Keeping an Open Mind about Possible Connections between Radio Phenomena and the High-Energy Emission of AGN

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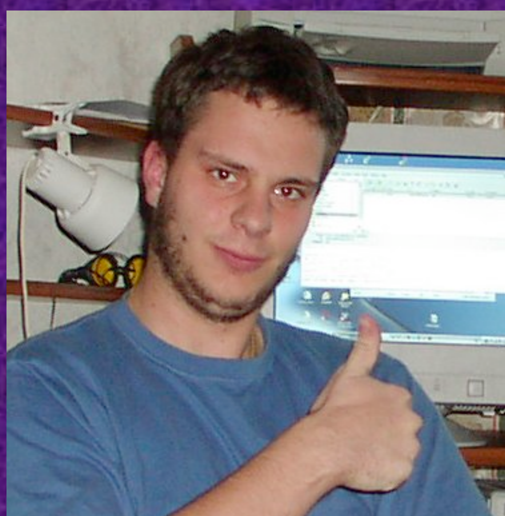

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Mehreen Mahmud (UCC)

Shane O'Sullivan (UCC)

Focus of talk – two intrinsically low-frequency phenomena:

- Faraday rotation of the plane of linear polarisation
- Faraday conversion of linear to circular polarisation

•Circular polarisation (CP) of synchrotron radiation – very low (less than 0.1%) for B fields thought to be typical (~100 μG)

First measurements on parsec scales – Homan & Wardle (1999); Homan, Attridge & Wardle (2001)

MOJAVE* CP Measurements (Homan & Lister 2006)

– 34 of 133 objects had detectable CP at 15 GHz (2 cm), mostly levels of few tenths of a %, mostly in VLBI core

– Homan & Lister (2006) searched for correlations between degree of CP and more than 20 parameters – virtually no evidence for any correlations

*(MOJAVE – Monitoring of Jets in AGN with VLBA Experiments)

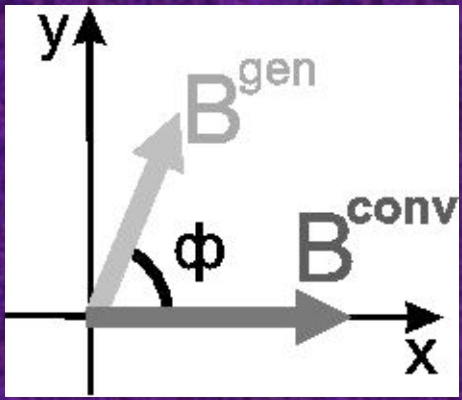
Prime suspect for mechanism generating CP: Faraday conversion of LP to CP when EM wave travels through magnetised plasma.

Charges can move only *along* B in conversion region: component of polarisation E field parallel to B is absorbed & re-emitted by free charges, but component perpendicular to B is not → delay of "E parallel" relative to "E perpendicular"

⇒ Manifest as introduction of small amount of CP

Angle between plane of LP (E) and conversion B field determines sign of CP produced.

If optically thin background region with field B_{gen} emits synchrotron radiation with $E \perp B_{gen}$, and foreground region with field B_{conv} converts some of incident LP to CP, can formulate problem in terms of angle φ between B_{gen} and B_{conv}:

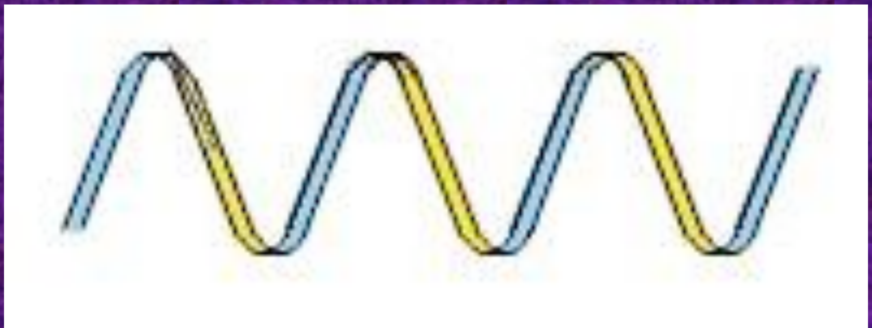


It is essentially the angle φ between B_{gen} and B_{conv} that determines the sign of the CP:

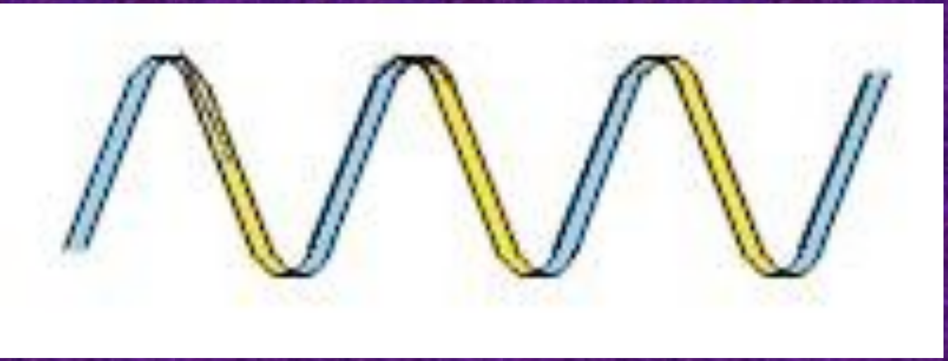
$0 < \varphi < 90 \rightarrow -$ $90 < \varphi < 180 \rightarrow +$

$180 < \varphi < 270 \rightarrow -$ $270 < \varphi < 360 \rightarrow +$

Helical B-field geometry can facilitate conversion – LP emitted at “back” of helix is converted to CP as it passes through “front” of helix.



Angle between background and foreground B fields is determined by (1) pitch angle and (2) helicity of the helical field.



For pitch angle ψ (angle between axis and direction of B):

$0 < \psi < 45 \rightarrow$ – CP for right-handed helix ($0 < \varphi < 90$)

+ CP for left-handed helix ($270 < \varphi < 360$)

$45 < \psi < 90 \rightarrow$ + CP for right-handed helix ($90 < \varphi < 180$)

– CP for left-handed helix ($180 < \varphi < 270$)

If we can determine rough pitch angle and helicity for jets believed to have helical fields, can predict sign of CP – and in certain cases, we can:

1) Pitch angle – from observed LP structure (small pitch angle ⇒ dominant B field along jet, large pitch angle ⇒ dominant B field orthogonal to jet)
2) Helicity – from Faraday-rotation gradient across jet

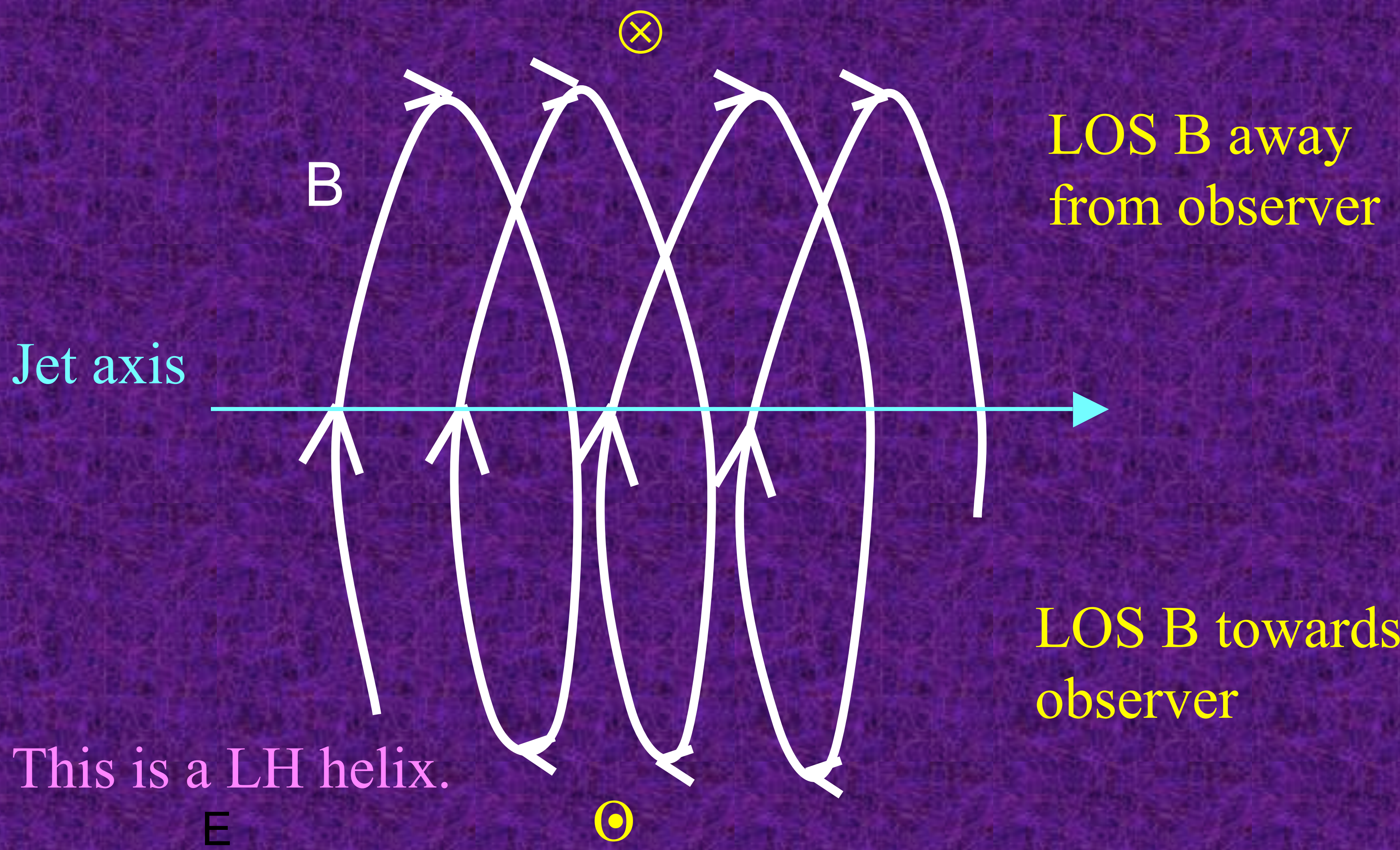
Faraday rotation – rotation of the observed plane of LP when polarised EM wave passes through a magnetised plasma, due to different propagation velocities of the RCP and LCP components of the EM wave in the plasma.

The amount of rotation is proportional to the square of the observing wavelength, and the sign of the rotation is determined by the direction of the line of sight B field:

$$\chi = \chi_o + RM\,\lambda^2$$

$$RM = (\text{constants}) \int n_e\, \mathbf{B} \cdot d\mathbf{l}$$

If jet has a helical B field, observe Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet.



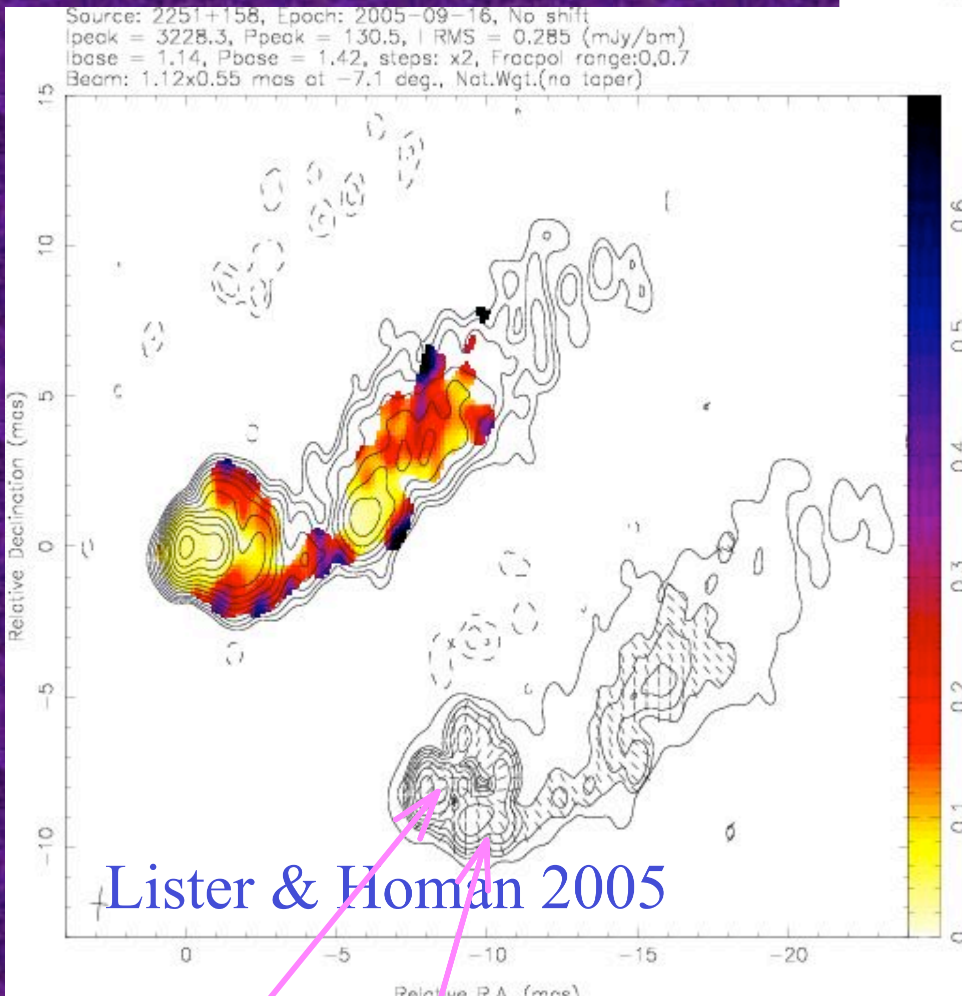
Of the 36 AGN with detected parsec-scale CP at 2 cm (Homan & Wardle 1999, Homan & Lister 2006, Vitrishchak & Gabuzda 2007), we have identified 8 with Faraday-rotation gradients across their jets (Asada et al. 2002; Taylor 1998, 2000; Zavala & Taylor 2003; Gabuzda et al. 2007) and reasonably clear linear polarisation structure:

Observed linear polarisation structure ⇒ pitch-angle regime

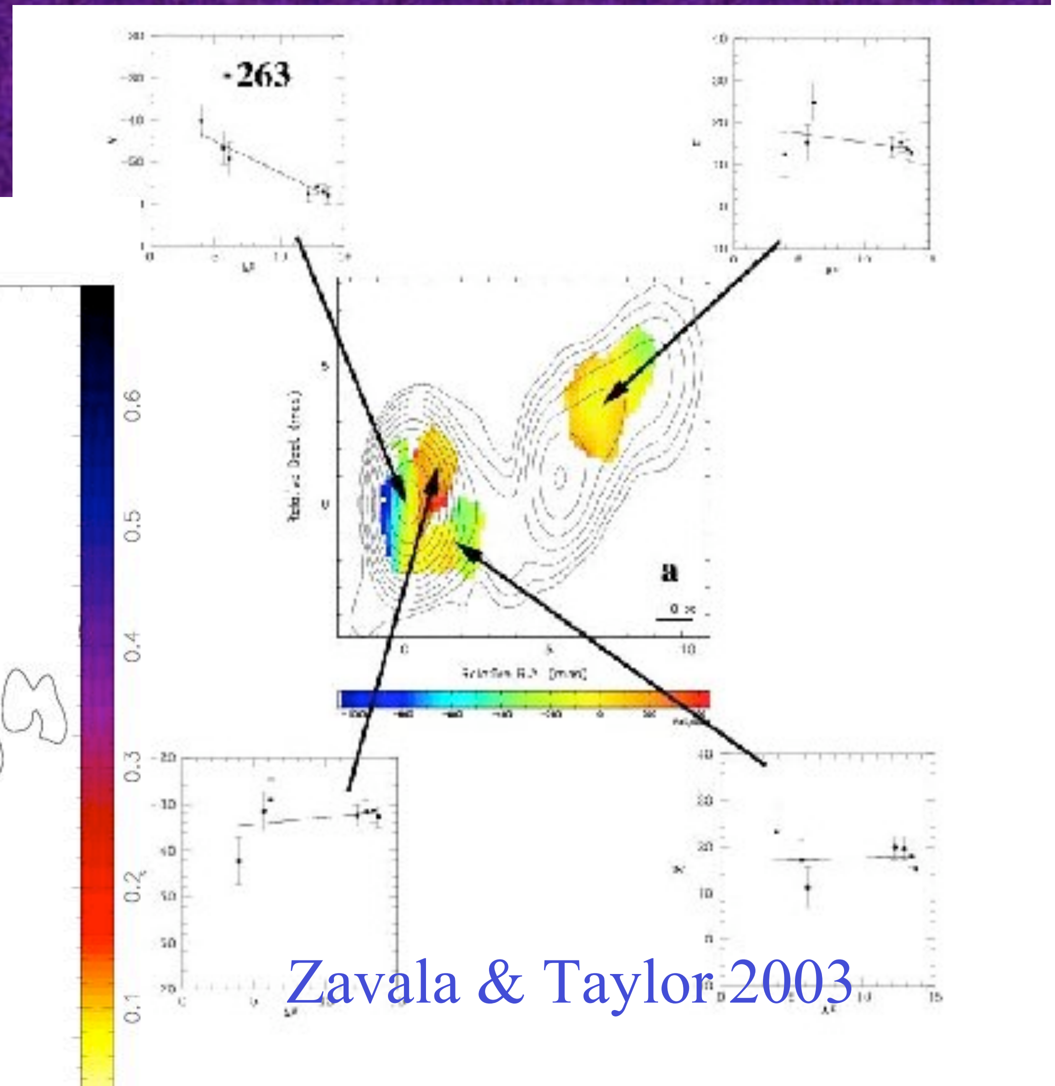
Direction of Faraday-rotation gradient ⇒ helicity.

Right-handed helical B field

2251+158



Lister & Homan 2005



Zavala & Taylor 2003

FR gradient across jet

“Spine+sheath” (⊥) B field

AGN	Jet B field	Pitch angle	Helicity	Predicted CP sign	Observed CP (%)	Match?
0735+178	⊥	Large	Left	–	– 0.30	Y
1156+295	⊥/SS	Large	Left	–	– 0.27	Y
3C273	||	Small	Right	–	– 0.45	Y
3C279	⊥	Large	Left	+	+ 0.30	Y
3C345	||	Small	Left	+	+ 0.17	Y
1749+096	⊥	Large	Left	–	– 0.42	Y
2230+114	||	Small	Right	–	– 0.48	Y
2251+158	⊥/SS	Large	Right	+	+ 0.23	Y

Predictions are correct in 8 of 8 cases!

Probability of this happening by "luck" is ~ 0.4% (according to binomial probability distribution).

Moral of this story:

There is now direct evidence that the CP of AGN is intrinsically linked to presence of helical jet B fields; variations in magnitude and sign of CP may reflect variations in configuration of associated helical fields.

Correlations between γ-ray and CP variations would imply direct connection between properties of γ-ray radiation and helical B-field structure.

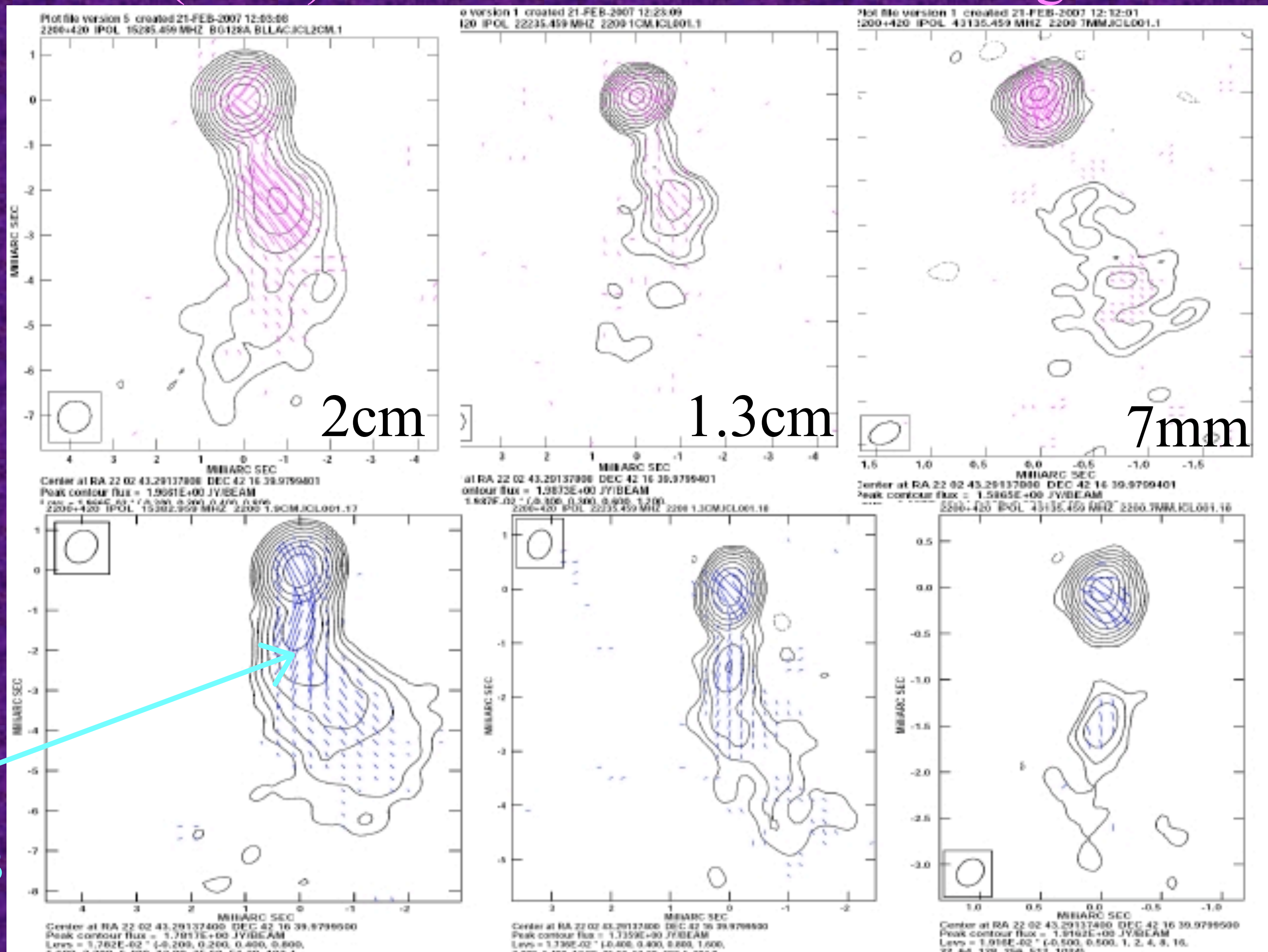
Faraday rotation measures of VLBI "cores" long known to be variable in magnitude (e.g., Taylor 2000).

We have found several cases where core RM is also variable in sign – we are now investigating this behaviour using VLBA observations of several AGN at 0.7+1.3+1.9+2.3+3.4+3.8+5.9+6.5cm (O'Sullivan & Gabuzda 2007, in prep).

Example – BL Lac: observations of Reynolds, Cawthorne & Gabuzda (2001) and Zavala & Taylor (2003) showed core RM of + a few hundred rad/m^2, while those of Gabuzda et al. (2006) and [Mutel & Denn] showed core RM of – a few thousand rad/m^2 .

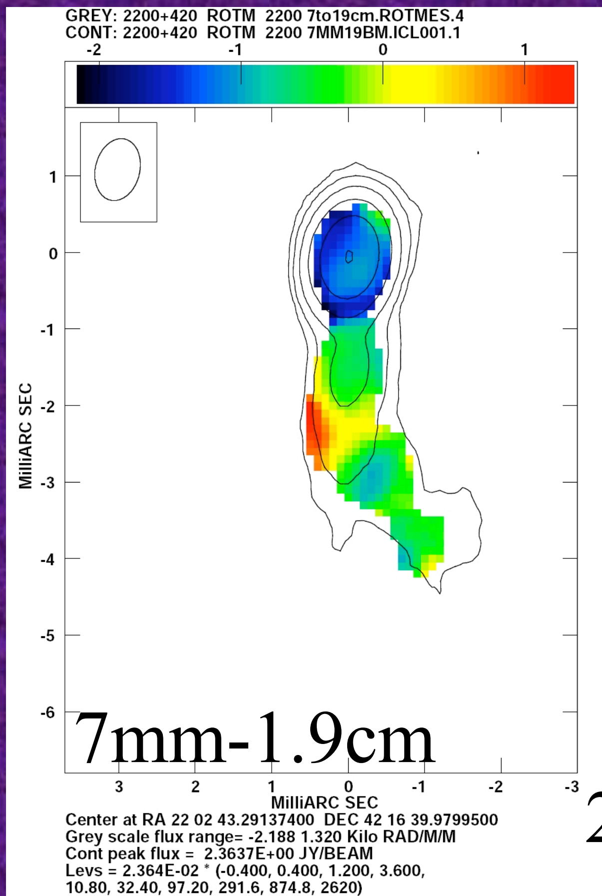
Gabuzda et al. (2006) – March 2004 – core RM large and +

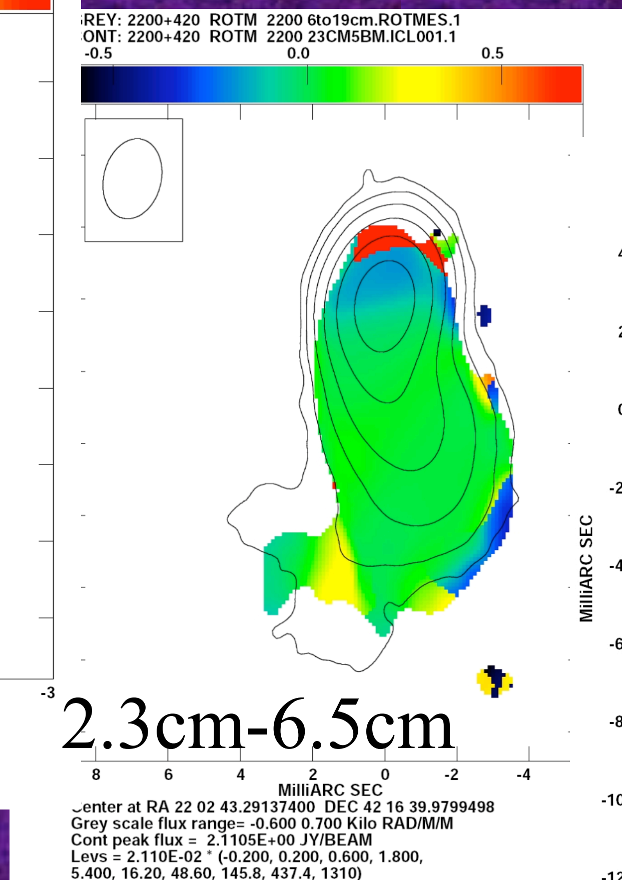
Note how well pol vectors track jet – natural if they represent toroidal component of helical B field!

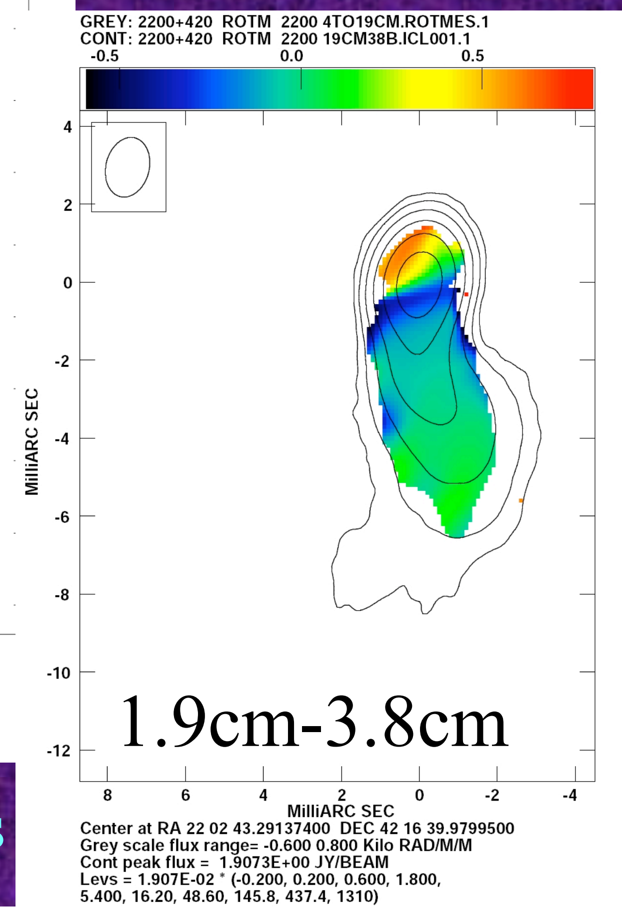


O'Sullivan & Gabuzda, in prep, July 2006 – core RM modest and —

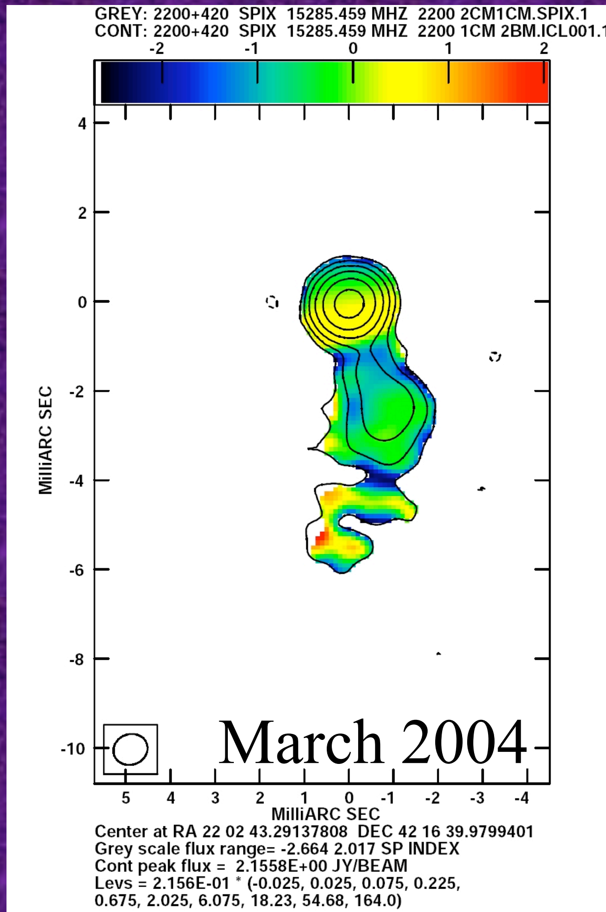
Results of new obs – both high- and low-frequency “core” clearly show negative RM, but region of positive RM also visible in northern core region

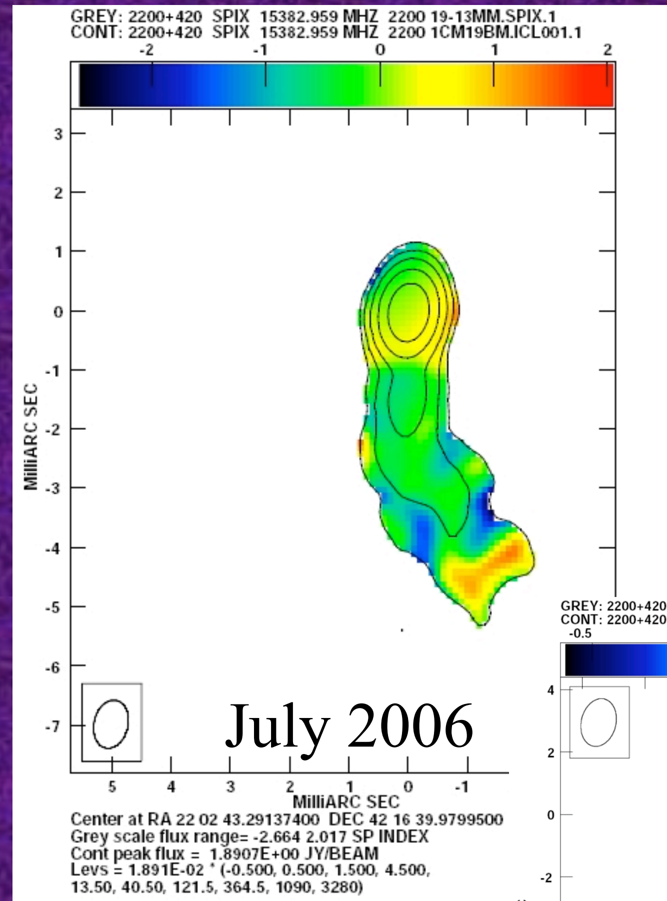


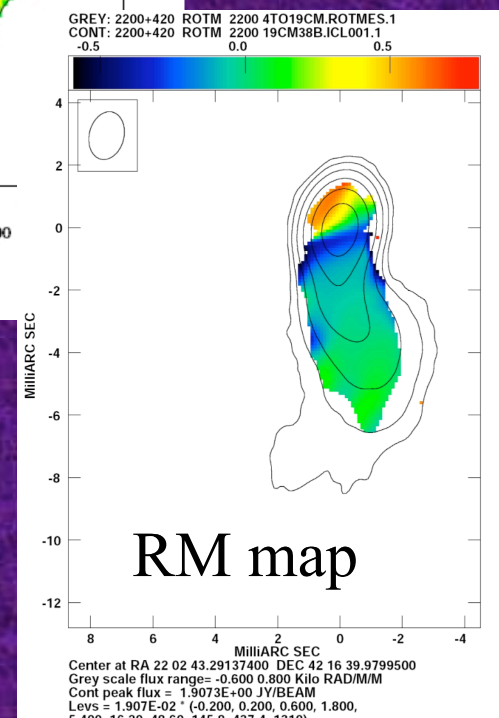




RM maps each based on 3–4 wavelengths







RM structure in core region has counterpart in spectral-index distribution – northern region with +RM has less flat spectral index

Moral of this story:

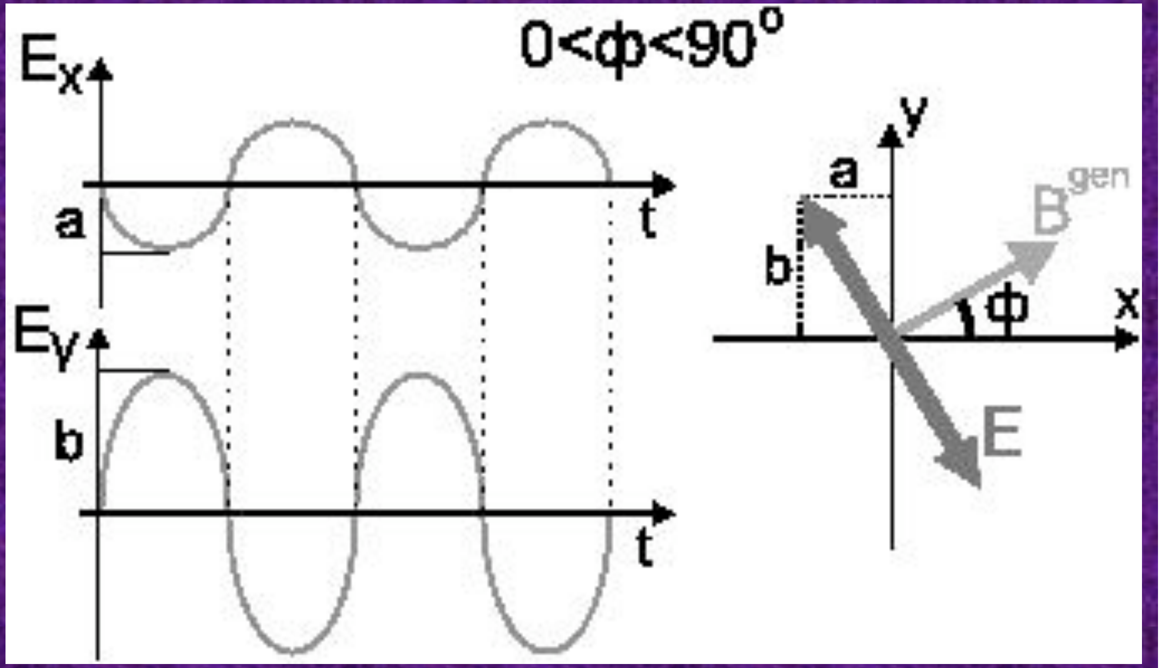
Large observed changes in the core properties, such as Faraday rotation measure, may be due to changing relative contributions of distinct sub-regions within the observed “core”.

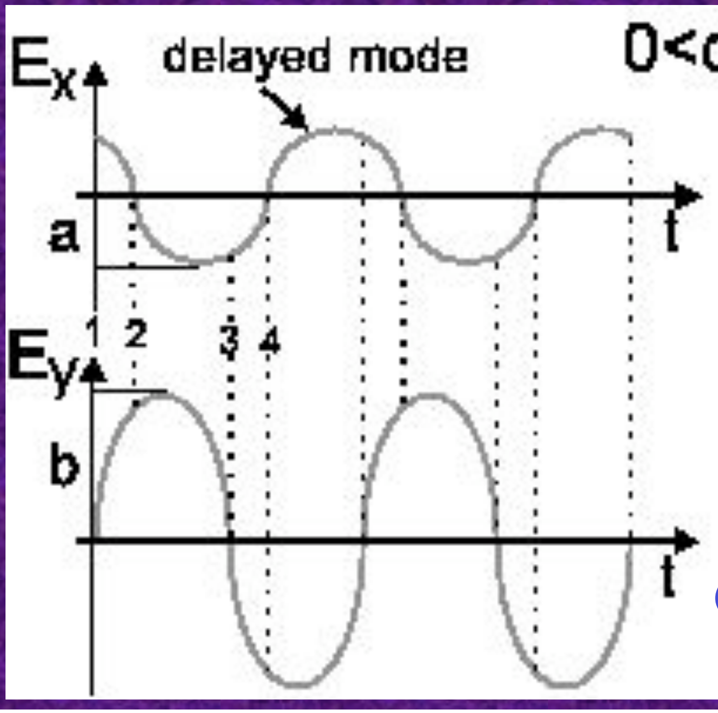
By looking for characteristic “core” state during γ-ray active/quiescent states, may be able to infer a particular core “sub-region” which is associated with the γ-ray emission. Core LP, CP or RM (both magnitude & sign) may play key roles in distinguishing between variations of B, n_e within a single core sub-region or variations in relative strengths of two or more sub-regions.

Joint VLBI–GLAST studies hold great promise – and should include "long-wavelength" effects such as Faraday rotation and Faraday conversion!

B_{conv} along +x direction, $E \perp B_{gen}$

Angle between B fields → relative phase between two E field components → direction of rotation of tip of E vector → sign of CP

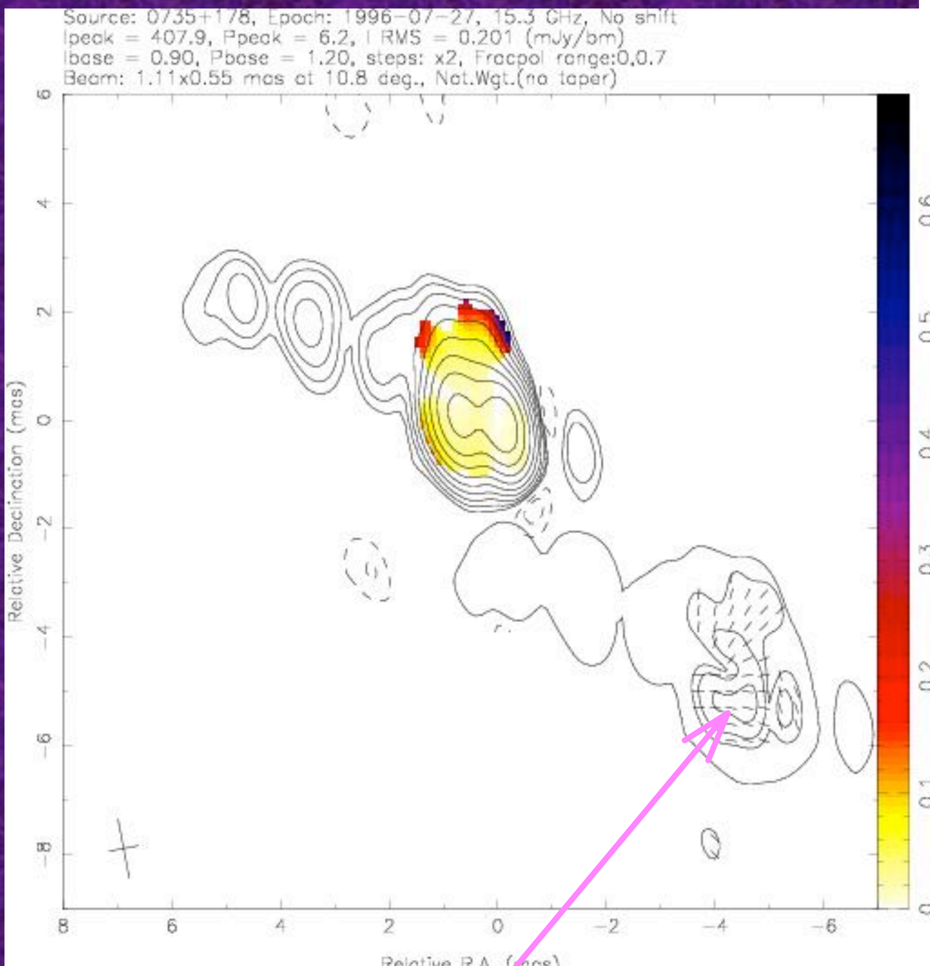


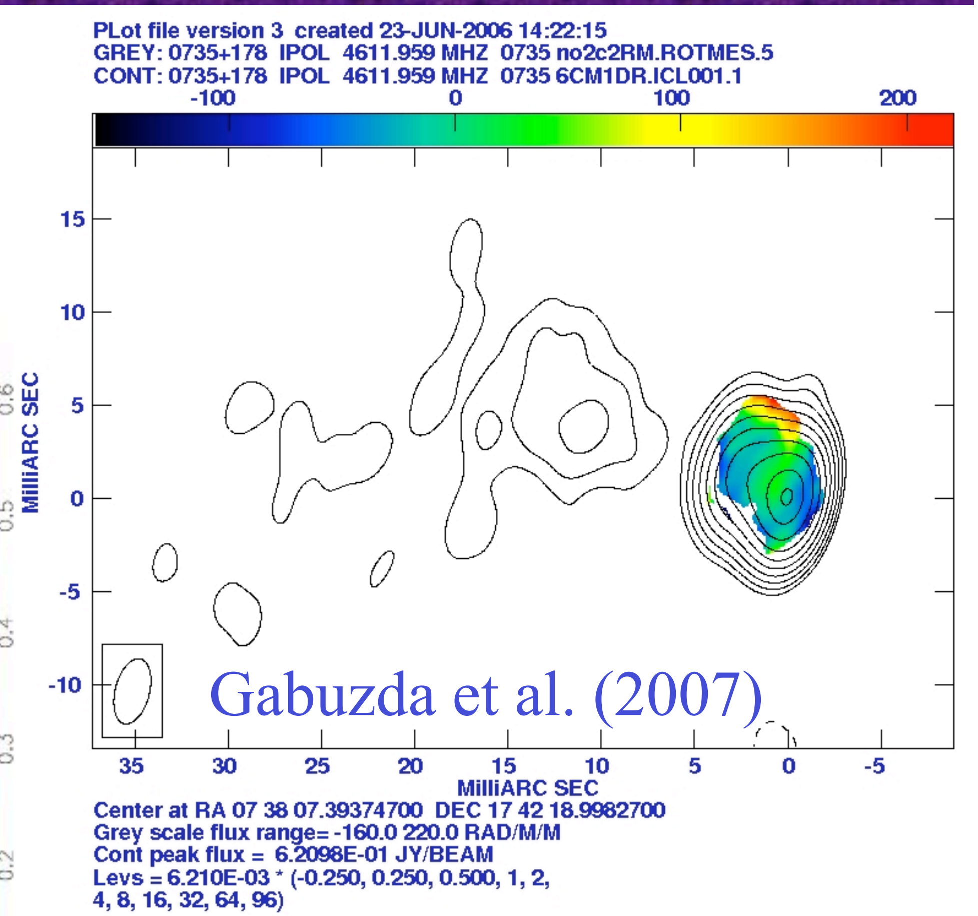


CCW = – CP

Left-handed helical B field

0735+178





Gabuzda et al. (2007)

FR gradient across jet

Predominantly ⊥ B field

Additional evidence helical B fields are involved: CP detected in jets of several sources!

This is very natural if the CP is associated with helical jet B fields.

Homan & Lister 2005

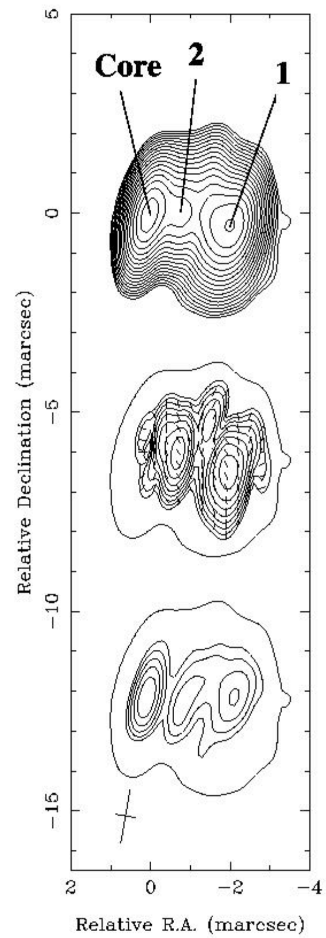


FIG. 11.—Stokes *I* contours (*top*), linear polarization (*middle*), and circular polarization (*bottom*) images of 2134+004 in 2002 May. A single Stokes *I* contour appears around the linear and circular polarization images to show registration. The Stokes *I* and linear polarization contours begin at 5 mJy beam^{-1}, and the circular polarization contours begin at ± 1 mJy beam^{-1}. All contours increase in steps of $\sqrt{2}$. Negative circular polarization is indicated by dashed contours. The FWHM dimensions of the common restoring beam are indicated by a cross in the lower left corner of the image. Electric vector position angles for the linear polarization are indicated by tick marks in the middle image. The locations of circular polarization measurements are indicated on the Stokes *I* map.

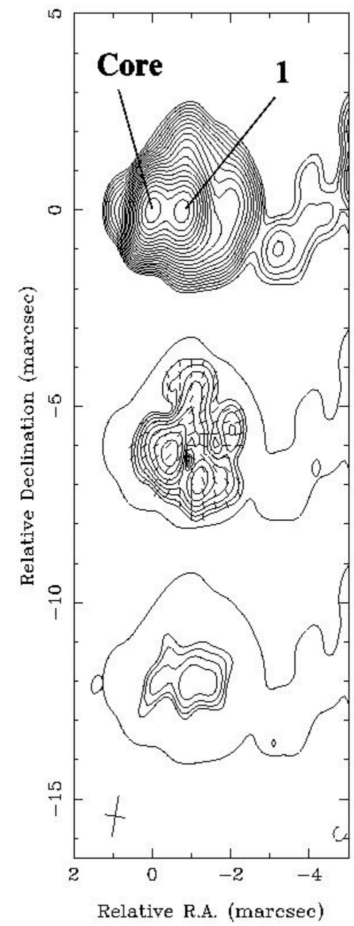


FIG. 12.—Stokes *I* contours (*top*), linear polarization (*middle*), and circular polarization (*bottom*) images of the inner 4 mas of the jet of 3C 454.3 in 2003 March. A single Stokes *I* contour appears around the linear and circular polarization images to show registration. The Stokes *I* and linear polarization contours begin at 5 mJy beam^{-1}, and the circular polarization contours begin at ± 3 mJy beam^{-1}. All contours increase in steps of $\sqrt{2}$. Negative circular polarization is indicated by dashed contours. The FWHM dimensions of the common restoring beam are indicated by a cross in the lower left corner of the image. Electric vector position angles for the linear polarization are indicated by tick marks in the middle image. The locations of circular polarization measurements are indicated on the Stokes *I* map.