The Radio Jets of AGN

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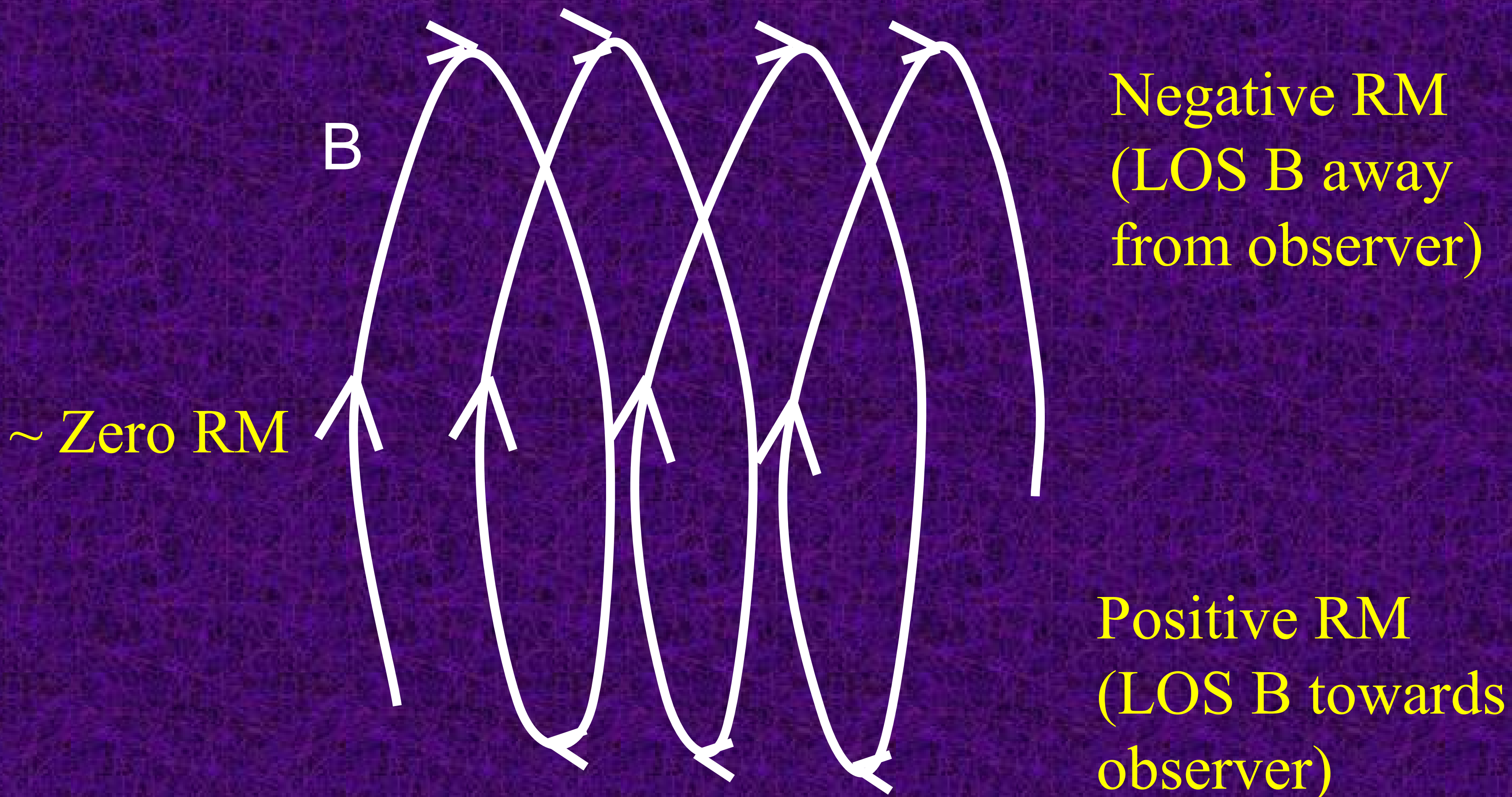
- Recent results considered in framework of the hypothesis that (many or even all) jets have helical magnetic (B) fields (rotation-measure gradients, linear polarization, spectral tomography analyses, circular polarization)
- Coordinated optical and VLBI polarization observations
- Potential of Faraday-rotation sign to yield information about 3D structure of jet B fields
- Summary and future work

Powerful diagnostic for presence of toroidal/helical B fields: Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet. If jet is viewed at ~90° to jet axis in source frame (~ 1/γ in observer's frame):



RM-gradient results published thus far (also talk by Wardle):

- Asada et al. 2002 – 3C273
- Gabuzda, Murray & Cronin 2004 – Four BL Lac objects
- Zavala & Taylor 2005 – 3C273
- Attridge, Homan & Wardle 2005 – 3C273 at 3mm/7mm

Recent results:

- Mahmud & Gabuzda – 6-frequency 2cm-6cm study of sample of 34 BL Lac objects – 3-5 new cases thus far
- Gabuzda, O’Dowd, Aller & Aller – 3-frequency 2cm-6cm study of Michigan BL Lac sample – several candidates
- “Missed” cases from Zavala & Taylor (2003, 2004)?

3C273 – best studied case

Zavala & Taylor 2005

Attridge et al. 2005

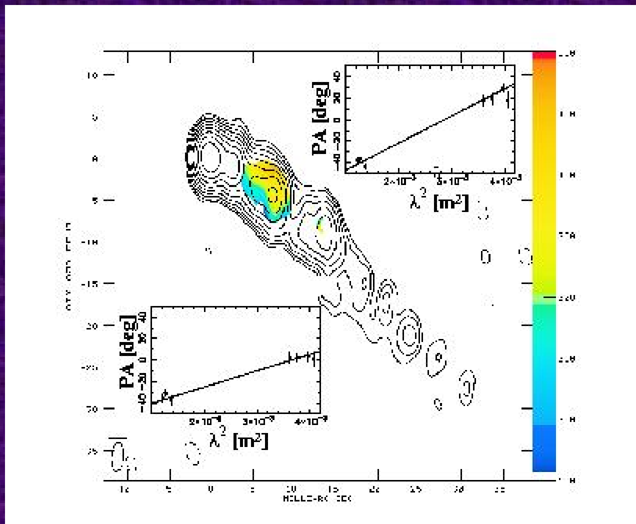


Fig. 3.

Asada et al. 2002

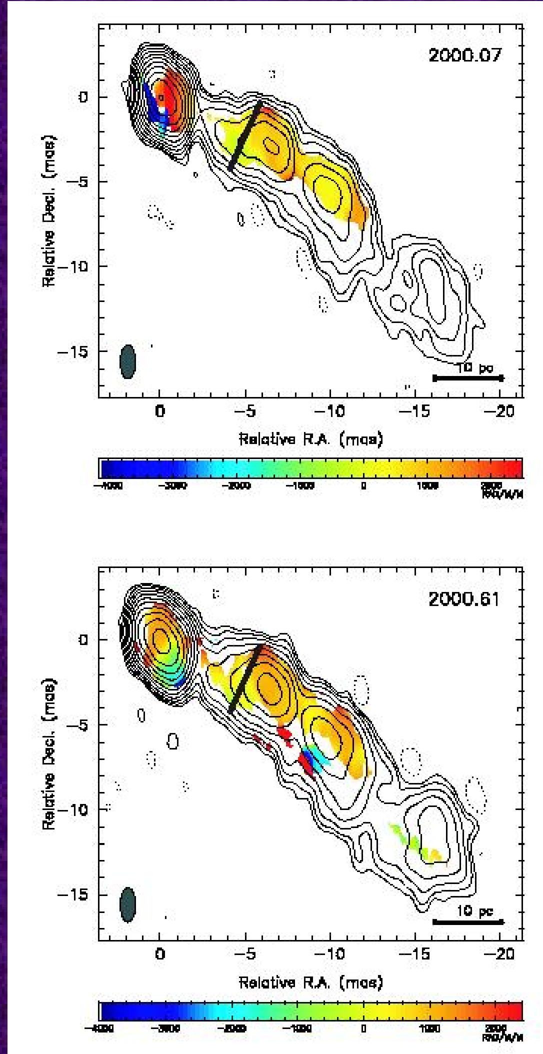


FIG. 1.—Rotation measure image for 3C 273 at two epochs. Total intensity contours at 12.1 GHz are overlaid with contour levels starting at 12 and 6.6 mJy beam^{-1} for epochs 2000.07 and 2000.61, respectively, and increase by factors of 2. The synthesized beam is drawn in the lower left corner and has dimensions of 2.0 × 0.9 mas at 0° for both epochs. The thick lines indicate the location of the slices shown in Fig. 3.

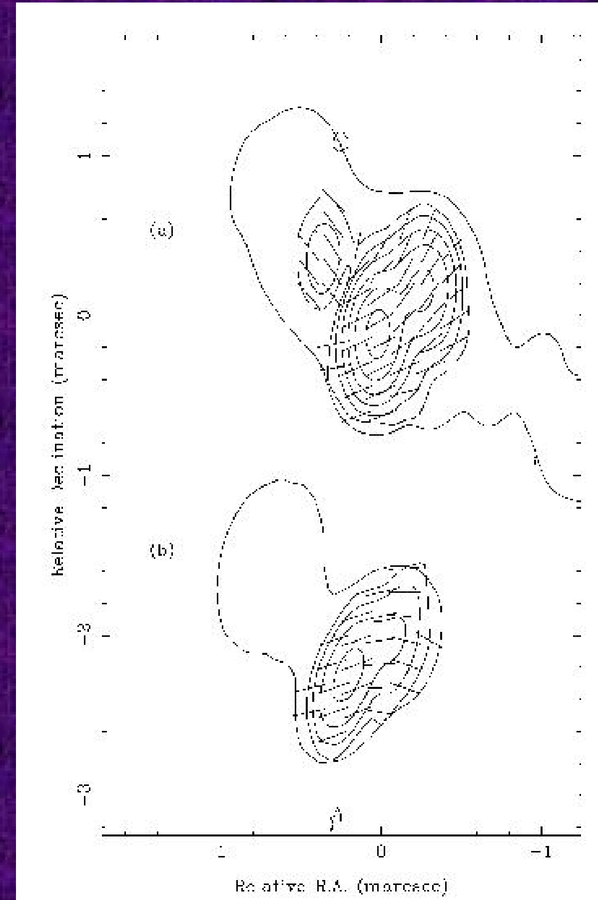
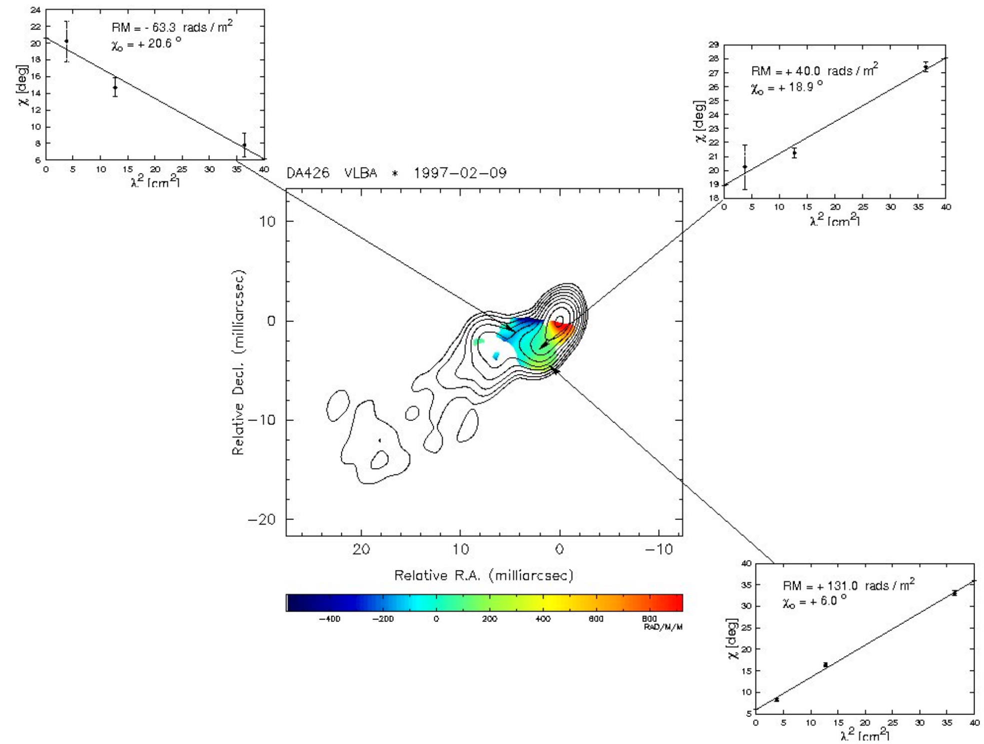
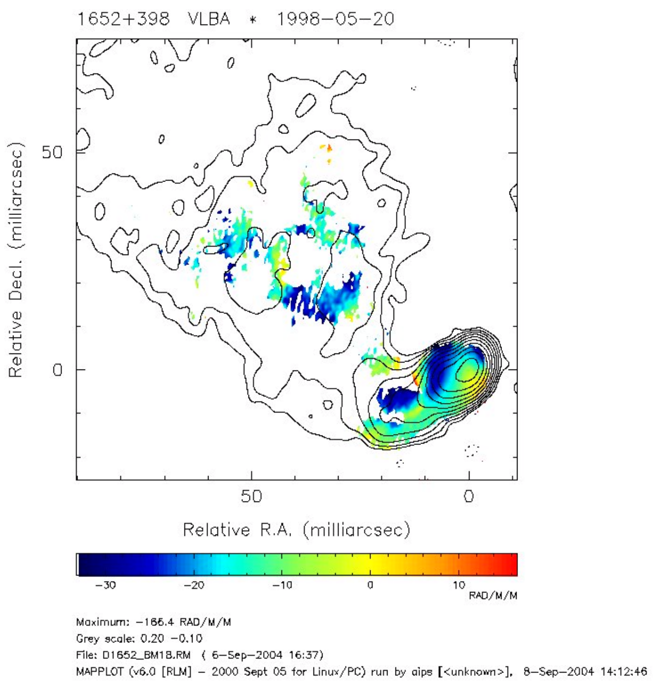


FIG. 2.—Zoomed linear polarization distributions from Fig. 1 more clearly reveal the orientation of the EVPAs as discussed in § 4; (*a*) is at 43 GHz and (*b*) is at 86 GHz, both showing every second contour.

Three independent RM measurements, all show transverse gradient in same sense

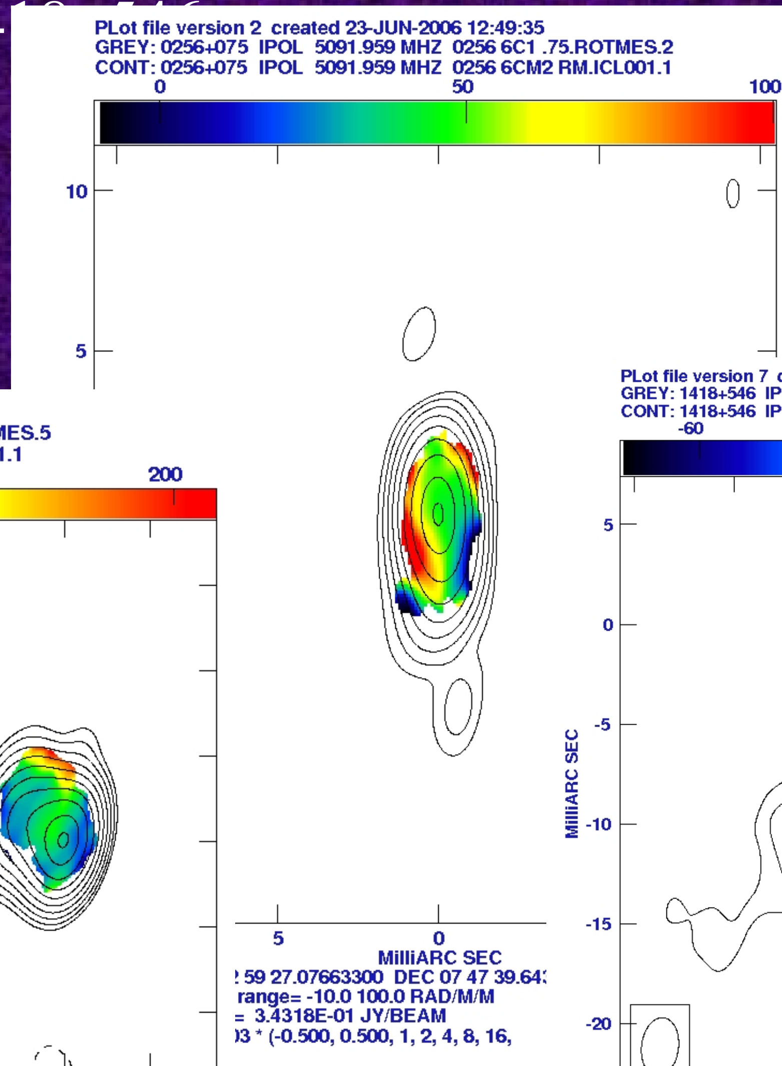
Gabuzda, Murray, Cronin 2004: Found expected behaviour for toroidal/helical B field viewed at 90º to jet axis in source frame in Mrk501

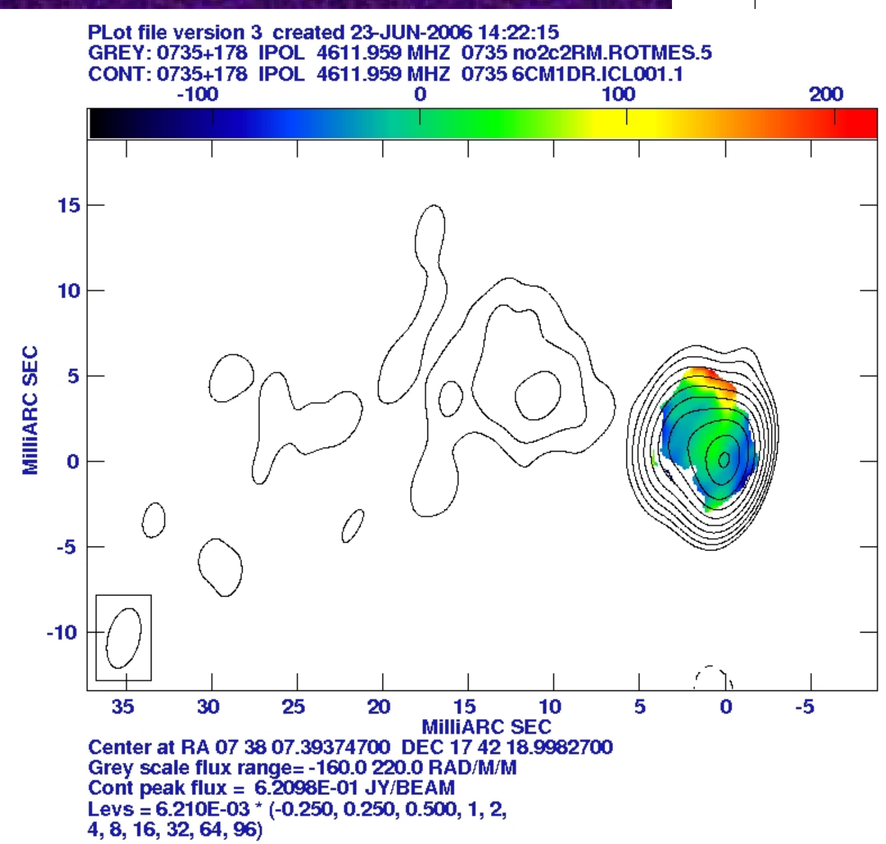


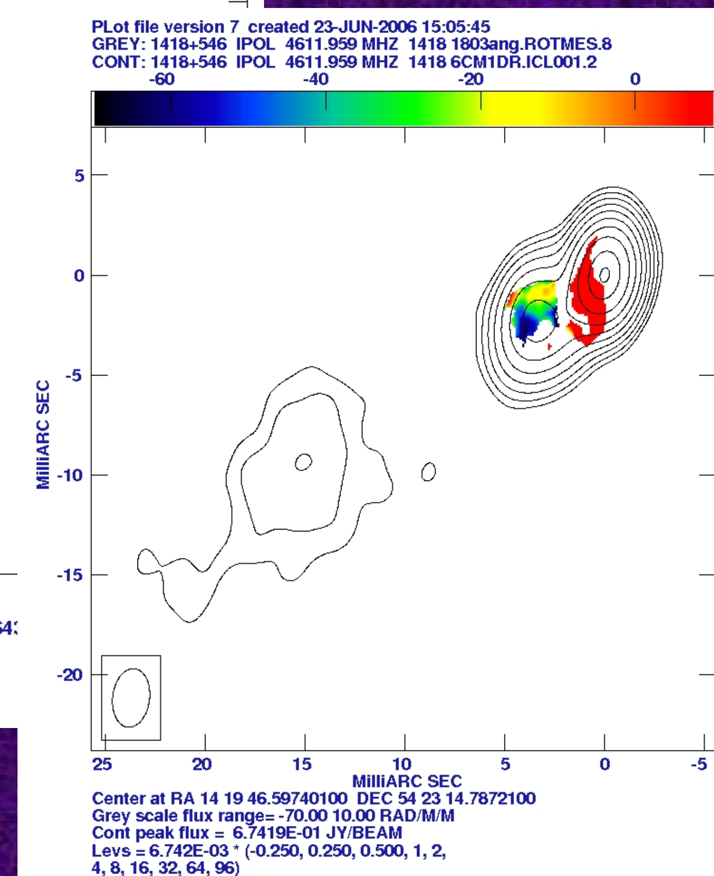


Croke & Gabuzda (in prep): RM gradient with same sense detected using 3.6+6+13+18cm VLBA data

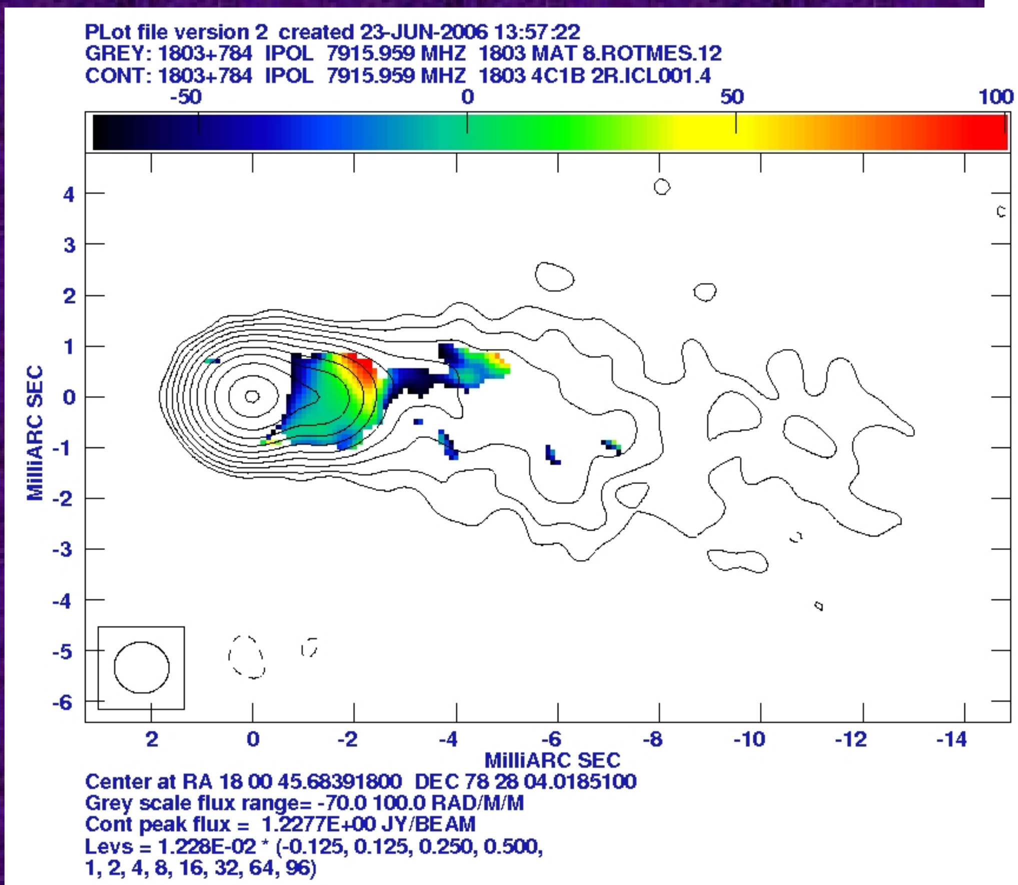
Mahmud & Gabuzda -- new transverse RM gradients in 0256+075, 0735+178, 14



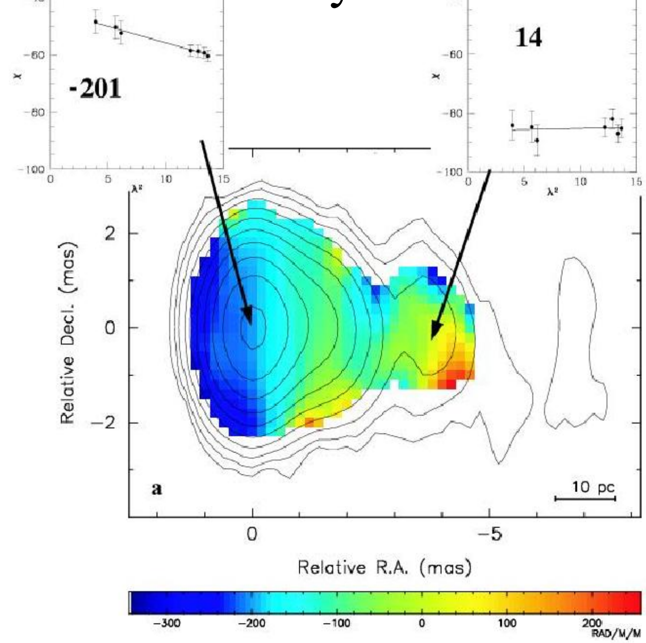




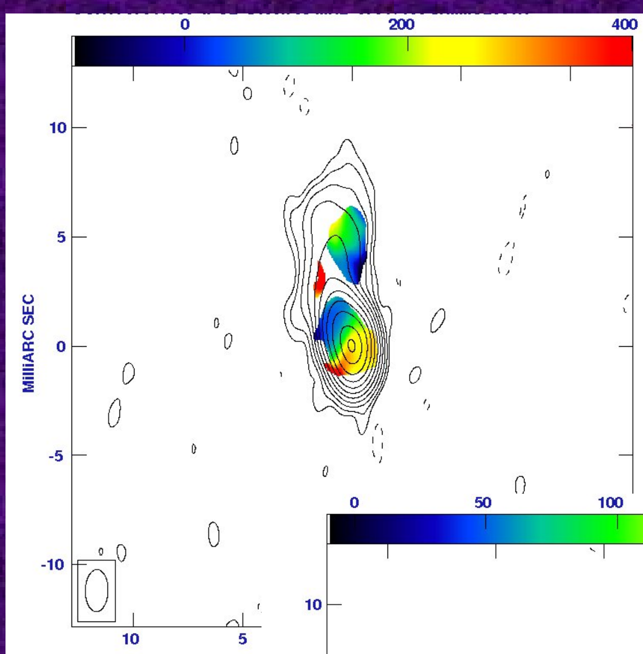
… and 1803+784 — but in the opposite sense to the gradient visible in RM image of Zavala & Taylor (2003) — change of winding direction for helix?

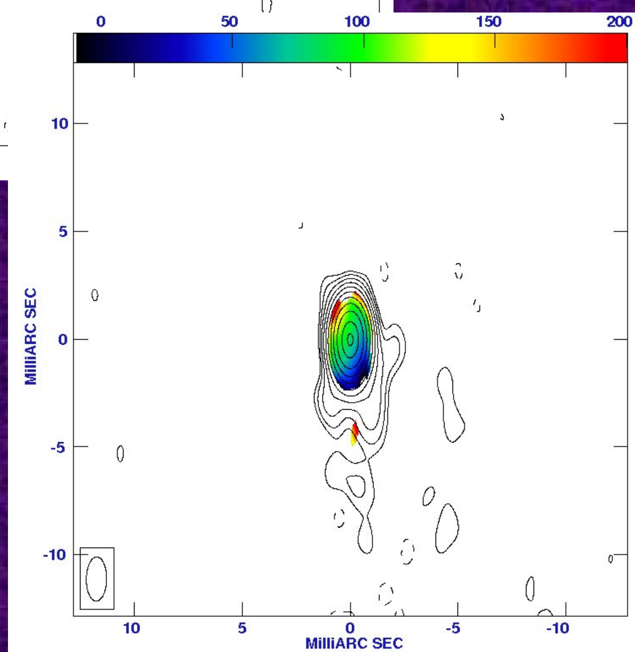


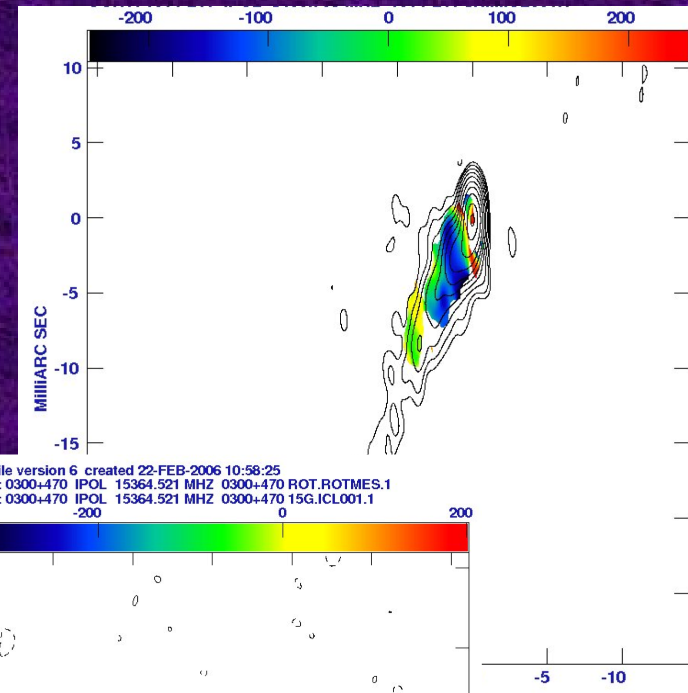
Zavala & Taylor 2003

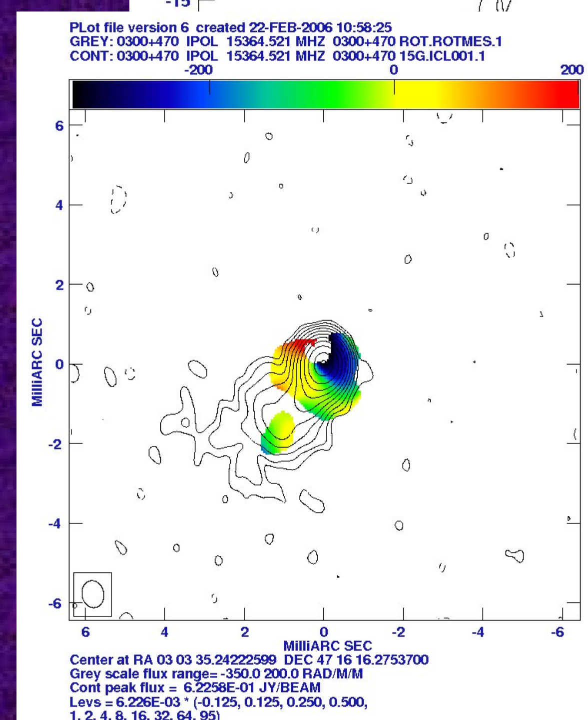


Possible transverse RM gradients in Michigan BL Lac sample









• Transverse RM gradients do exist, and appear to be fairly common

• Difficult to know just how common, due to difficulty of detecting small differences in RM across the jet:

– accurate polarization angle calibration crucial
– if thermal electron density is low, RM signal will be weak, making it effectively impossible to detect RM

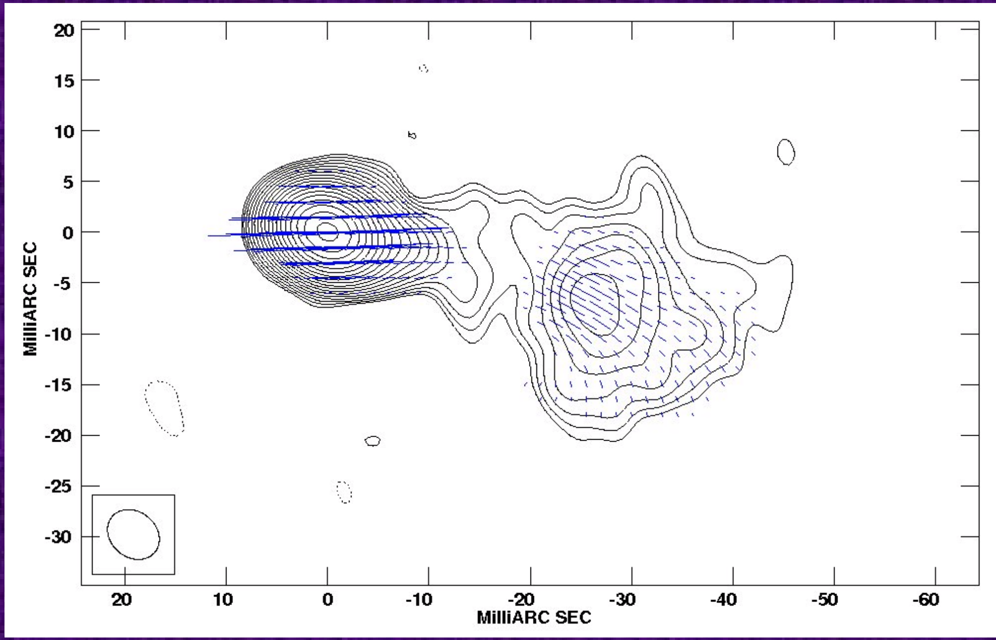
• Starting to get at least tentative evidence for changes in direction of helical "winding" with epoch (or equivalently with distance from core)

• Could thermal plasma around jet giving rise to Faraday rotation correspond to "matter-dominated hollow cone" in simulations (Krolik's talk)?

MOJAVE 2cm VLBA linear polarization survey (Lister & Homan 2005; more from Matt Lister; here my own quirky view)

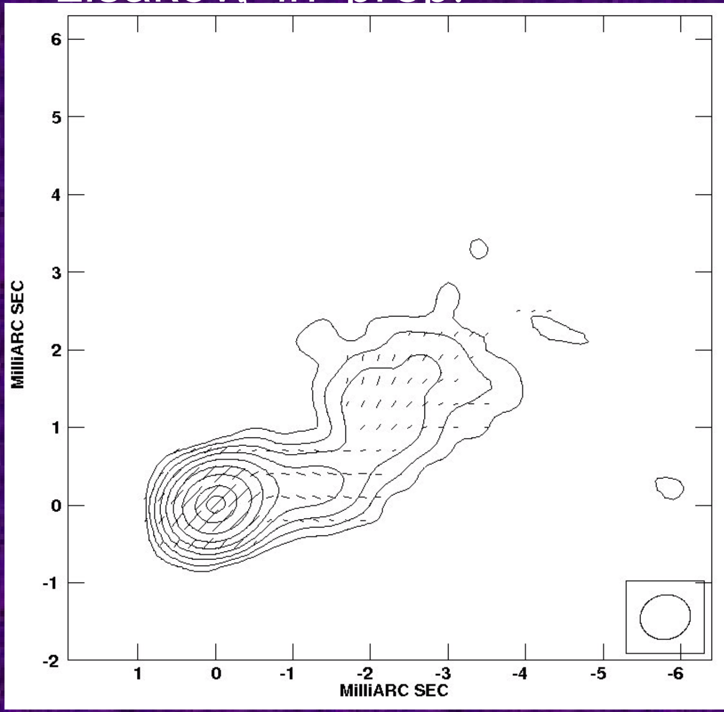
- Multi-epoch 2cm VLBA I and P images of more than a hundred compact AGN
- How to look for signs of helical jet B fields?

Extended regions of transverse jet B field (aligned E vectors) — could be series of shocks, but more natural explanation is helical B field

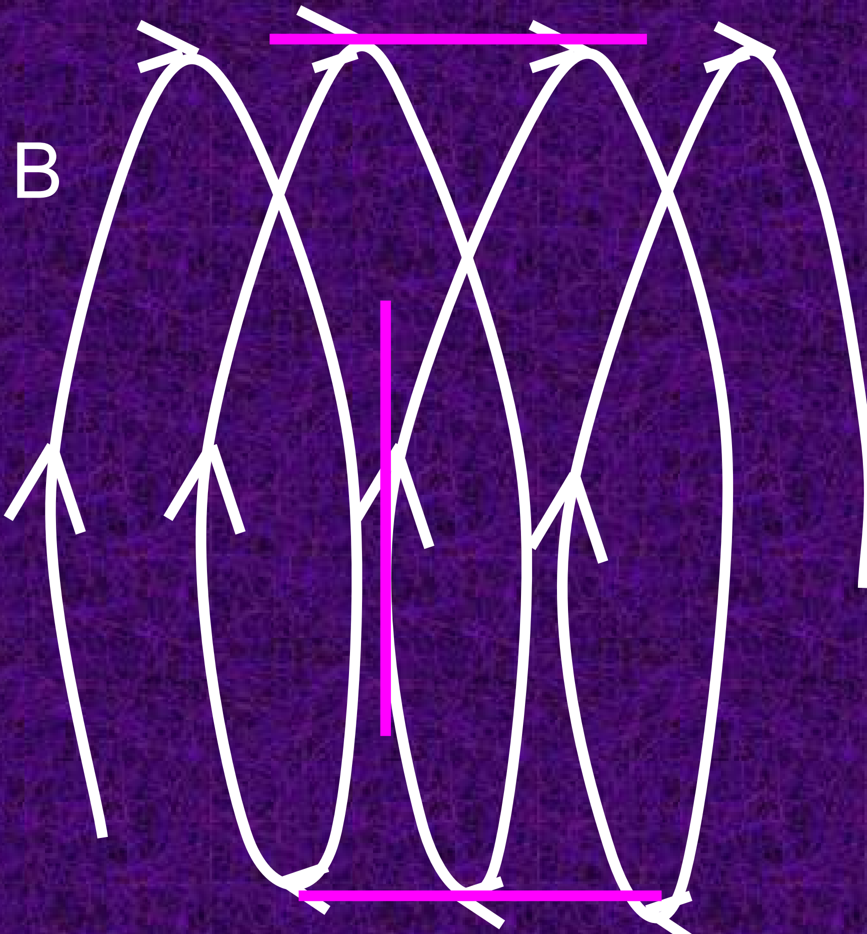


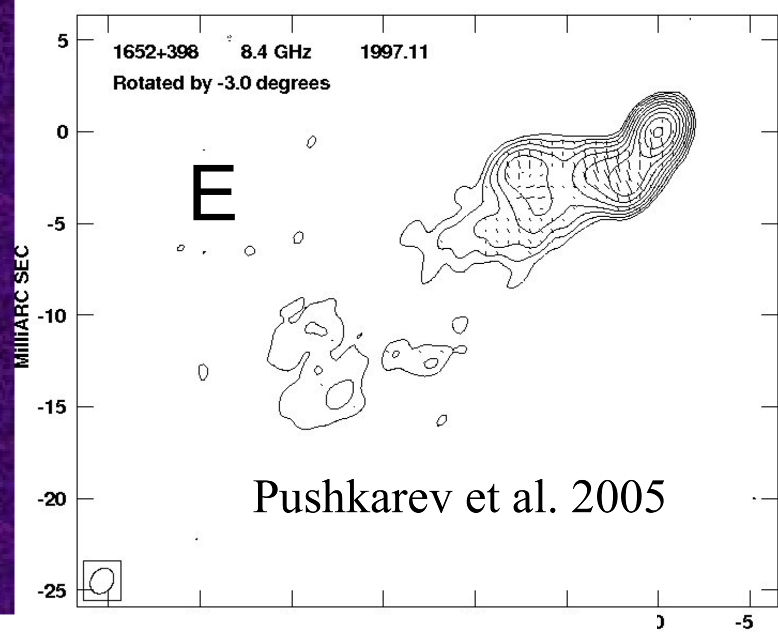
18cm VLBA map of 1803+784; Gabuzda & Chernetskii 2003

2cm VLBA map of 1749+701; Gabuzda & Lisakov, in prep.



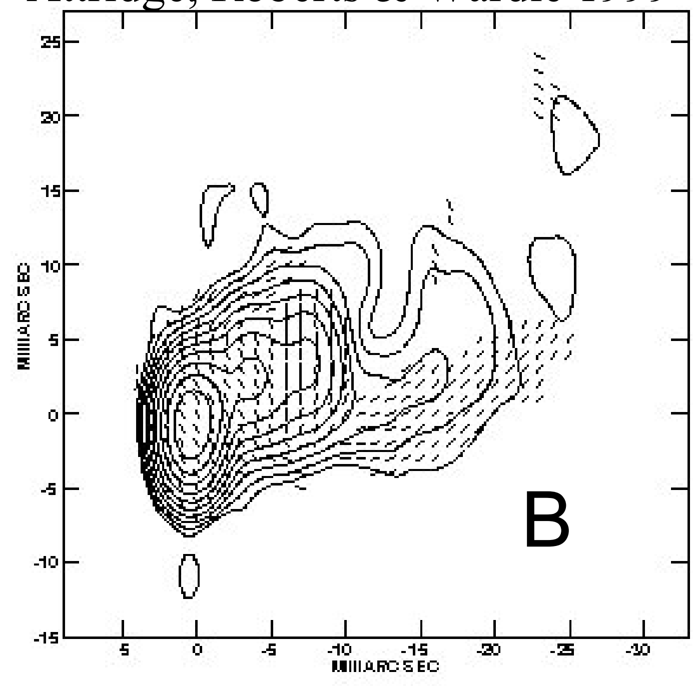
“Sheath-like” jet pol structures – maybe interaction with surrounding medium, but more natural explanation is helical B field:



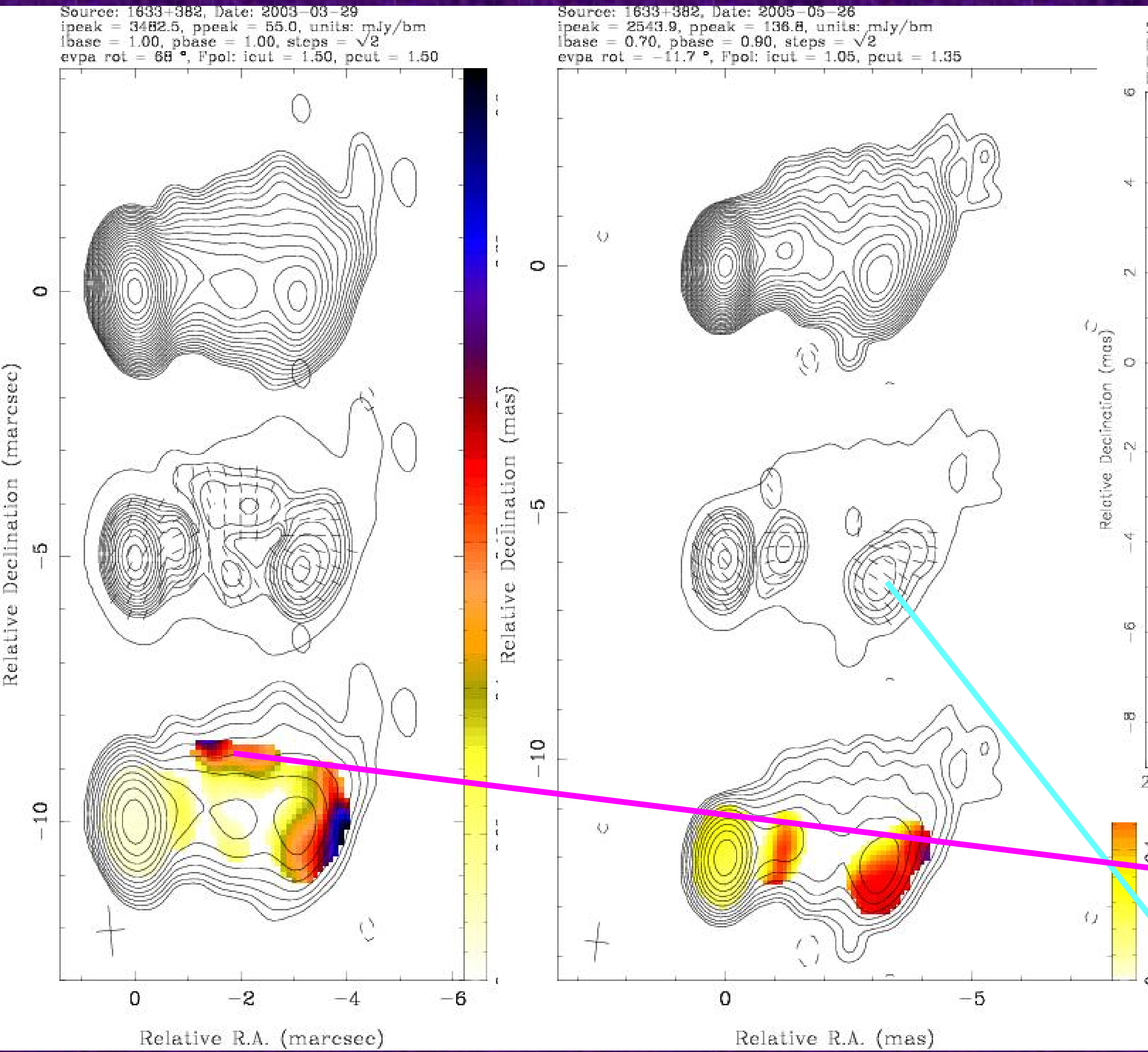


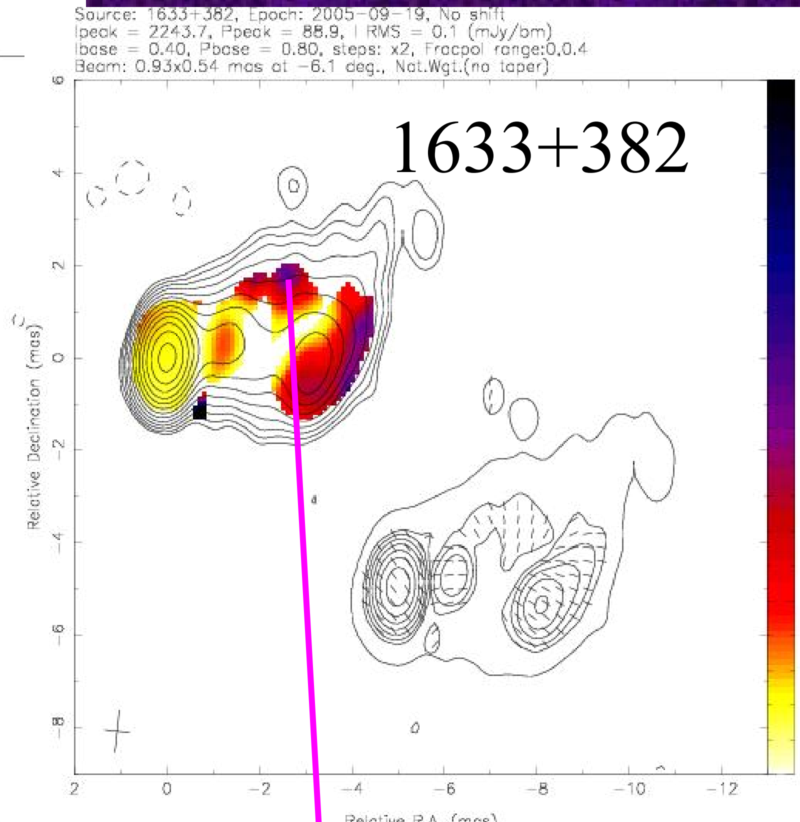
Pushkarev et al. 2005

Attridge, Roberts & Wardle 1999



“Sheath-like” polarization structures appear to be reasonably common…



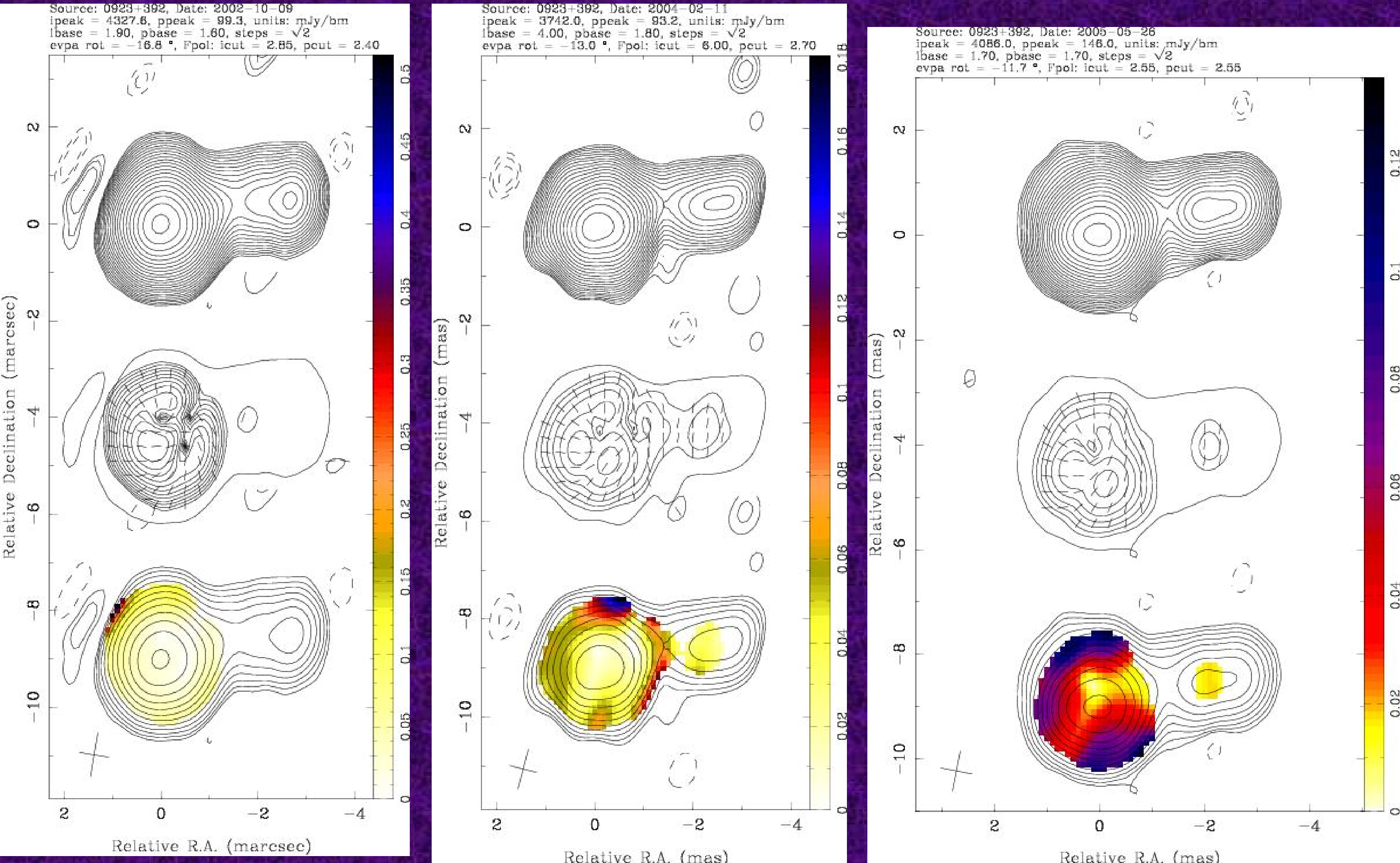


Note increase in degree of pol at edge of jet

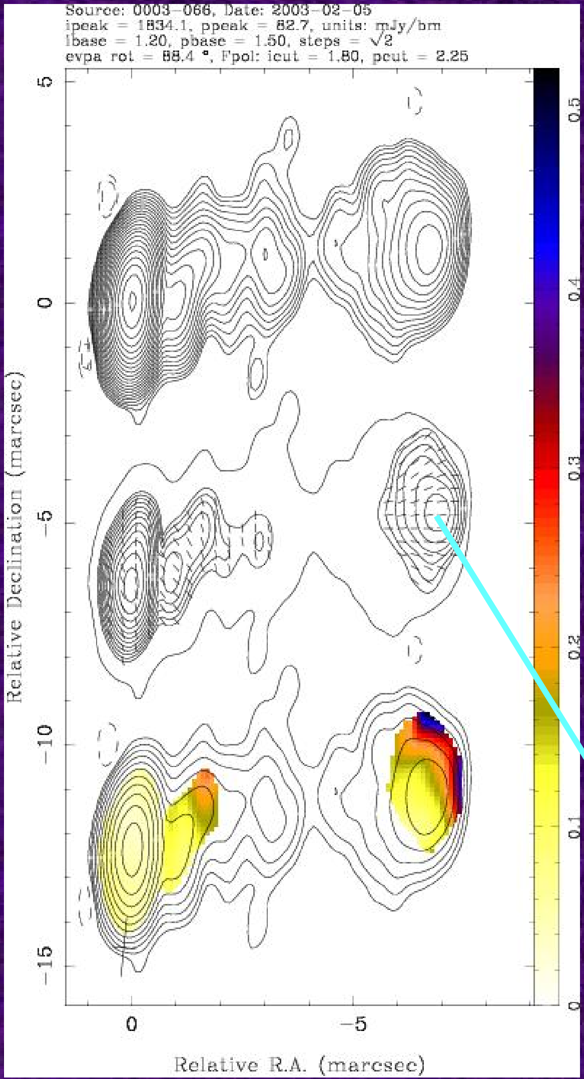
Extended region of transverse B

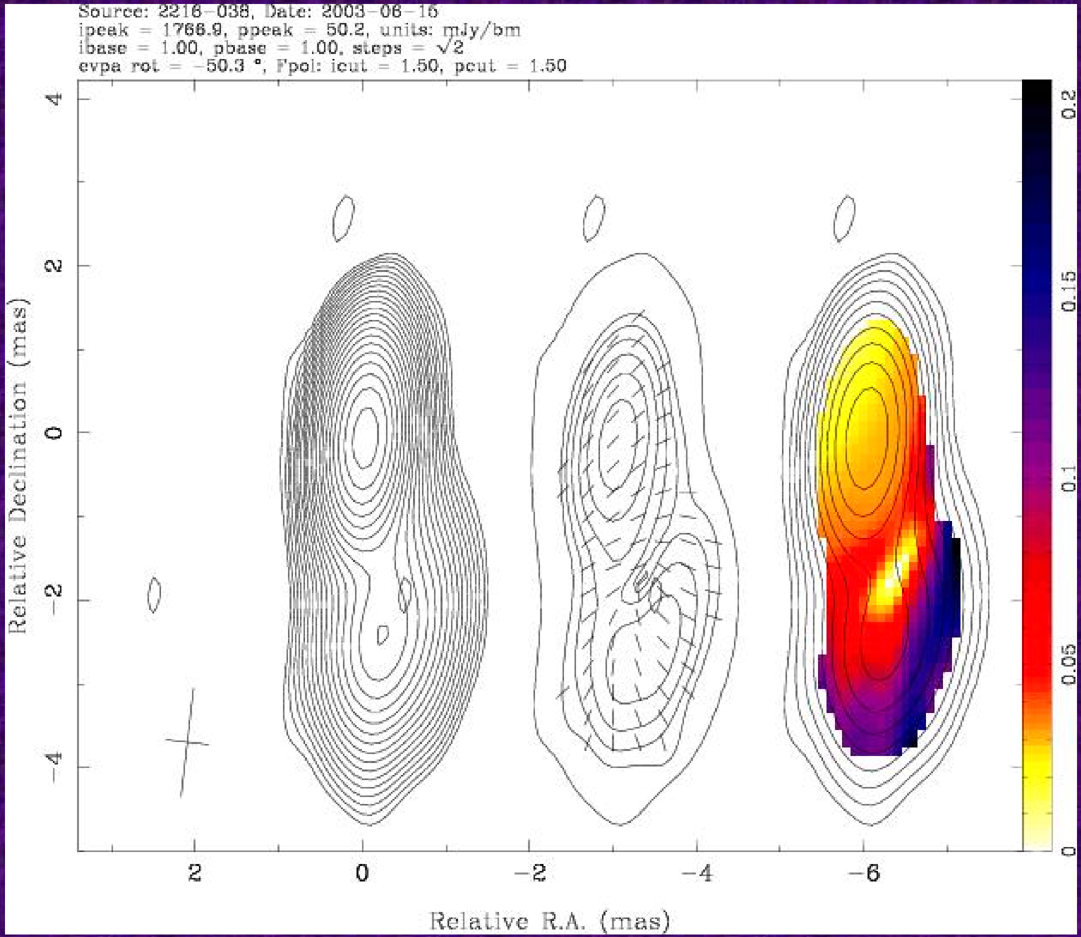
… but not always equally obvious at all epochs.

Another example: 0934+392



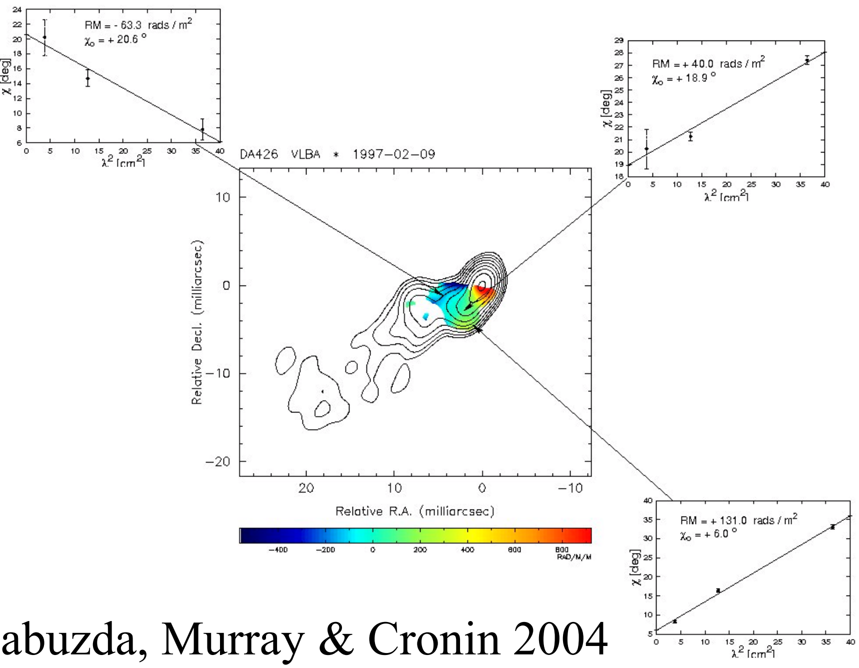
Two more MOJAVE polarization structures suggestive of "sheaths"



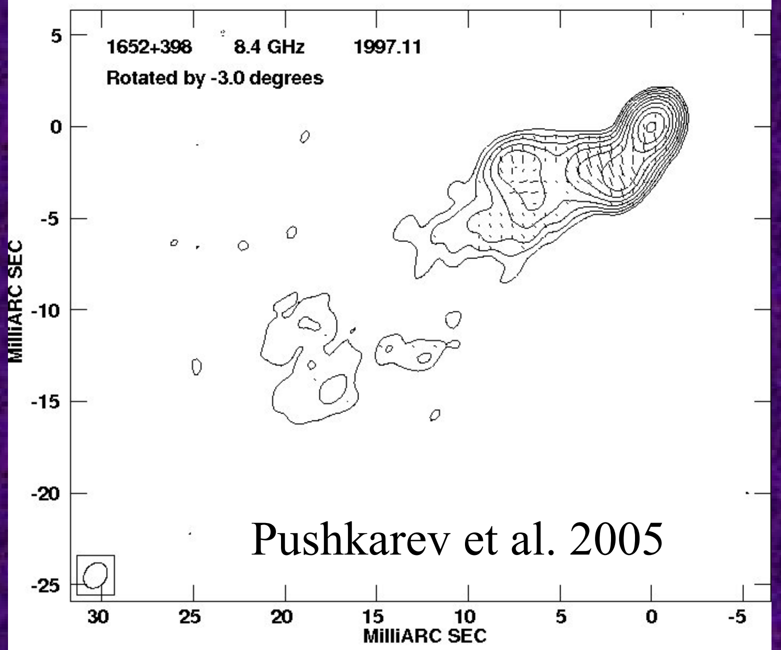


May suggest RMs of different sign at edges of extended region of transverse B – will be able to check if RM grad is present (Mahmud & Gabuzda)

If polarization "sheaths" are associated with helical B fields, some sources with "sheaths" should display RM gradients as well … and they do!



Gabuzda, Murray & Cronin 2004

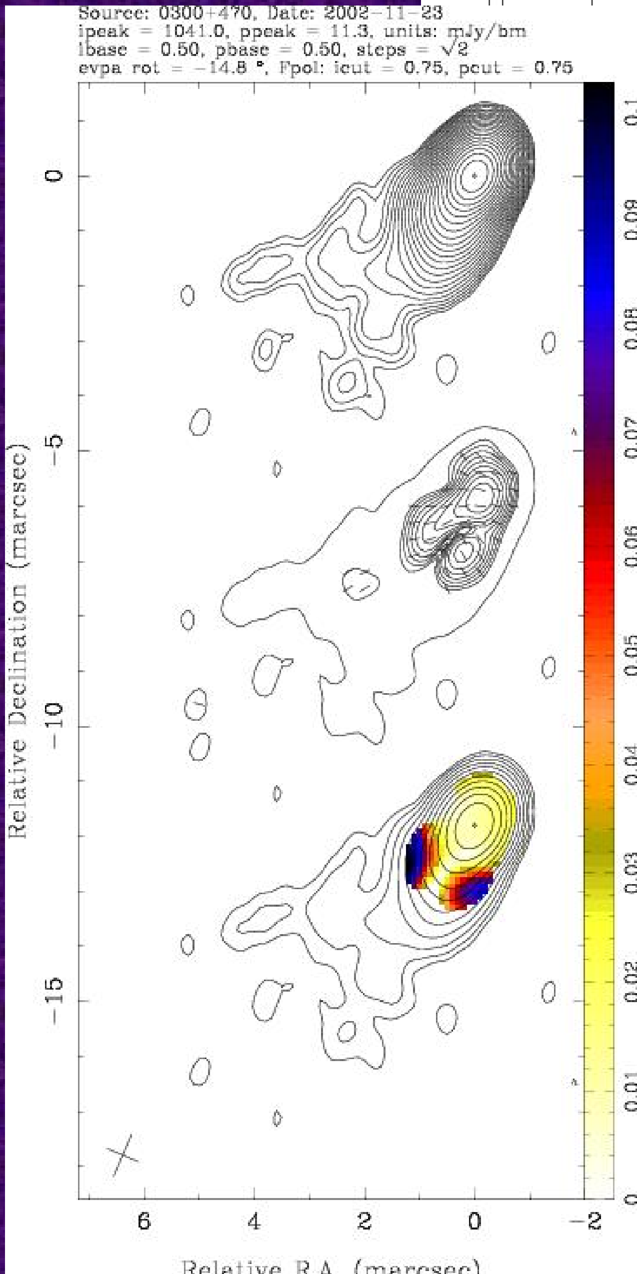


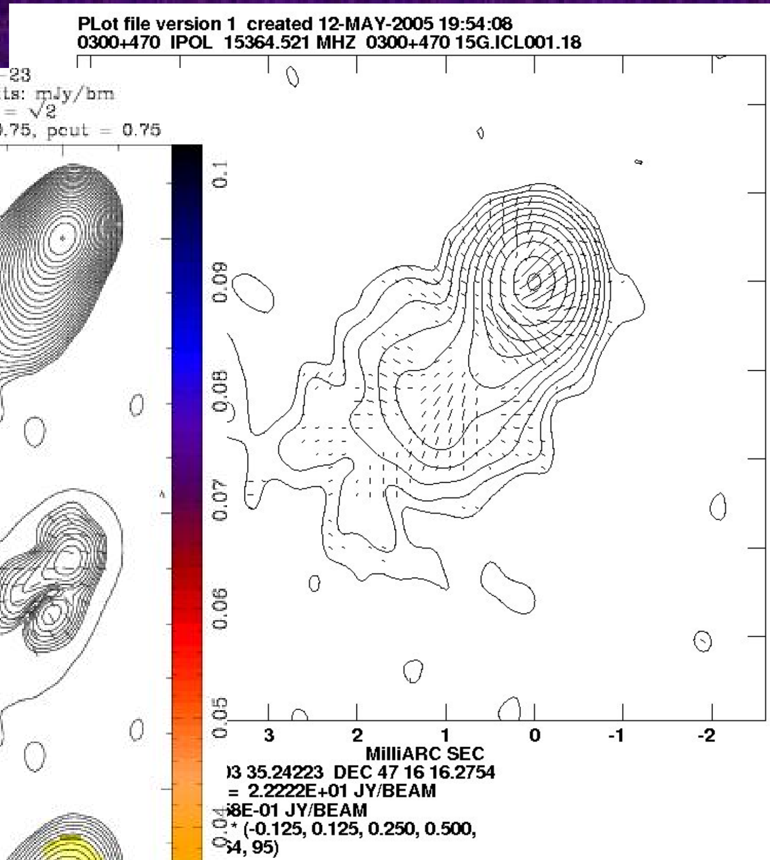
Pushkarev et al. 2005

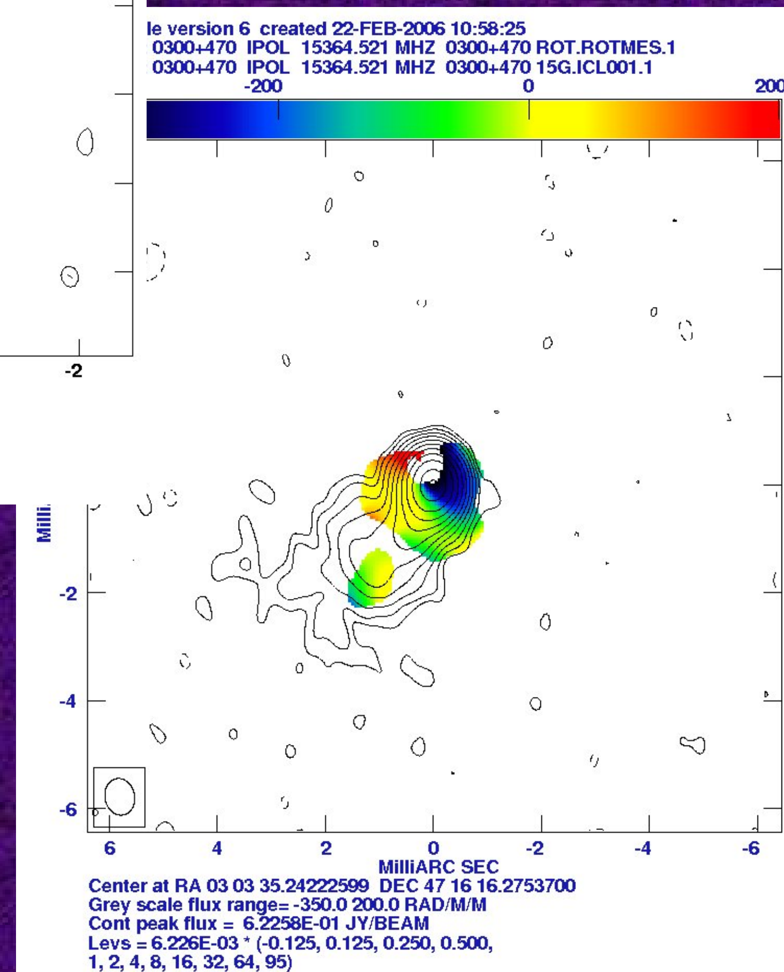
Mrk501

0300+470

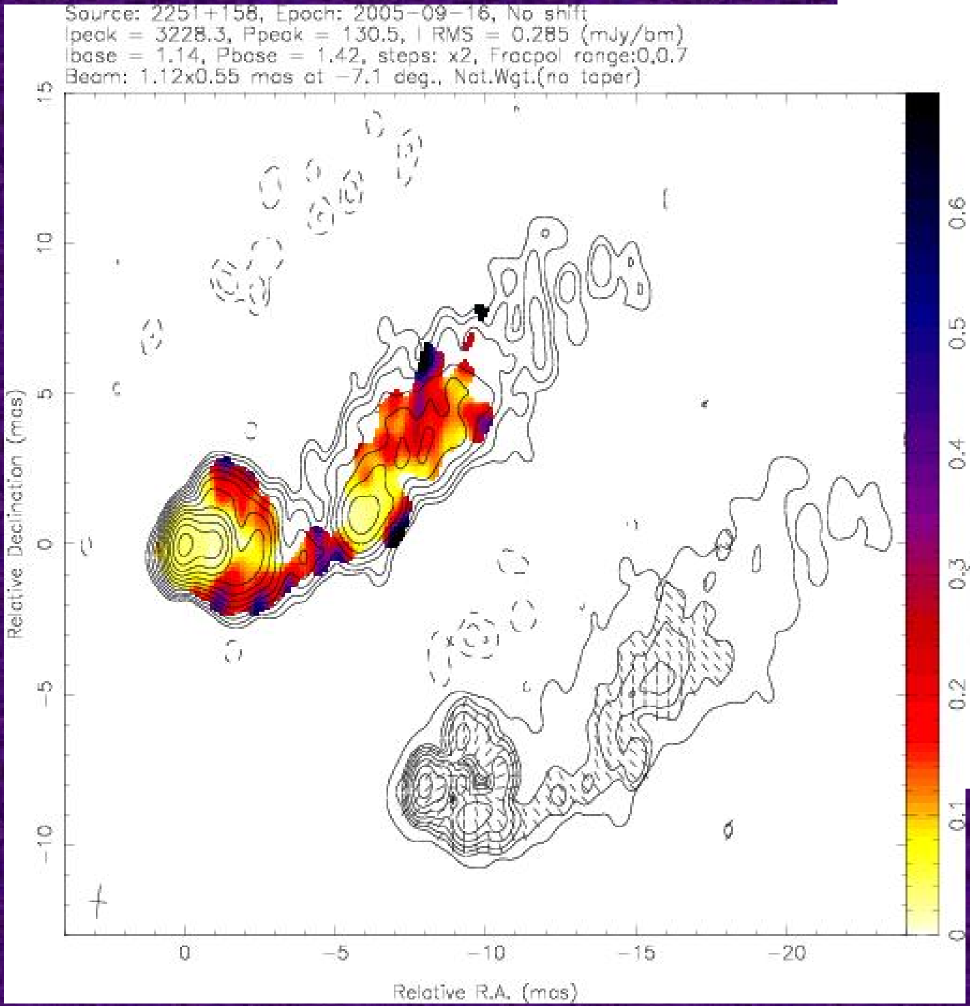
(in Michigan sample)

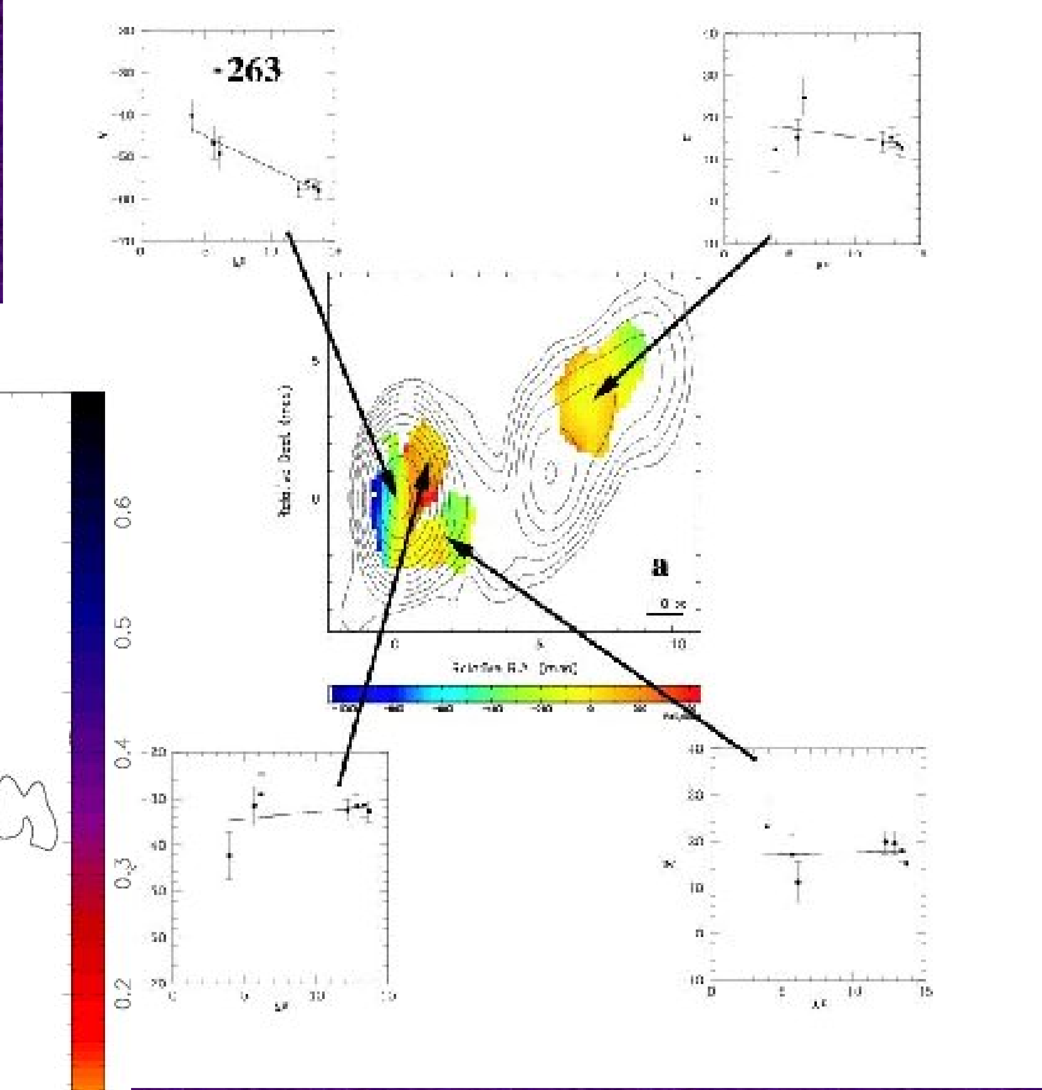






2251+158

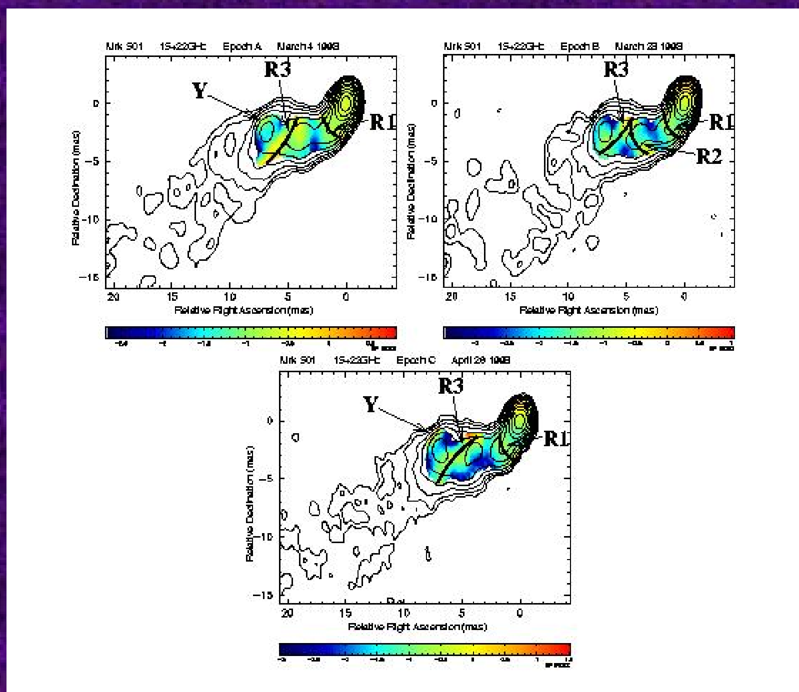




Zavala & Taylor 2003

Promising little studied technique for probing complex jet structures – spectral "tomography" (Katz-Stone & Rudnick 1997) – can be especially effective for studying layered sub-structures

$$I_{tom}(\alpha_t) = I_{\nu_1} - \left(\frac{\nu_1}{\nu_2}\right)^{\alpha_t} I_{\nu_2}$$



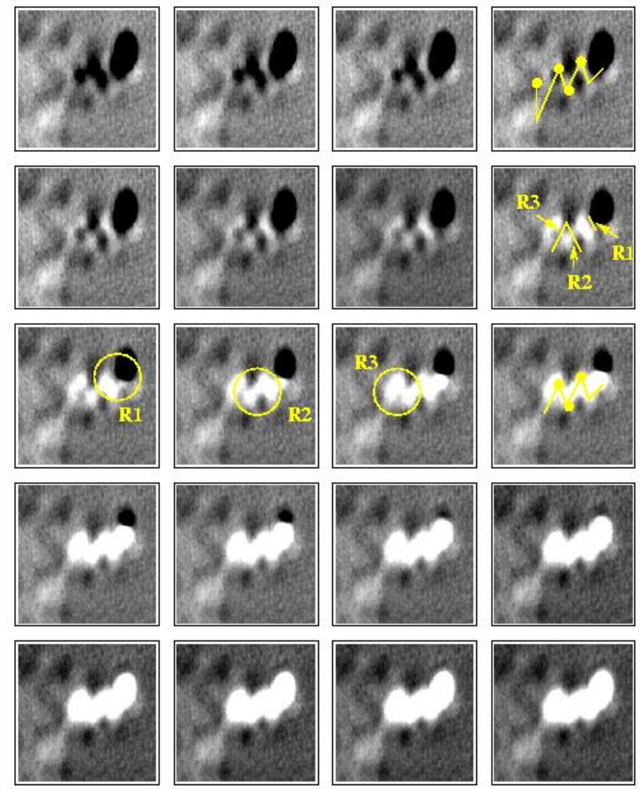
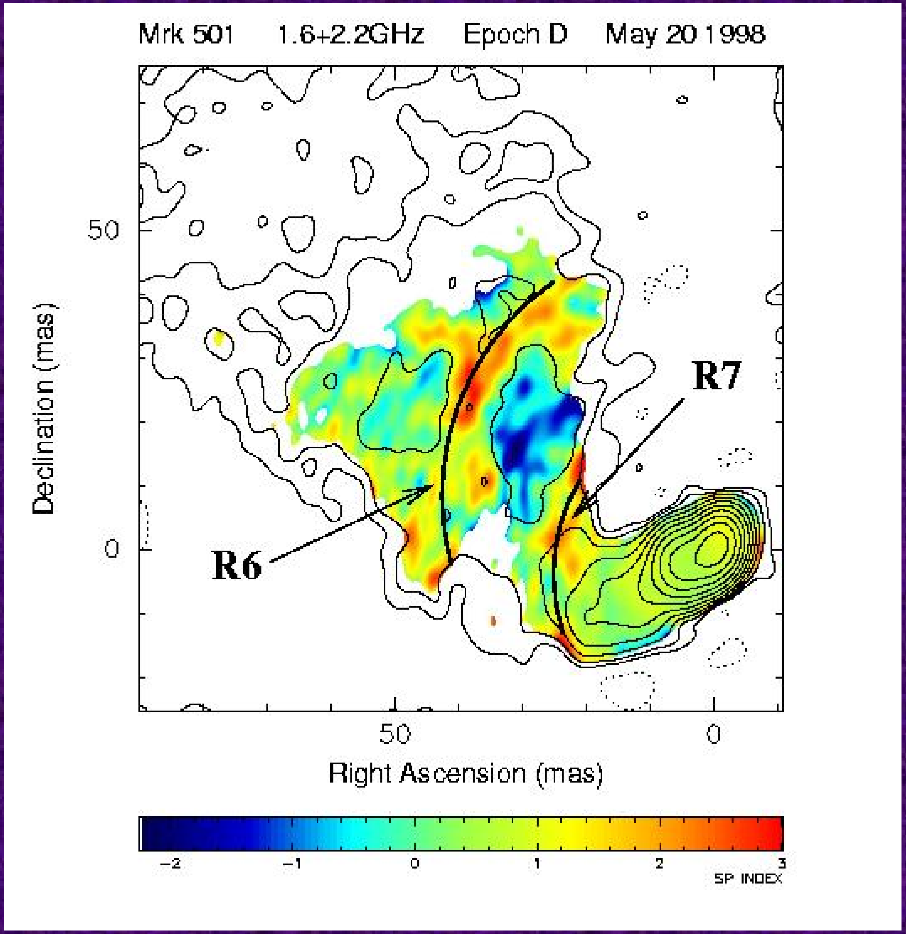


Figure 4.8: Spectral tomography gallery for Epoch B 15+22GHz data. The range in α_t is from -2.0 (top left) to -0.1 (bottom right). The increment in α_t between maps is 0.1. The area covered by the maps is from +16 to -5 mas in Right Ascension, and from -14 to +7 mas in Declination.

Regions of flat/inverted spectral index trace out bands crossing the jet (Croke & Gabuzda, in prep)

Spectral index distribution can delineate jet sub-structures that are not (as) obvious in intensity maps



Regions of inverted spectral index seem to describe helical structures wrapped around the jet – evidence that the jet itself has helical sub-structures (will be followed up by Shane O'Sullivan)?

MOJAVE Circular Polarization Measurements (Homan and Lister 2006; talks by Macquart and M. Aller, posters by Homan, Aller & Aller)

Prime suspect for mechanism generating circular polarization is Faraday conversion of LP to CP – but no obvious correlation between degree of CP and other source properties (degree of LP, spectral index, etc.).

For conversion, polarization E vector must have non-zero component along local B in conversion region.

Helical B-field geometry facilitates conversion – polarization emitted at “back” of helix is converted as it passes through “front” of helix, since helical B structure ensures polarization E from back is not completely orthogonal to B at front (can also get CP when E at back of jet is orthogonal to B at front of jet, but requires Faraday rotation (thermal electrons) in the jet volume

Can we find any hints that CP in MOJAVE sources is associated with presence of helical B fields?

35 MOJAVE sources had detectable CP in first-epoch measurements – many of these displayed “symptoms” of helical jet B fields: transverse RM gradients, sheath-like polarization structures, transverse B fields

Tentative RM gradient found

Note: CP in 0851+202 (OJ287), 1253-055 (3C279), 1334-127 also detected by Vitrishchak & Gabuzda with same sign.

MOJAVE CIRCULAR-POLARISATION DETECTIONS

	Source	Possible Signs of Helical B Fields			
		Trans. RM Grad	(Spine+)Sheath B	Trans. B	Refs
	0133+476	N			Z&T03
*	0215+015			Y	
*	0333+321		Y?		
	0642+449				
*	0716+714	Being reduced		Y	
*	0730+504		Y?		
**	0735+178	Y	Y?	Y	M&G
**	0736+017	Y?		Y	Z&T04
	0836+710				
*	0851+202[1]	Being reduced		Y	
*	0945+408		Y?		
**	1055+018	Y?	Y	Y	Pushkarev05
*	1127-145		Y?		
	1156+295	Being reduced			
**	1226+023	Y	Y?		Several
	1228+126	N			Z&T03
**	1253−055[1]	Y?		Y	Z&T03
*	1334−127[1]	Being reduced		Y	
*	1504−166		Y?		
	1510−089				
*	1633+382		Y		
	1655+077				
**	1749+096[2]	Y?, Being reduced		Y	Z&T04
*	1800+440		Y?		
	1823+568	N, Being reduced		Y	Z&T03
	1849+670				
*	1928+738	N	Y?		T00
*	1936−155			Y	
*	1958−179			Y	
	2126−123				
*	2134+044	N	Y		T00
*	2136+141			Y?	
*	2201+171			Y	
**	2251+158	Y	Y		Z&T03
*	2345−167		Y?		

[1]Also detected by Vitrishchak & Gabuzda (2006) with same sign.
[2]Detected by Vitrishchak & Gabuzda (2006).

CP also detected in jets of several sources!

3C273 – has transverse RM grad

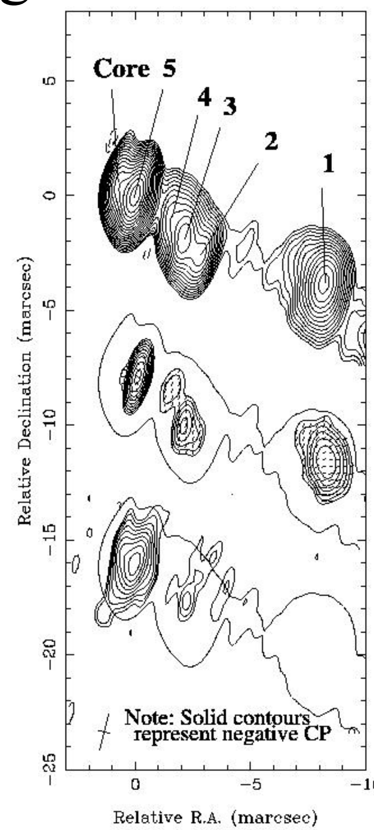


FIG. 7.—Stokes *I* contours (*top*), linear polarization (*middle*), and circular polarization (*bottom*) images of the inner 10 mas of the jet of 3C 273 in 2002 October. A single Stokes *I* contour appears around the linear and circular polarization images to show registration. The Stokes *I* and linear polarization contours begin at 20 mJy beam^{-1}, and the circular polarization contours begin at ±2 mJy beam^{-1}. All contours increase in steps of $\sqrt{2}$. In this image, negative circular polarization is indicated by solid 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.

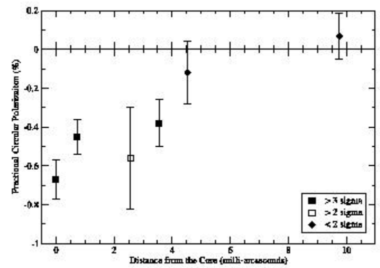


FIG. 8.—Fractional circular polarization as a function of distance from the jet core for 3C 273. Note that the circular polarization in 3C 273 predominantly has a *negative* sign and becomes weaker (going to smaller absolute values) at greater distances from the core. For the purposes of this plot, we have plotted all the values with their corresponding error bars, including those of ≤2 σ significance.

with the emergence of a new jet component. The core was very opaque at this time, and HW99 showed that the appearance of the circular polarization was tied to the flattening of the core's spectral index due to the emergence of the new component. As cataloged in WdP83 and K84, 3C 273 was repeatedly detected in integrated measurements during the 1970s and early 1980s at 8 GHz and below, where it had a consistently negative sign of circular polarization.

1228+126 (M87): Figure 9 shows our 15 GHz VLBA image of the jet of M87 in 2003 February. No linear polarization is detected, but strong circular polarization, $m_c = -0.49\% \pm 0.10\%$, is seen at the peak of the core.

M87 was studied at the Very Large Array (VLA) in 2000 April by Bower et al. (2002), who found no significant circular polarization

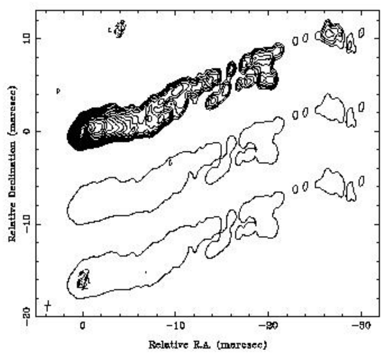
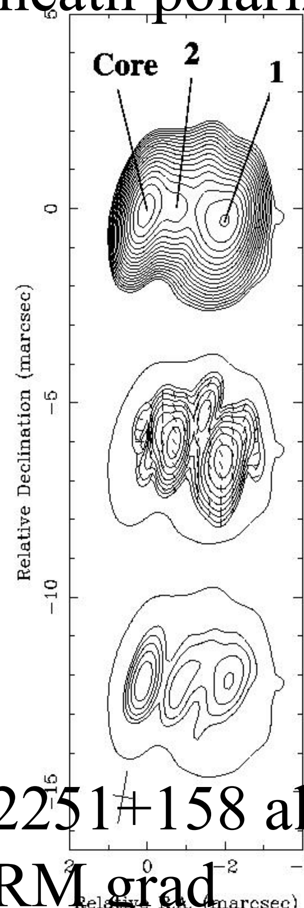
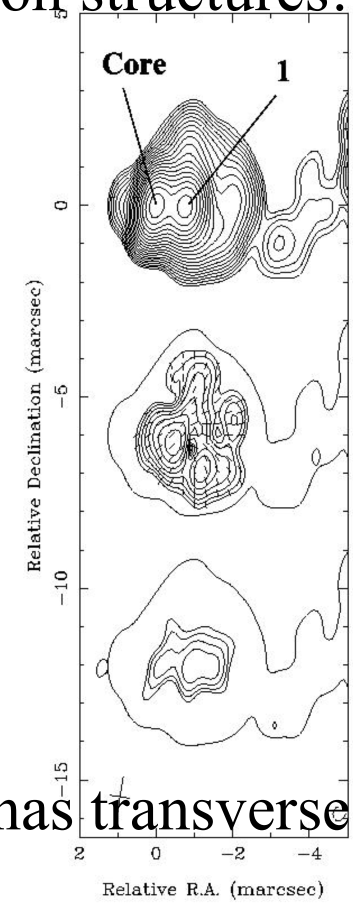


FIG. 9.—Stokes *I* contours (*top*), linear polarization (*middle*), and circular polarization (*bottom*) images of the VLBI jet of M87 in 2003 February. A single Stokes *I* contour appears around the linear and circular polarization images to show registration. All contours begin at ±1 mJy beam^{-1} and 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.

2134+004, 2251+158 – note sheath polarization structures!



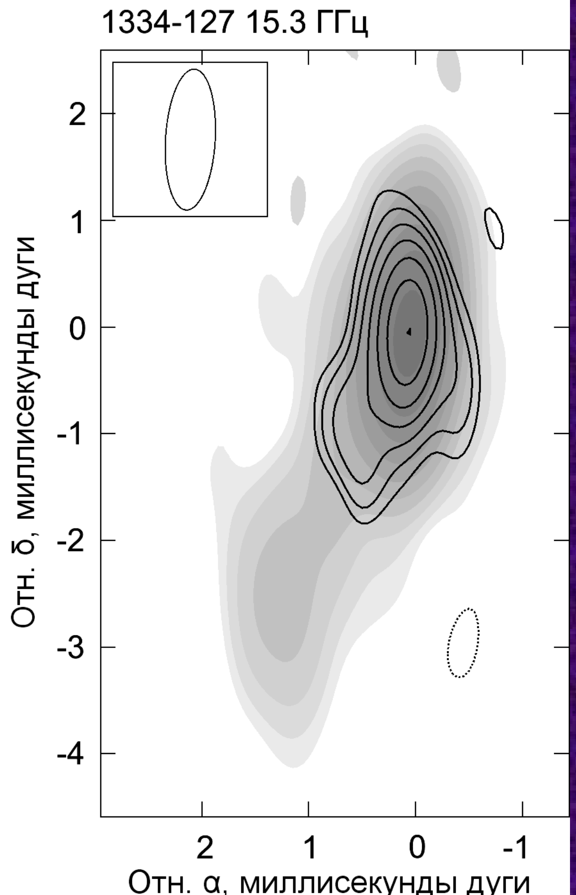


2251+158 also has transverse RM grad

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.

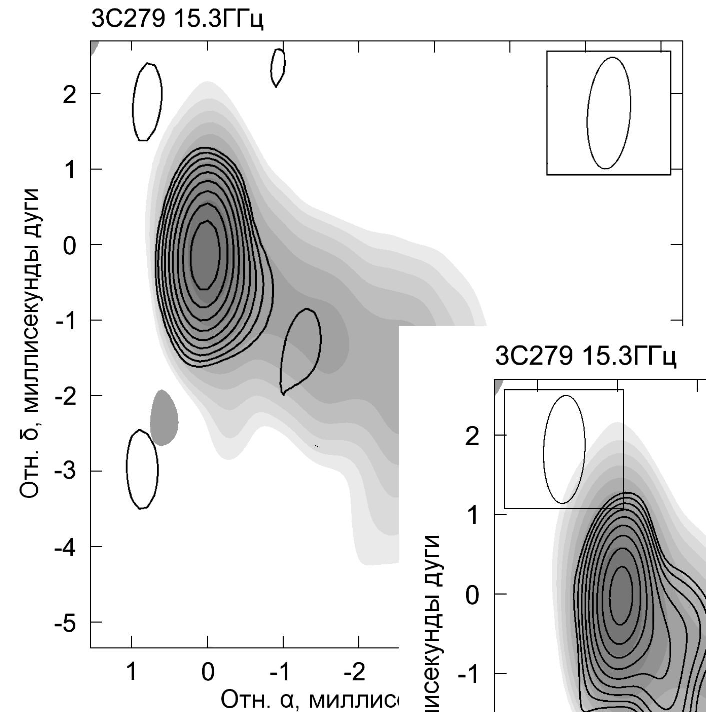
FIG. 12.—Stokes *I* contours (*top*), linear polarization (*middle*), and circular polarization (*bottom*) images of the inner 4 mas of the jet of 3C 454.3 in 2003 March. A single Stokes *I* contour appears around the linear and circular polarization images to show registration. The Stokes *I* and linear 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.

More CP in jets from results of Vitrishchak & Gabuzda



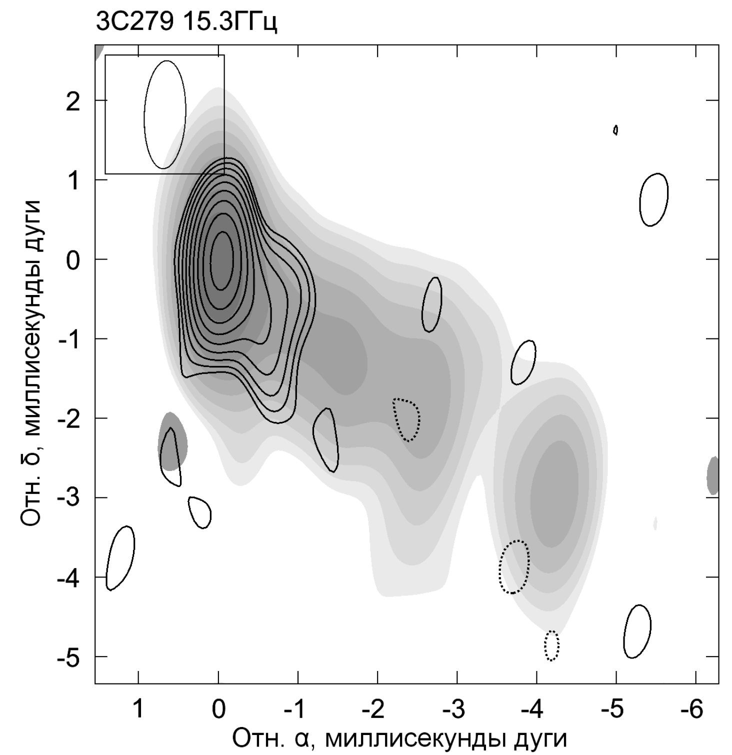
max V = 11.8 mЯн/ДН
max mc = 0.25%
Уровни V: -1.5, 1.5, 2.1, 3.0, 4.2, 5.9, 8.3, 11.8 mЯн/ДН

1334-127



max V = 46.1 mЯн/ДН
max mc = %
Уровни V: -2.3, 2.3, 3.2, 4.5
17.7, 25.0, 35.2

3C279



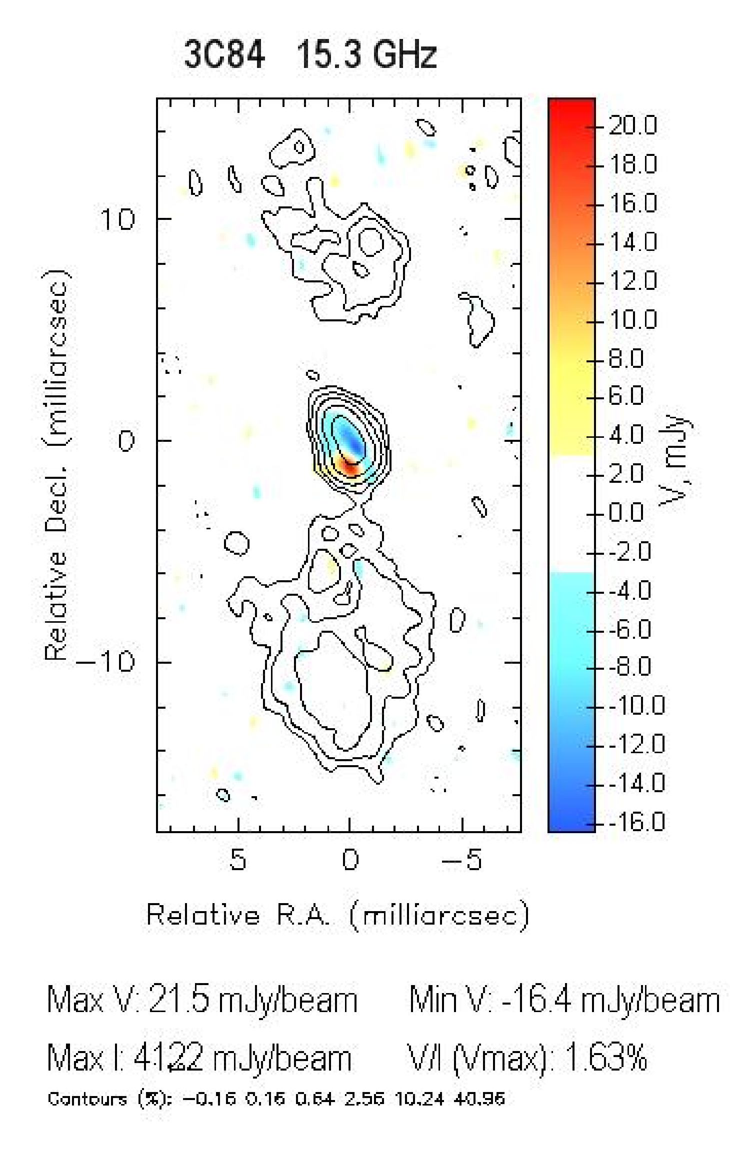
max V = 40.9 mЯн/ДН
max mc = 1.41%
Уровни V: -2.1, 2.1, 3.0, 4.2, 6.0, 8.4, 11.9, 16.8, 23.7, 33.4 mЯн/ДН

• AGN with detectable parsec-scale circular polarization often display transverse RM gradients, sheath-like polarization structures, and extended regions of transverse B.

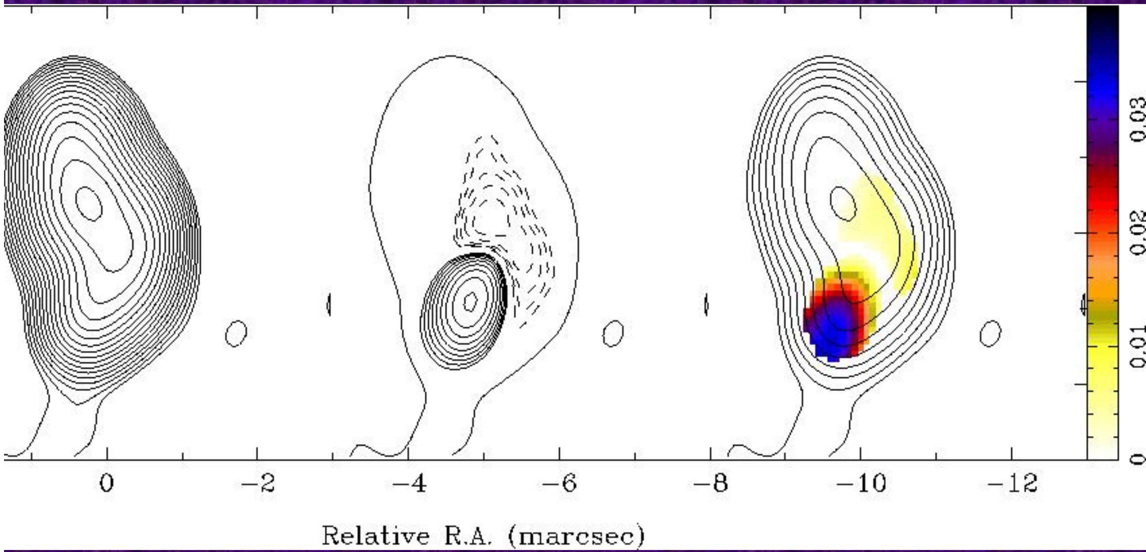
• CP has been detected in the JETS of about half a dozen AGN, far from the optically thick core region — mechanism generating CP can be efficient in optically thin regions.

— These two observations provide qualitative evidence that an appreciable amount of the detected CP may be associated with the presence of helical B fields (even in observed “core”, could be due to helical B in jet on scales below angular resolution).

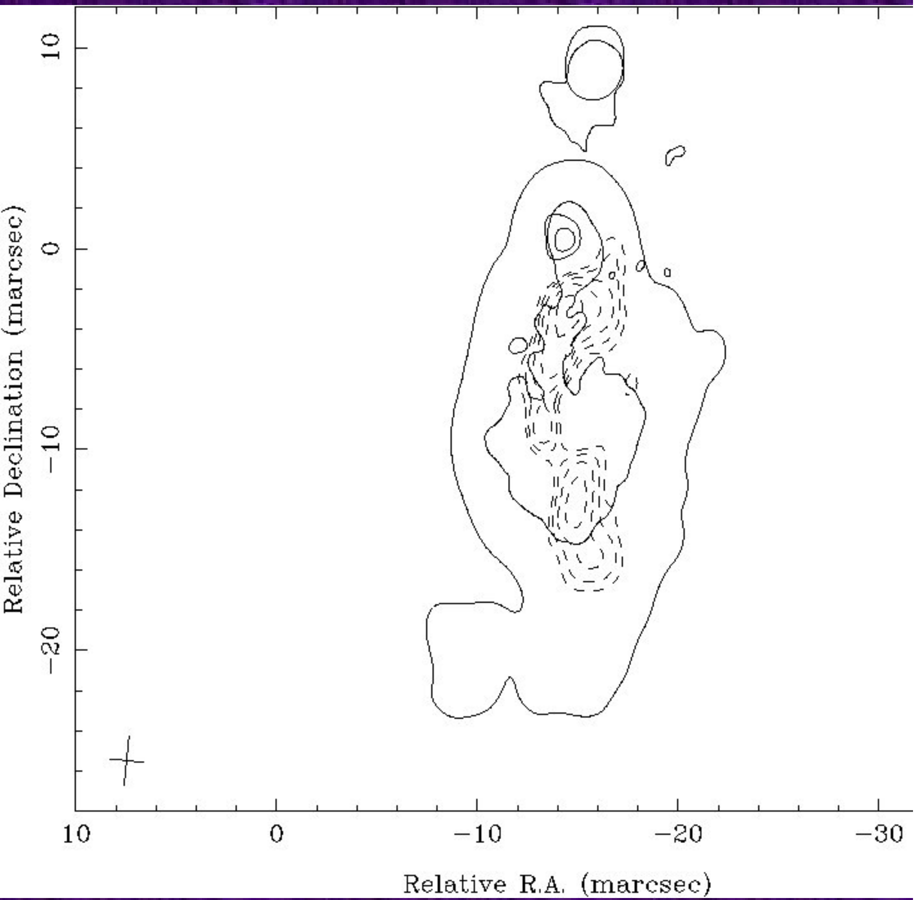
Also striking agreement of complex CP distribution obtained for 3C84 by Vitrishchak & Gabuzda (left, in prep) and Homan & Wardle (2005)

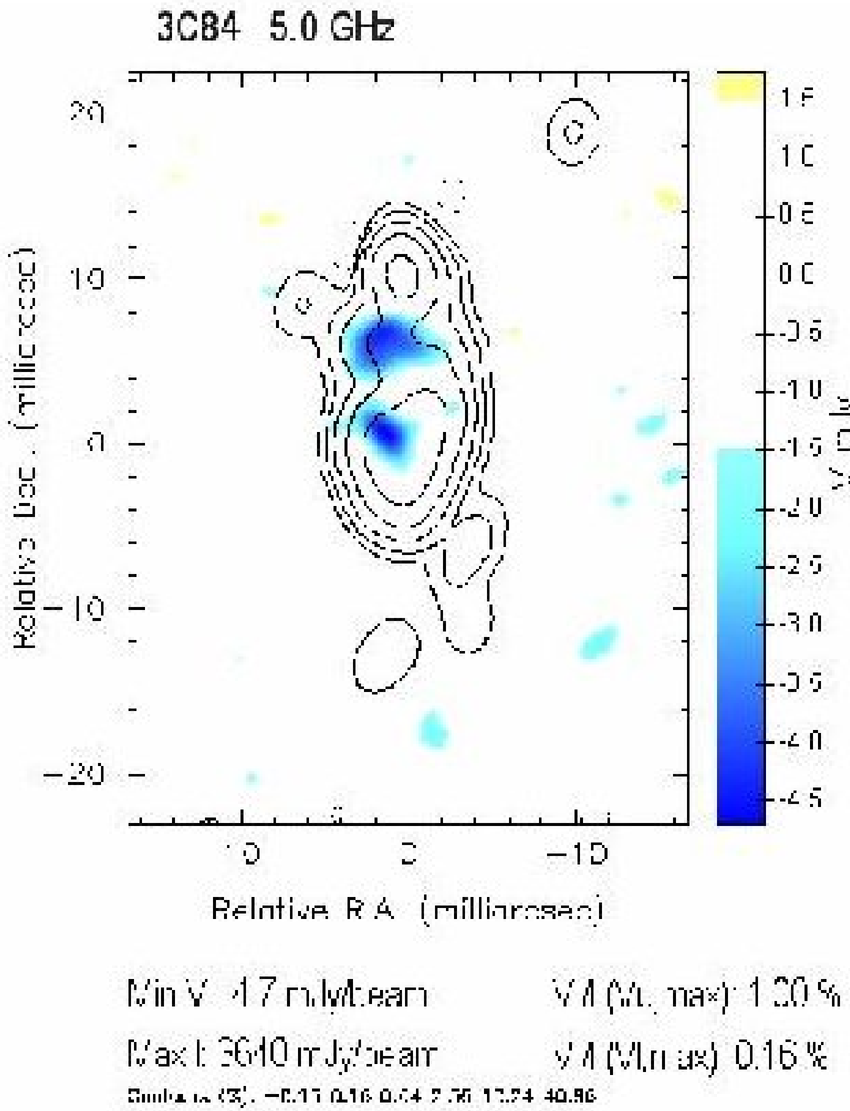


At 2cm…



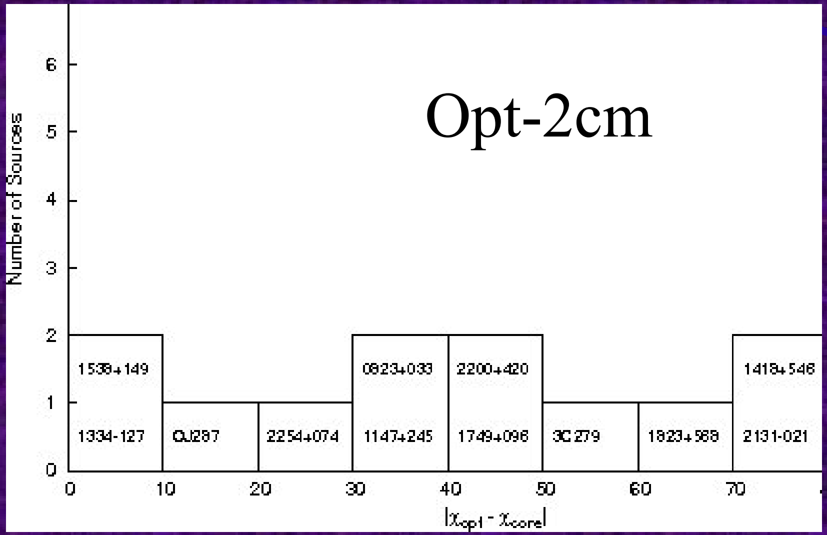
…and 6cm (Homan, Vitrishchak et al. in prep.)

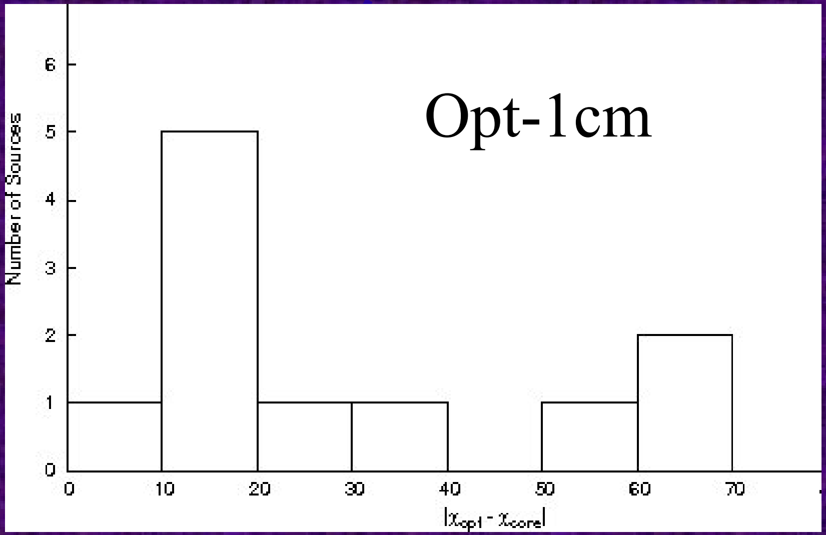


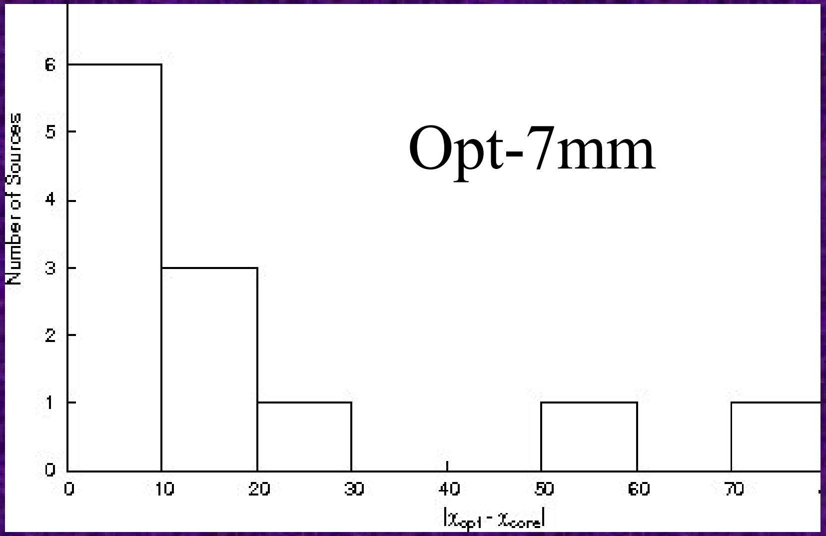


Again, mechanism must be able to generate extended regions of CP in jets

Correlations between Optical and VLBI core polarization angles (Gabuzda et al. 2006)

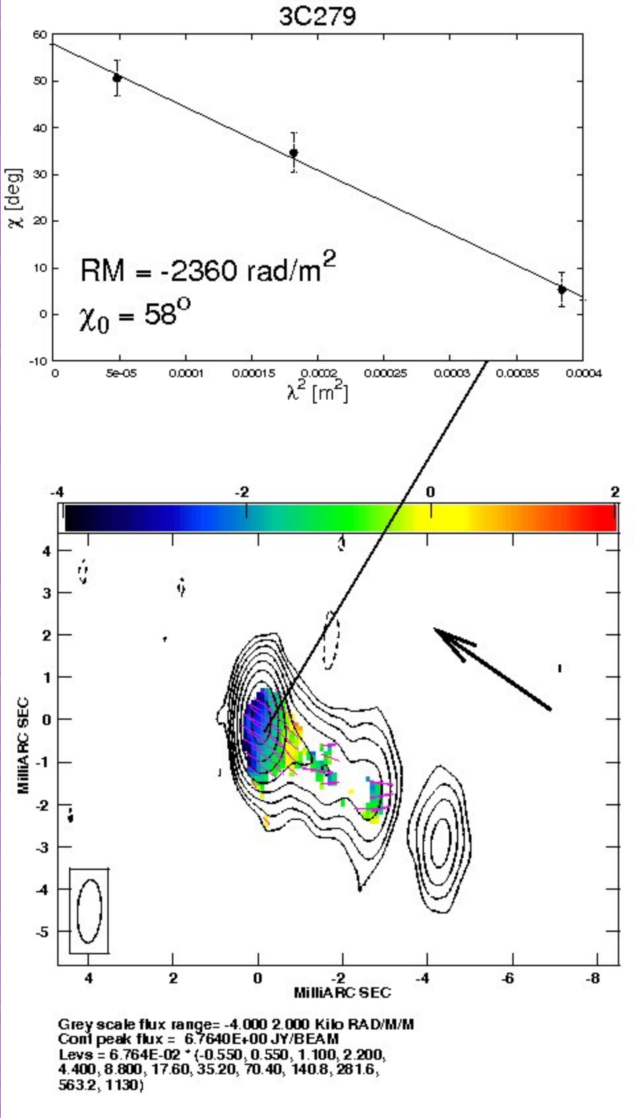


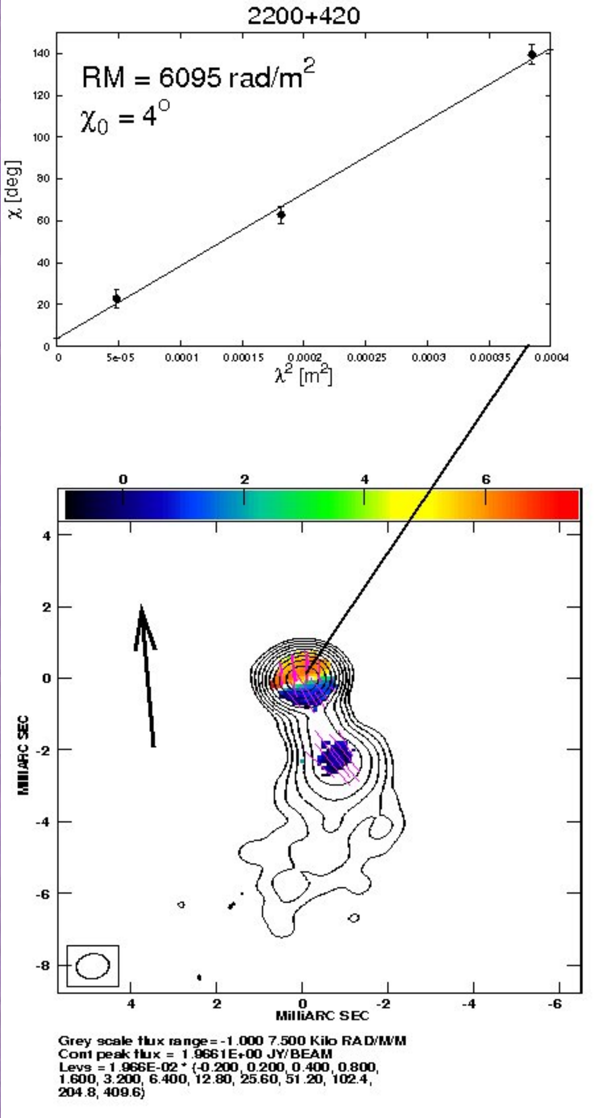


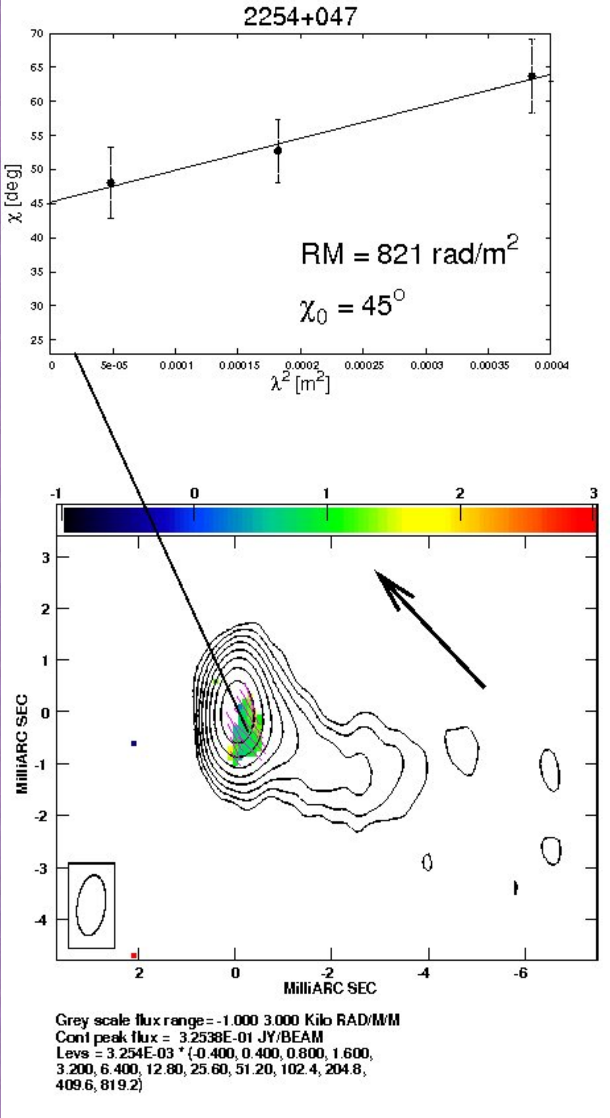


Improvement in correlation towards shorter wavelength due to increased resolution and decreased Faraday rotation in cores

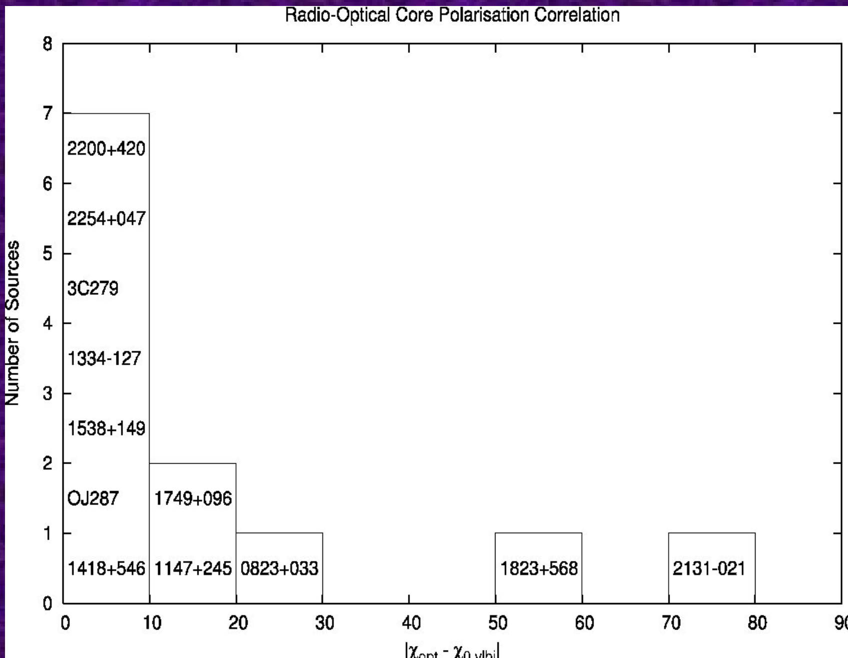
Determining intrinsic radio polarization angle using RM of VLBI core

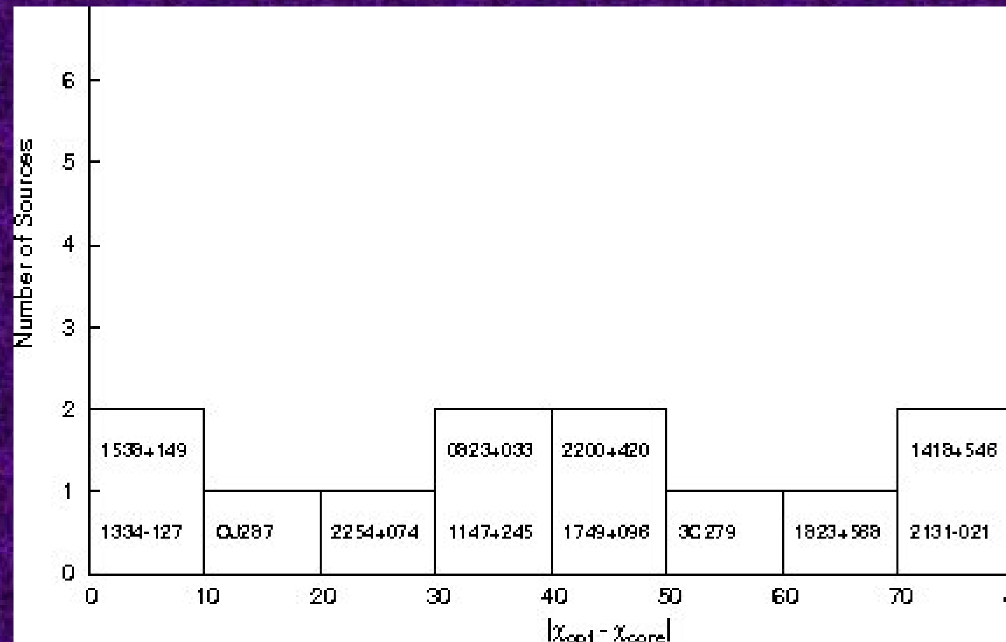






Comparison between simultaneously measured optical chi and RM-corrected radio core chi (left)

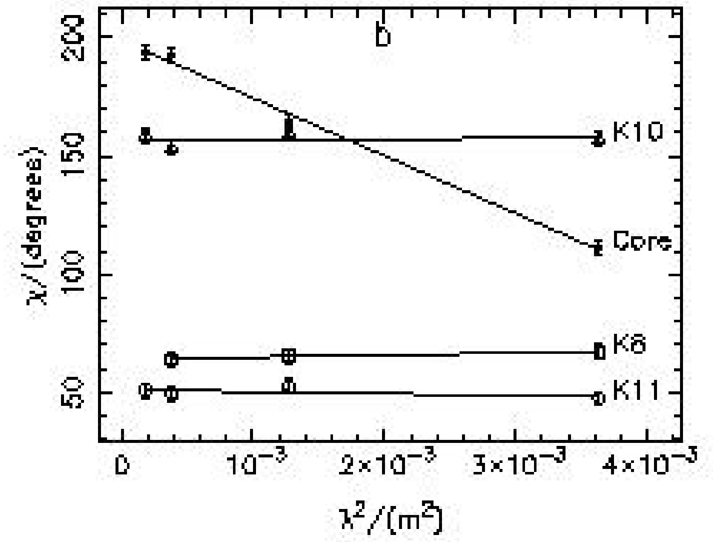




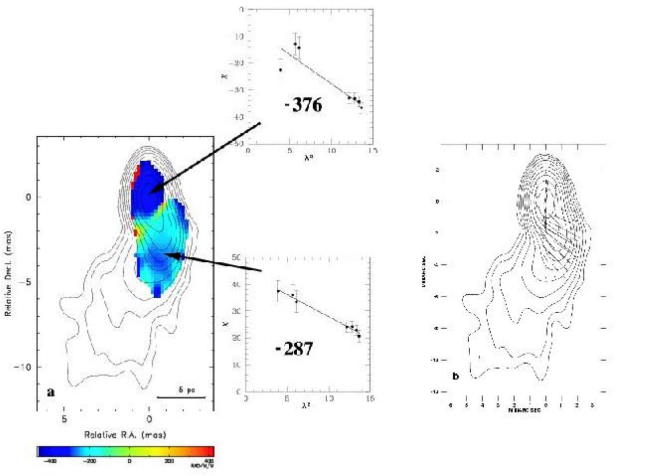
Opt— RM-corrected histogram

For comparison:
Opt—2cm histogram

Conclusion: optical and radio polarization arise in essentially same location within core region (or if in quite different regions, jets are very straight!)



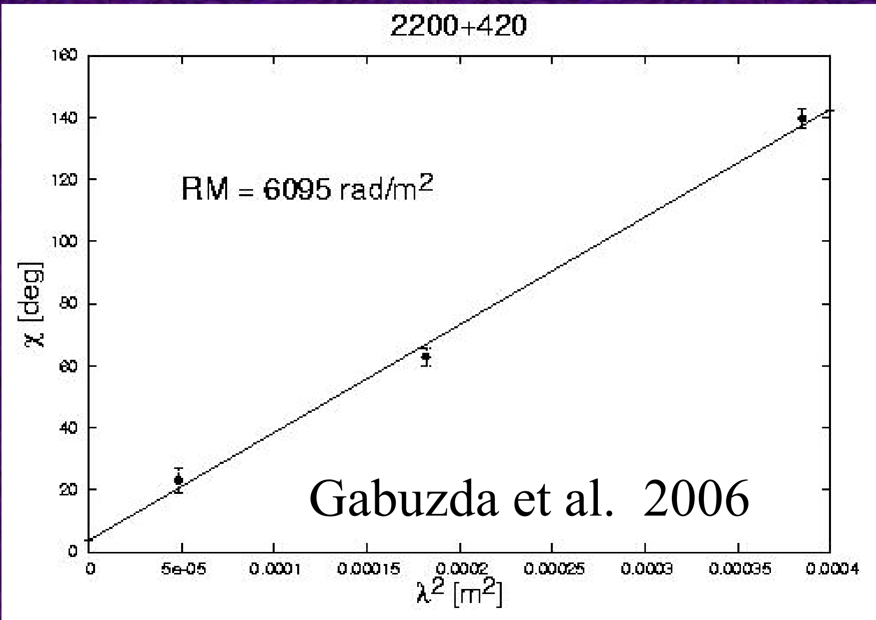
Reynolds, Cawthorne & Gabuzda 2000



Zavala & Taylor 2003

Fig. 25.— a) Rotation measure image (color) for BL Lacertae overlaid on Stokes I contours at 15 GHz. The insets show plots of EVPA χ (deg) versus λ^2 (cm²). (b) Electric vectors (1 mas = 25 mJy beam^{-1} polarized flux density) corrected for Faraday Rotation overlaid on Stokes I contours. Contours start at 2.2 mJy beam^{-1} and increase by factors of two.

Core RM measurements for BL Lac at 1.3-6cm and 2-4cm indicate MINUS several HUNDRED rad/m², but new measurements at 7mm-2cm yield PLUS several THOUSAND rad/m² (note also previous reports by Mutel & Denn)!



Gabuzda et al. 2006

How can this occur?

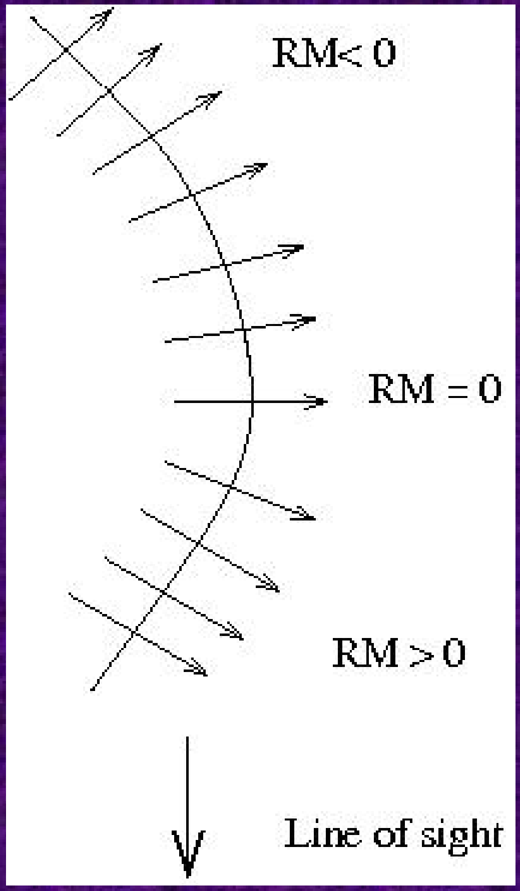
• Difference in direction of dominant LOS B field on different scales

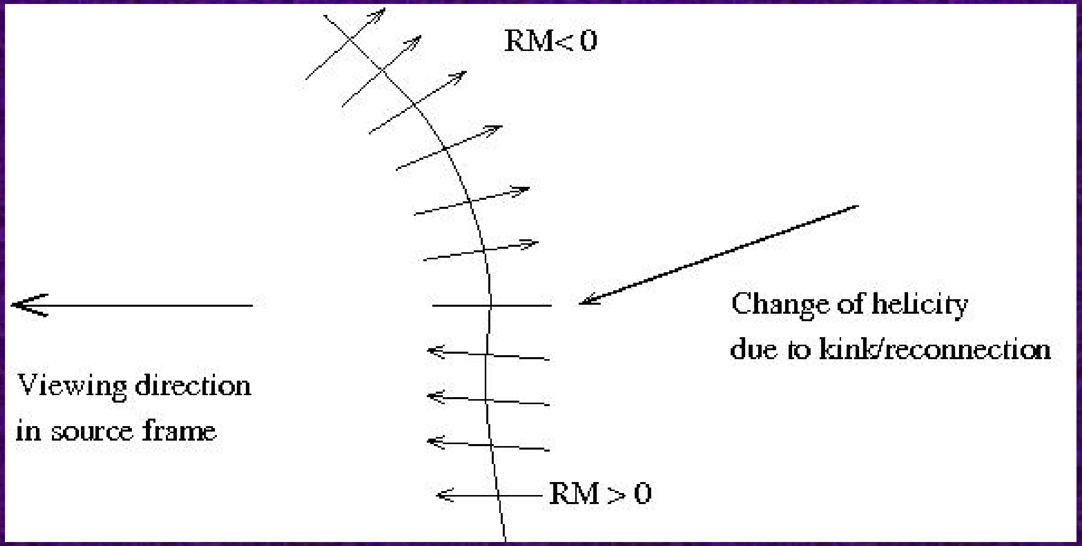
• Observations at different frequencies with different resolutions predominantly sample different scales

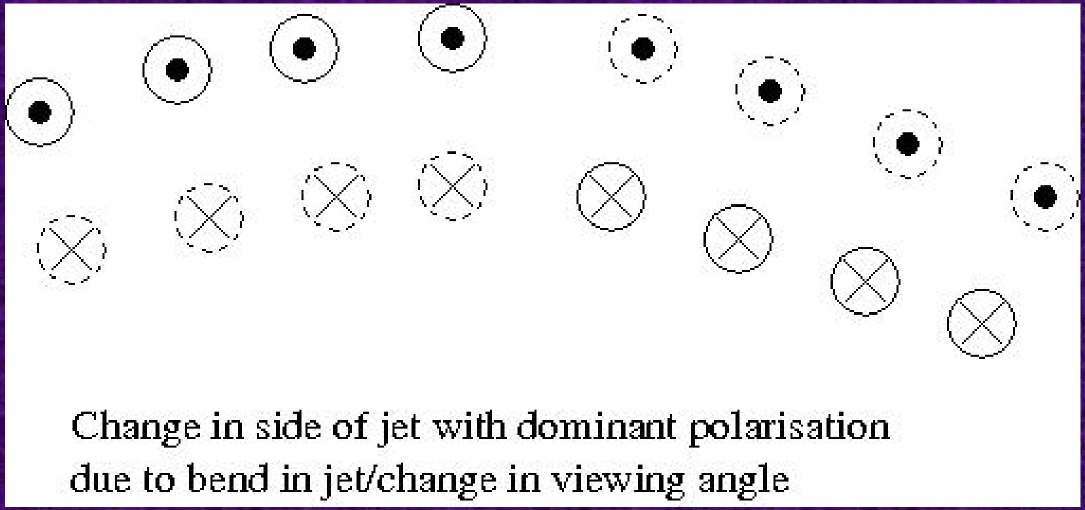
— New 7mm+1.3cm+2cm+3.6cm+6cm VLBA polarization observations planned to directly test this hypothesis (O'Sullivan & Gabuzda)

— May be possible to use changes in sign of RM along jet to reconstruct 3D B field structure to some extent

Schematics – how sign of RM can potentially change due to bends or kinks in jet with helical B field







We should not neglect opportunity to use the SIGN of the rotation measure to investigate the direction of the LOS magnetic field.

Summary/Future Work

• RM gradients transverse to VLBI jets are not uncommon, provide direct evidence for toroidal/helical fields

— Implies that jets carry current

— Getting first tentative evidence for changes in "winding" direction of helix

— Analysis of 6-frequency VLBA data for sample of 34 BL Lac objects ongoing (Mehreen Mahmud)

• "Sheath-like" polarization structures are also common, can be naturally interpreted as reflecting presence of helical jet B field

— MOJAVE; modelling of observed structures in helical field models (e.g. Papageorgiou & Cawthorne, in prep); new data for "sheath" sources await reduction at UCC, including intensity and polarization "tomography" (Shane O'Sullivan)

Summary/Future Work (2)

• Helical B fields provide favorable geometry for generation of circular polarization via Faraday conversion, many sources with CP display “symptoms” of helical B fields

• Clear CP detections in JETS have been made for about 6 AGN

— Is CP observed on parsec scales (in both cores and jets) associated with helical B fields?

— Could CP detection provide discriminator between helical and toroidal fields?

—MOJAVE; CP analysis for roughly 40 AGNs (Vasilii Vitrishchak); likely many data in VLBA archive amenable to a CP analysis

Summary/Future Work (3)

• Striking correlation between simultaneously measured optical and 7mm/RM-corrected VLBI core polarizations

— Optical and radio emission may be co-spatial (15 BL Lacs)

— New data for another 25 AGN await reduction (Juan Carlos Algaba)

• Firm evidence for different SIGNS of core rotation measure on different scales

— may reflect changes in winding direction and/or angle to LOS of helical B field associated with jet

— new 7mm–6cm data confirm and investigate (Shane O'Sullivan)

• Studying jets in context of helical B field models may provide opportunities to tie together seemingly disparate information about the CP properties, LP structure, and RM structure on subparsec to decaparsec scales (Slava Bezrukovs, Peter Veres)

Many thanks to all my research students, without whom I wouldn’t get an effing bit of research done:

Liza Rastorgueva (PhD, Tuorla Observatory)

Vasilii Vitrishchak (PhD, Moscow State University)

Brian Moloney (PhD, University College Cork)

Askea O’Dowd (Masters, University College Cork)

Mehreen Mahmud (PhD, University College Cork)

Vladislavs Bezrukovs (PhD, Cork Insitute of Technology)

Alexander Lebedev (starting Masters, Moscow State University)

Juan Carlos Algaba (starting PhD at University College Cork)

Peter Veres (starting PhD at University College Cork)

Shane O’Sullivan (starting PhD at University College Cork)

Challenges of Imaging Non-Relativistic Jets