Circular Polarisation in AGN Jets

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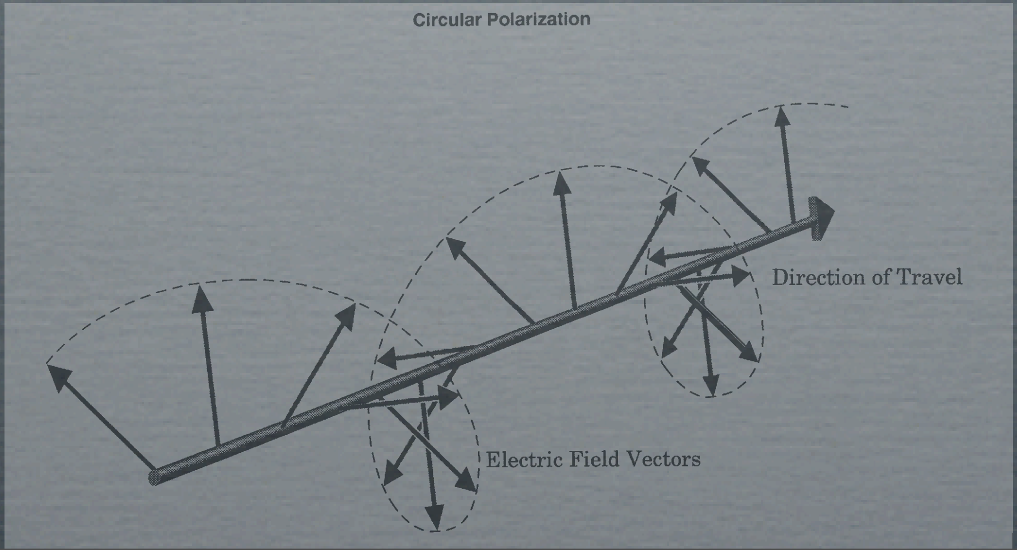


Why Bother?

- Linear polarisation in AGN long associated with synchrotron emission
  - Degree: magnetic field disorder
  - Position angle: magnetic field direction on the sky
  - Faraday rotation: measure $\mathrm{RM} \propto \oint n_e \mathbf{B} \cdot d\mathbf{l}$
- V is the only Stokes parameter whose origin we do not understand (certainly at radio wavelengths)
  - Composition of the jet?
  - Reflection of underlying B polarity?

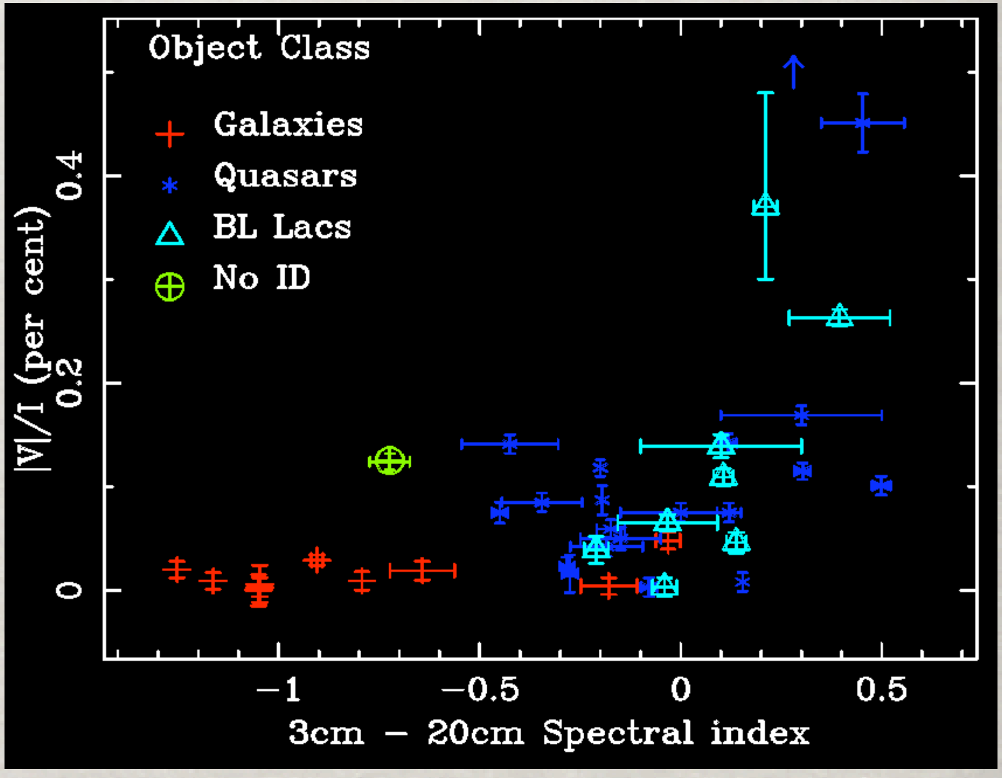
OBSERVATIONS

Observational Overview

- Typically 0.01-1%
- Often highly variable
  - Large fractional changes relative to I
  - V often poorly correlated with I

$$\left(\frac{\langle \delta V^2 \rangle^{1/2}}{\langle V \rangle} \gg \frac{\langle \delta P^2 \rangle^{1/2}}{\langle P \rangle} \gg \frac{\langle \delta I^2 \rangle^{1/2}}{\langle I \rangle}\right)$$

  - Flat/inverted spectrum sources show more CP
  - CP *usually* has preferred handedness between outbursts
  - CP usually strongest after an outburst and before the LP is strong

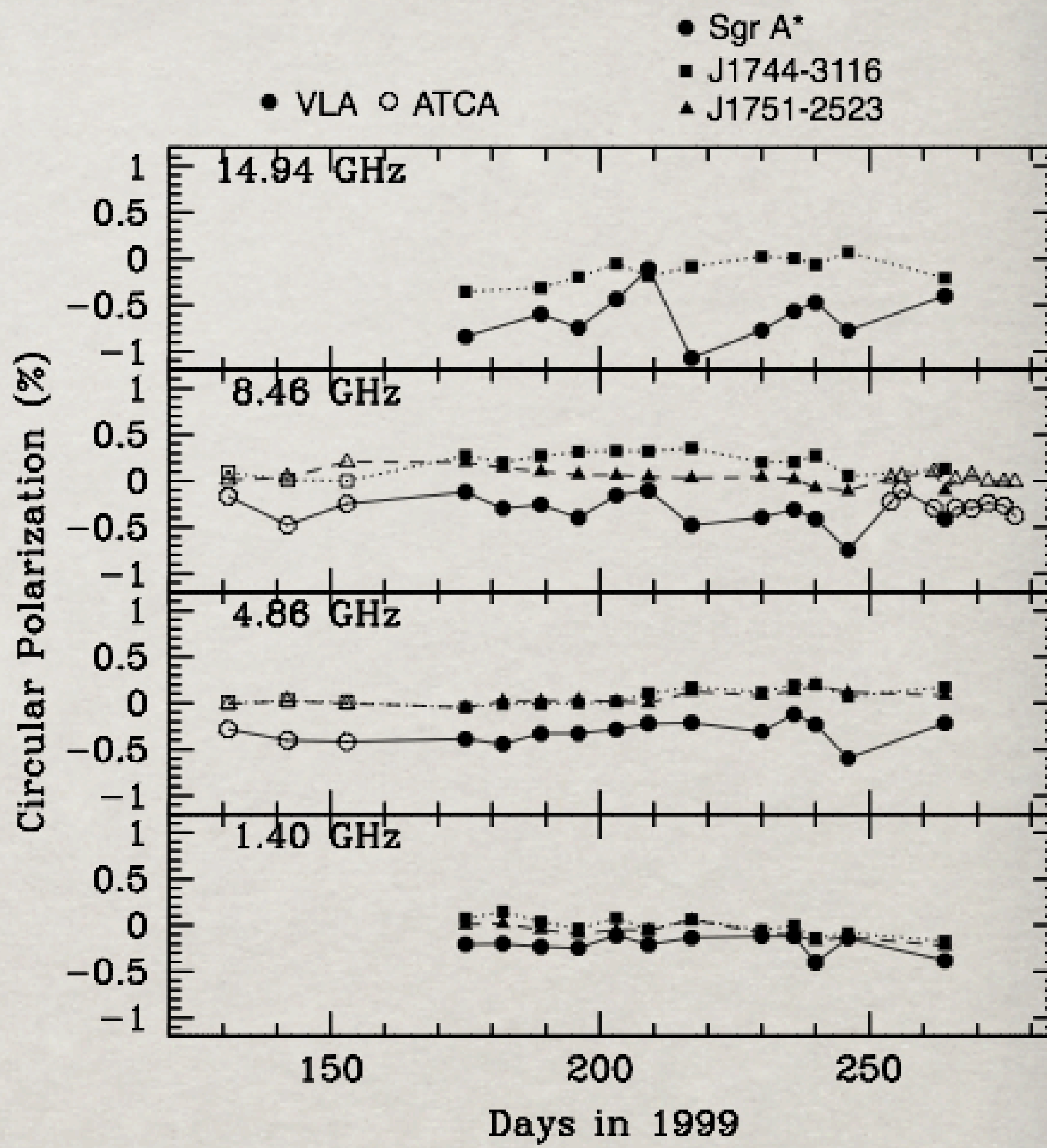


Rayner, Norris & Sault 2000

Earlier measurements Komesaroff et al. 1984 (Parkes), Weiler & de Pater 1980,2,3 (Westerbork)

Sgr A*

- V varies but no sign change
- Historical VLA data shows sign is stable over 20 years at 5 GHz
- <V/I> = -0.3% at 5 GHz
- 25% change in I over 2 hrs but V can go from -10 to -20 mJy
- At ν>8GHz V flares when I flares
- V detected in M81* has similar properties to Sgr A* (Brunthaler, Bower, Falcke 2006)



Bower et al. 2001

[Sgr A* RM]

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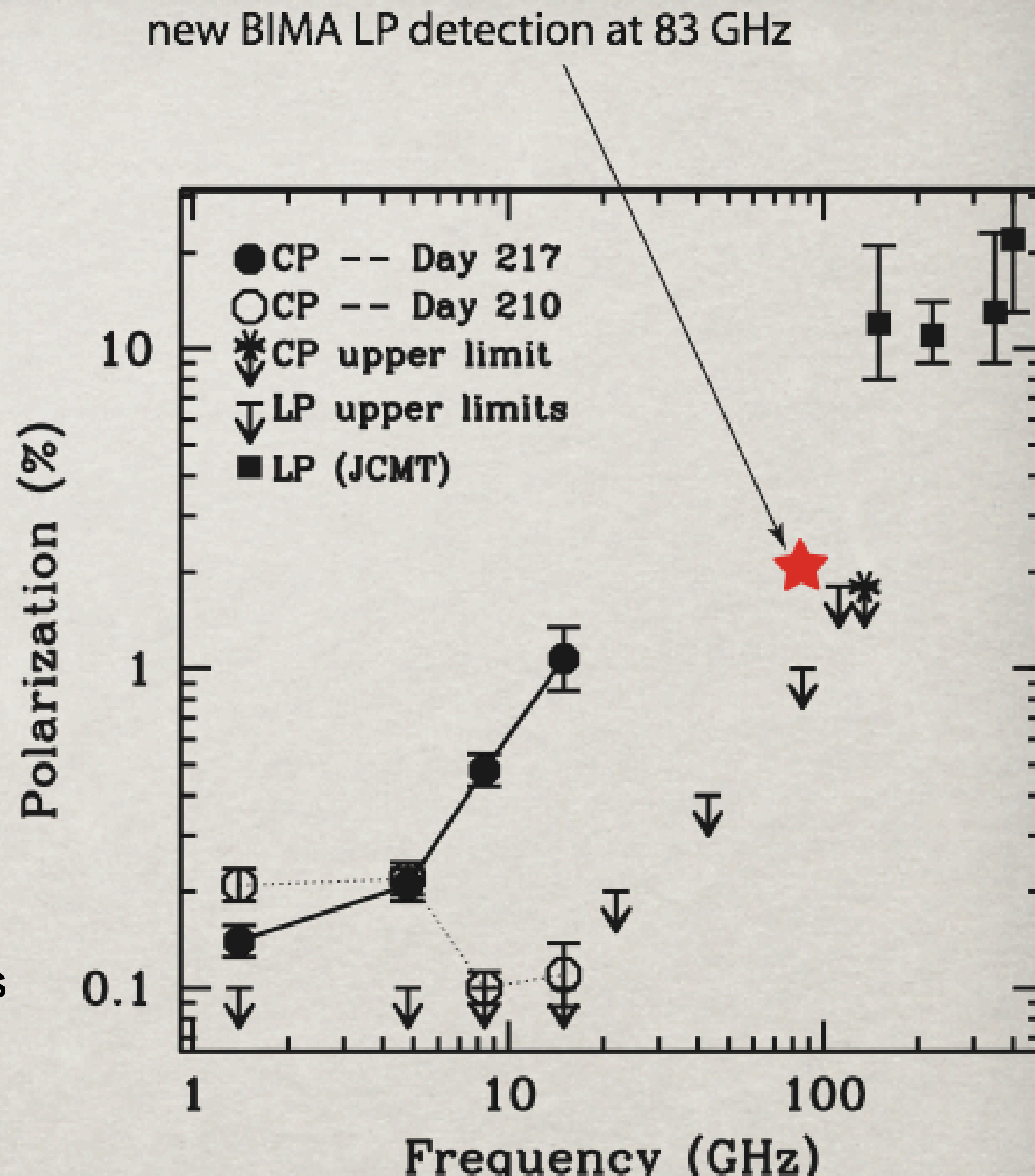


Bower et al. 2001

Sgr A* RM

VLBI-scale CP (Homan & Wardle)

- few % CP on mas scales
- CP near core/jet base
- Frequency dependence steeper than ν^{-1}, argued in terms of polarization conversion in a relativistic plasma
- sometimes see a sign change in V as outburst evolves

3C 84 - Homan & Wardle 1999

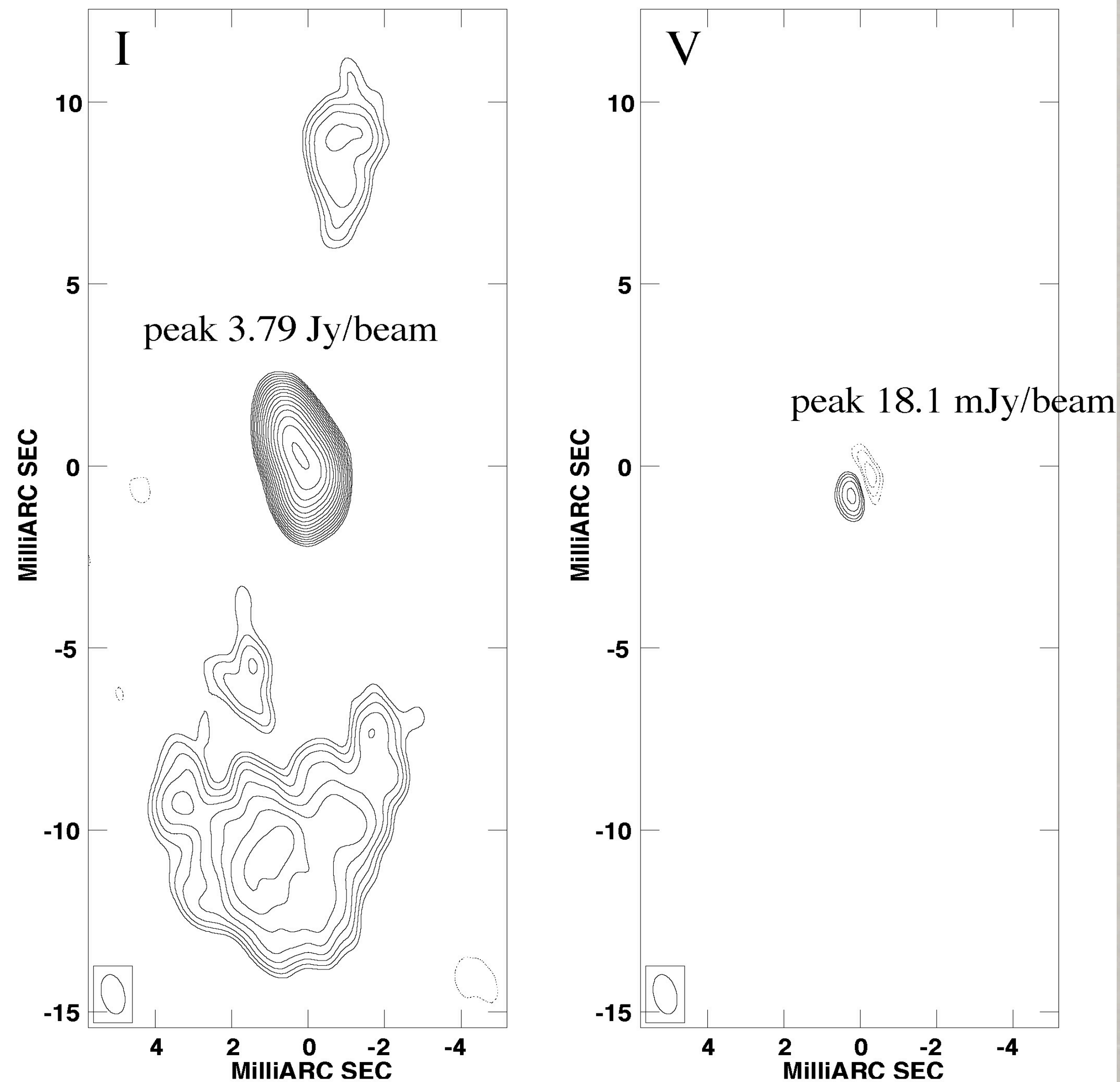
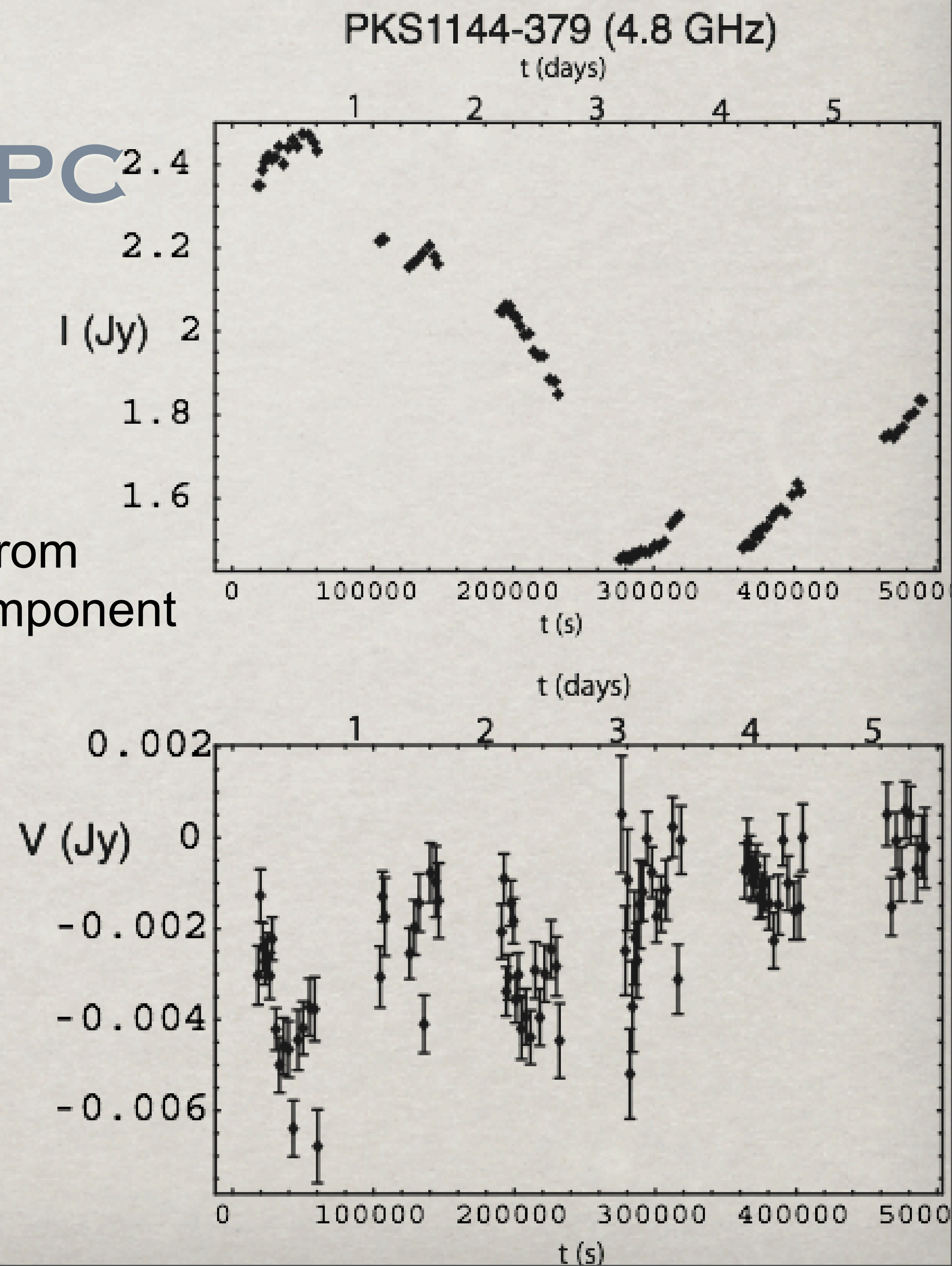


FIG. 4.» Naturally weighted images of 3C 84 (1996 September). (a) Total intensity J 2 contours beginning at 0.020 Jy beam~1. The map peak is 3.79 Jy beam~1. (b) Circular polarization intensity map produced with the Zero-V self-cal technique, with J 2 contours beginning at ^ 4 mJy beam~1. The map peak is] 18.1 mJy beam~1.

Intra-Day Variable Sources(Sub-pc CP)

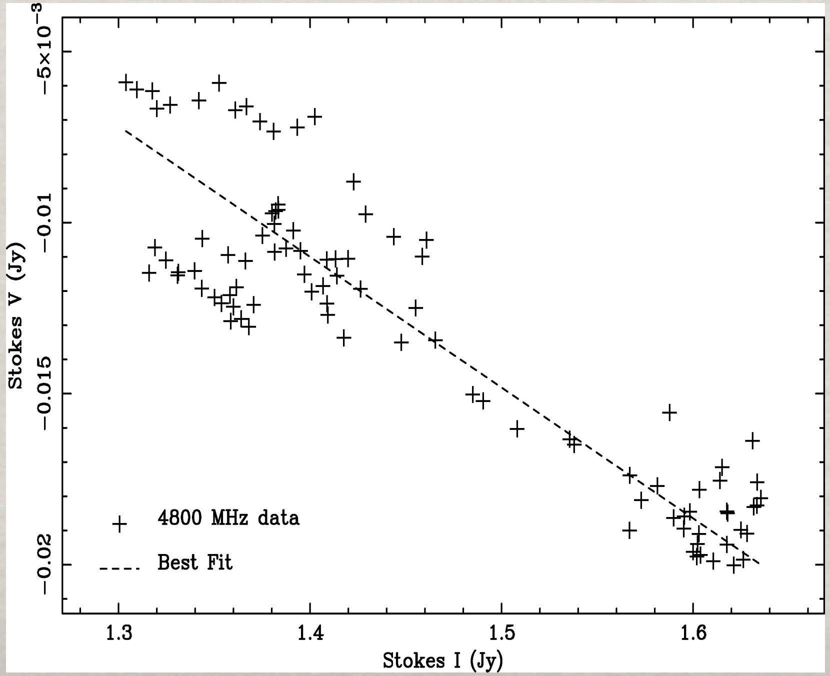
- V-I correlation poor
- V often varies faster ⇒more V from sub-component compact
- Δ I corresponding to Δ V changes ⇒high poln. fraction

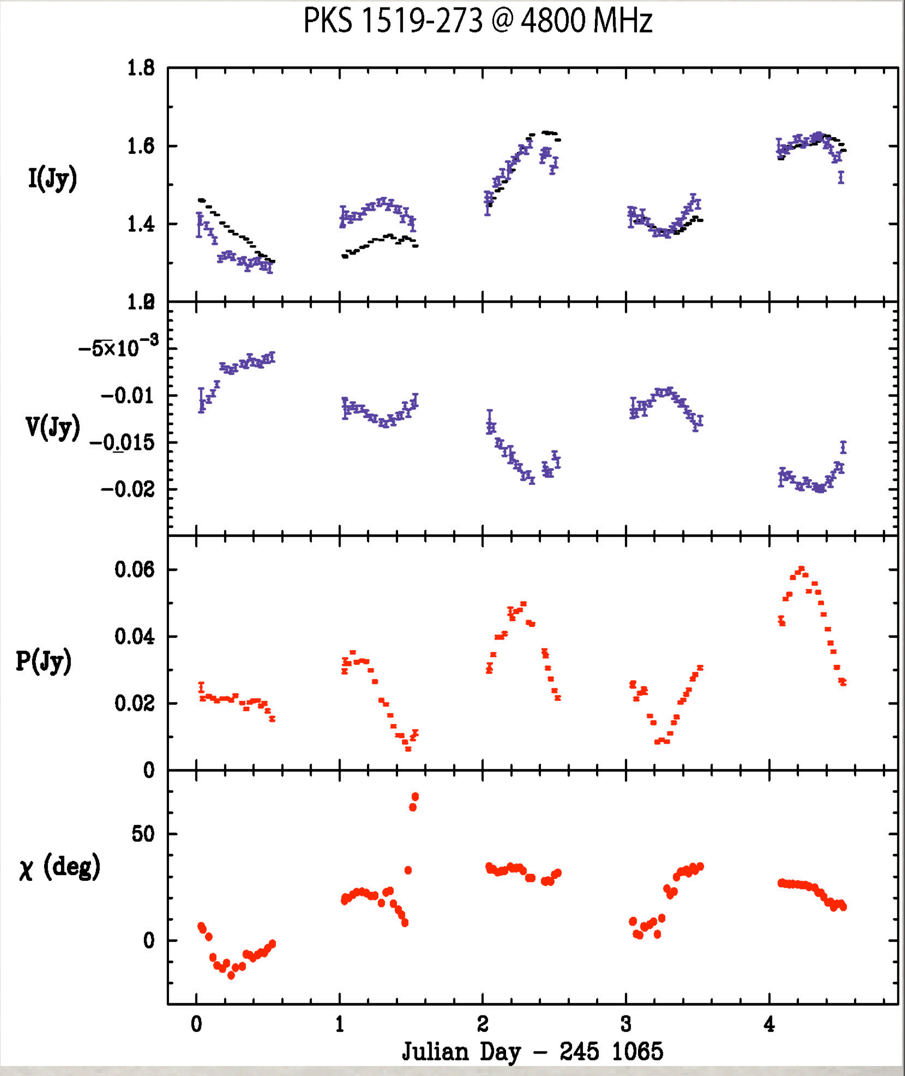


PKS 1519-273

- V & I lightcurves strikingly similar
- 4% CP in scintillating component at 5 GHz
- Proof of scintillation: annual cycle in I & V (Jauncey et al. 2002)
- VSOP upper limit on size of scattering disk (@1.4GHz) and timescale of I flucts gives

$$\theta_{\rm src} < 35\mu{\rm as} \quad \text{and} \quad T_B > 5\times10^{13}\,K$$





Macquart et al. 2000

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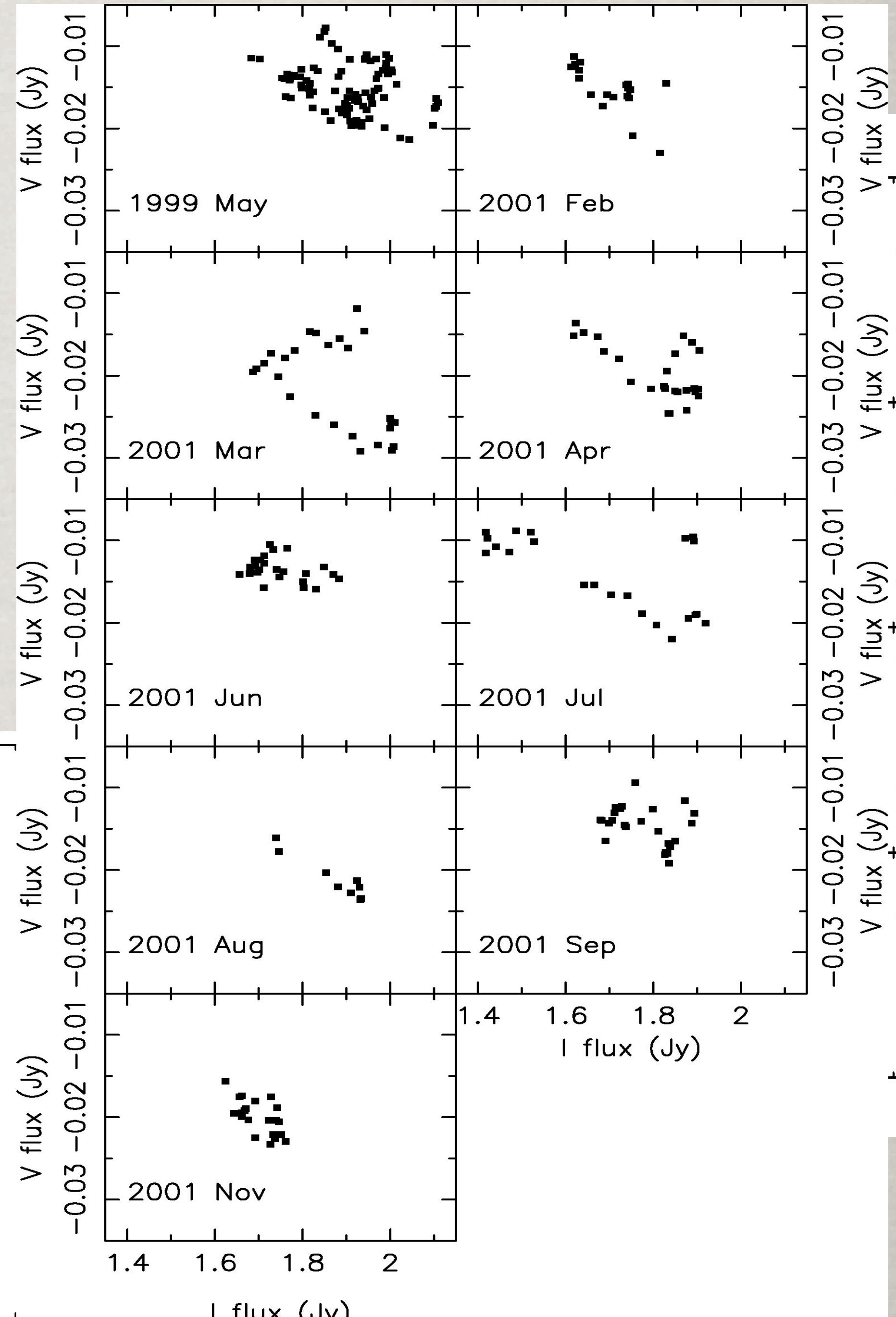
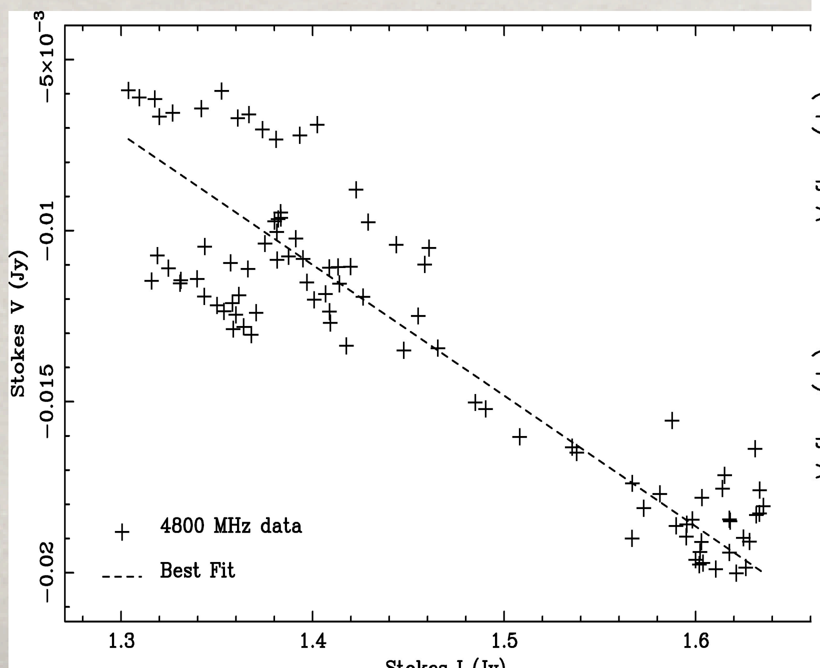
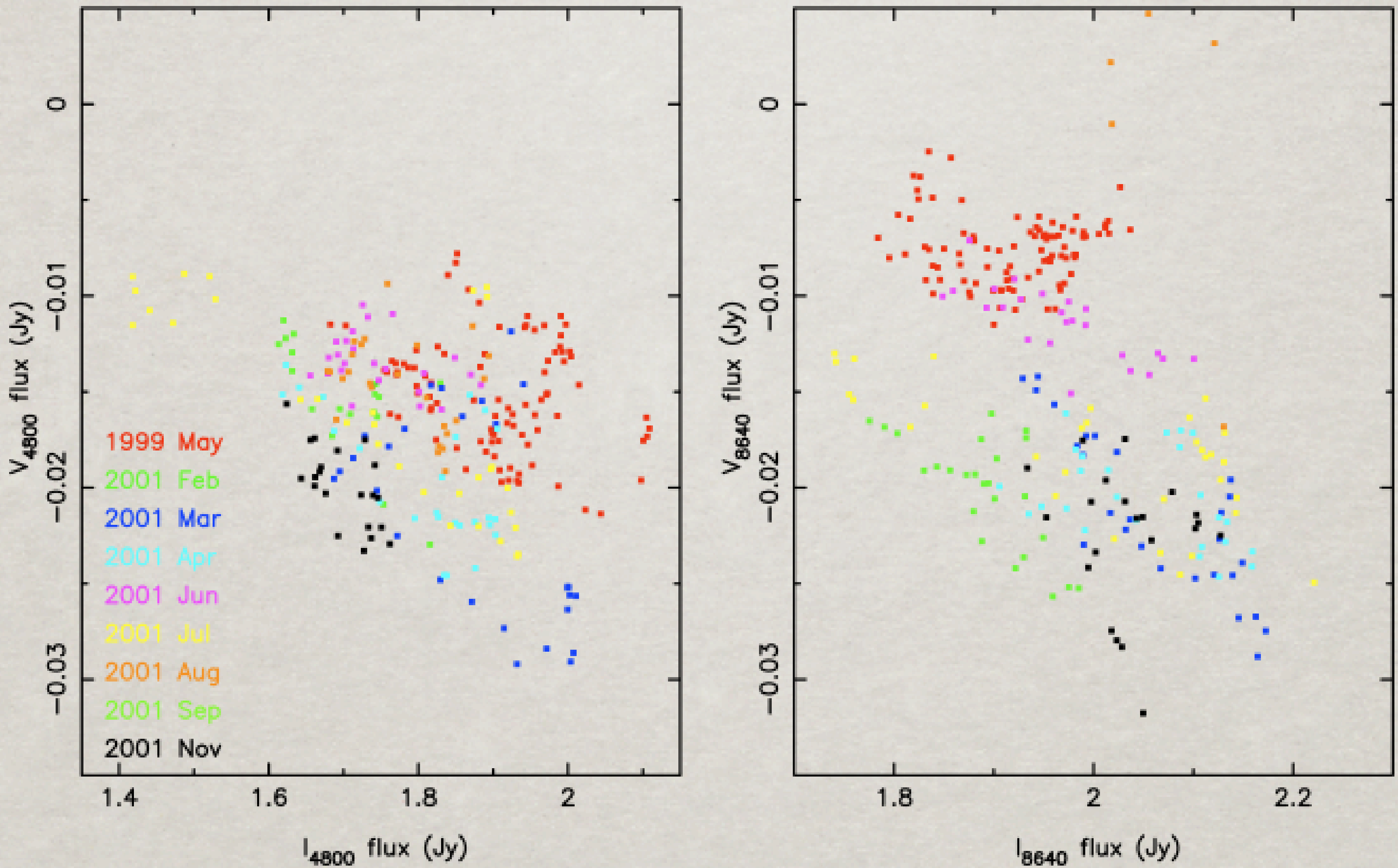




1519-273: Rich Structure

Johnston et al. (unpublished)



Changes in V structure compared to I,
with intermittent presence of V component with opposite handedness

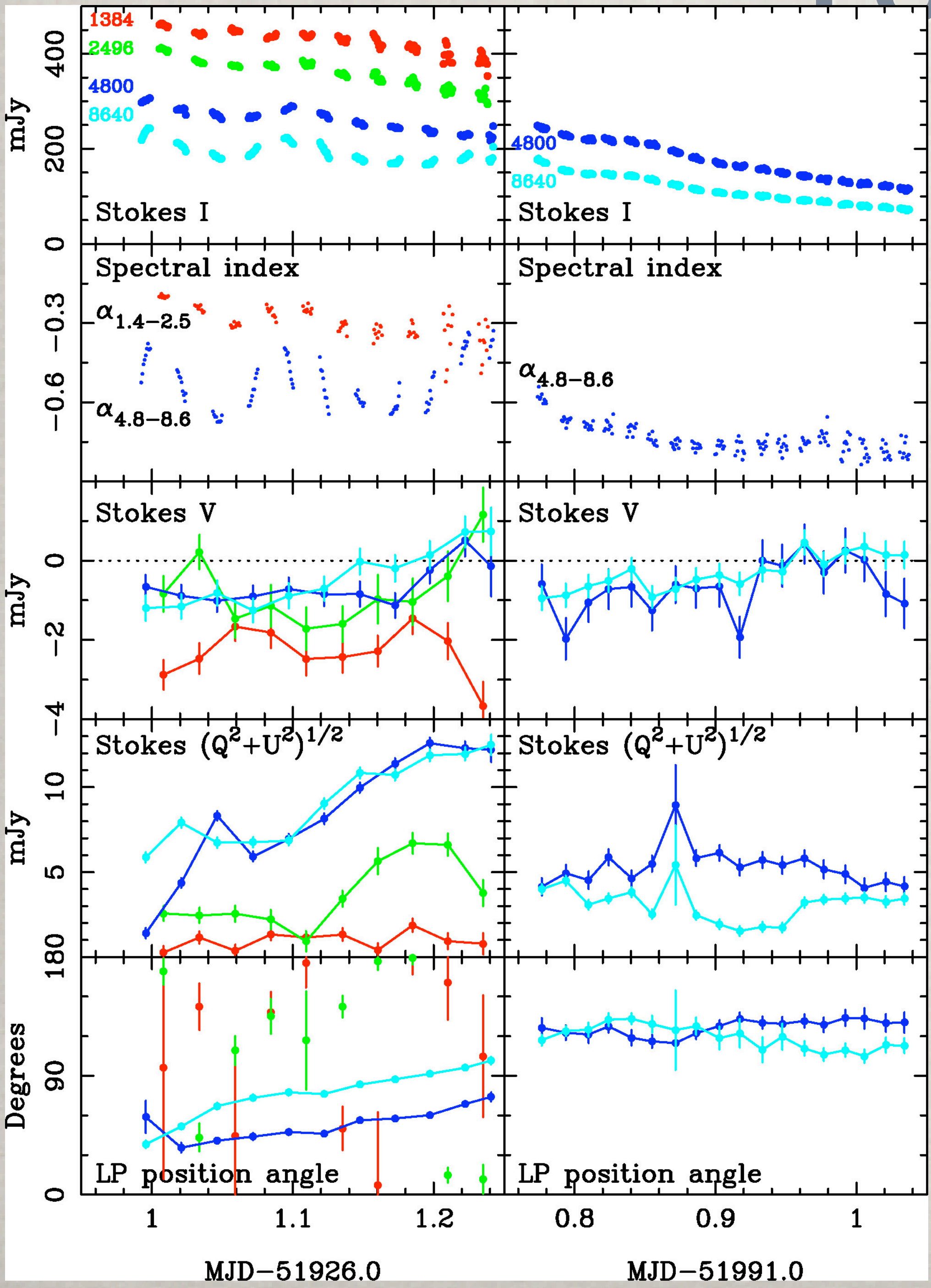
Brightness Temperature Connection

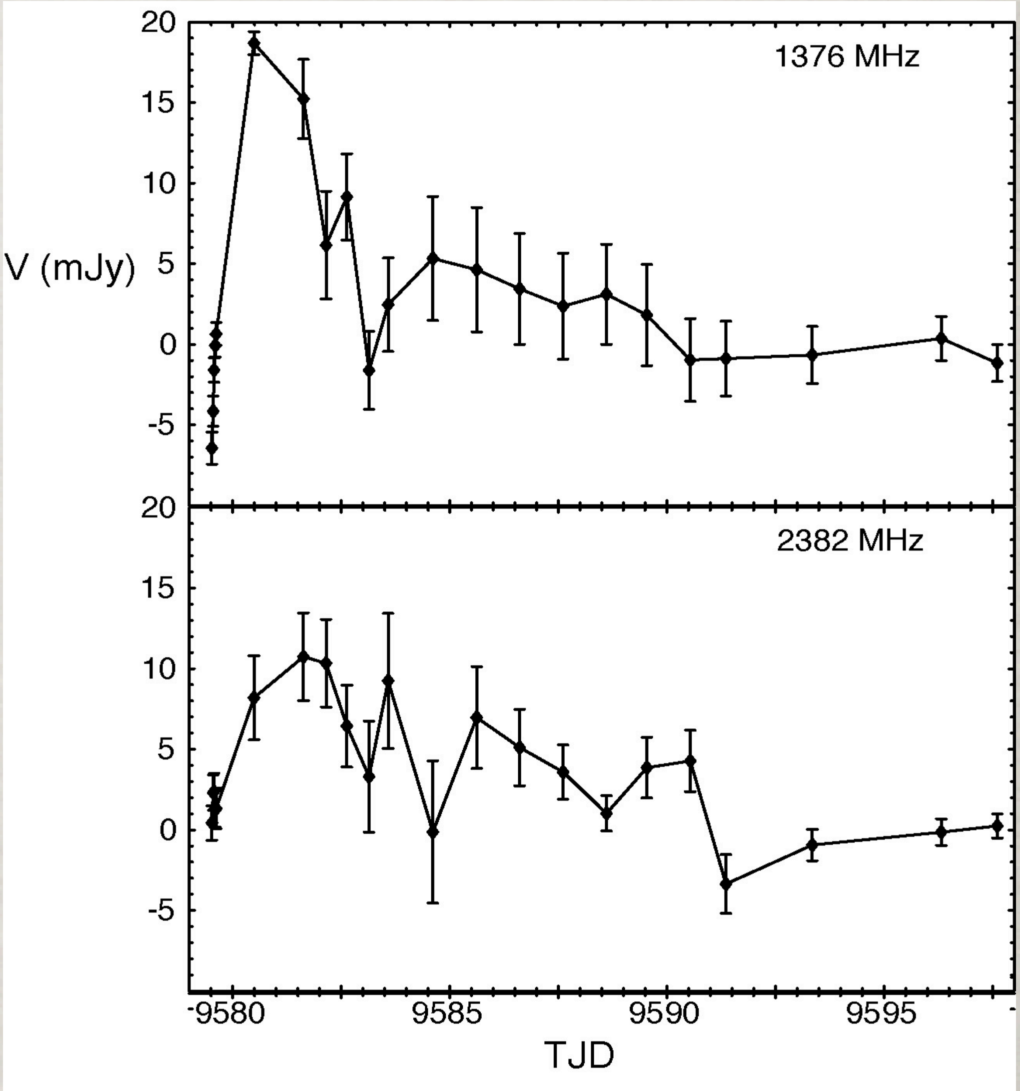
- Several other IDVs show comparably strong CP variations (e.g. PKS 0405-385)
- Tendency for core active, bright sources to show CP?
- T_B estimate complicated by distance to ISM screen responsible for the variations
- $T_B \propto D^2$
    - Varies between sources (fast variations in one source might imply a lower T_B than slow variations in another)

Galactic Jet Sources

- 3 sources detected with CP
- Not all sources show CP (orientation?)
- SS433, GRS 1915+105 (Fender et al. 2000,2002)
- GRO J1655-40 (Macquart et al. 2002)
  - CP undergoes sign flip during outburst
  - CP up to 3% (from comparison of I & V changes)
- Similar properties to AGN CP

GRS 1915 GRO 1655





Macquart et al. 2002

Fender et al. 2002

THEORIES

Synchrotron Emission

$$m_c \approx \gamma^{-1} \quad \left(m_c \sim \sqrt{\frac{2.8 B_{\mathrm{Gauss}} \sin\epsilon}{\nu_{\mathrm{MHz}}}} \cot\epsilon \right)$$

Legg & Westfold 1968

$$m_c = -1.6\Lambda \sqrt{\frac{\nu_{B\perp}}{\nu}} \left(\frac{B_u}{B_\perp} \right) \sin\epsilon,$$

$$\epsilon = \text{angle between jet normal and line of sight}$$

– Reduced by magnetic field inhomogeneities

- Depolarisation factor Λ depends on field geometry

– Sign flip as source becomes optically thick

- Unlikely except for Galactic jet sources (possible large B in emission region)

Cyclotron Emission

- γ-1<<1, $T_B < 5 \times 10^9$K: easily diluted by synchrotron emission
- Coherent emission mechanisms:
  - Pulsars emission is coherent and exhibits high CP
    - Could be a magnetospheric propagation effect
  - Electron cyclotron maser emission proposed to explain IDV brightness temperatures (Begelman, Ergun & Rees 2005)
    - naturally gives high CP (e.g. Jovian decametric radiation), but strongly diluted if emission comes from multiple patches and B is inhomogeneous (as expected).

Steep (aka Monoenergetic) e⁻ Distribution?

Kirk & Tsang 2006

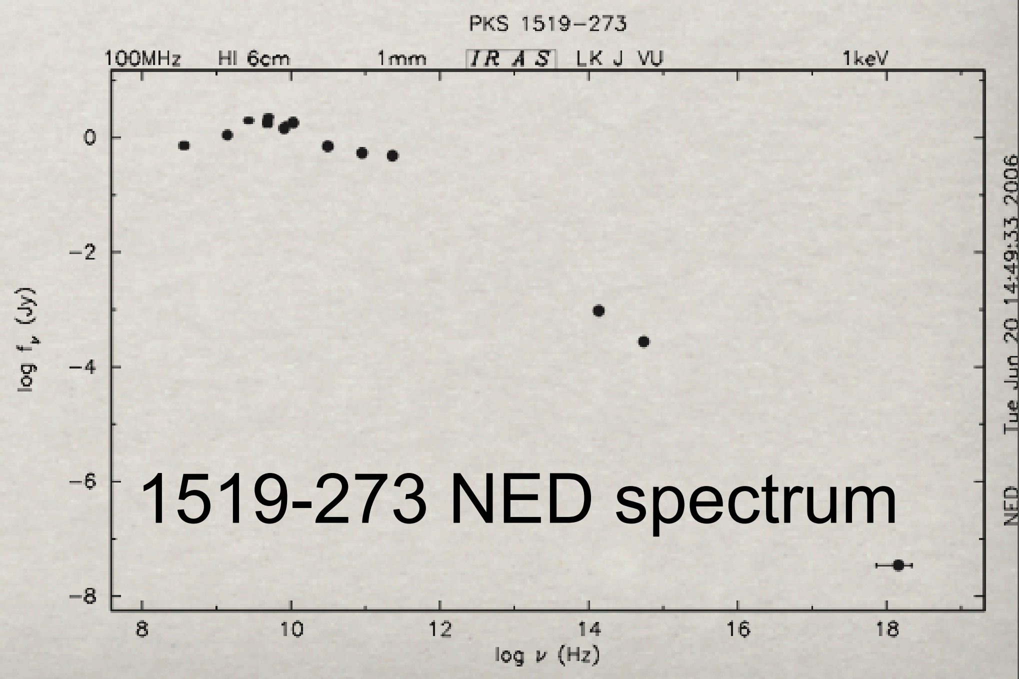
- Propose a steep e⁻ distribution
- More low energy photons can escape without absorption by low-energy e⁻:

$$T_B = 1.2\times10^{14}\,\zeta^{6/5}(1+z)^{-6/5}\left(\frac{\mathcal{D}}{10}\right)^{6/5}\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-1/3}\left(\frac{\nu_{\max}}{10^5\,\mathrm{GHz}}\right)^{2/15}\left(\frac{1-e^{-\tau_s}}{\tau_s^{1/5}}\right)\mathrm{K}$$

- Predicts few % CP:

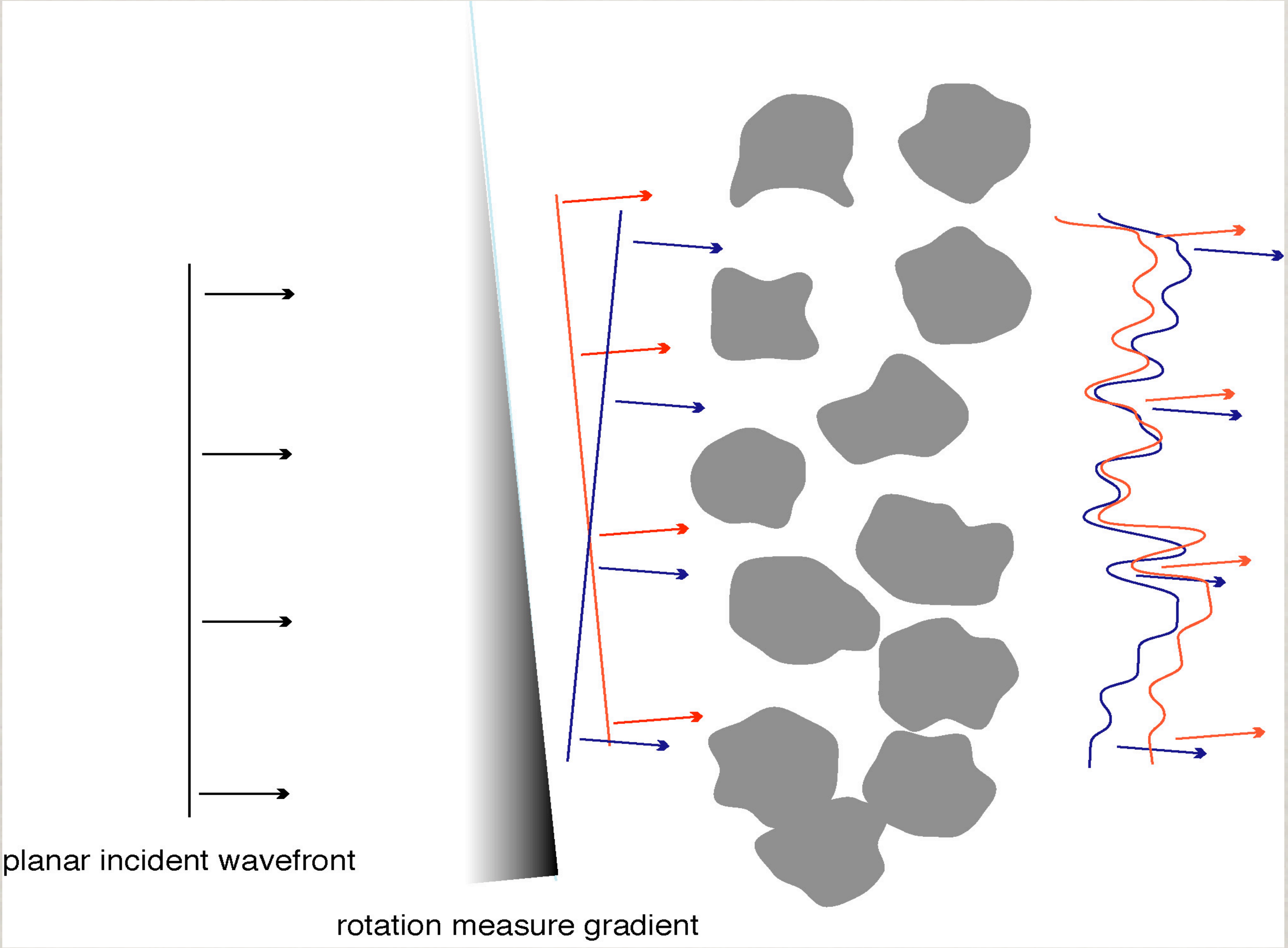
$$m_c = 0.019\,\zeta^{-\frac{1}{5}}\tau_s^{\frac{1}{5}}(1+z)^{\frac{1}{5}}\left(\frac{\mathcal{D}}{10}\right)^{-\frac{1}{5}}\left(\frac{\nu_{\max}}{10^5\,\mathrm{GHz}}\right)^{\frac{1}{5}}\cot\theta$$

- Prediction: $I_\nu \sim \nu^{1/3}$ up to IR energies and IC component in the MeV to GeV range



Scintillation-Induced CP

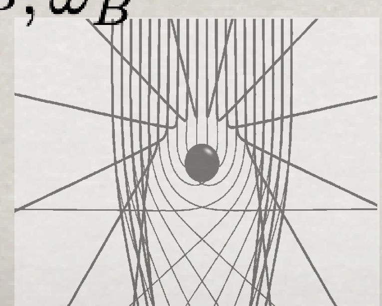
- Unlikely since it predicts sign changes (<V>=0)



Macquart & Melrose 2000a,b (Phys. Rev. E & ApJ)

General-Relativistic Plasma Propagation Effects

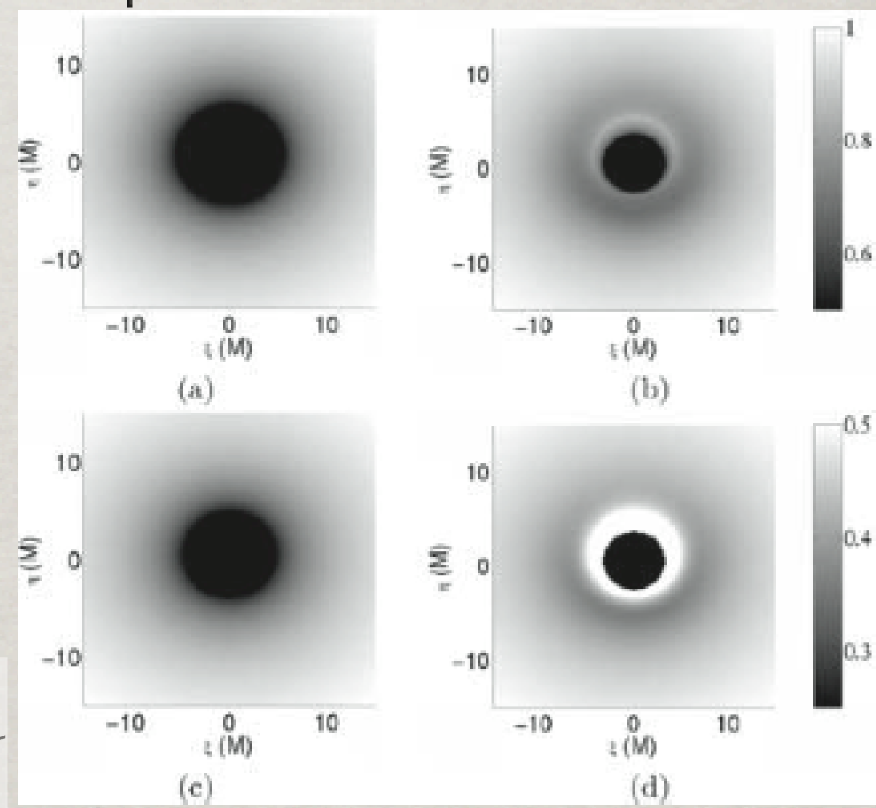
- Effects associated with a plasma in a curved spacetime
  - plasma frequency acts like a mass term
  - “mass” depends on position through the plasma density
  - photons no longer follow null geodesics
  - geodesics different for ordinary and extraordinary modes
  - Photons from one mode can be captured by BH while the other escapes
- Probably not viable for AGN since fraction of emission coming from near BH is small
- Requires emission at $\omega \sim \omega_P, \omega_B$



Broderick & Blandford 2003,4

Optically think Shakura-Sunyaev accretion disk near a Schwarzschild BH

No plasma effects | Plasma effects included

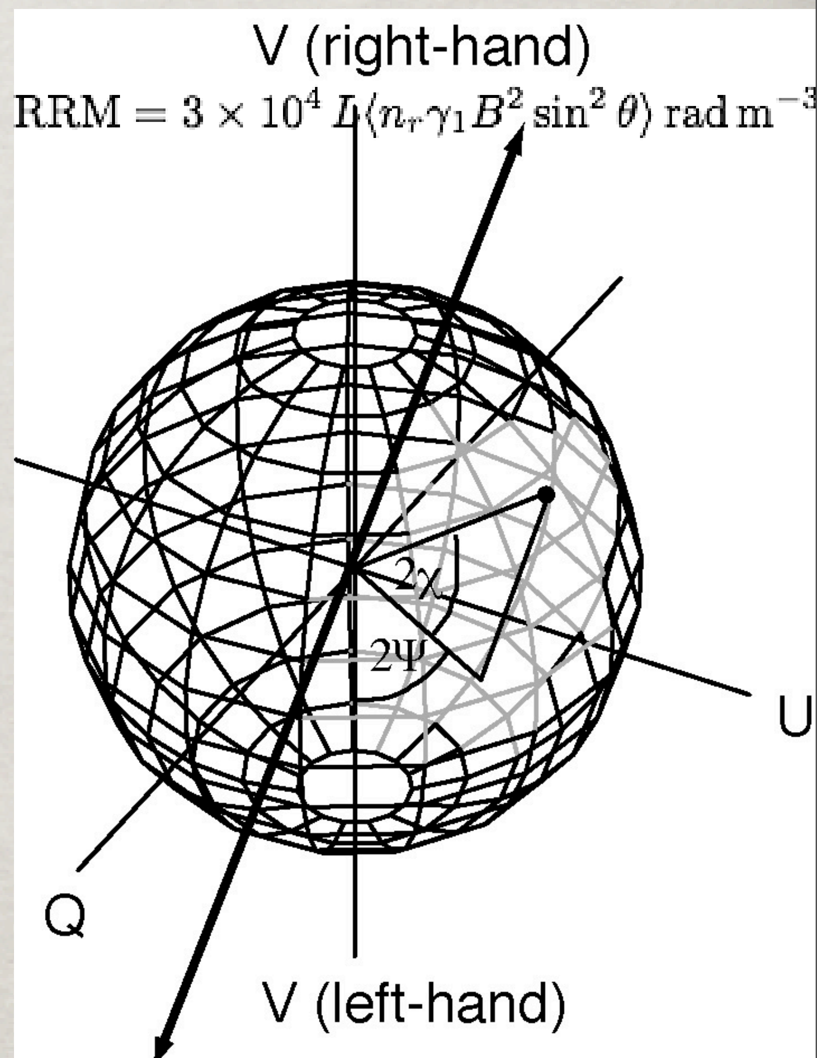


Left-handed CP (ordinary mode) only | Right-handed CP (extraordinary mode) only

Polarisation Conversion in a Relativistic Plasma (I)

Sazonov 1969; Pacholczyk 1973; Jones & O'Dell 1977

- Converts LP to CP
- Conversion only on Stokes U, so need field line re-orientation or Faraday rotation
- Strongest near τ~1
- Sign flip possible as optical depth increases
  - Blandford-Königl jet: self-similarity can give CP of consistent sign and magnitude with ν
- Beckert & Falcke 2002, Ruszkowski & Begelman 2002 - conversion in a stochastic magnetic field with weak <B> to keep persistent handedness of V.
- Mean LP and CP depend on number of field reversals
- High Faraday rotativity without depolarisation



Kennett & Melrose 1998

Circular Repolarisation - e^-/e^+ Jets?

- VLBA - detection of CP in 3C 279 (Wardle et al. 1998)
  - 1% CP found near core/jet base LP~10%
  - Argued for a propagation effect in a relativistic plasma from ν dependence
  - Must have γ_{min} ~100 for e^-/p jet to avoid Faraday depolarisation and large jet kinetic power
    - Detailed polarisation modelling: optically thin synchrotron with a bias in B, and only a few field reversals $\Rightarrow \gamma_{min} < 20$. Hence need pair plasma.
- Both Ruszkowski & Begelman and Beckert & Falcke dispute the claim of an e^-/e^+ jet based on CP
  - Models with large numbers of field reversals along line of sight
  - Different γ_{min}, $n_{cold}/n_{relativistic}$, $n_- - n_+$ and bias (level of B relative to fluctuations) can lead to same rotativity and convertability

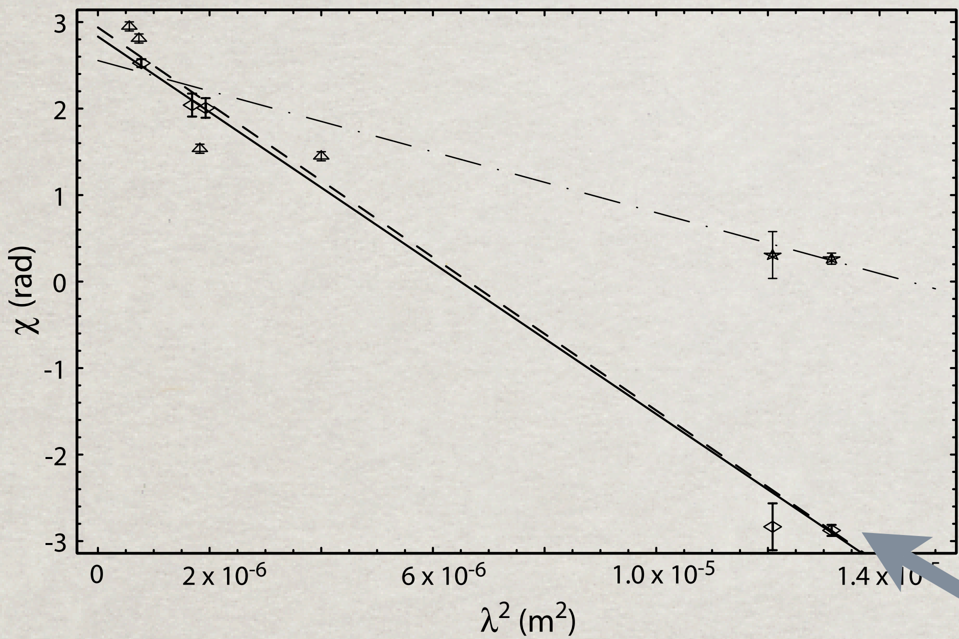
Conclusions

- Associated with active cores (in AGNs and XRBs)
  - High CP during ejections
  - Highly variable
  - High CP on mas and μas scales
- Mechanisms
  - Polarisation conversion in relativistic plasma most favoured
  - Sign stability ⇒ B polarity stable?
  - Others: synchrotron, scintillation-induced, GR effects, coherent emission

“The most significant result of the project is that we now know less about circular polarisation than we thought we did when we started.”

- Ray Norris, on the completion of Dave Rayner’s thesis to measure circular polarization in blazars to 0.01% using ATCA

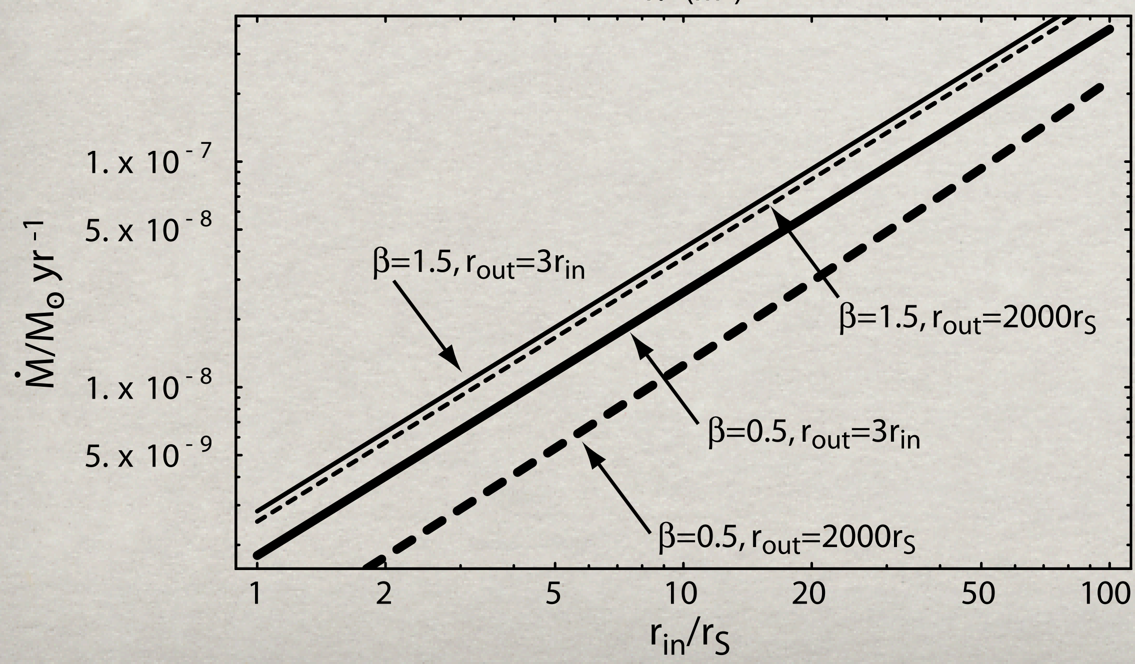
The Rotation Measure of Sgr A*



$$\mathrm{RM} = -4.4 \pm 0.3 \times 10^5\,\mathrm{rad\,m^{-2}}$$

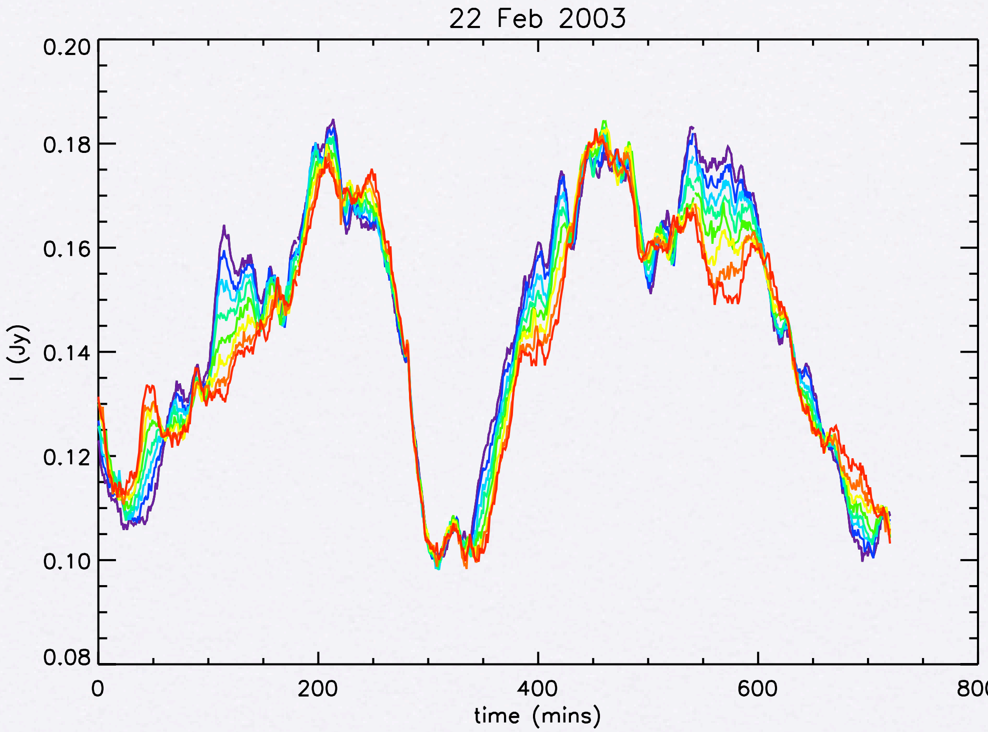
Macquart et al. (2006) Ap.J. Lett. in press astro-ph/0606381

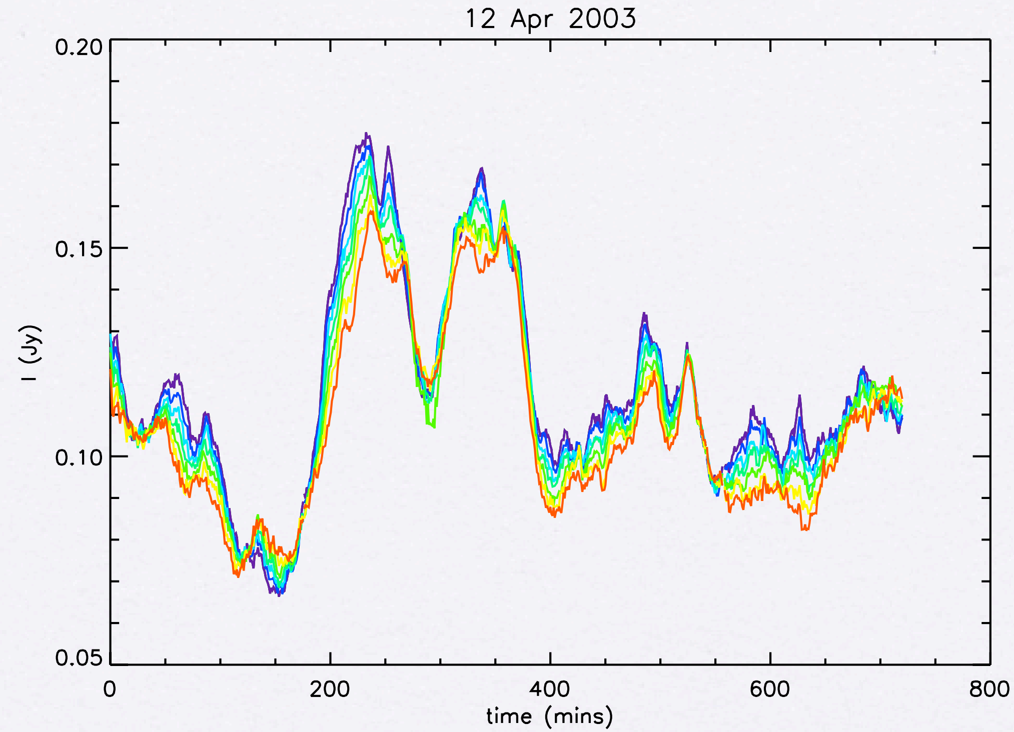
3.5mm detections



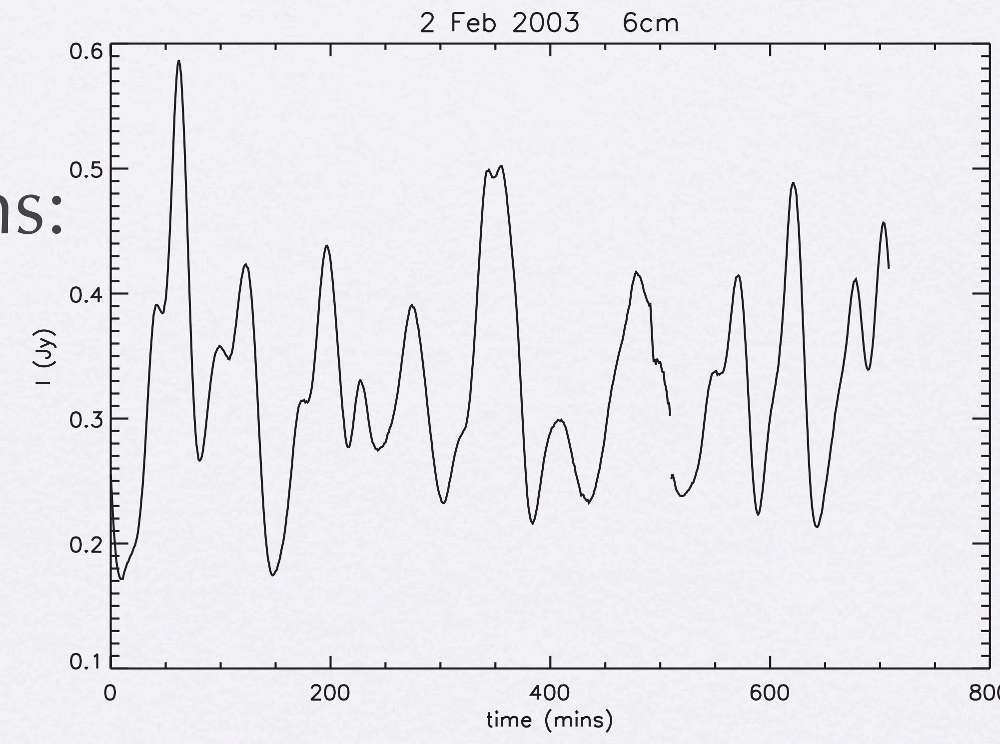
low accretion rate rules out ADAF/Bondi accretion

21 cm variations (in 8x20MHz sub-bands)





by comparison...6 cm variations:

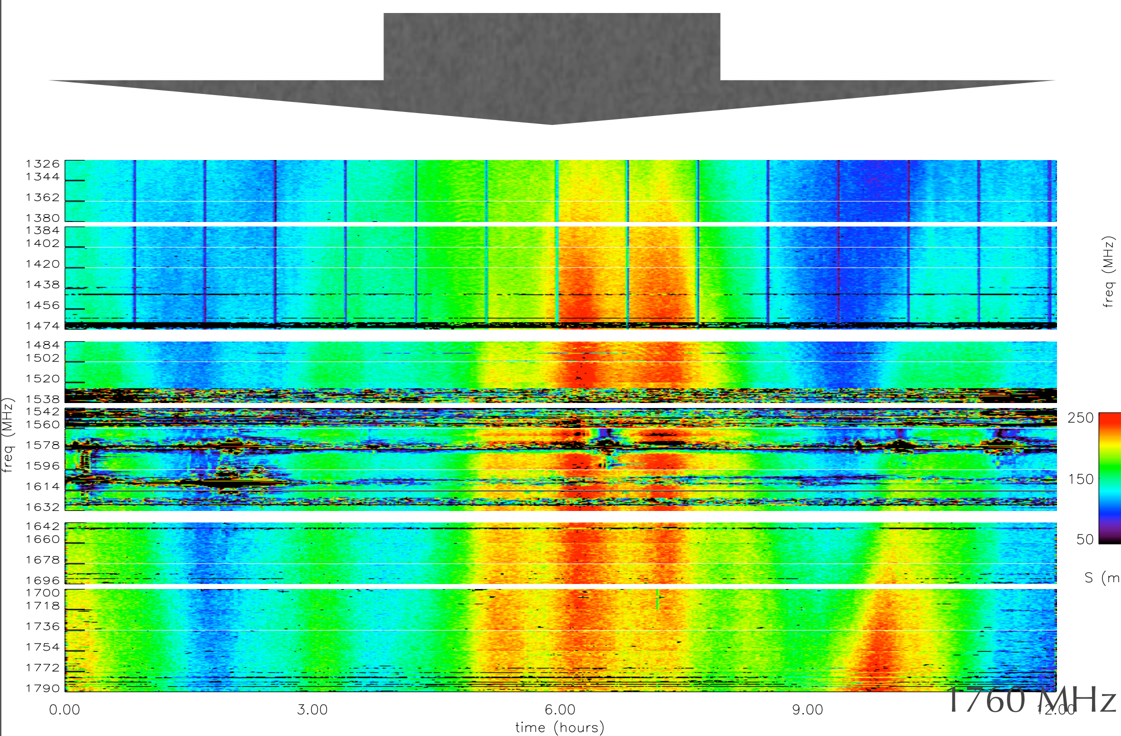


(Quenched) Diffractive Scintillation at 1.4 GHz

Macquart & de Bruyn, A&A 2006

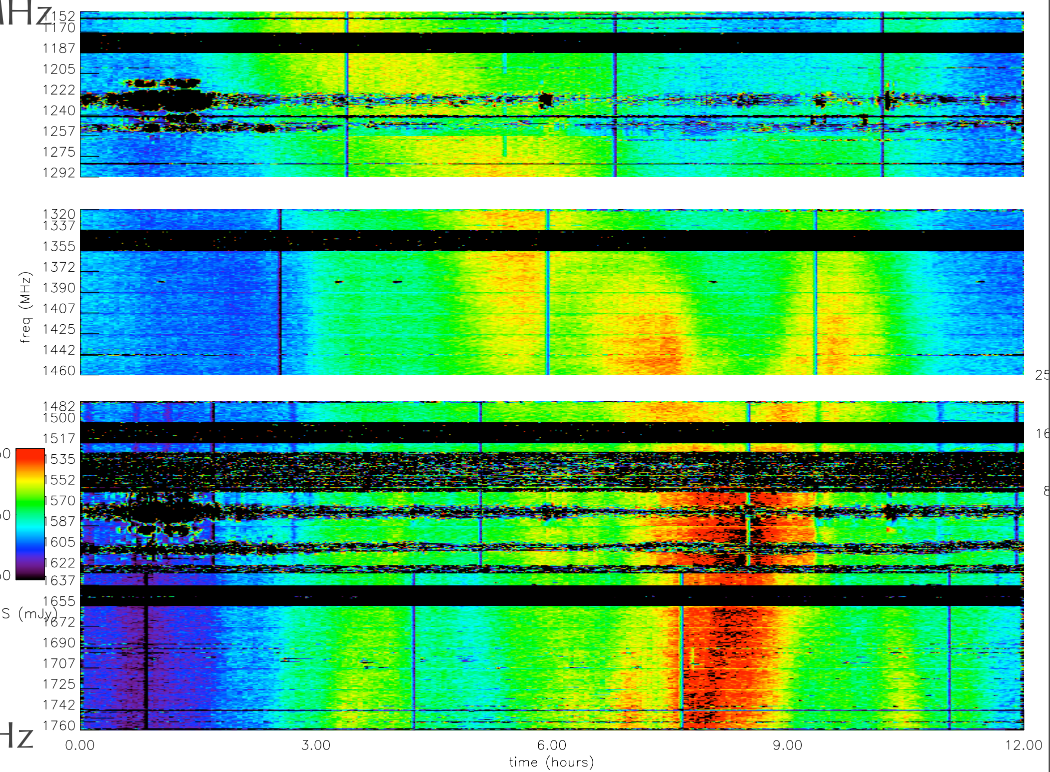
(i) caused by interference between sub-images on the scattering disk (intensity fluctuations are strongly frequency-dependent).
(ii) occurs in strong scattering (and thus at long wavelength)
(iii) requires a component of the source to be compact
(iv) ii & iii require source to possess a high brightness temperature

12 hours



25 Jan 2004

1150 MHz



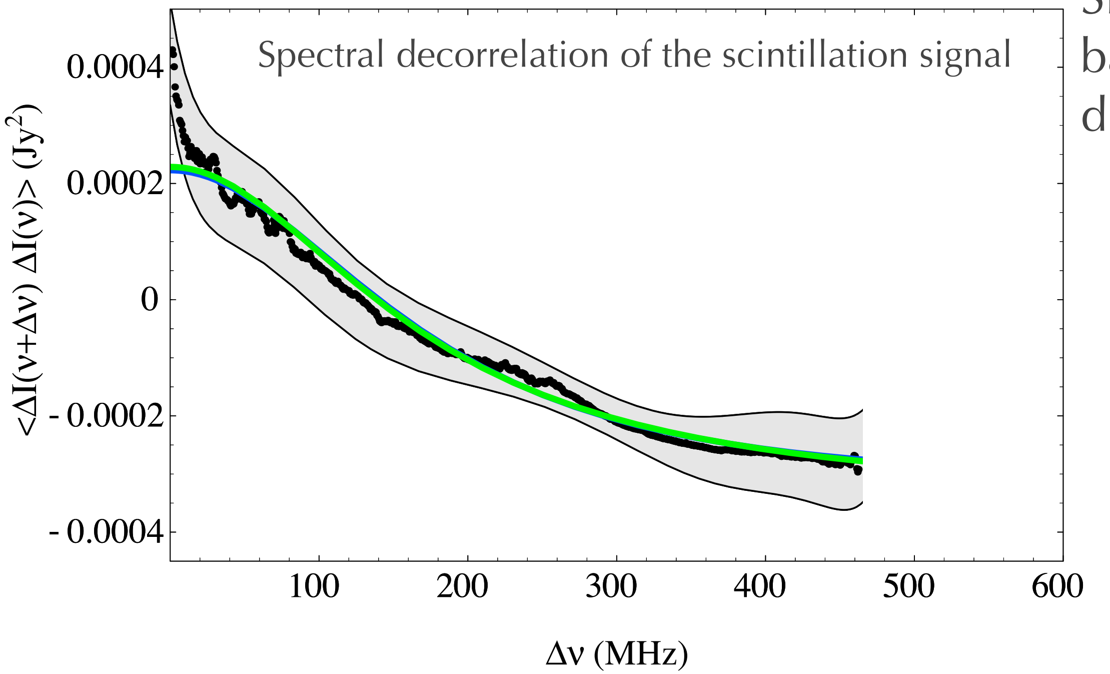
1760 MHz

30 Jan 2005

Wideband (frequency-mosaiced) WSRT observations

Source implications

22 Feb 2004



Simple estimate: 170 MHz decorrelation bandwidth gives source size for a given screen distance:

$$\frac{\Delta\nu_{\rm obs}}{\Delta\nu_{\rm pt\ src}} = \frac{\theta_{\rm src}}{\theta_{\rm diff}}$$

$$T_{\rm B} = 5 \times 10^{13} \left(\frac{z}{10\,{\rm pc}} \right) {\rm K}$$

$$\theta_{\rm src} = 7.4 \left(\frac{z}{1\,{\rm pc}} \right)^{-1/2} \left(\frac{\nu_t}{1\,{\rm GHz}} \right)^{17/10} \mu{\rm as}$$

scattering screen distance Dennett-Thorpe & de Bruyn 2003 suggest 4pc<z<12pc but do not take medium anisotropy at 6cm into account.

More complicated estimate without assuming a screen distance: use decorrelation bandwidth and time scale of fast variations to find z (as a function of flux density associated with compact component, $S_{\rm diff}$):

$$T_b = 2 \times 10^{14}\,{\rm K} \qquad S_{\rm diff} = 150{\rm mJy}$$

$$T_b = 1 \times 10^{15}\,{\rm K} \qquad S_{\rm diff} = 50{\rm mJy}$$

Caveat: scintillation models do not take into account anisotropy in source or turbulence. But none indicated by 21cm annual cycle in diffractive time scale so far.