Pc-scale rotation measures across radio galaxy jets

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Faraday Rotation

Rotation of the plane of polarization of an electromagnetic wave as it traverses through a magnetoionic medium

$$\text{RM} \propto \int n_e B_{\parallel} \, dl$$

Rotation measures on pc-scales obtained by polarization-sensitive Very Long Baseline Interferometry (VLBI).

Typically Doppler-beamed radio-loud AGNs, i.e., Quasars & BL Lacs observed.


Very few radio galaxies looked at – pc-scale polarization detected in only a handful.

Only the FRI galaxy - M87 & the FRII galaxies - 3C111, 3C120 & 3C166, have pc-scale RM estimates.
New Observations of 3 FRIs

Three nearby FRI radio galaxies – 3C66B, 3C78 & 3C264.

10 antennas of the Very Long Baseline Array (VLBA) & 100-m Effelsberg antenna at 5.0, 8.4 & 15.3 GHz, in September 2005.

3C66B - elliptical galaxy ~91 Mpc away - part of dumbbell galaxy pair close to Abell cluster 347.

3C78 – small E/S0 galaxy ~124 Mpc away – relatively isolated.

3C264 – S0 galaxy ~93 Mpc away – lies in dense part of the Abell cluster 1367.

Scale: 1 mas ~ 0.5 pc
Results

3C66B

3C78

3C264

5.0 GHz

8.4 GHz

15.3 GHz
Results: 3C264

In 3C264, RM b/w 5 & 8 GHz - subject to $\pm n\pi$ ambiguities that cannot be resolved. RM varies from $\sim +250$ to -300 rad/m$^2$.

Degree of polarization increases along one edge of the jet.

After the effects of RM removed, the magnetic field is aligned with the jet direction.


RM non-uniform on pc-scales - major contribution not from our Galaxy or host galaxy but intrinsic to the AGN.
Results: 3C78

Pc-scale RM across the jet ranges from +200 to -400 rad/m$^2$ ($\sigma_{\text{RM}} \sim 50$ rad/m$^2$).

Transverse RM gradient across jet > 300 rad/m$^2$ over ~5 mas (~3 pc, ~2 beams)

Polarization angle rotates by ~90° – thermal electrons not completely mixed in with the synchrotron emitting electrons but external (Burn B., 1966, MNRAS)

Degree of polarization increases along jet edge. After removing effects of RM, inner jet B-field aligned with jet direction.

Depolarization parameter = $DP = m_l/m_h$

Mean $DP$ in inner jet: b/w 5-8 GHz = $0.98 \pm 0.11$; b/w 8-15 GHz = $0.79 \pm 0.15$

$DP \approx 1$ implies that there is little depolarization at longer wavelengths.
Faraday Rotating Medium

RM gradient and the increase in the degree of polarization along the jet edge supports the presence of a helical magnetic field.  

\[ (\text{Blandford R., 1993, Astrophysical Jets}) \]

Polarization could also increase at jet edges due to shear.

Transverse RM gradients in jet also observed in FRIIs – 3C166 & 3C120


Gas in the Broad-line region < 1 pc; Gas in the Narrow-line region can extend to 100 pc and have large covering factors ~30% - 50% - could in principle contribute to the RM.

Transverse RM gradient, increase in degree of polarization at jet edge, large rotation in polarization angles & low value of depolarization supports the idea of a thin layer or “sheath” surrounding the jet w/ a sufficient number of thermal electrons mixed in with synchrotron emitting electrons & a helical magnetic field threading it, as the Faraday rotating medium.
**Spine-sheath structure & Helical B-fields**

*Hubble Space Telescope* imaging polarimetry by Perlman E. et al. (2006)

Magnetic field geometry in 3C78 & 3C264 suggests a “Spine-sheath” structure 
(e.g., *Laing R. 1996, ASPC, 100*)

Scale: 3C66B – 440 pc/arcsec  
Red > 30% polarization

3C78 – 600 pc/arcsec  
Red > 40% polarization

3C264 – 440 pc/arcsec  
Red > 45% polarization

“The spine-sheath” B-field structure could arise due to shear and/or a helical magnetic field 
(e.g., *Lyutikov M. et al., 2005, MNRAS*)

The fact that we see aligned magnetic fields after RM effects removed, is consistent with a “spine-sheath” jet structure, with a tightly wound helical B-field in the sheath, and a loosely wound helical B-field in the spine.  
Summary

◆ 3 nearby FRI radio galaxies – 3C66B, 3C78 & 3C264 – observed with VLBI polarimetry at 5, 8 & 15 GHz. Polarized emission detected in all of them.

◆ Rotation Measure using all 3 frequencies was obtained only for 3C78. In 3C78, the pc-scale RM across the jet ranges from +200 to -400 rad/m².

◆ RM gradient is observed across the jet in 3C78 in a region ~2 beamwidths across.

◆ The degree of polarization increases along the jet edge in both 3C78 & 3C264, consistent with shear and/or a helical jet magnetic field.

◆ The polarization angles rotate by ~90° b/w the 3 frequencies. Mean DP close to unity in the jet, suggesting low depolarization at longer wavelengths.

◆ Support the idea of the Faraday rotating medium being a sheath around the jet with sufficient thermal electrons mixed in with the synchrotron electrons and a helical magnetic field threading it.

◆ After correcting for the RM, the B-field in 3C78 and 3C264 seems to be aligned with the inner jet direction. This would be consistent with the helical B-field being tightly wound in the sheath, but loosely wound in the spine of the jet.

◆ Need to observe more radio galaxies at multiple frequencies.