Observational Signatures of Large Scale Magnetic Fields in Parsec Scale AGN Jets.

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Polarization and EVPA orientation can be explained by:

- Shocks/shearing
- Helical B-Fields

BL Lac object 1749+701

Lyutikov et al 2005
Gabuzda et al. 2001

Meier et al 2001
Outline

• Helical Fields imprint themselves on synchrotron radiation by producing asymmetries in:
  
  – Intensity
  
  
  – Polarization
  
  – Spectral Index?
  
  – Rotation Measure

• Correlations between the above observables are then expected
Asymmetry of Helical Magnetic Field

- jet assumed to be cylinder
- We assume jet opening angle is smaller than typical viewing angle
- Only in calculating spectral index does core distance matter

\[
\text{observable} = \int_{0}^{S} f(B, n, \Gamma, K, p) ds
\]

\[
dn = K e^{-p} d\gamma
\]
Structure of Jet

Magnetic field:

\[ \mathbf{j} \times \mathbf{B} = 0 \]

\[ B_\phi = B_0 J_1(k\rho) \]

\[ B_z = B_0 J_0(k\rho) \]

(e.g. Choudhuri et al. 1986)

Pitch angle varies with cylindrical radius:

Relativistic particle density:

- Realistic Gaussian profile gives qualitatively identical results to constant profile
Intensity: Theory

\[ I \propto \int_0^S (B'(s) \sin \chi'(s))^{(p+1)/2} \, ds \]

Note that:

- Peaks are off center (undetectable)
- Profiles are skewed (detectable)
Intensity: Observations

**symmetric:**
Parsec scale cut of 3C 78

**skewed:**
Parsec scale cut of NRAO 140

Clausen-Brown et al. (in prep)
Linear Polarization: Theory (unconvolved)

\[ Q'_{\text{int}} \propto \int_{0}^{S'} \left( B \sin \chi' \right)^{(p+1)/2} \cos 2 (\tilde{\chi} - \Delta \chi_F(s')) ds' \]

\[ U'_{\text{int}} \propto \int_{0}^{S'} \left( B \sin \chi' \right)^{(p+1)/2} \sin 2 (\tilde{\chi} - \Delta \chi_F(s')) ds' \]

\[ \Pi = \frac{\sqrt{Q^2 + U^2}}{I} \]

• For cylindrical jets, U=0

• Bump corresponds to an EVPA parallel to the jet axis

• Outer wings correspond to EVPA perpendicular to jet axis

• Bump is not a robust result (depends on B-field config., viewing angle, etc)

• For now, no Faraday depolarization included.
Polarization: Observations

- Error increases towards the edge of the jet
- Sharp features are suspect considering beamwidth
Polarization: Observations

- Error increases towards the edge of the jet.
- Sharp features are suspect considering the beamwidth.

Parsec scale cut of 3C 78: location 2
Polarization: Theory (convolved)

Calculation details:

- Jet width $\sim 4$ beamwidths (FWHM).
- Stokes I, Q, U each separately convolved with beam.

Results:

- Polarization lower on one side than the other
- Characteristic bump difficult to obtain for some beamsizes and other uncertainties: B-field profile and n(relativistic)
Spectral Index Gradients, \( F_\nu \propto \nu^{-\alpha} \)

- Optical depth depends on angle between B-field and LoS
- Left side of jet is thinner than right side

\[ \kappa \propto \left| \sin \chi' \right|^{(p+2)/2} \]

In the \( \tau \sim 1 \) region:
  - left side has optically thin index
  - right side has optically thick spectrum

Alternative scenario:
  - asymmetric electron distribution function (see e.g. Lloyd & Petrosian 2000)
Spectral Index Gradients

Expected result depends on core radius:

- Symmetric core → spectral index gradient (\(\tau \sim 1\) region) → symmetric optically thin region

Calculations:

- To show transitions we add the following scaling to the absorption coefficient and the emission function:

\[
\kappa \propto z^{-(p+6)/2} \\
j \propto z^{-(p+5)/2}
\]

- Derived from typical conical jet scalings (\(B \sim 1/z, \rho \sim 1/z^2\))

- Numerically solved polarization transfer equations for Stokes parameters using polarized absorption and emission coefficients.
Spectral index gradient: theory vs. observation

- Theoretical scenario (thick $\rightarrow$ asymmetry $\rightarrow$ thin) consistent with BL Lac 0954+658, but not 3C 78.

O'Sullivan & Gabuzda 2009
Rotation Measure

\[
\Delta \tilde{\chi} = \frac{16\pi^3 e^3}{m_e^2 c^4} \chi'^2 \int n'_T B'_\parallel ds'
\]

\[ n_T \propto \rho^6 \exp(-\rho^2) \]

- Shape of RM profile (linear-ish or bendy) depends on thermal plasma density profile.

Left: Clausen-Brown et al
Right: O’Sullivan & Gabuzda 2009
Correlations

If:

- $n'_\parallel B'$
- $\sin\chi' \sim 0$

Then:

- Intensity profile has long tail on left.
- Sharper gradient to left.
- Polarization lower on left.

Caveat: Intensity/Polarization applies in optically thin case. Can’t compare with spectral index gradients in the same cut.

Closer to optically thin spectrum on left.
Correlations: inconsistent with helical fields for 3C 78

- Symmetric
- Lower polarization on left side
- Optically thin on right side further down the jet
Correlations: consistent with helical fields for Mrk 501

Positively skewed

Lower Polarization on right side
Correlations and RM

- RM gradient direction gives information polarity of B
- Which side has a greater $|RM|$ gives direction on which side is $B$ \parallel n$.

Higher $|RM|$ on right $\rightarrow$ $B$ \parallel n on right side
Conclusions

• Correlations between intensity, polarization, and sometimes spectral index allow us to infer:
  – the presence of helical fields
  – Which side of the jet has $B \parallel n$

• RM profile reveals how sheath B-field is correlated with jet B-field.

• Future work: Statistics from MOJAVE.
REFERENCES

• Meier D. L., Koide S., Uchida Y., 2001, Science, 291, 84
B is parallel to Line of Sight on left side of jet = $B_{\text{para Left}}$.

$B$ is parallel to Line of Sight on right side of jet = $B_{\text{para Right}}$.

<table>
<thead>
<tr>
<th></th>
<th>Left side of jet</th>
<th>Right side of jet</th>
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<tbody>
<tr>
<td>Polarization is lower on</td>
<td>$B_{\text{para Left}}$</td>
<td>$B_{\text{para Right}}$</td>
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<tr>
<td>(Gradient is steeper on</td>
<td></td>
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<tr>
<td>____). Bump (if it exists) is on the ______</td>
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<tr>
<td>Intensity profile is</td>
<td>$B_{\text{para Left}}$</td>
<td>$B_{\text{para Right}}$</td>
</tr>
<tr>
<td>longer on the ______</td>
<td></td>
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<tr>
<td>Closer to steep spectrum on the ______</td>
<td>$B_{\text{para Left}}$</td>
<td>$B_{\text{para Right}}$</td>
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$n_T \propto \rho^2 \exp\left(-\rho^2\right)$
Figure 1 With internal Faraday rotation