

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.

RM across the pc-scale jets lie in the range of 100-500 rad/m²

(e.g., Zavala R. & Taylor G., 2003, 2004, *ApJ*)

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.

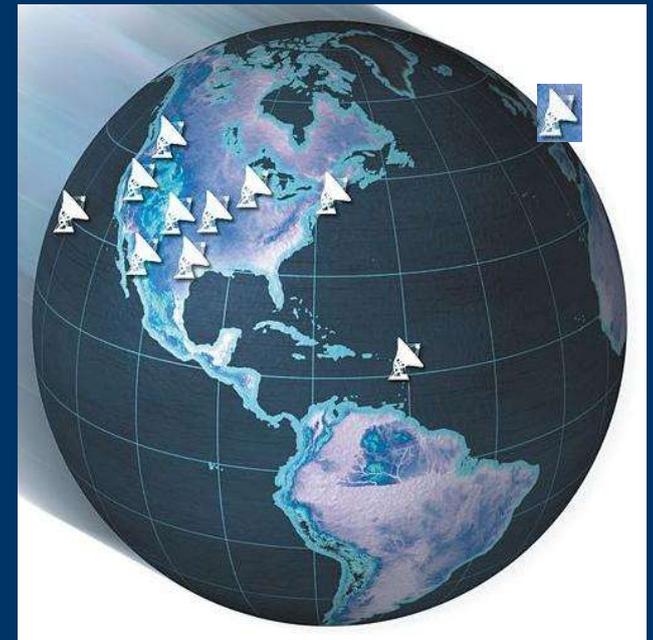
10 antennas of the Very Long Baseline Array (VLBA) & 100-m Effelsberg antenna at 5.0, 8.4 & 15.3 GHz, in September 2005.

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.

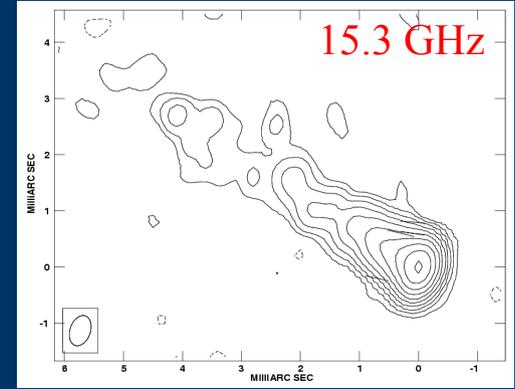
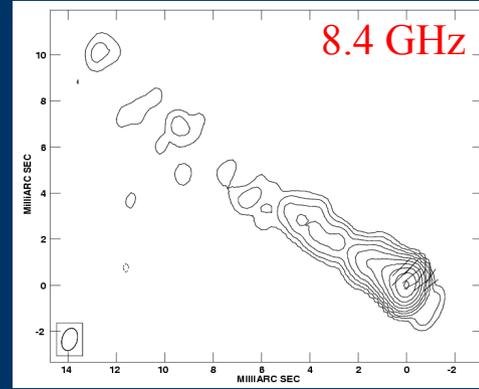
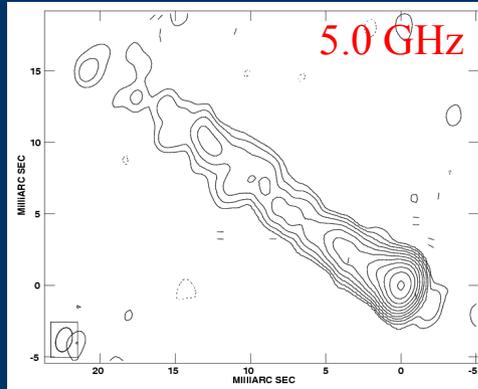
3C264 – S0 galaxy ~93 Mpc away – lies in dense part of the Abell cluster 1367.

Scale: 1 mas ~ 0.5 pc

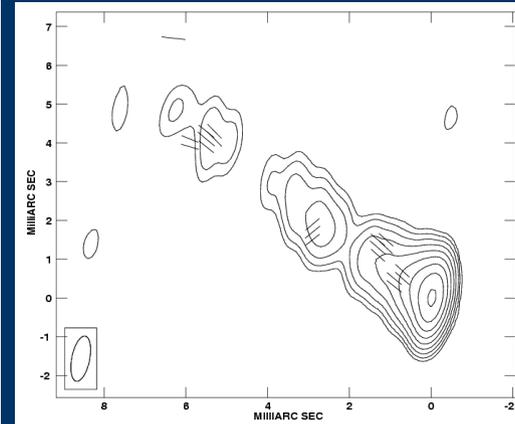
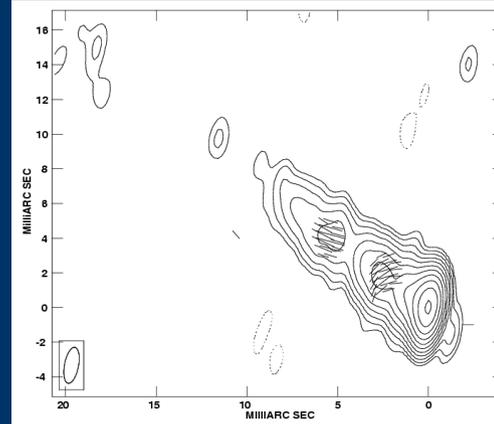
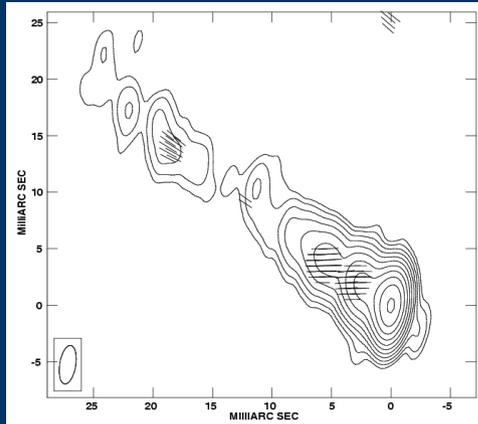


Results

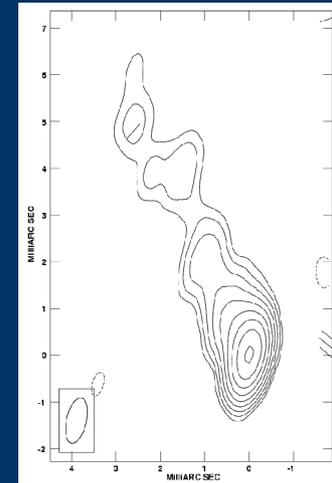
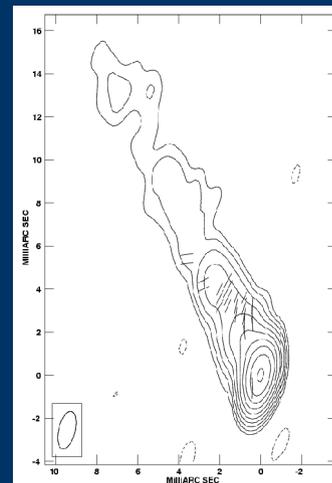
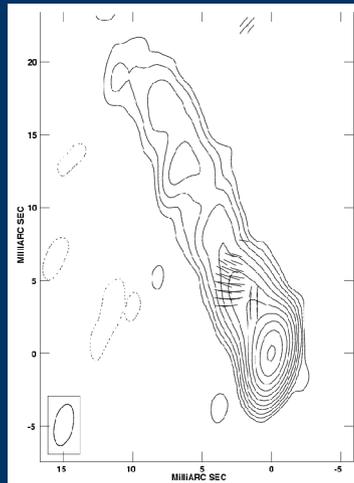
3C66B



3C78



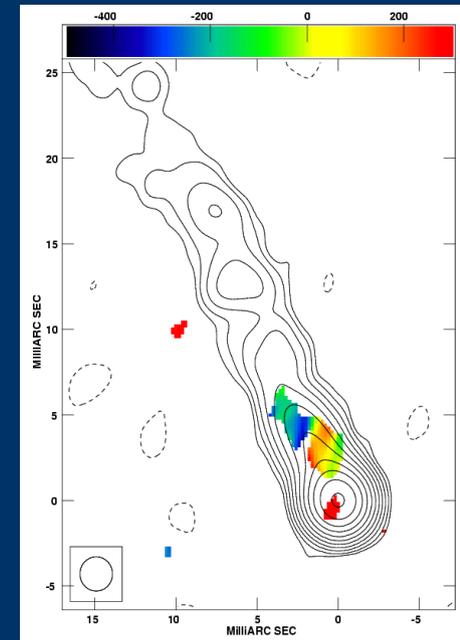
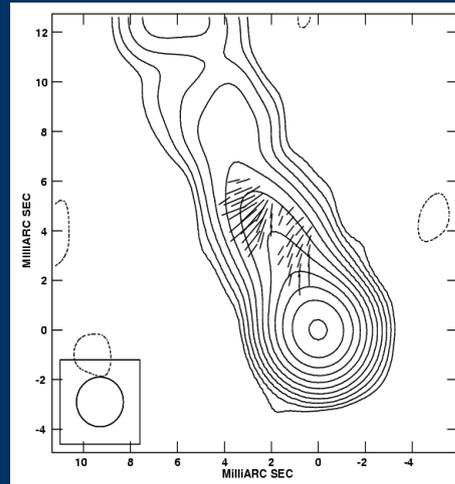
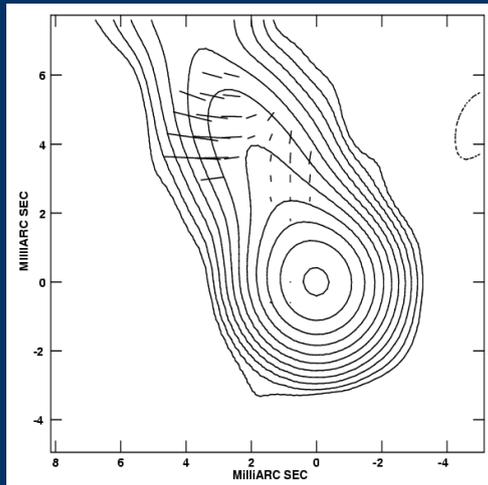
3C264



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/m²

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.

The FR II radio galaxies – 3C111, 3C120 & 3C166 – have pc-scale jet RMs varying from $+100$ to -750 rad/m² (Zavala R. & Taylor G., 2002, *ApJ Letter*; Taylor G. et al., 2001, *ApJ*)

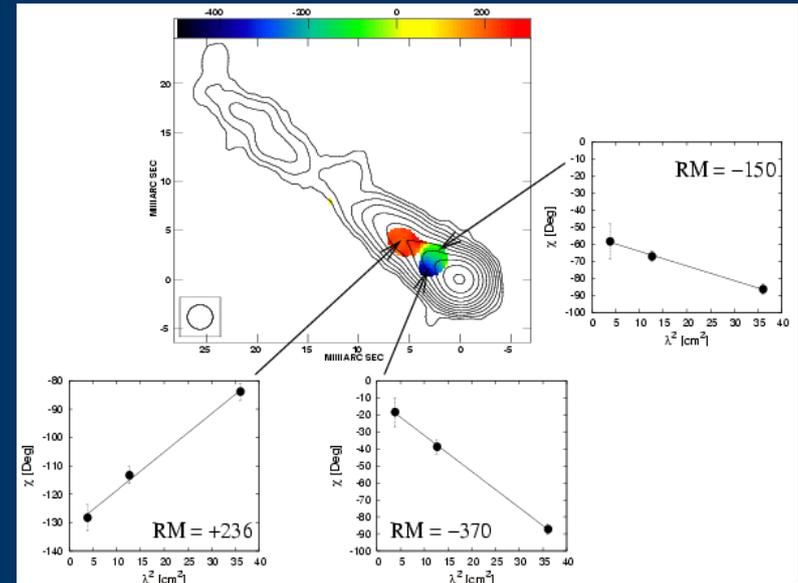
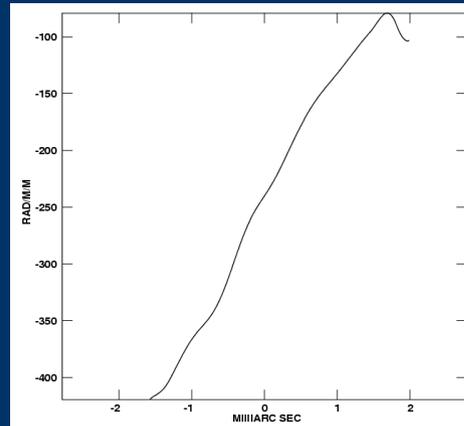
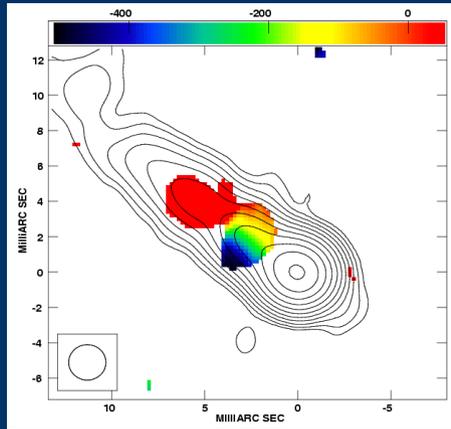
Recent observations of 3C120 indicate jet RM of a few 1000 rad/m² (Gomez et al. 2008, ApJ Letter in press)

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

Results: 3C78

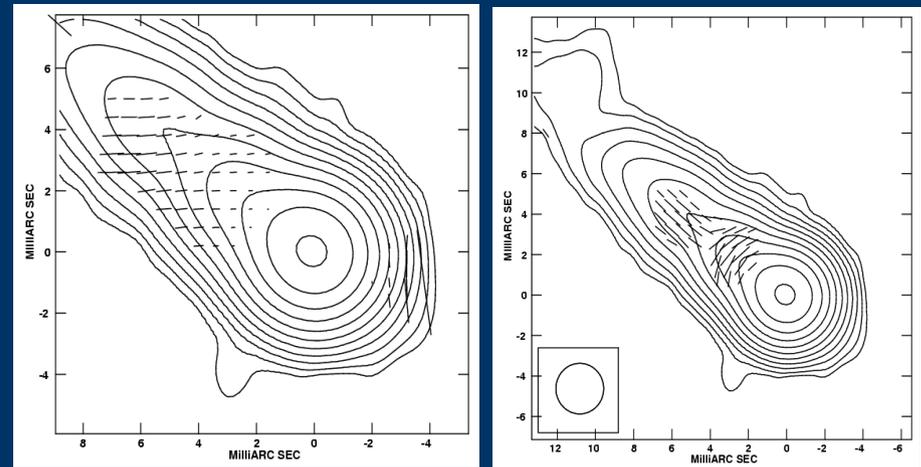
Pc-scale RM across the jet ranges from +200 to -400 rad/m² ($\sigma_{\text{RM}} \sim 50 \text{ rad/m}^2$)

Transverse RM gradient across jet > 300 rad/m² over ~5 mas (~3 pc, ~2 beams)



Polarization angle rotates by $\sim 90^\circ$ – 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.



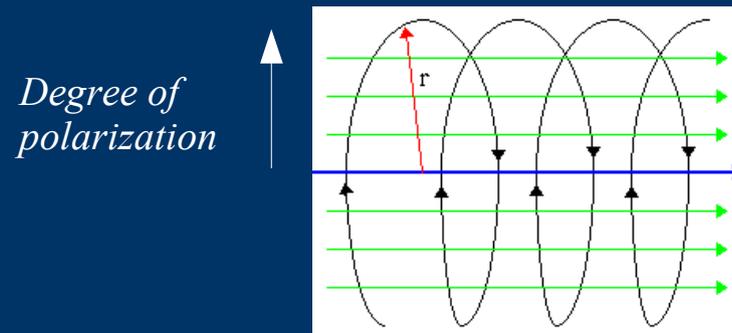
Depolarization parameter = $DP = m_l/m_h$

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

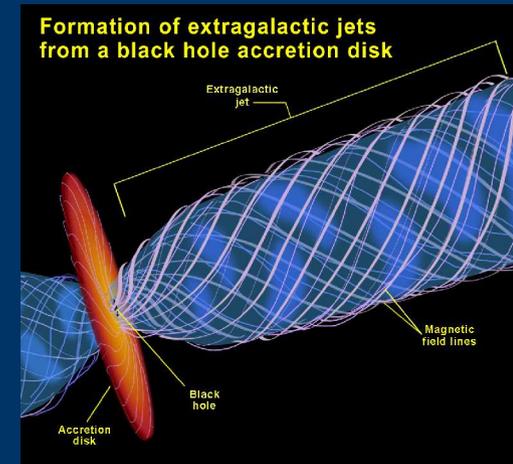
DP~1 implies that there is little depolarization at longer wavelengths.

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. *(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

(Taylor G. et al., 2001, ApJ; Gomez J. et al., 2008, ApJL in press)

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

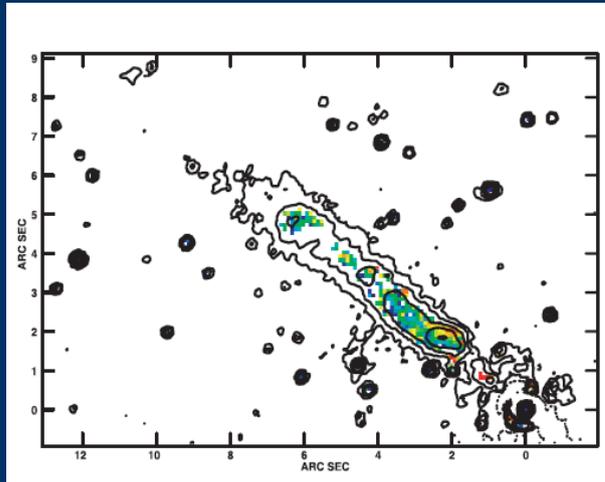
Transverse RM gradient, increase in degree of polarization at jet edge, large rotation in polarization angles & low value of depolarization supports the idea of a thin layer or “sheath” surrounding the jet w/ a sufficient number of thermal electrons mixed in with synchrotron emitting electrons & a helical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

Spine-sheath structure & Helical B-fields

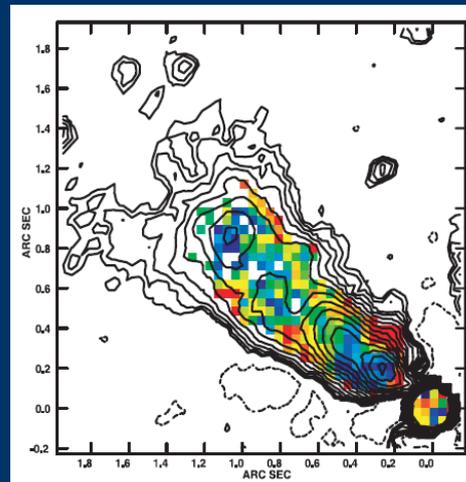
Hubble Space Telescope imaging polarimetry by Perlman E. et al. (2006)

Magnetic field geometry in 3C78 & 3C264 suggests a “Spine-sheath” structure

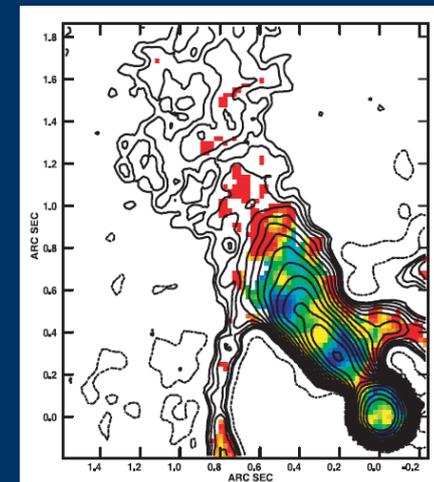
(e.g., Laing R. 1996, *ASPC*, 100)



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



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



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

“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.

(*NRAO140*, Asada K. et al. 2008, *ApJ in press*)

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.
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