Magnetic fields in blazar jets

Talvikki Hovatta
Tuorla Observatory

In collaboration with MOJAVE and RoboPol teams + Shane O’Sullivan, Ivan Marti-Vidal, Alexander Tchekhovskoy
Outline

• Motivation
• How to observe magnetic fields
• ALMA observations of 3C273
• Statistical studies on magnetic fields in radio and optical bands
• Conclusions
Role of magnetic fields in jet launching and emission

Formation of extragalactic jets from black hole accretion disk

Credit: NASA and Ann Field (Space Telescope Science Institute)
Role of magnetic fields in jet launching and emission

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Marscher et al. 2010
Open questions

1. What is the magnetic field structure near the base of the jet?
   • Helical as in simulations?
   • How to observe it?
   • Can we use observations to constrain the simulations?

2. What is the connection between magnetic fields and emission?
   • Is there a connection between magnetic fields and high-energy emission?
   • Can we use magnetic field observations to constrain the emission models?
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Polarization as a probe of magnetic fields

- Synchrotron emission is produced by relativistic electrons spiraling in a magnetic field
- Intrinsically highly polarized (70%) in a uniform magnetic field
- Can be expressed with 4 Stokes parameters, I, Q, U and V
  - In an optically thin (nonrelativistic) source, the EVPA is perpendicular to the magnetic field
- 3D polarization structure through Faraday rotation

Linear polarization fraction

\[ P = (Q^2 + U^2)^{1/2} \]
\[ m_c = \frac{P}{I}. \]

Electric Vector position angle (EVPA)

\[ \chi = \frac{1}{2} \arctan(U/Q) \]

Faraday Rotation

\[ \chi_{\text{obs}} = \chi_0 + 0.81 \int n_e B \cdot dl = \chi_0 + RM \lambda^2. \]
Is the magnetic field helical?

- Best evidence from Faraday rotation observations of 3C273
- Helical (or toroidal) field could show up as a gradient in the Faraday rotation measure
  - RM is positive when the field is towards the observer, negative when going away

\[ \text{EVPA}_{\text{obs}} = \text{EVPA}_{\text{em}} + \text{RM} \lambda^2 \]

VLBA observations at 8-15 GHz

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VLBA observations at 8-15 GHz

ALMA 1mm polarization observations probe the optically thin emission somewhere near the black hole

Torino, June 2018
talvikki.hovatta@utu.fi
3C273 with ALMA at 1mm

~ 60 kpc
3C273 with ALMA at 1mm
Polarization spectrum in the ALMA observations between 224-242 GHz

ArXiv: 1803:09982

Faraday Rotation measure
3.6 x 10^5 rad / m^2
Frequency-dependence of RM in 3C273

\[ RM \propto \nu^{1.9 \pm 0.2} \]

- Asada et al. 2002: RM \( \sim 350 \text{ rad/m}^2 \)
- Zavala & Taylor 2005: RM \( \sim 1000 \text{ rad/m}^2 \)
- Hada et al. 2016, Attridge et al. 2005: RM \( \sim 20000 \text{ rad/m}^2 \)
- Hovatta et al. in prep.

See also Wardle 2018

Savolainen in prep.

ALMA
Hovatta et al. 2018

Torino, June 2018
Frequency-dependence of RM in 3C273

\[ \text{RM} \propto \nu^{1.9 \pm 0.2} \]

See also Wardle 2018

Consistent with a conically expanding jet surrounded by a sheath

ALMA
Hovatta et al. 2018

Savolainen in prep.
Hada et al. 2016,
Attridge et al. 2005
RM \sim 20\,000\,\text{rad/m}^2

Hovatta et al. in prep.
Zavala & Taylor 2005
RM \sim 1000\,\text{rad/m}^2

Asada et al. 2002
RM \sim 350\,\text{rad/m}^2

RM \sim 100\,\text{rad/m}^2

RM \sim 1 \times 10^2\,\text{rad/m}^2

RM \sim 1 \times 10^3\,\text{rad/m}^2

RM \sim 1 \times 10^4\,\text{rad/m}^2

RM \sim 1 \times 10^5\,\text{rad/m}^2

RM \sim 1 \times 10^6\,\text{rad/m}^2

Frequency [GHz]
Two plausible models that explain the Q/U behavior and depolarization

Ordered external screen:
- Requires a rotation measure gradient $\Delta \text{RM}$ of
  $\sim 9 \times 10^5 \text{ rad/m}^2$

Turbulent external screen:
- Requires the Faraday dispersion of the RM screen to be
  $\sim 2.7 \times 10^5 \text{ rad/m}^2$

\[ P = p_1 \text{sinc}(\Delta \text{RM} \lambda^2) e^{2i(\Psi_0 + \text{RM} \lambda^2)} \]

\[ P = p_0 e^{-2\sigma_{\text{RM}}^2 \lambda^4} e^{2i(\Psi_0 + \text{RM} \lambda^2)} \]

Sokoloff et al. 1998, O’Sullivan et al. 2017
Comparison to jet formation simulations will allow us to connect observations and theory

- Magnetically arrested disk (large-scale magnetic field)
- Standard and Normal Evolution (no large-scale poloidal field needed)

Foucart et al. (2017)
Evidence for a longitudinal magnetic field in the sheath layer on pc scales

Poster by A. Pushkarev

**Fig. 2.** VLBA maps BL Lac at 15 GHz. Degree of polarization is depicted by color and overlaid with I contours (left panel). Stiks show EVPAs overlaid with P contours (right panel). The western jet edge shows a sheath of longitudinal magnetic field.

**Fig. 3.** 2D histogram of fractional polarization vs EVPA deviation from the local jet direction beyond 1.5 beam offset from the jet ridgeline. EVPA is predominantly transverse to the jet indicating a presence of a sheath of the longitudinal B-field.
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Fractional polarization as a function of SED peak

Hodge et al. 2018 (MOJAVE XVI) 15 GHz from MOJAVE

FSRQs occupy a similar region as LSP BL Lacs,

HSP sources seem to form their own low polarization tail both in radio and optical observations

Note the resemblance to the luminosity and speed plots in Lister’s talk on Monday!
In the optical band sources with higher synchrotron peak seem to have more stable EVPAs

**EVPA distribution as a function of SED peak in RoboPol sources**

Angelakis et al. 2016, 2017

Hovatta et al. 2016

TeV-emitting BL Lacs with preferred EVPA distribution

EVPA – jet PA

See also Angel et al. 1978, Jannuzi et al. 1994, Lister & Smith 2000, Jorstad et al. 2007
Connection between magnetic fields and high-energy emission

- In the optical band, the gamma-ray loud objects are seen to be more polarized
  - Perhaps a more ordered field, or connection to flaring?
- In the radio the connection is not as clear
  - Hovatta et al. 2010 showed higher polarization fraction in Fermi-detected sources
  - This trend is not seen in the analysis of Hodge et al. 2018 when 3FGL detections are used
  - Should be tested with gamma-ray luminosities
Polarization angle rotations are statistically always coincident with gamma-ray flares

Blinov et al. 2015

Blinov et al. 2015

Blinov et al. 2018

Blinov et al. 2016

Torino, June 2018
talvikki.hovatta@utu.fi
What models can explain the trends?

Angelakis et al. 2016

- Shock in a helical field
  - Lower polarization in HSPs because of a larger emitting volume
  - Preferred angle in HSPs due to the dominance of the toroidal / helical magnetic field component
  - Gamma-ray emission more likely to be produced when field is more compressed and particles accelerate to higher energies

Ghisellini et al. 2005

- Spine-sheath structures
  - Sheath with a helical (or toroidal) field dominates the radio / optical emission in HSP sources, resulting in a preferred EVPA
  - Consistent with slow HBL speeds (see Piner & Edwards 2018 for a model description)
Conclusions

• ALMA has opened a new window for studying Faraday rotation at the base of blazar jets
  • A very high RM of ~4x10^5 rad/m^2 is seen in 3C273
  • Consistent with a sheath surrounding a conically expanding flow

• Statistical studies of polarization in the jets in both radio and optical bands reveal trends as a function of SED peak and class
  • HSP BL Lacs show more often a preferred EVPA parallel to the direction of the jet position angle
    • toroidal field component? Dominance of a sheath layer?

• Optical polarization fraction and EVPA rotations seem to be connected to gamma-ray flaring
  • Connection to particle acceleration mechanism?
Monitoring the Non-Thermal Universe

Workshop: Towards a global multi-wavelength network

Networking

From...

- theory to TeV
- radio to relativity
- polarization to periodicity

Synergy of energy and time lapse without gaps
Maximizing physics insights from multi-frequency monitoring

September 18 - 21, 2018
at Cochem, Germany

Local Organisation:
Thomas Bretz, Daniela Dorner

Program Committee:
Thomas Bretz (RWTH Aachen University)
Daniela Dorner (Univ. Würzburg)
Talvikki Hovatta (Aalto University)
Azadeh Keivani (PennState Univ.)
Stefan Wagner (LSW Heidelberg)
Michael Zacharias (North-West Univ. Potchefstroom)

Contact: hap-monitor@lists.rwth-aachen.de
http://indico.scc.kit.edu/indico/e/Monitoring-2018

Supported by the city of Cochem
backup slides
Wider frequency coverage will help as the expected depolarization signal is very different.