text{ (ADAF)} \quad 3/2 \text{ (CDAF)} \quad 1/2 - 3/2 \text{ (ADIOS)} \\
n(r) &= n_0 (r/r_S)^{-\beta} \\
B(r) &= \sqrt{4\pi c^2 m_\text{H} n_0 \left(\frac{r}{r_S}\right)^{-\beta+1}}/2 \\
\dot{M}_{\text{in}} &= 4\pi r_{\text{in}}^2 m_\text{H} n(r_{\text{in}}) v(r_{\text{in}}) = 4\pi r_S^2 m_\text{H} n_0 c (r_{\text{in}}/r_S)^{3/2-\beta} \\
RM &= (3.4 \times 10^{19}) \left(\frac{M_{\text{BH}}}{3.5 \times 10^6 M_\odot}\right)^{-2}
\times r_{\text{in}}^{(6\beta-9)/4} \dot{M}_{\text{in}}^{3/2} \int_{r_{\text{in}}}^{r_{\text{out}}} r^{-3/2} \ln^{(3\beta+1)/2} dr.
\end{align*}
\]
Accretion Flows

How to investigate the RIAF?

- Method 1: Fitting the SED (e.g., Narayan+95, Manmoto+97, Yuan+03)
- Method 2: Rotation Measure caused by accretion flow (e.g., Agol+2000, Bower+2003, Marrone+2006, Macquart+2006)

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

\[
n(r) = n_0 (r/r_S)^{-\beta}
\]

\[
B(r) = \sqrt{4\pi c^2 m_H n_0} \left( \frac{r}{r_S} \right)^{-(\beta+1)/2}
\]

\[
\dot{M}_{in} = 4\pi r_{in}^2 m_H n(r_{in}) v(r_{in}) = 4\pi r_S^2 m_H n_0 c (r_{in}/r_S)^{3/2-\beta}
\]

\[
RM = (3.4 \times 10^{19}) \left( \frac{M_{BH}}{3.5 \times 10^6 M_\odot} \right)^{-2}
\times r_{in}^{(6\beta-9)/3} \dot{M}_{in}^{3/2} \int_{r_{in}}^{r_{out}} r^{-(3\beta+1)/2} dr.
\]
Accretion Flows in M87

- Follow this methodology for M87
  - Backlight is the synchrotron jet
    \[
    \dot{M} = 1.1 \times 10^{-8} \left[ 1 - \left( \frac{r_{\text{out}}}{r_{\text{in}}} \right)^{-(3\beta-1)/2} \right]^{-2/3} \times \left( \frac{M_\bullet}{6.6 \times 10^9 M_\odot} \right)^{4/3} \left( \frac{2}{3\beta - 1} \right)^{-2/3} r_{\text{in}}^{7/6} R M^{2/3}
    \]

- Resolving M87's Bondi Radius
  - \( r_B \sim 230 \text{ pc} \sim 3 \times 10^5 r_s \sim 1 \text{ arcsec} \)

- Caveats for polarization observations
  - M87 core is depolarized at cm
  - Need of mm/sub-mm obs.

- SMA/ALMA
Accretion Flows in M87

- SMA Observations @ 230 GHz

Assuming no time variability, \( \langle \text{RM} \rangle = (-1.8\pm0.3) \times 10^5 \text{ rad/m}^2 \).

- \( \dot{M} = (3.6\pm1.1) \times 10^{-4} \text{ M}_\odot/\text{yr} = (2.9\pm0.9) \times 10^{-3} \text{ M}_\odot \)
- Substantial decrease of mass accretion rate: Strong constraint for RIAF
- Jet power > Accreting power (<10%): Other possibilities for jet power... spin?
Probing the jet properties
Jet properties of M87

- Jet power is not the only intriguing thing about the M87 outflow
- M87's kiloparsec jet complex morphology cannot be explained by pure hydrodynamics
  - High degree of polarization (e.g. Perlman+99)
  - Trails of components upstream the jet (e.g., Nakamura+04)
  - Collimation and acceleration (e.g., Nakamura & Asada 2015)
  - Velocity field (e.g., Meyer+14)
- Open questions
  - Magnetic to Kinetic conversion on kpc scales?
  - Morphology of magnetic fields
Jet Properties of M87

- Does M87, Rosetta stone for AGN host any signs re its jet magnetic field morphology (e.g., helical B field...)?

Owen, Eilek & Keel (1990)
Jet Properties of M87

- Does M87, Rosetta stone for AGN host any signs re its jet magnetic field morphology (e.g., helical B field...)?

![Diagram showing Flux, Pol, RM with 8 - 43 GHz data.](image)
Jet Properties of M87

- Bimodal distribution of the RM
  - Gaussian
  - Off-centered
  - In agreement with a turbulent, isotropic B-field with a larger scale structure

- However...
Jet Properties of M87

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- However...

- Power spectrum index
  - $2.5 < 3$ (Guidetti+12) $< 3.6$
  - Flatter than 3D Kolmogorov
  - Incompatible with 2D Kolmogorov
  - More complex morphology
  - More ordered B-fields
Jet Properties of M87

- Owen+90: “The jet shows the lowest RM. The foreground screen is associated with the lobes [...] and *most* of the lobe structure should be behind the jet

- Power spectrum index decreases when we compare larger (lobes) with smaller (jet) scales
  - Ordering of B-fields

- Combination of
  - a more tangled and isotropic magnetic field from a small region of the lobes in our line of sight and
  - the more ordered magnetic fields from the jet

- Connection with the MHD properties of the jet

Jet: $\sim 200 \text{rad/m}^2; a=2.5$

Lobe: $\sim 1000 \text{rad/m}^2; a=3$
Conclusions
Conclusions

- RM is a powerful tool to investigate I/O of AGN: accretion flow and jets
- M87's accretion rate significantly decreasing towards innermost regions
  - Accretion method consistent with CDAF, ADIOS
  - Accreting power may not be enough to hold the M87 jet power
- Kiloparsec structure of the RM in M87 is not simple
  - Various components may appear superposed along our line of sight
  - Combination may difficult to isolate RM only from jet, preventing to observe 'smoking gun' for jet-related B-field morphology
  - Magnetic structure well ordered in the kpc scales
  - Magnetic field dissipates into more turbulent (but still not Kolmogorov type!) in the lobes
[Poster 1] Frequency Phase Transfer to push VLBI obs to >129 GHz

\[ \phi_{\text{high}} \propto \frac{\nu_{\text{high}}}{\nu_{\text{low}}} \phi_{\text{low}} = R \phi_{\text{low}} \]

(Jung+, in prep)
[Poster 12] Structural Transition in the NGC6251 Jet

[Poster 5] Accretion Rate on Cygnus A
Thank You
Rotation Measure

- Faraday rotation effect on extragalactic jets
  - Wave in plasma with magnetic field: rotation of the polarization angle
  \[ RM \propto \int n_e B_{\text{los}} \cdot dl \]
  \[ \chi = \chi_0 + RM \lambda^2 \]

- If Helical magnetic field morphology
  - Toroidal component produces RM gradient transverse to the jet

Adapted from Algaba+12

\[ B \cdot dl > 0 \]
\[ \star \quad RM > 0 \]
\[ B \cdot dl < 0 \]
\[ \bigotimes \quad RM < 0 \]
MHD Jet for M87

- M87's jet complex morphology cannot be explained by pure hydrodynamics
  - High degree of polarization (60%)
MHD Jet for M87

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  - Trails of components
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Nakamura+2010

Nakamura & Asada 2013

Meyer+14
MHD Jet for M87

- Extras

**Fig. 1.** Illustration of rotation measure fits for typical regions on knots A, B and C.
Fig. 6.— Blanking of single realizations of random gaussian field with initial power index $a = 2.5$ (left), 3.0 (middle) and 3.5 (right). Top: original realizations, with a black contour superimposed showing the clipping of the data to emulate that of the actual observation. Bottom: power spectrum. Power index fitted to the reliable region of the slope is shown in the top right corner of each graphic. Fit is shown by the dashed line.
Helical Magnetic Fields

- But not seeing a spine/sheath structure does not imply the absence of helical B fields
  - On the contrary!
  - Helical vs pure toroidal B-fields

- Helix configuration may induce **asymmetries** in the transverse observed polarization properties

- Transverse B-field structure changes
  - Pitch / viewing angles
  - Velocity profiles
Rotation Measure

- If the B-field morphology is helical...
  - Toroidal component of the B-field: gradient transverse to the jet
  - Change of sign of the RM!

- Complications arise if we take into account pitch and/or viewing angles
  - But in all cases we still have a gradient

- RM gradients are an excellent helical B-field tracer

Jet viewed at 60°, with B field at various pitch angles

B field with pitch angle 45° at various viewing angles
Reliability of the RM gradients

2. Spurious RM gradients

- Check the statistical occurrence of spurious RM gradients due to errors and limited baseline VLBA coverage
- Various frequency ranges studied
  - 1.3 - 1.7 GHz (Murphy & Gabuzda 2013)
  - 8 - 15 GHz (Hovatta+ 2012)
  - 12 - 43 GHz (Algaba 2012)

Robustness of RM gradients
- Fewer than 1% simulations gave rise to spurious 3σ gradients

- Non meaningful to impose a beam size-only based width on RM gradients
- Reliability based on monotonicity of RM gradient and range over 3σ.