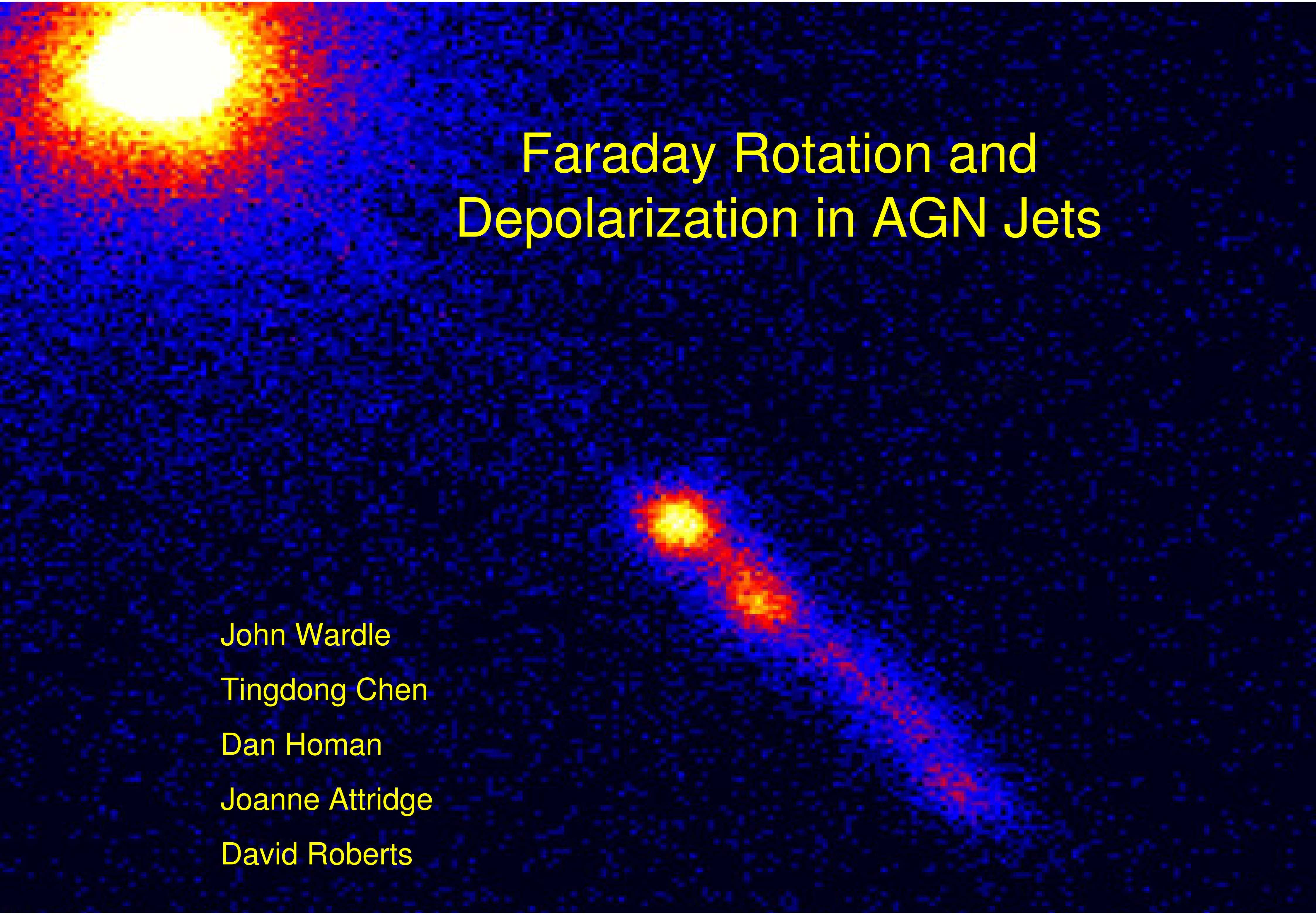

Faraday Rotation and Depolarization in AGN Jets

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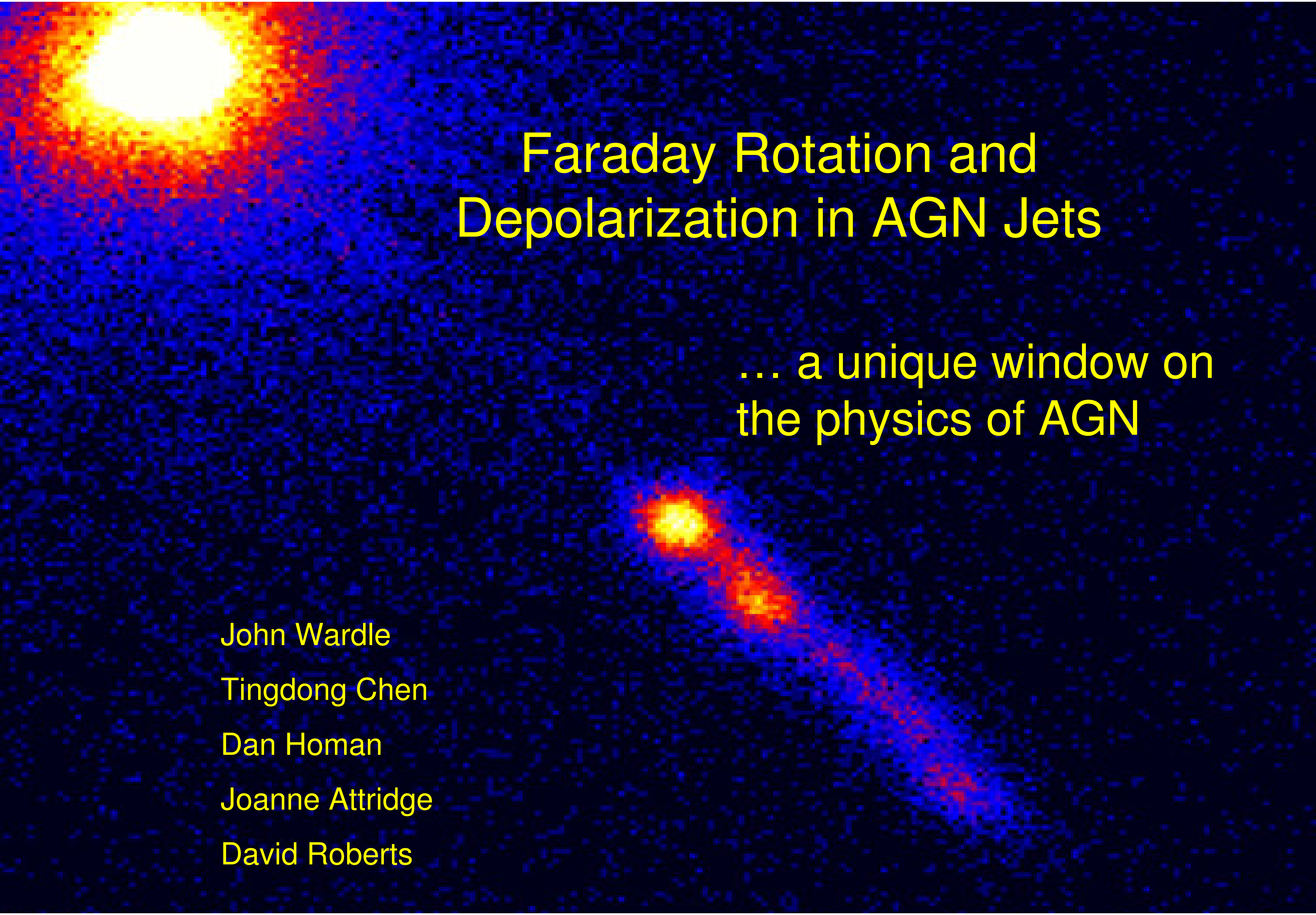

Faraday Rotation and Depolarization in AGN Jets

… a unique window on the physics of AGN

John Wardle

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OUTLINE

1. Preliminaries – Faraday rotation and depolarization

2. Pre-VLBA core rotation measures; why so small?

3. The radial distribution of Rotation Measure

4. The transverse gradient of Rotation Measure

Preliminaries

(1) $$\chi(\lambda) = \chi_o + RM \,.\, \lambda^2$$

(2) $$RM = 8.1\text{x}10^5 \int f_c N_e \, \mathbf{B.dl} \quad \text{rad m}^{-2} \quad : (\text{cm}^{-3}, \text{G}, \text{pc})$$

Preliminaries

(1) $\chi(\lambda) = \chi_o + RM \,.\, \lambda^2$

(2) $RM = 8.1\times10^5 \int f_c N_e \, \mathbf{B.dl}$ rad m^{-2} : (cm^{-3}, G, pc)

(2a) $f_c = (N^- - N^+)/(N^- + N^+) = N_{protons}/N_{leptons}$: include pairs

(2b) for relativistic particles, $n(\gamma) = K\,\gamma^{-p}$, $\gamma > \gamma_{min}$

$n_{eq} = (p-1)(p+2)/(p+1)\;\; n_{rel} \ln \gamma_{min}/\gamma_{min}^2 \quad \sim \quad K\,\gamma_{min}^{-(1+p)}$

(2c) $\langle \mathbf{B.dl} \rangle = \langle |B| \rangle\, L\, f_B$: field reversals, loops etc.

Caution about Cores:

1) The structure is unresolved, and often contains substructure with a range of Faraday depths.

2) Strong spectral effects

3) In an inhomogeneous jet most of the radiation comes from near the $\tau=1$ surface. Its location changes with wavelength ($R(\tau=1) \sim \lambda$, Blandford-Königl), so at different wavelengths you may be looking through different Faraday screens.

Faraday rotation + opacity is difficult to analyze.

Faraday Depolarization:

This is due to the ***spread*** of rotation measures, Δ **RM**. It comes in two varieties:

a) "Side-side" ----------- by an external screen, which tells you about the environment ***outside*** the jet

b) "Front-back" ----------- internal Faraday rotation, which tells you about the particles and fields ***inside*** the jet.

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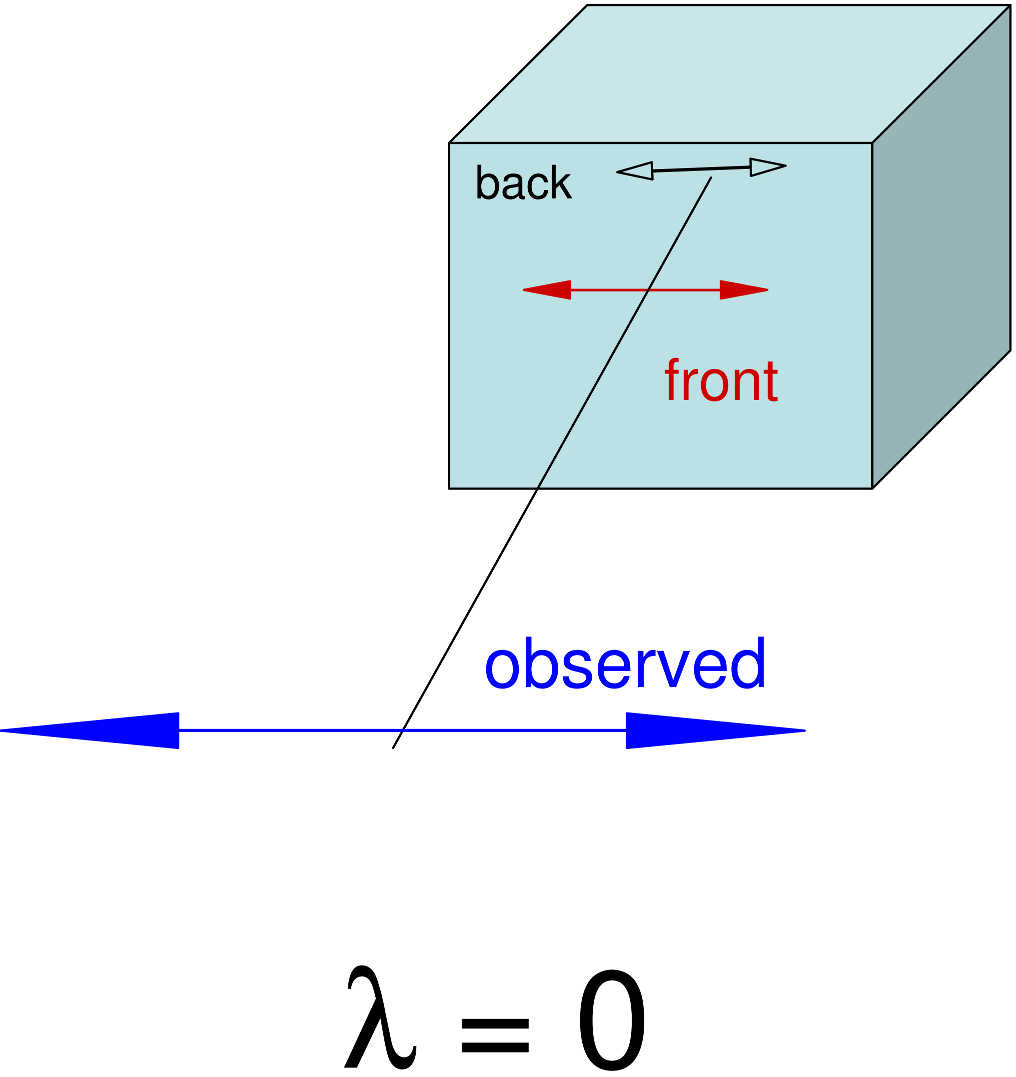
In either case (Burn 1966):

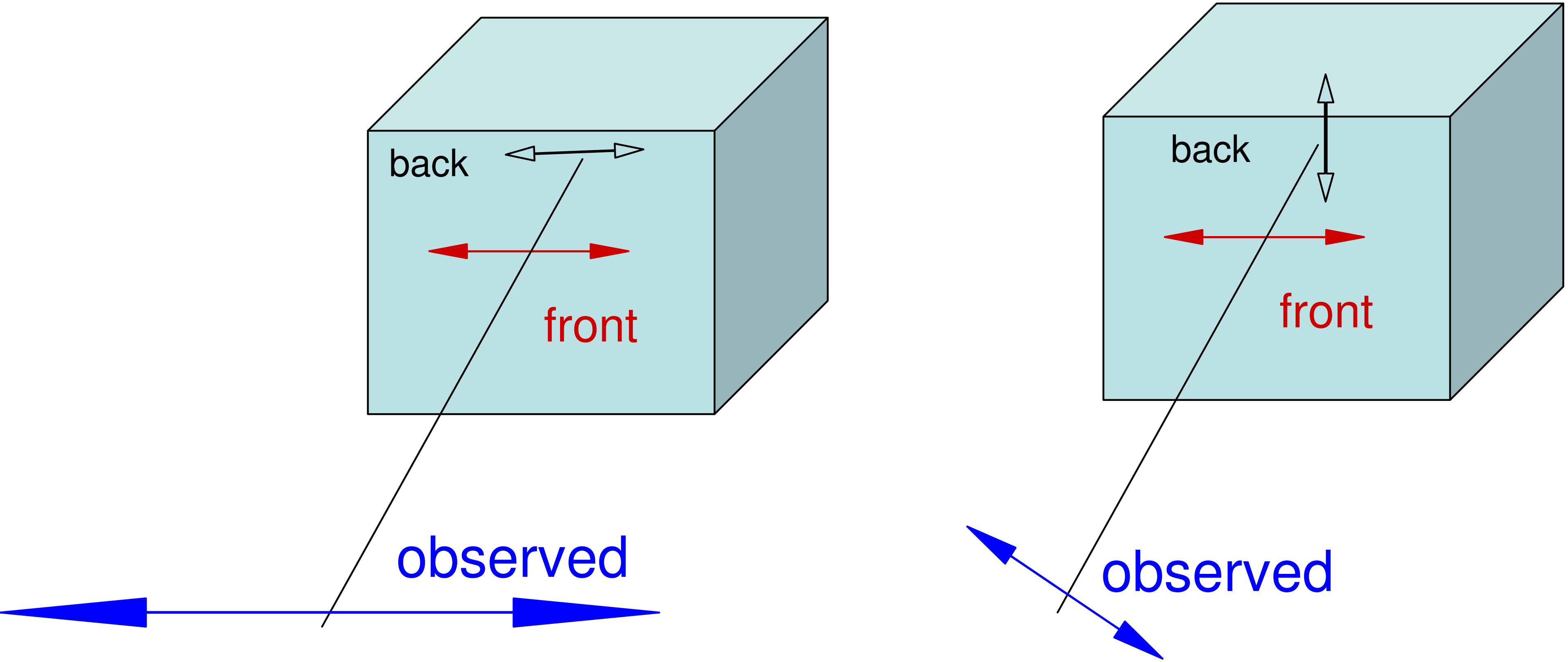
$$p(\lambda^2) \sim p(0) \exp - (\Delta \mathbf{RM}\, \lambda^2)^2$$

So how CAN you distinguish between internal and external Faraday rotation?



INTERNAL FARADAY ROTATION:

For $\lambda > 0$, polarized radiation from the back of the source is rotated, while radiation from the front is not.



$$\lambda = 0$$

$$\lambda = \lambda_{1/2}$$

$$\Delta\chi = 45^{o}$$

$$\mathbf{p(\lambda) \sim 0.5\ p(0)}$$

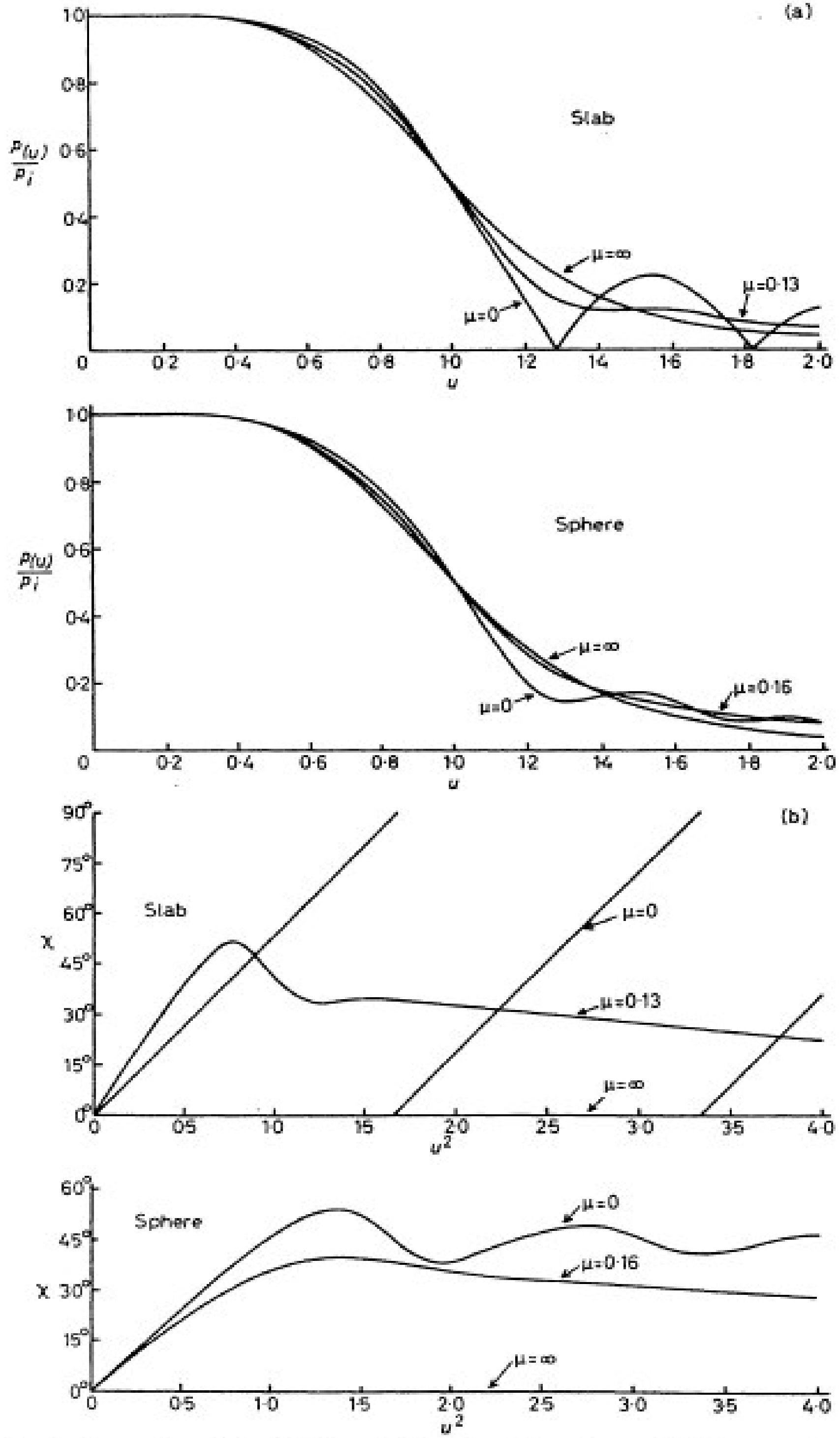


FIG. 2. *Polarization of models of internal Faraday dispersion. (a) Degree of polarization; (b) angle of polarization.*

Burn's (1966) model for internal Faraday rotation

Here, u is a scaled wavelength ($u = \lambda/\lambda_{1/2}$), and μ is the ratio of the random and uniform components of rotation measure.

For $\mu > 0$ and $u > 1$, χ is not ~ constant, but in fact executes a random walk.

Corollary: If the observed EVPA rotates through much more than 45^o, without a decrease in the fractional polarization, then the Faraday rotation **MUST be external** to the emitting region.

The Observations

a) Pre-VLBA core rotation measures

b) Radial distributions of rotation measure

c) Transverse gradients of rotation measure

"Core" rotation measures pre-VLBA

VLA observations of compact sources typically measure just a few hundred radians/m^2 (e.g. Rudnick & Jones 1983, O'Dea 1989)

"Expected" values for the NLR: $N_eT \sim 10^8$ Kcm^{-3}

so in the hot inter-cloud medium $N_e \sim 10$ cm^{-3}

$B_{eq} \sim 10^{-3}$ G

$L \sim 100$ pc

this gives RM ~ 2 x 10^5 rad/m^2 ------- 1000 times too big

So $B \ll B_{eq}$ or the field is very tangled ($f_B \ll 1$) etc

Polarization variations

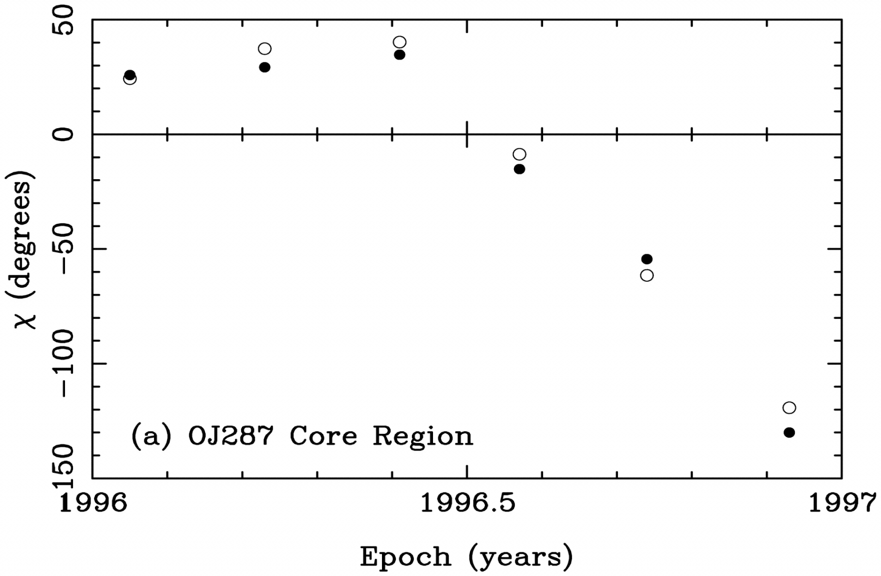
Altschuler & Wardle 1975 - 77 (3-element interferometer), Aller[2] UMRAO 85'

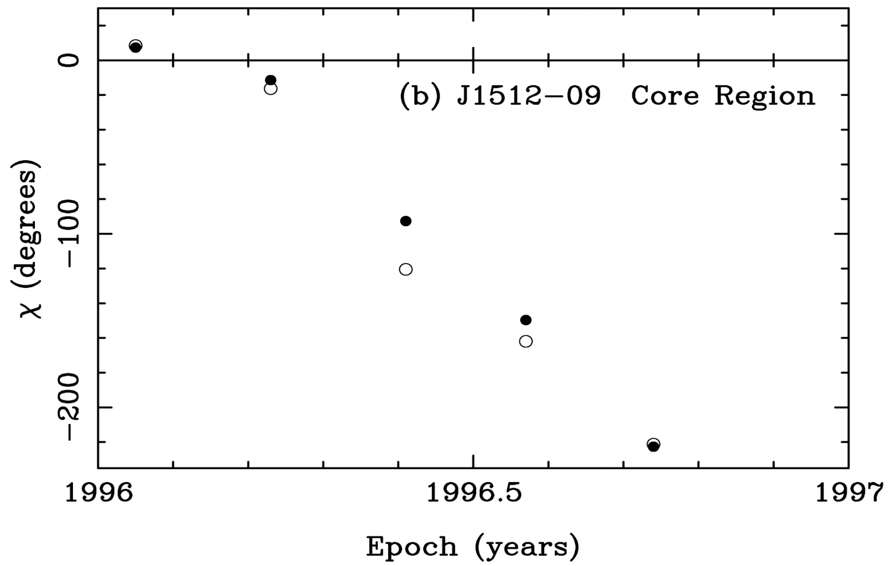
Homan, Ojha et al 2000 - 04 (VLBA), Marscher, Jorstad et al (VLBA)

Variations in χ are NOT primarily due to variable rotation measure.

Upper limits on internal Faraday rotation are so low that $\gamma_{min} > 100$,

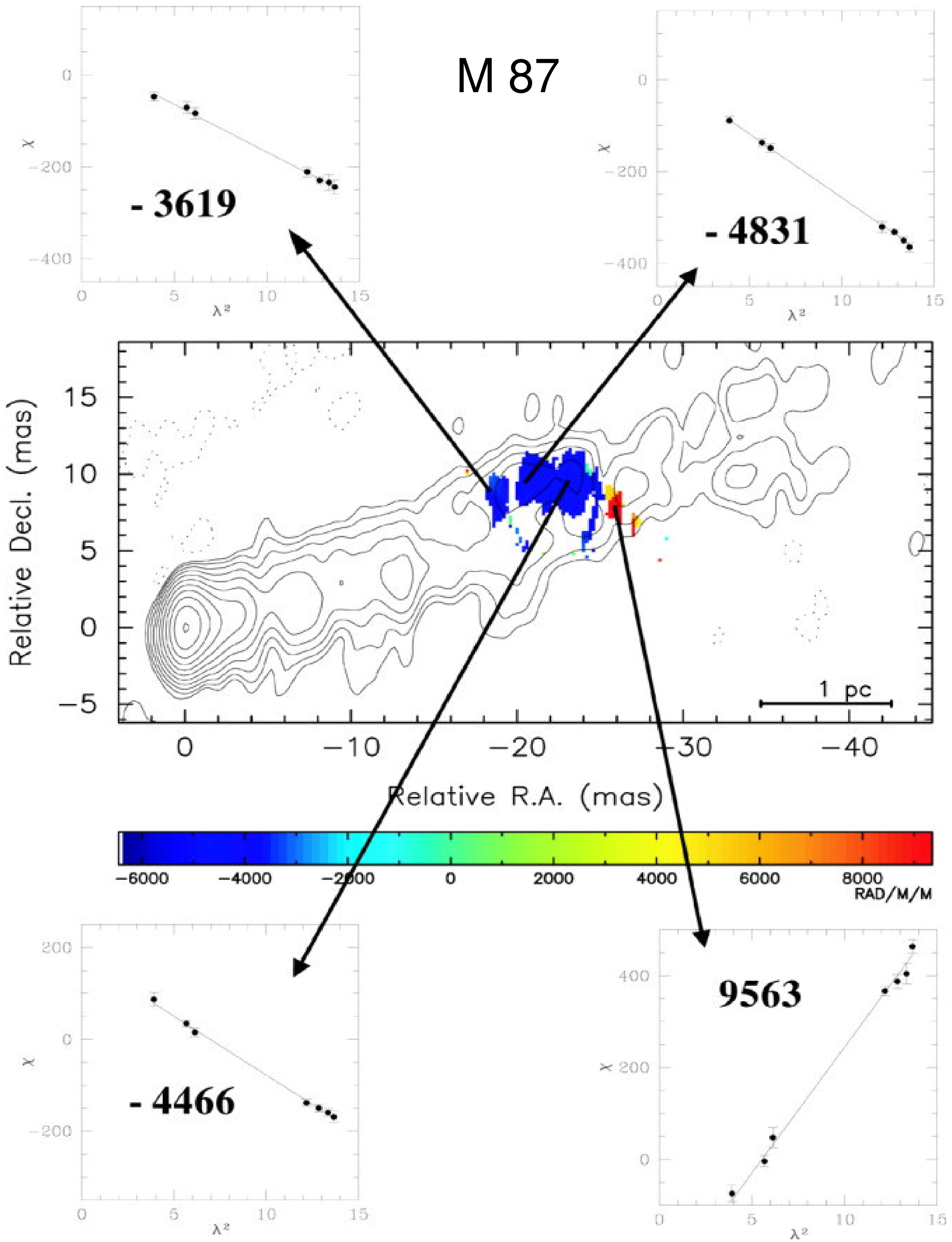
or the source is pair dominated.

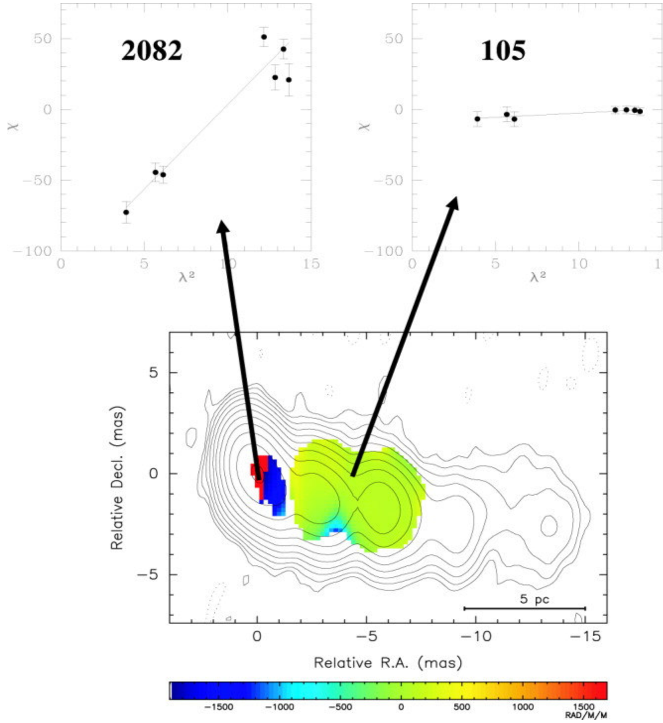




Radial distribution of rotation measure

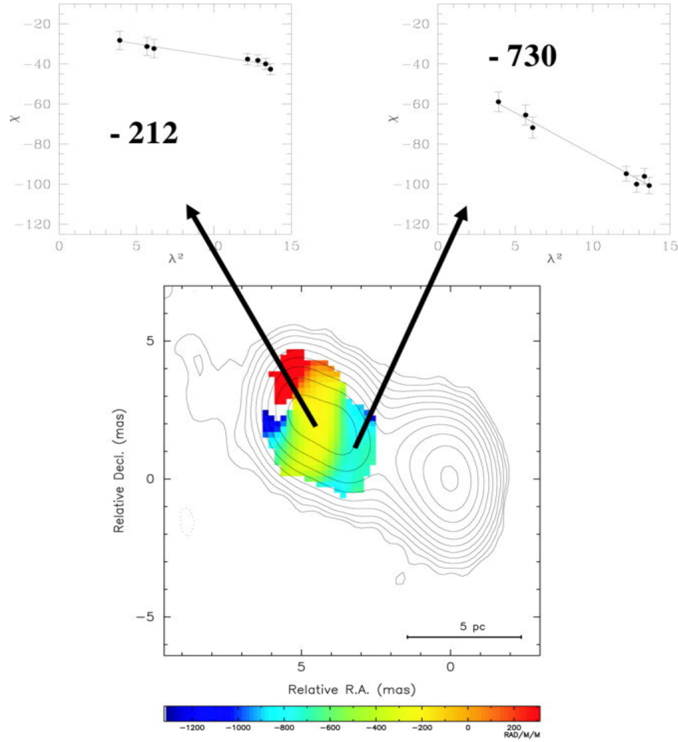
GALAXIES:





3C 120

3C 111



Zavala & Taylor 2002

QUASARS:

Taylor 1998, 2000

3C 273

3C 345

3C 279

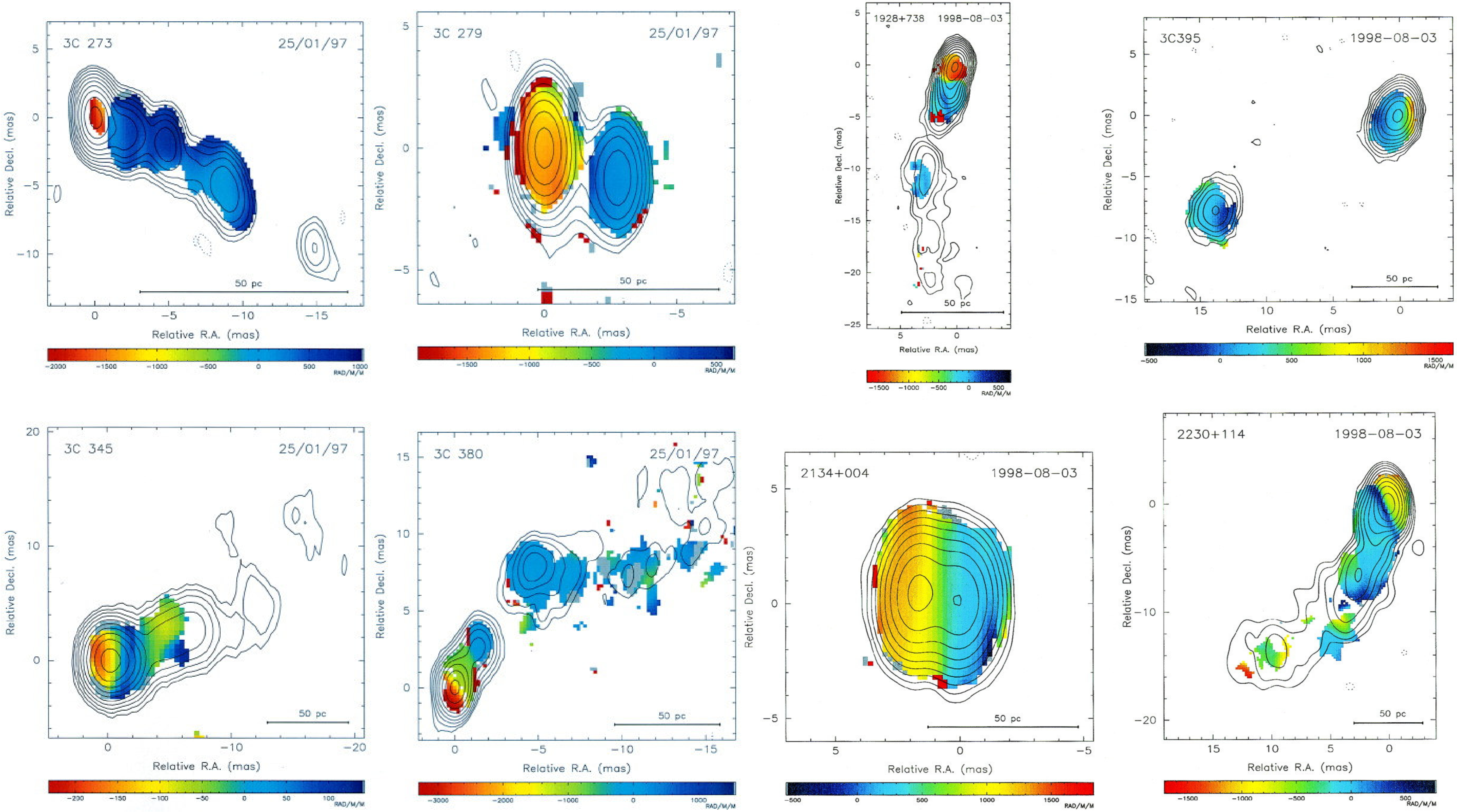
3C380

1928+738

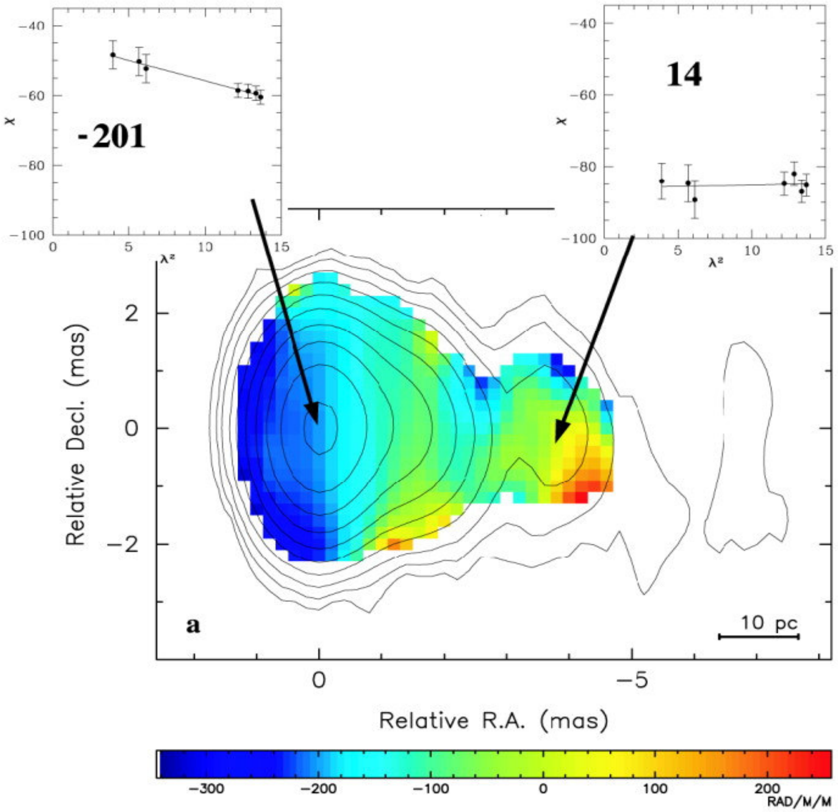
2134+004

3C 395

CTA 102

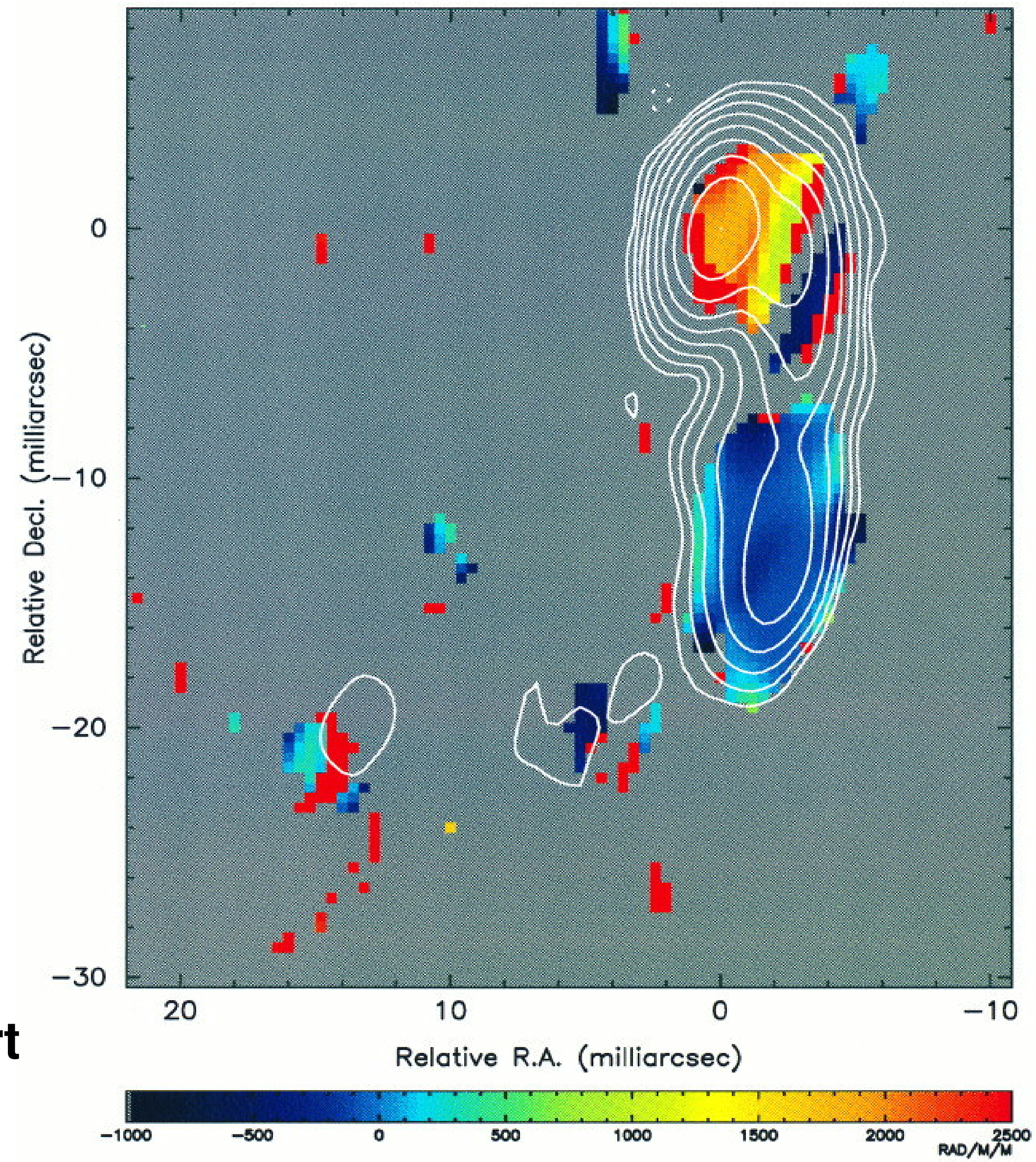


1803+784 (BL Lac Object, z=0.68)



Zavala & Taylor 2003

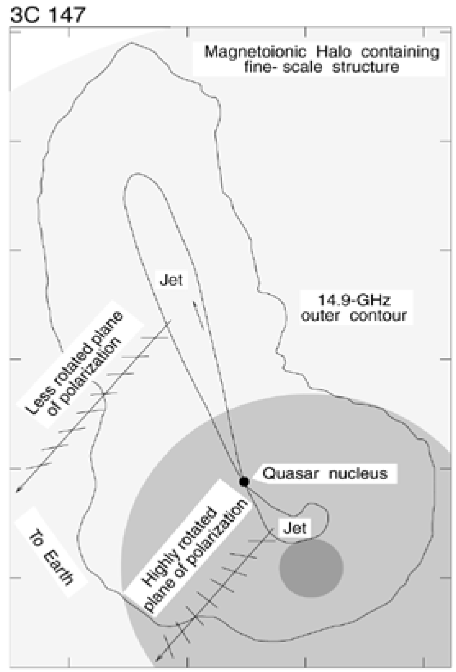
Udomprasert et al. 1997



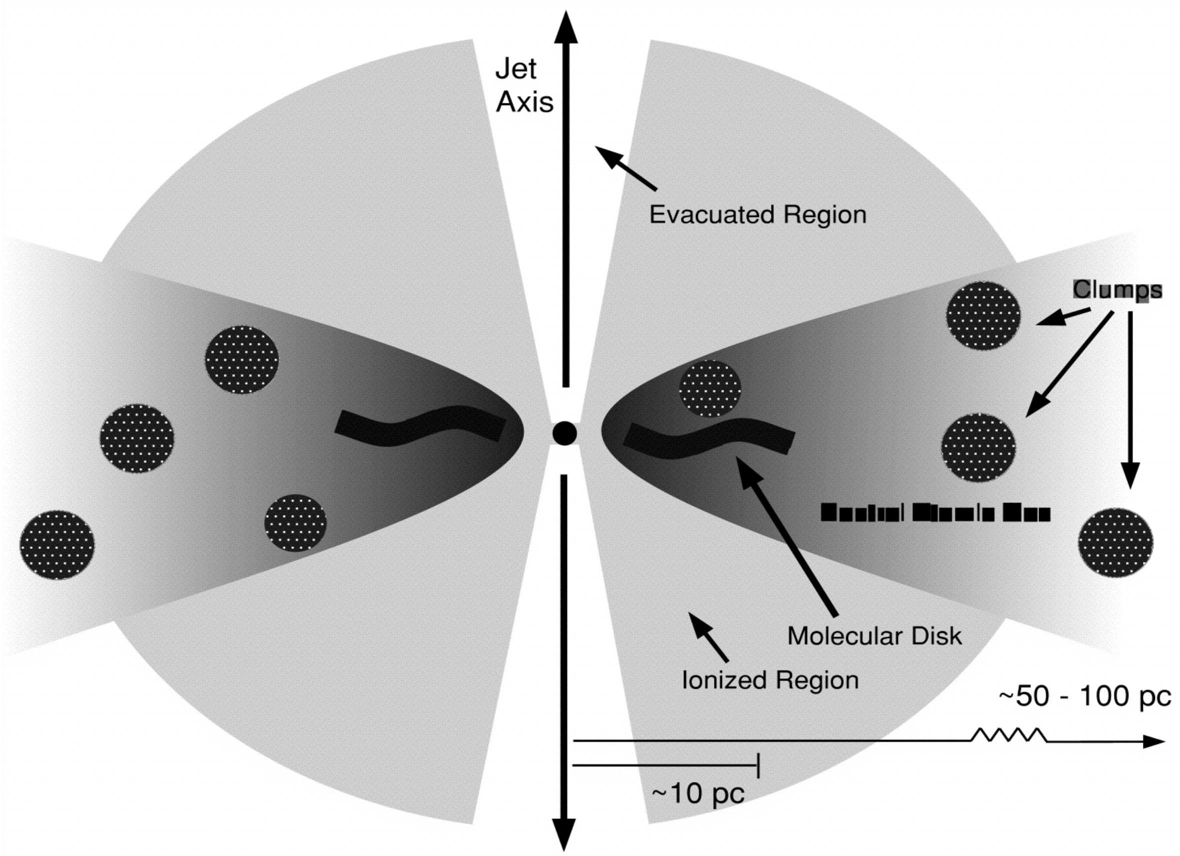
OQ 172 (quasar, z = 3.53)

Host galaxy rest frame RM is larger by $(1+z)^2$ = 20.5 here. For *internal* rotation in the jet, the comoving frame RM also includes (Doppler factor) $^{-2}$, which will typically be larger than the redshift effect, and in the opposite direction.

CLUES ABOUT THE ENVIRONMENT

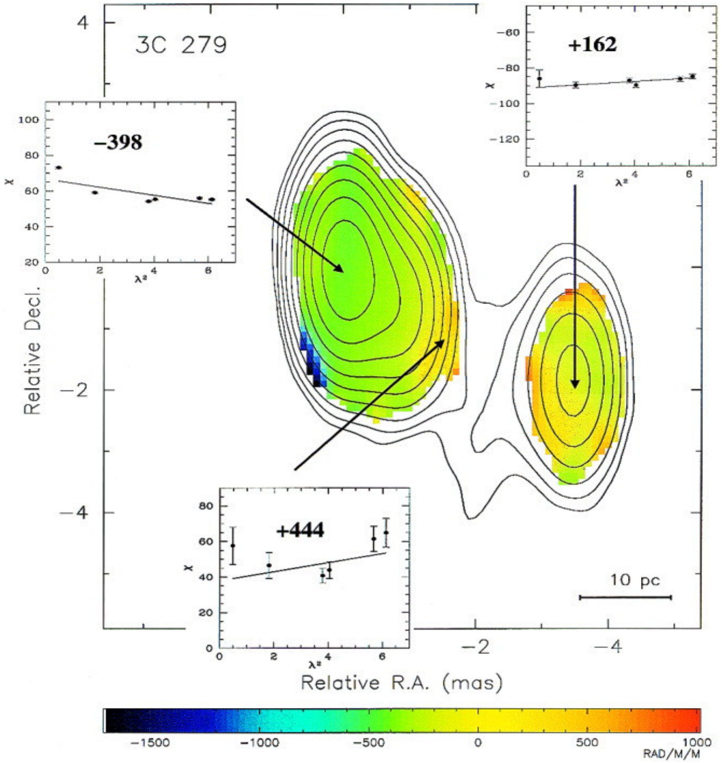


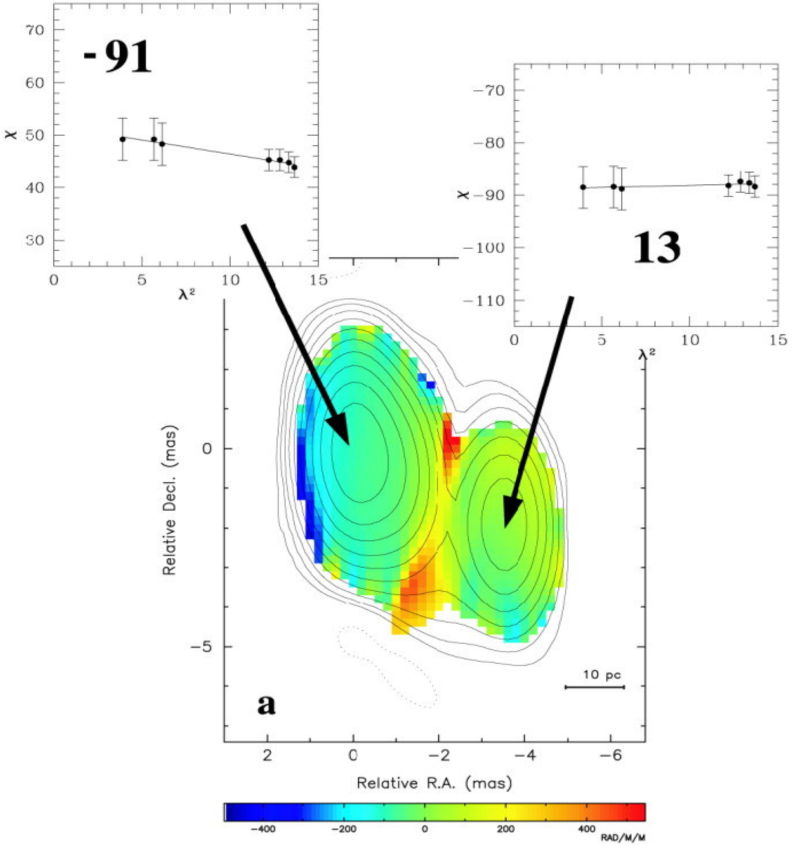
Connection to ISM, cloud interactions etc (Junor et al)

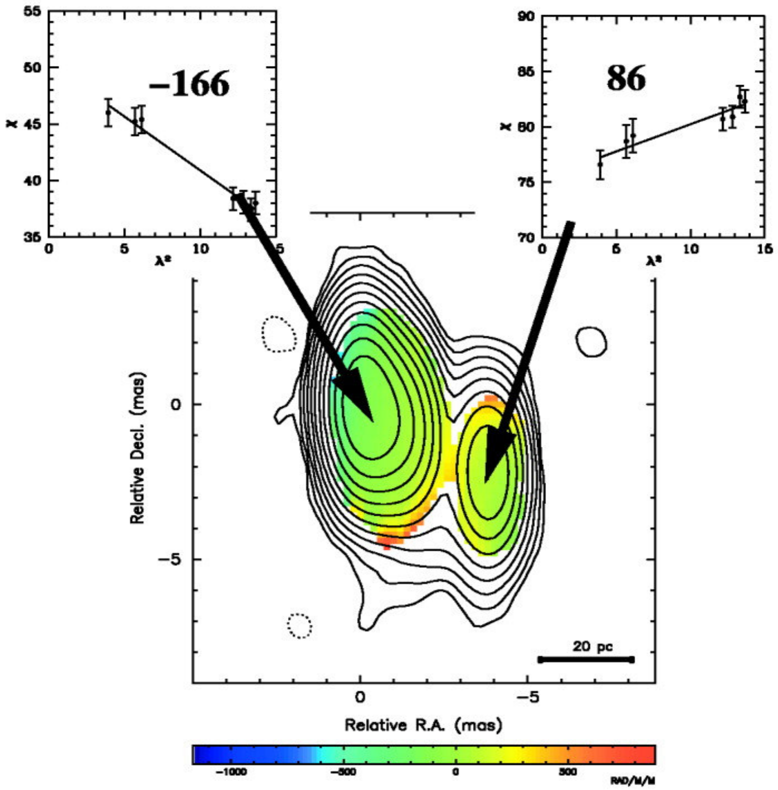


Connection to AGN structure, inflow, outflow, unified models etc (Taylor et al)

Variable jet rotation measures: 3C 279

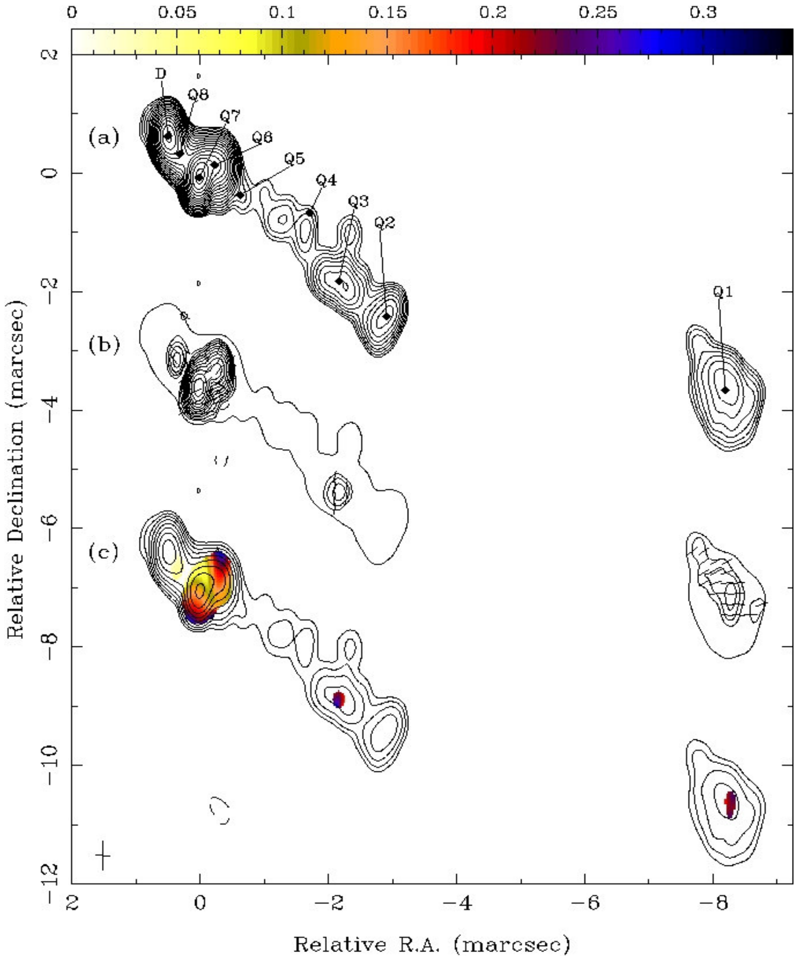


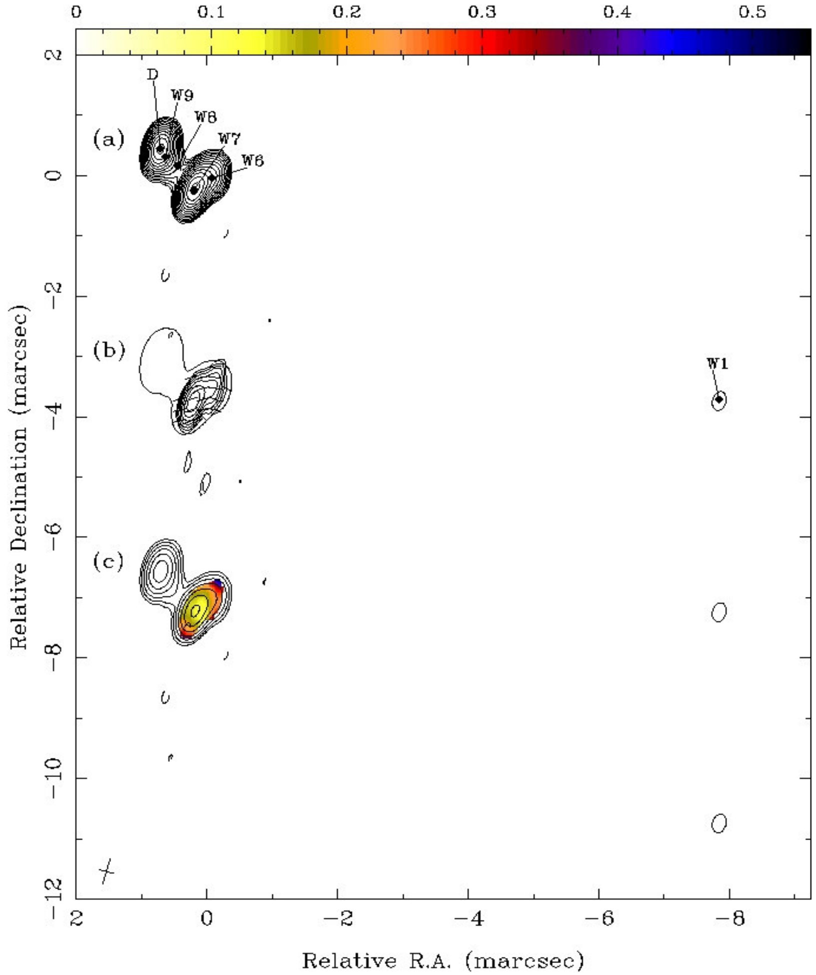




Taylor & Zavala

Core Depolarization





43 and 86 GHz (7.0 and 3.5 mm)

Attridge, Wardle & Homan 2005

Newspaper reporter: “Why do you rob banks”

Willy Sutton (famous American bank robber):

“That’s where the money is.”

(New York City, c. 1950)

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(New York City, c. 1950)

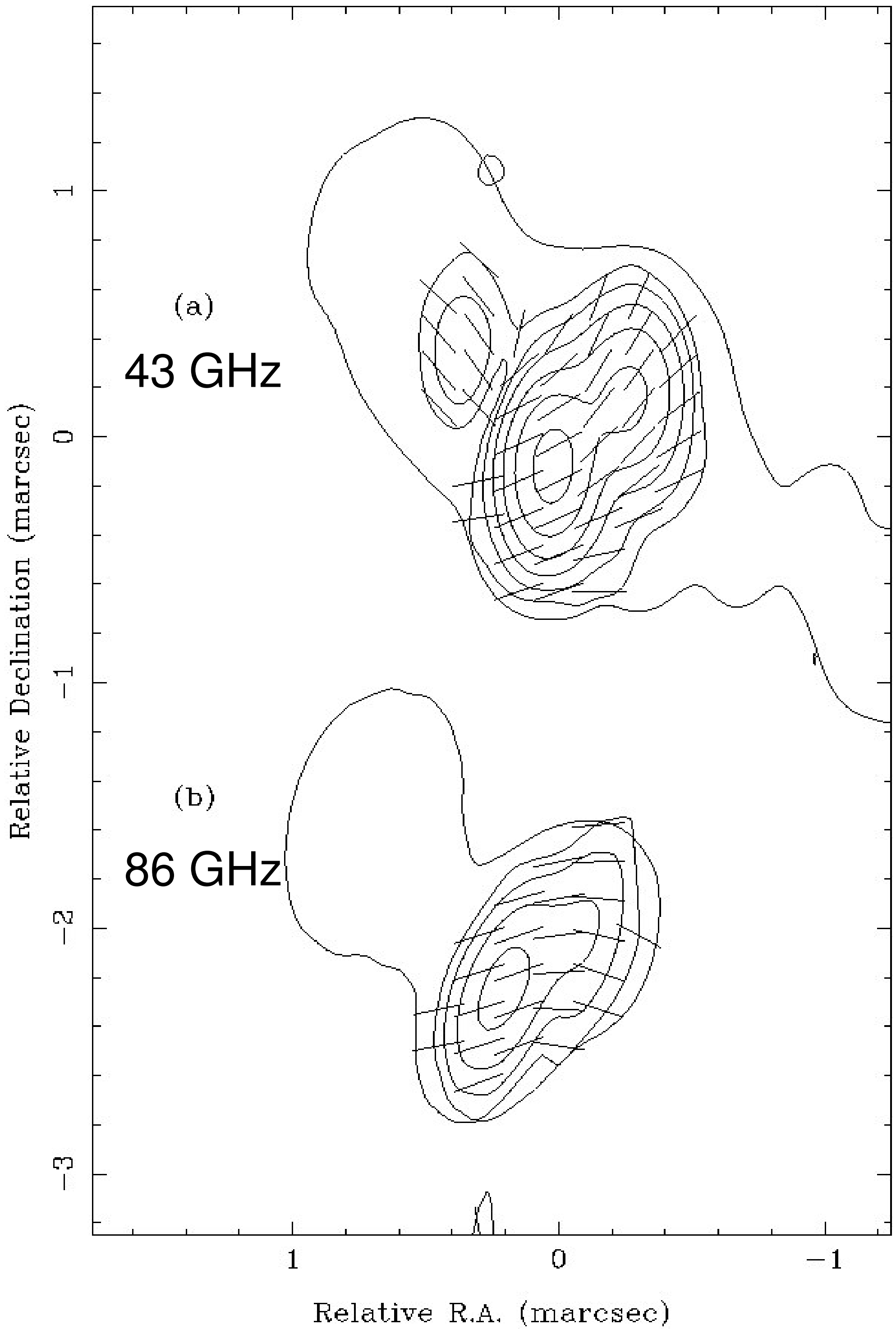
“Why observe polarization at millimeter wavelengths?”

J. Wardle (who hasn’t robbed any banks yet):

“That’s where the large rotation measures are.”

(Krakow, 2006)

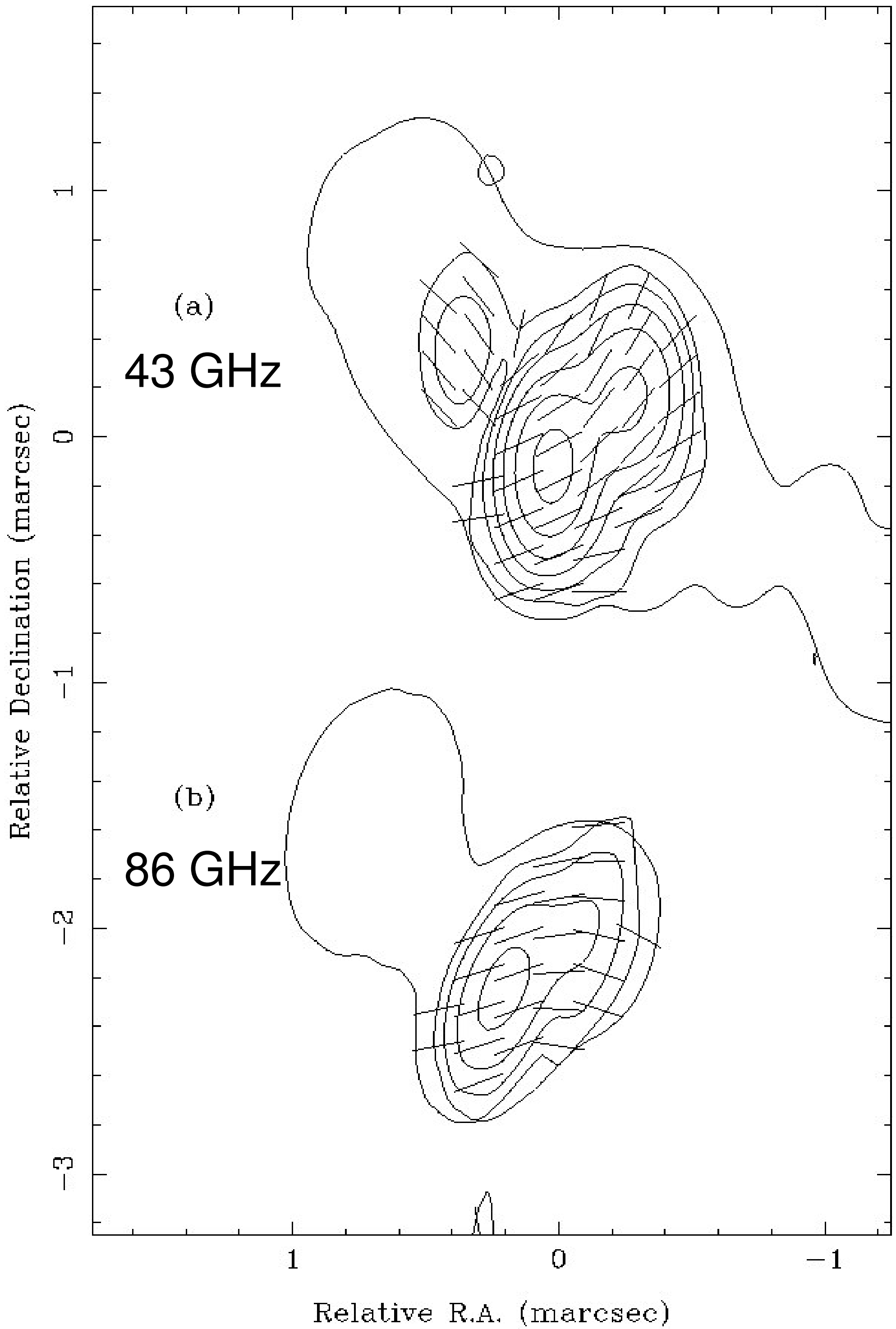
$\Delta\chi = 60^{o}$: minimum RMs are $\pm$ 21,000 rad/m^2



$\Delta\chi = 60^o$: minimum RMs are ± 20,000 rad/m^2

The base of the jet is still depolarized at 86 GHz and probably also at 300 GHz.

This is consistent with the observed steep RM gradient, and may be connected to the accretion flow, e.g. Sgr A*, or a disk wind.



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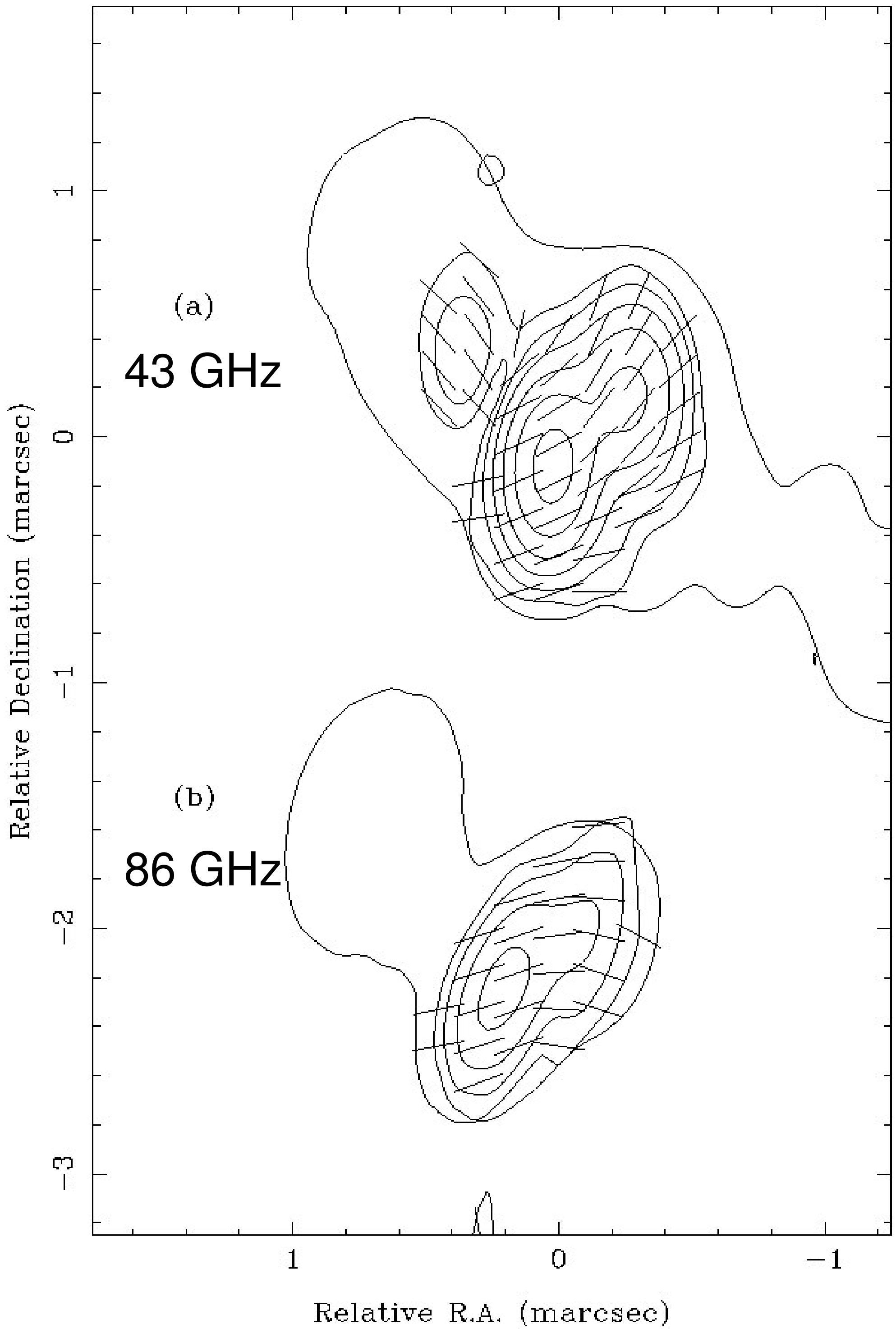
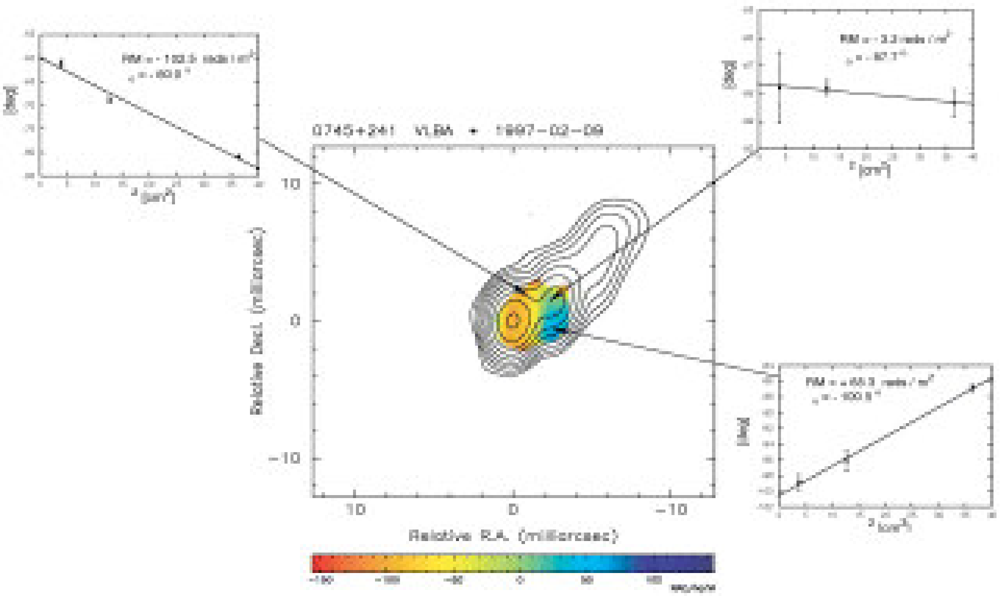
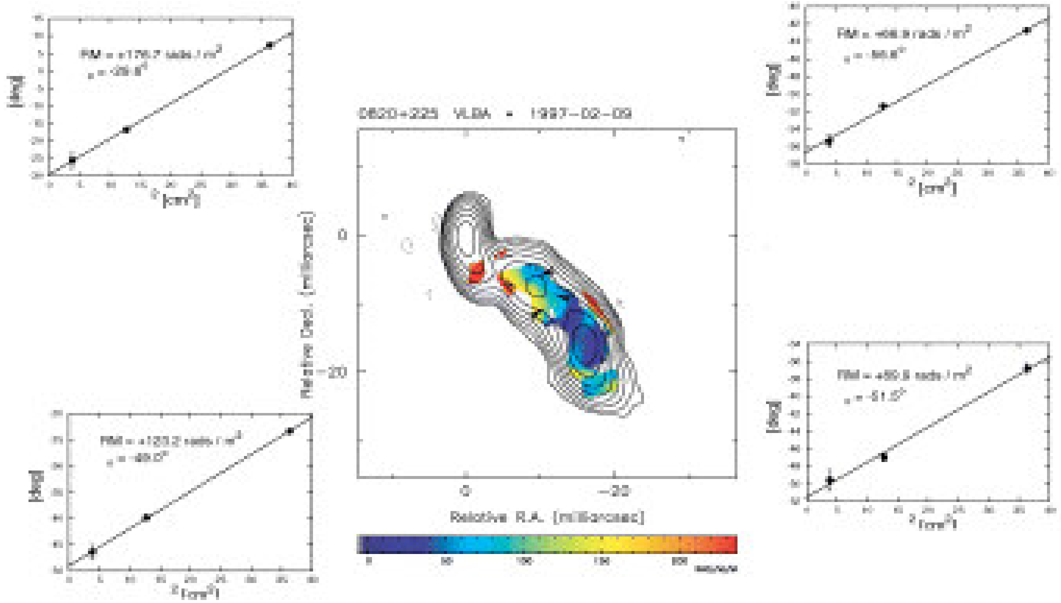
Other quasars observed at similar *linear* resolution, might well exhibit similar properties.



Transverse gradient of rotation measure

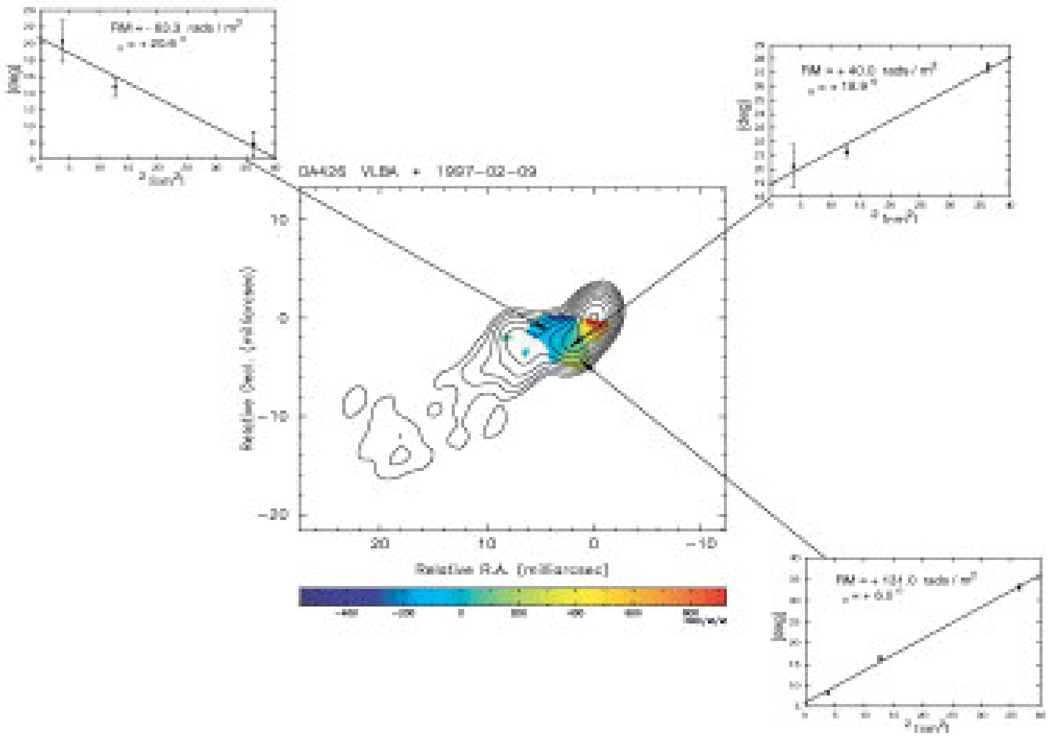


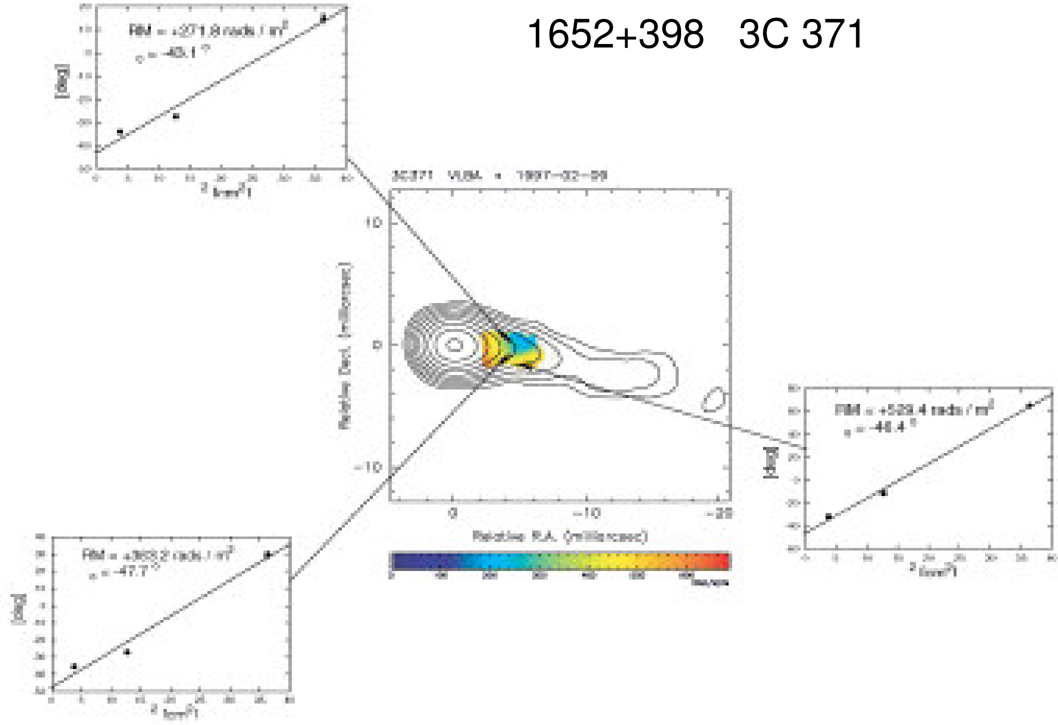


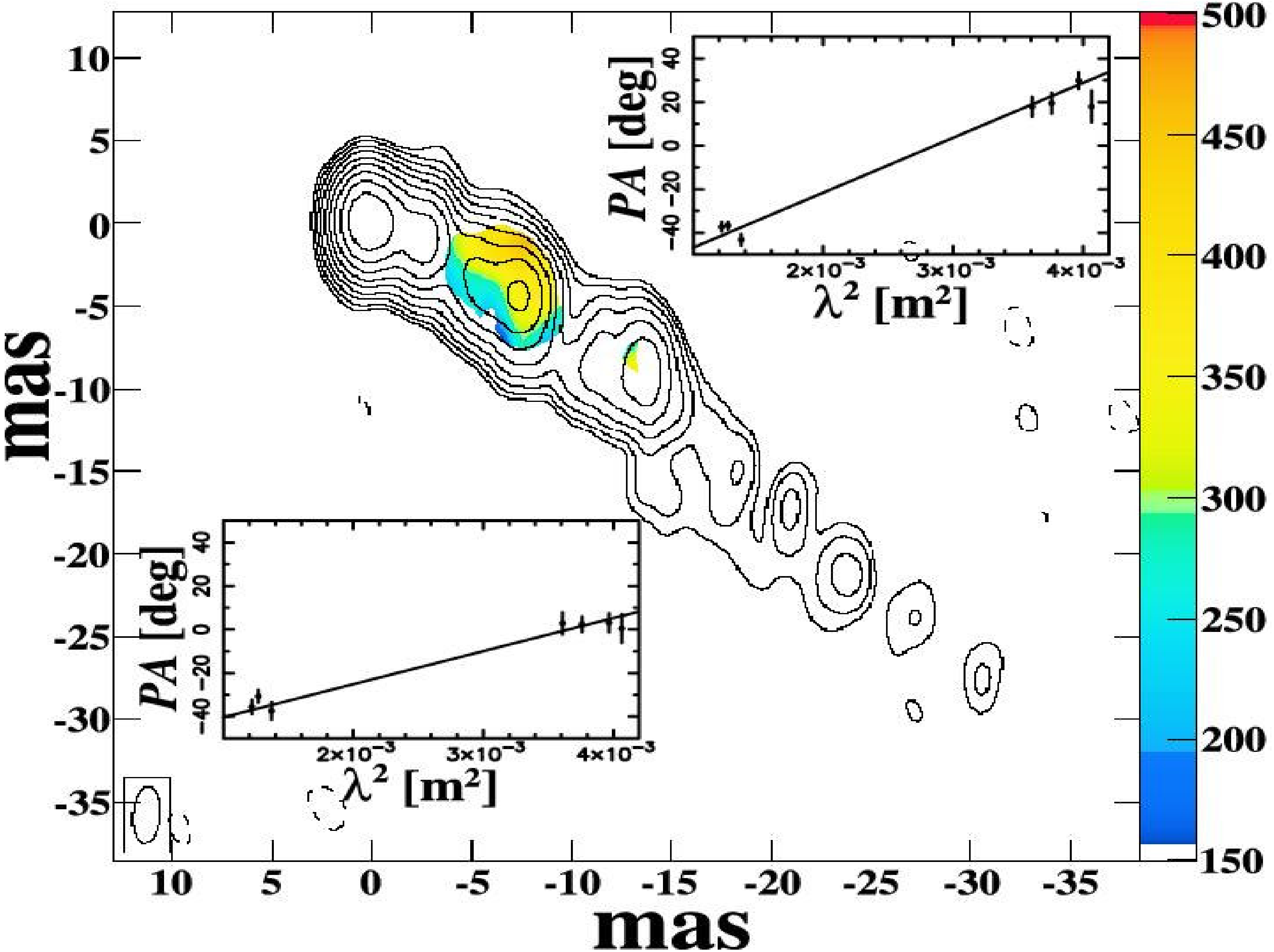
Gabuzda et al 2004: **RM gradients = 25 - 200 rad/m²/mas**

0745+241 0820+225

1652+398 3C 371

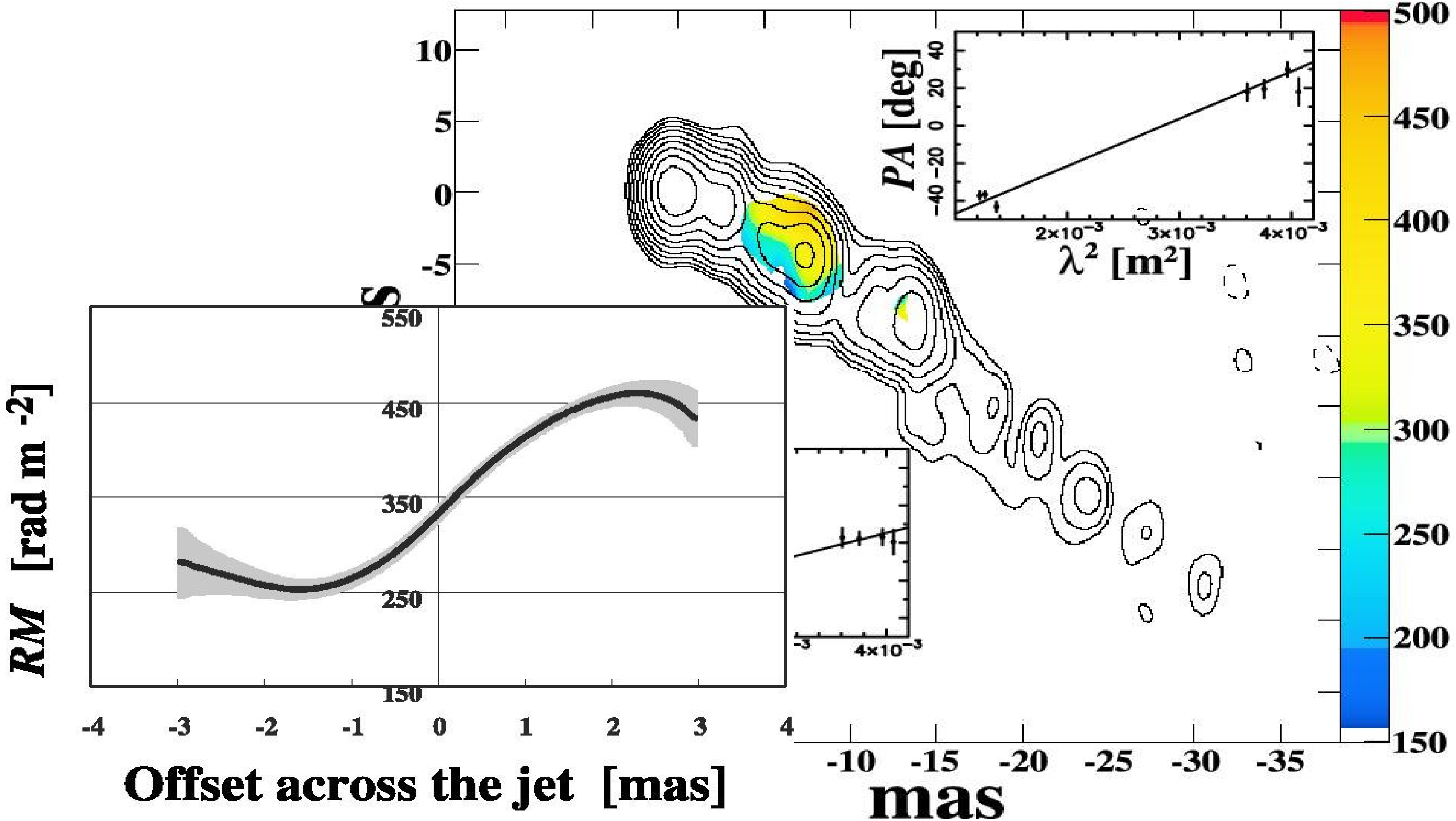






Asada et al 2002

RM gradient = 70 rad/m²/mas



Asada et al 2002

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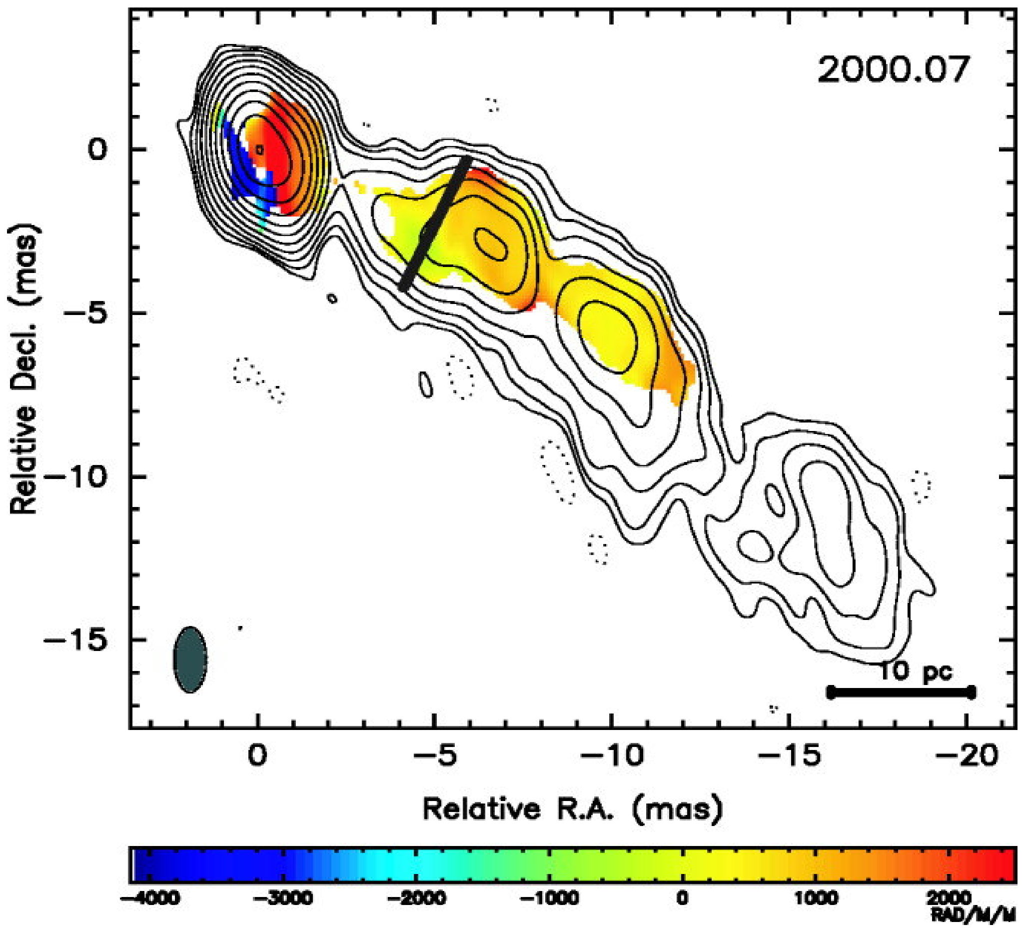
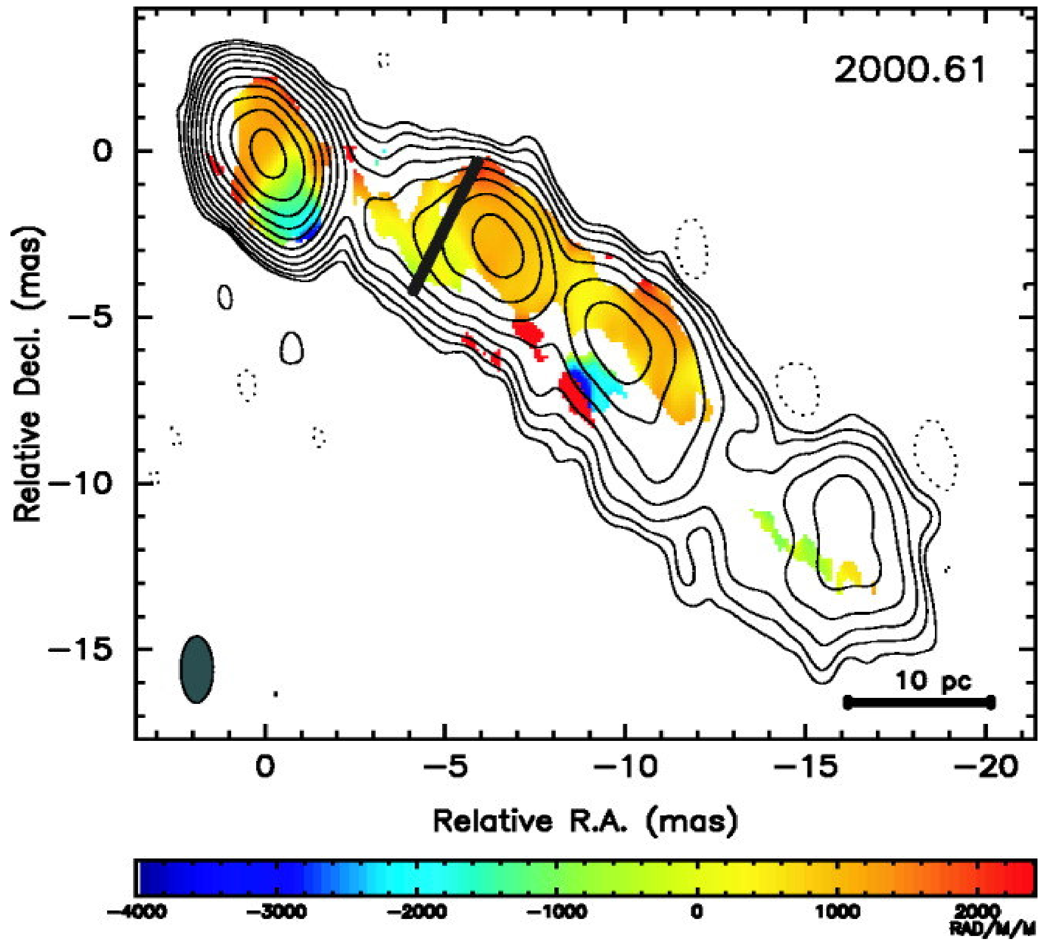
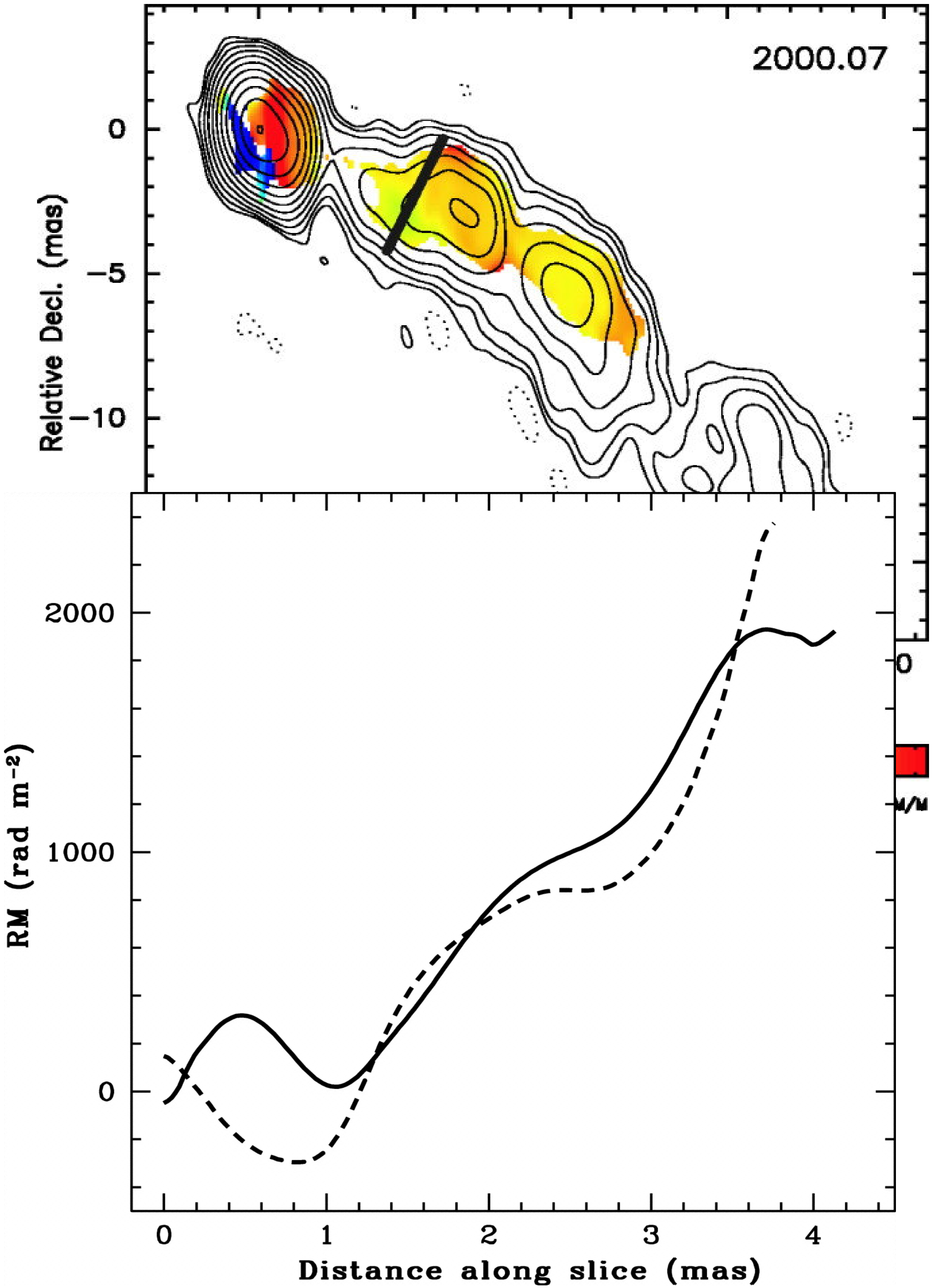


Zavala & Taylor 2005

RM gradient = 500 rad/m^2/mas





Zavala & Taylor 2005

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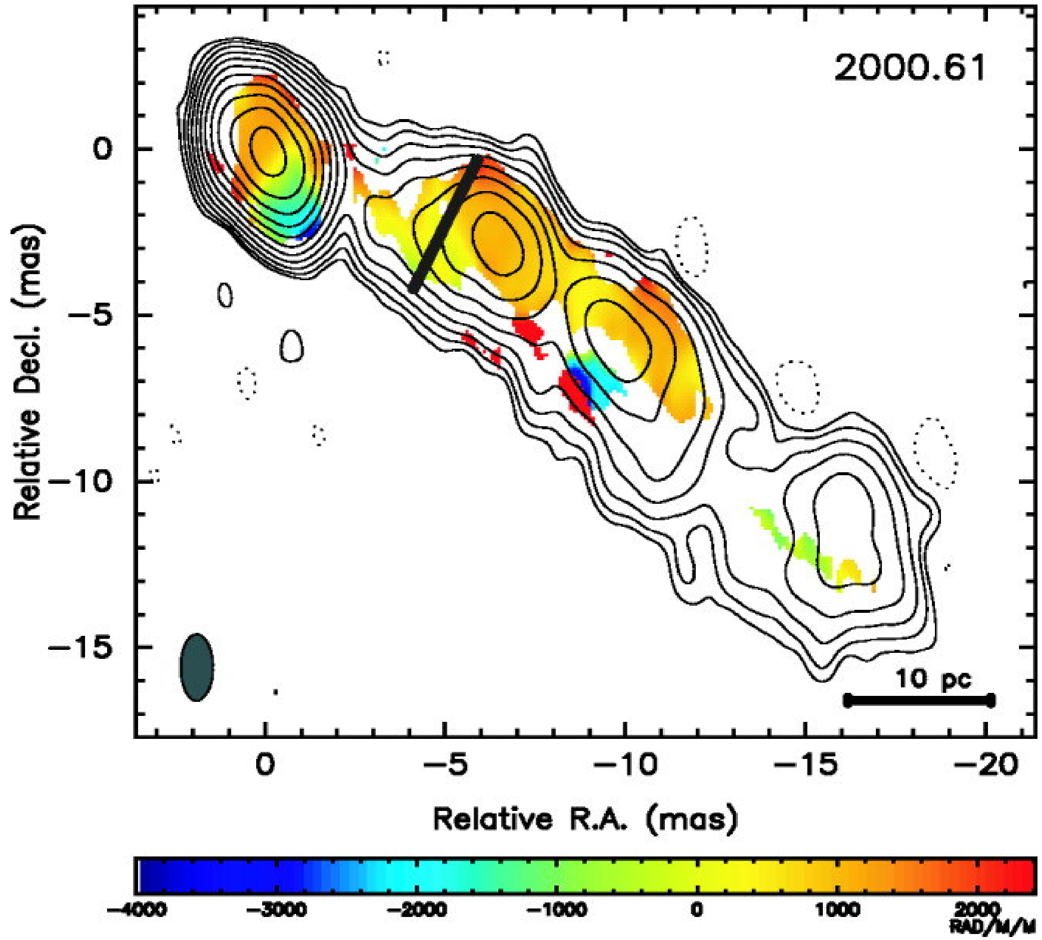
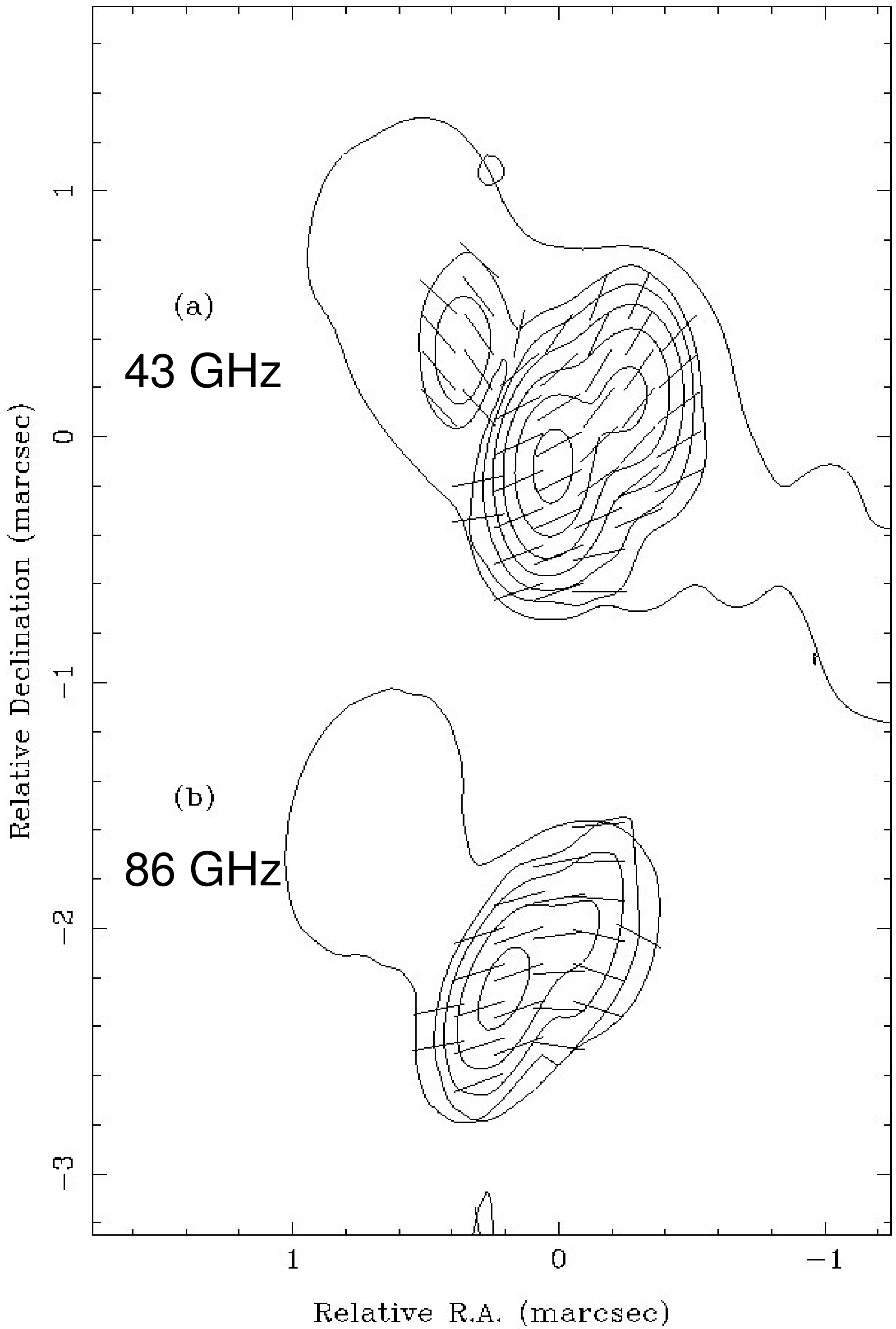


$\Delta\chi = 60^o$

Rotation measure *gradient* is 130,000 rad/m^2/mas

Attridge, Wardle and Homan (2005)



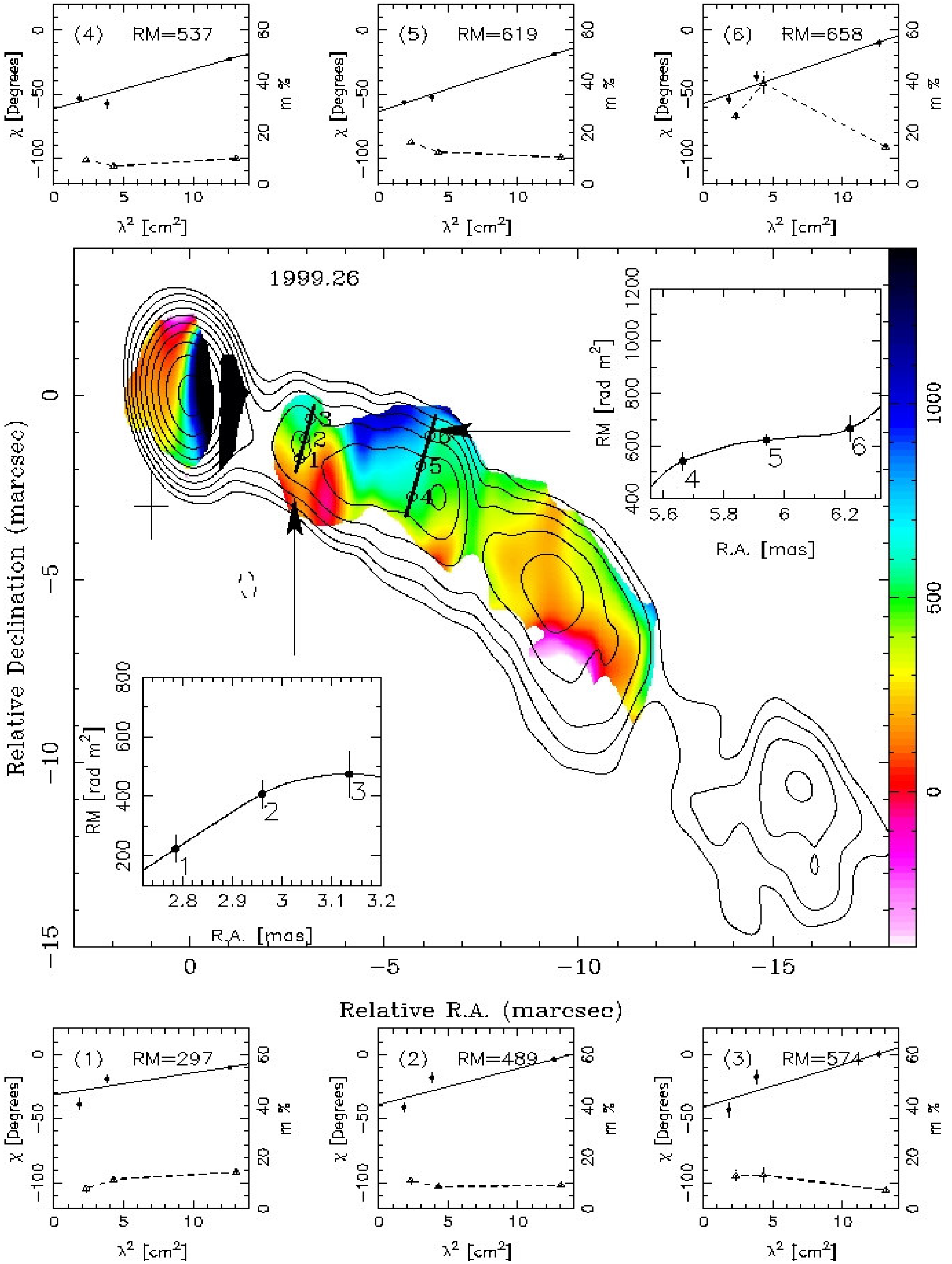
3C 273, epoch 1999.26,

from 8, 15 and 22 GHz data.

Tingdong Chen, 2005

PhD dissertation

Brandeis University



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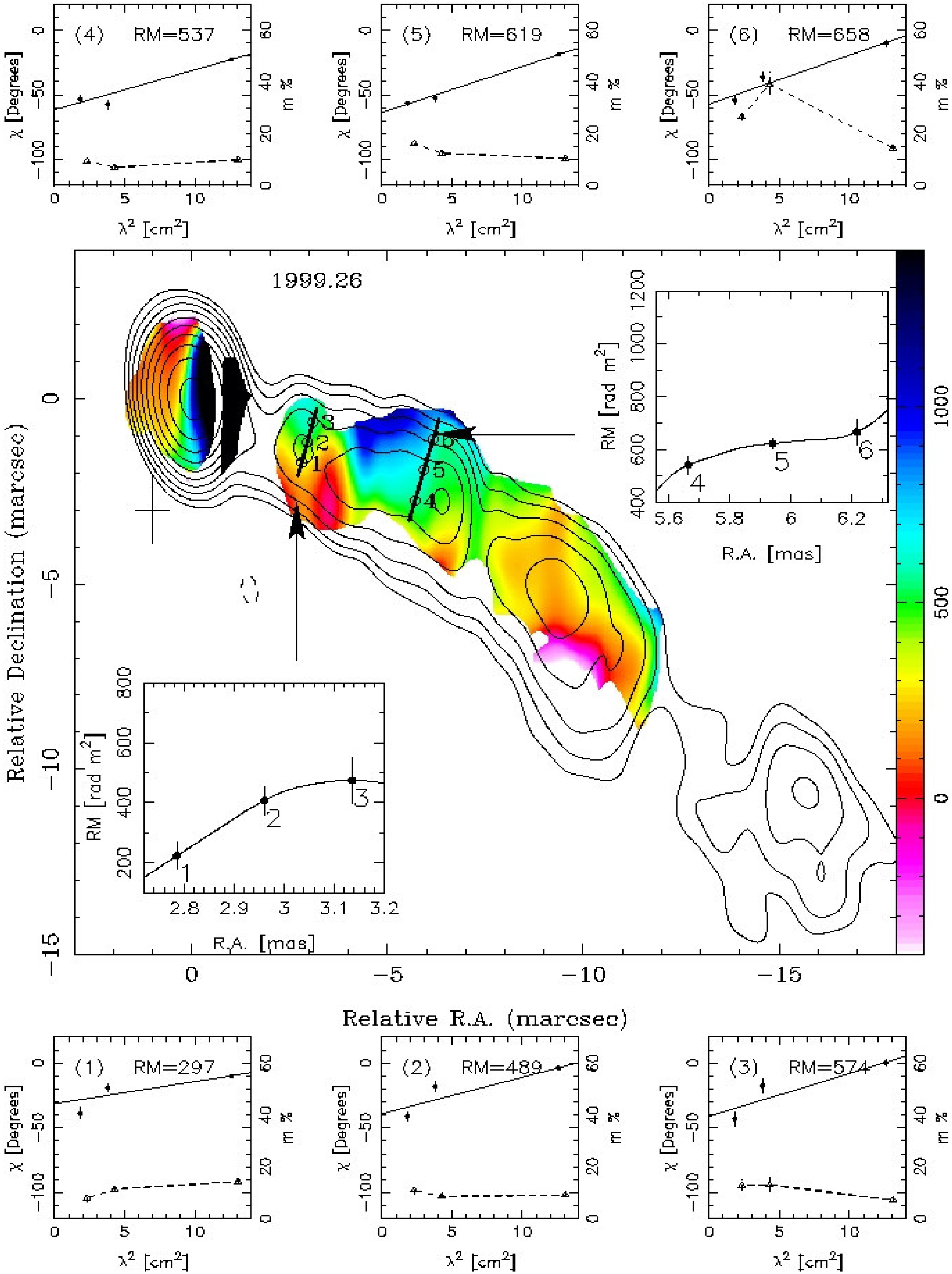
Tingdong Chen, 2005

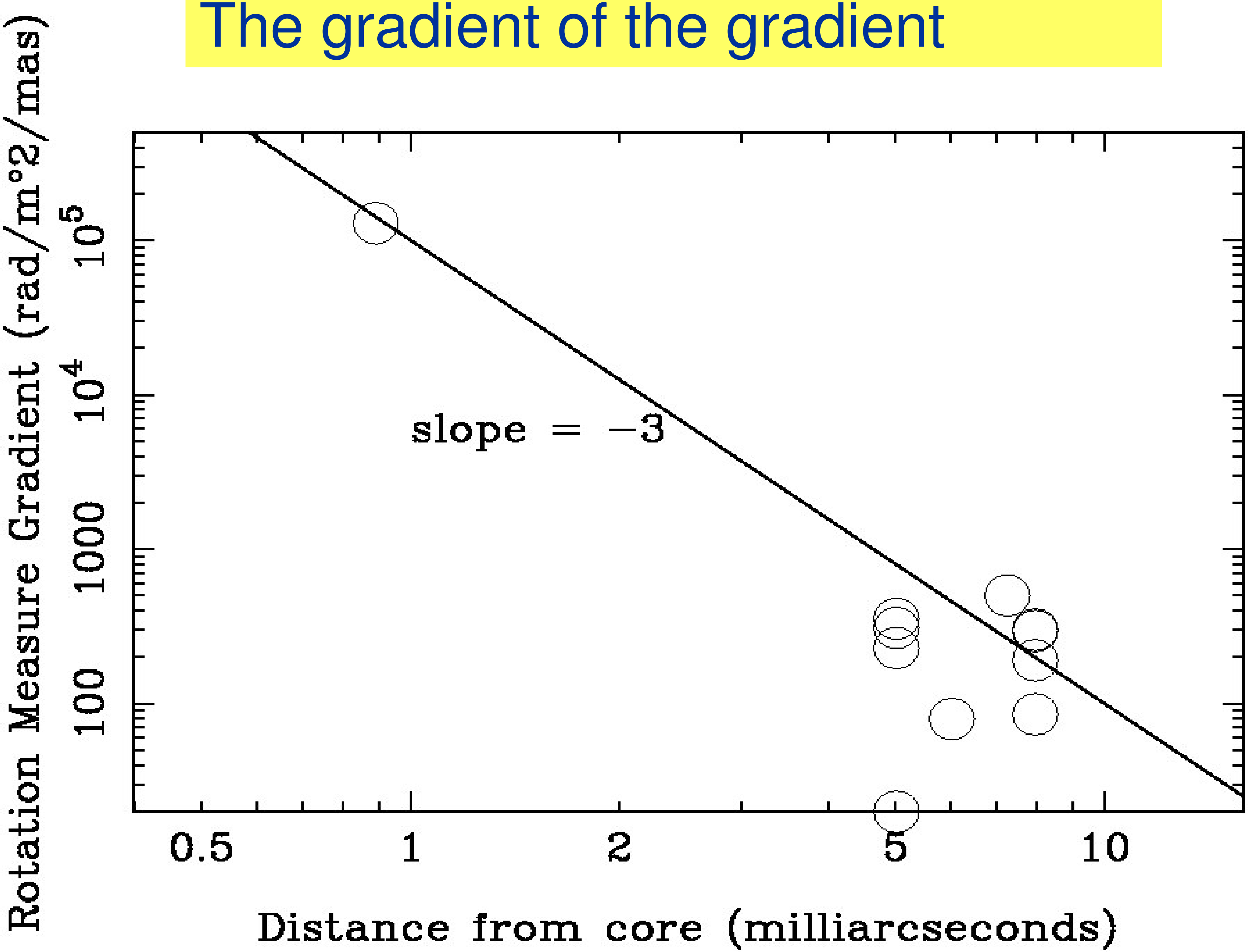
PhD dissertation

Brandeis University

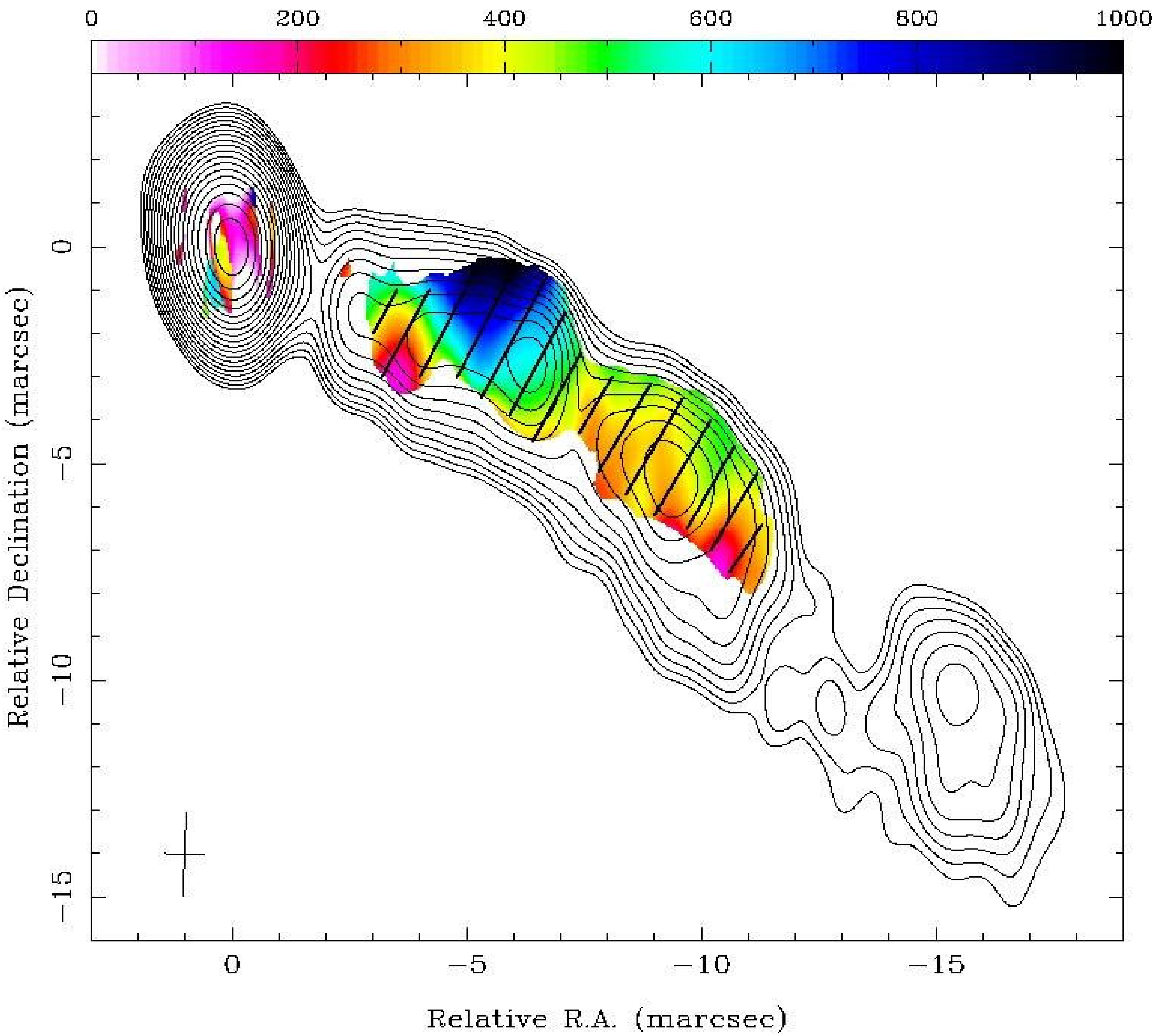
4 Epochs → Rotation Measures are variable



The gradient of the gradient



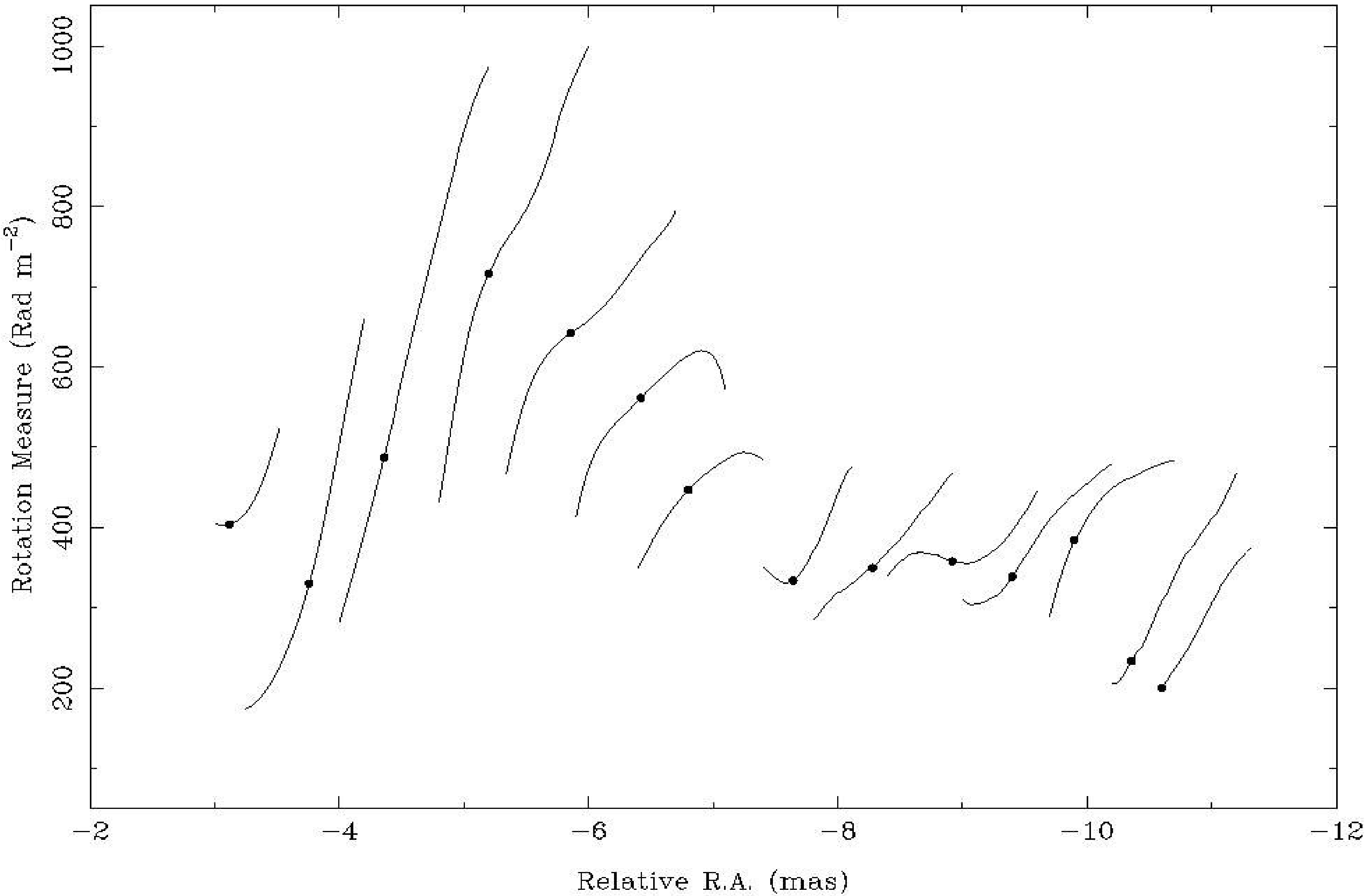
Is there a systematic component of the gradient?



Add the four maps together to make an “average” RM map.

Rotation measure profiles along the 14 cuts.

(The dots mark the brightest point on each cut)



There is a significant transverse gradient of rotation measure over at least 9 mas (25 pc projected distance, ~ 250 pc deprojected).

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This suggests a toroidal component of magnetic field in the Faraday screen along the length of the jet.

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This suggests a toroidal component of magnetic field in the Faraday screen along the length of the jet.

By Ampère's law, this would require a current along the jet. This may be carried in the jet itself (as in the BZ mechanism), or in a sheath, perhaps from a disk wind.

An upper limit on the current in the jet?

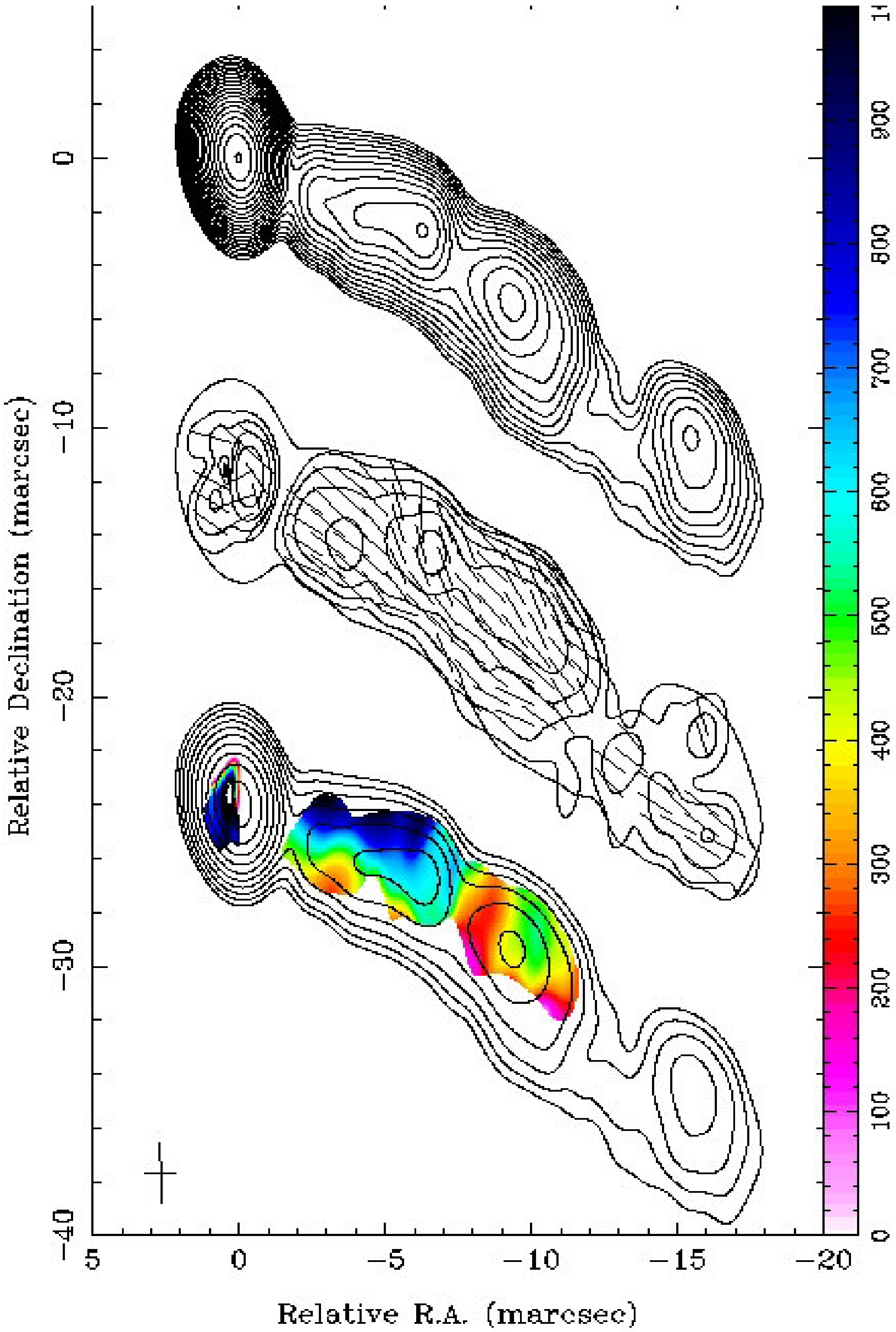
3C 273, epoch 1999.37

Total intensity, “B” vectors (derotated EVPA vectors +90^{o}), and RM distribution.

The “B” field is mostly parallel to the jet (except at U4 which looks like a shock).

We infer that $B_{torroidal}$ is not larger in magnitude than the B field in the synchrotron emitting region.

In U8 (v_{app} =11.7 c), the standard calculation yields B = 8 x 10^{-3} G (critical angle to the line of sight, equipartition, γ_{min} = 1). This is in the jet frame.



The upper limit on the interior current flowing in the jet, measured in the frame of the external medium, is therefore

$$I < 2 \pi r \gamma_{jet} B / \mu_o < 2 \times 10^{18} A$$

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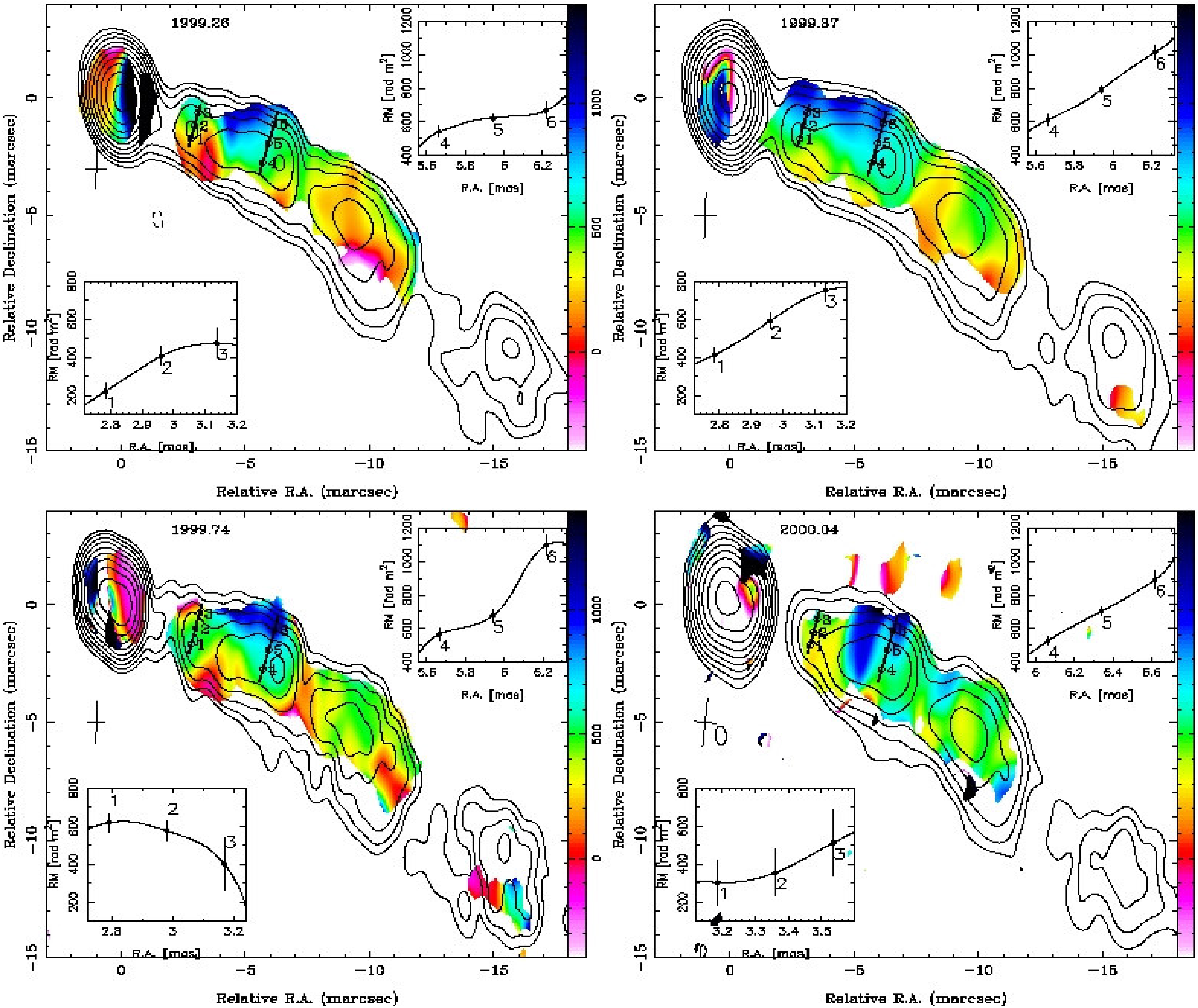
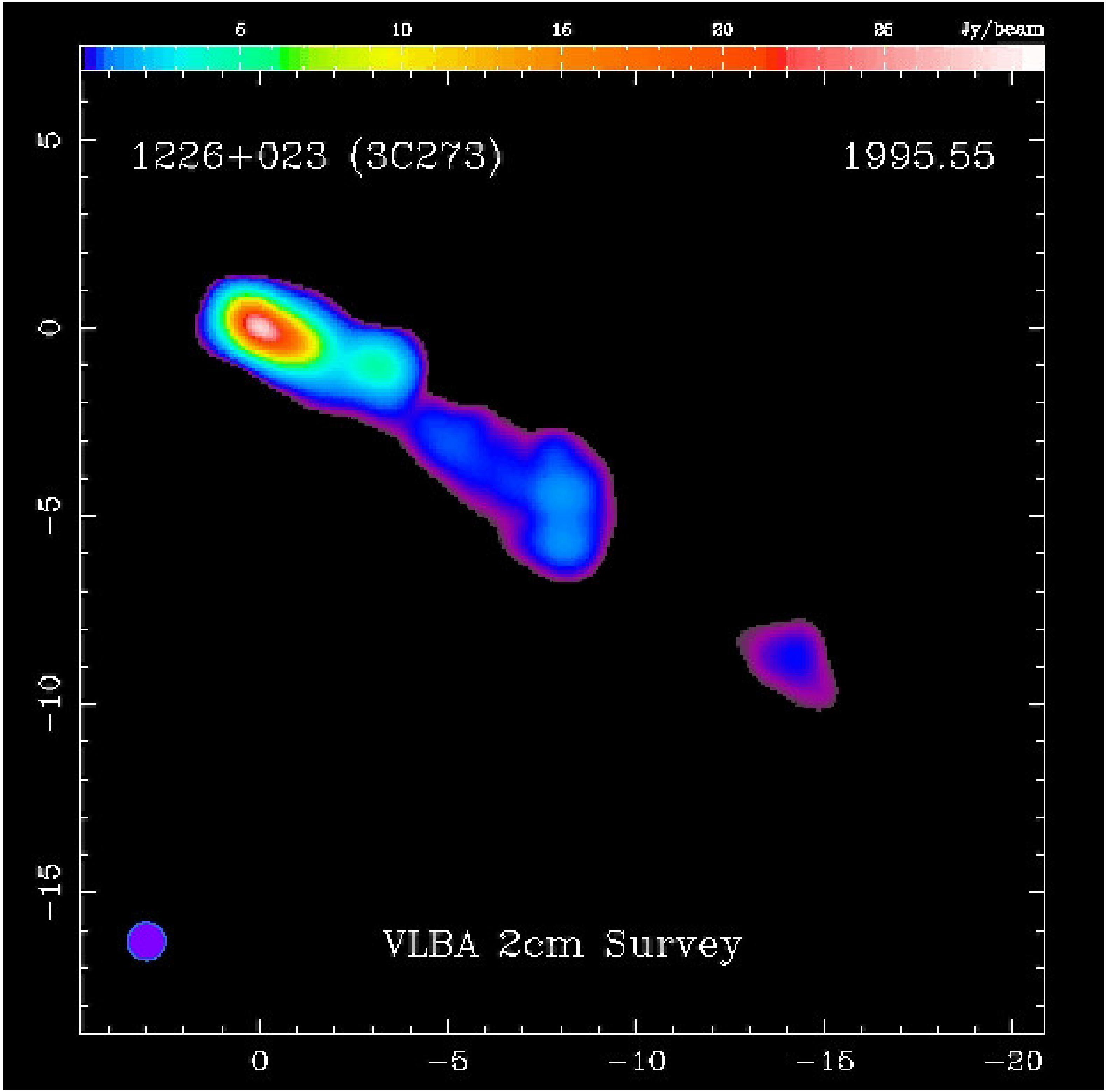
$$I < 2 \pi r \gamma_{jet} B / \mu_o < 2 \times 10^{18} A$$

This is in the range expected for certain models for energy extraction from a rotating black hole magnetosphere, and may therefore be of interest to the theorists.

Jet-Sheath Interactions



1999.26
1999.37
1999.74
2000.04
Relative Declination (marcsec)
Relative R.A. (marcsec)
RM [rad m^{-2}]
R.A. [mas]


Jy/beam
5
10
15
20
25
1226+023 (3C273)
1995.55
VLBA 2cm Survey
5
0
−5
−10
−15
0
−5
−10
−15
−20

KONIEC