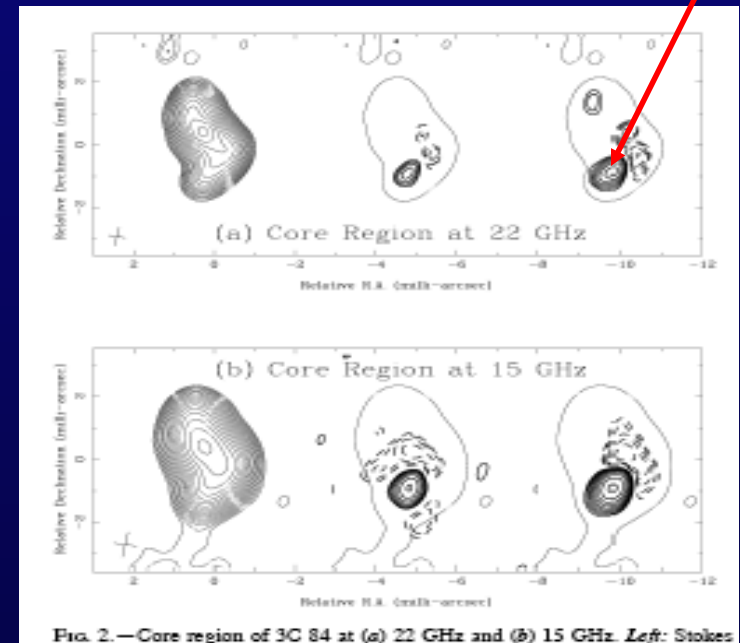
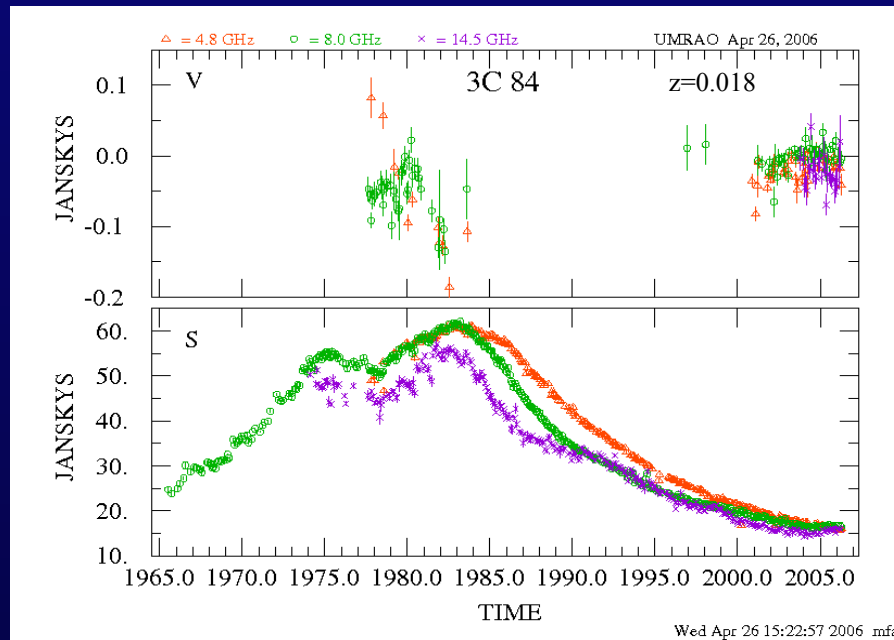


Circular Polarization from Blazars: Results from the UMRAO Program

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OUTLINE

- ♣ Overview of the Program: Why study CP?
- ♣ Source Selection and Limitations
- ♣ Observational Results
 - ♣ Relation to outburst state (total flux, LP)
 - ♣ Relation to VLBI imaging; spatial location of the emission
 - ♣ Evidence for variations in polarity
- ♣ Interpretation/Origin of the CP emission
 - ♣ The case for mode conversion
 - ♣ Jet properties from CP modeling : γ_{\min} , degree of order in B
 - ♣ Radio Jet/Central Engine Connection?
- ♣ Future Directions

Importance of CP Observations

- ♣ Emission in Stokes V is common in AGNs. (It is an underlying property of Blazar emission)
- ♣ It potentially provides information on the large scale structure of the embedded magnetic field via the polarity (link between jet and central engine?)
- ♣ It provides (model-dependent) limits on several poorly constrained jet properties: the small scale structure of the B field, the jet's energetics, and its particle composition (electron-proton vs electron-positron jets)

Detection Statistics: single dish and imaging

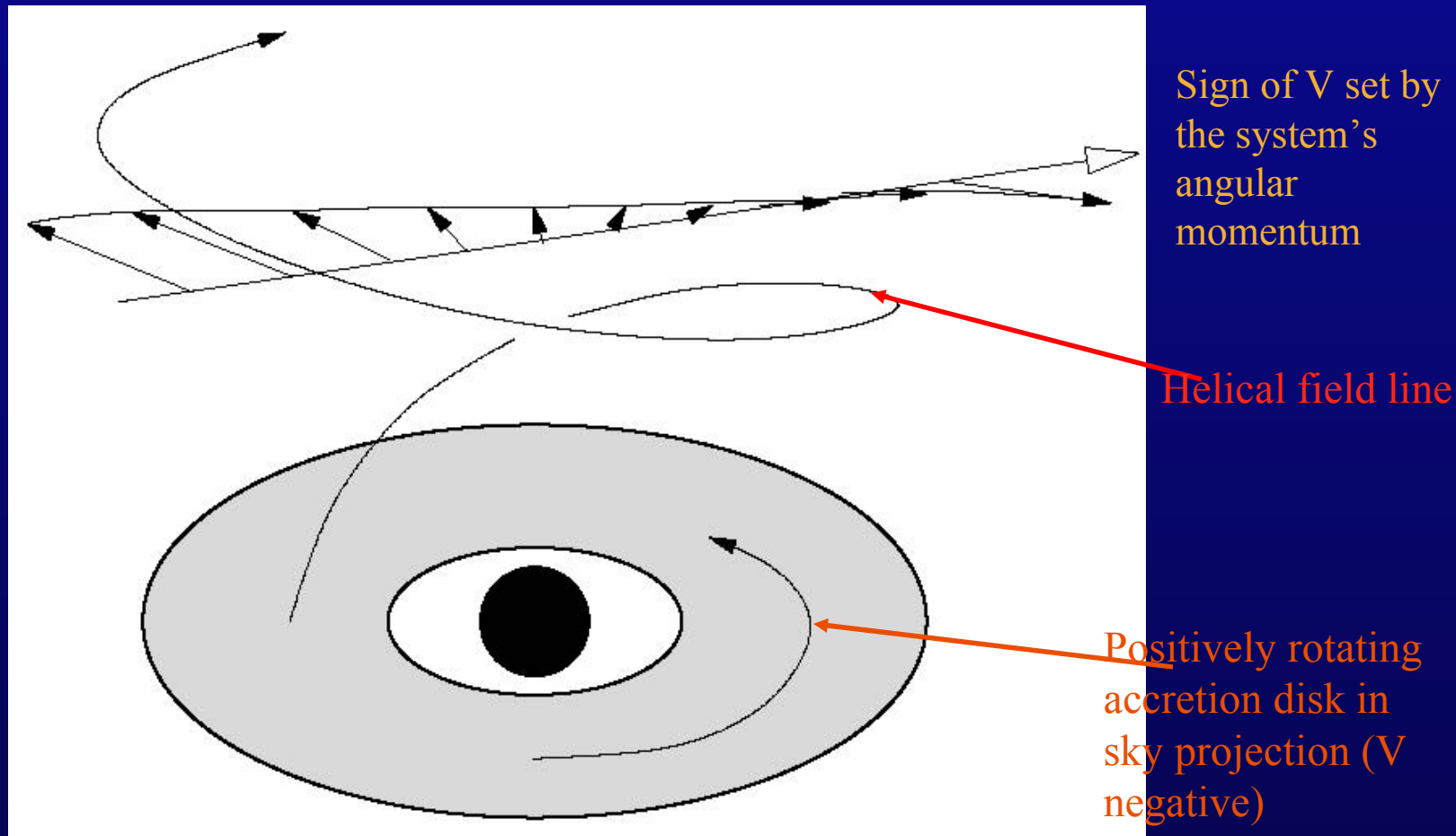
VLBA	15 GHz	17/133; $\sigma \geq 3$	Homan & Lister AJ 131, 262, 2006
UMRAO	5 GHz	11/15; $\sigma \geq 3$	Aller, Aller, & Plotkin Ap&SS, 288, 17, 2003
UMRAO	8 GHz	5/11; $\sigma \geq 3$	Aller, Aller, & Plotkin Ap&SS, 288, 17, 2003
VLBA	5 GHz	11/40; $\sigma \geq 3$	Homan, Attridge, & Wardle ApJ, 556, 113, 2001
ATCA	5 GHz	17/31; $\sigma \geq 5$	Rayner, Norris, & Sault MNRAS, 319, 484, 2000
VLBA	15 GHz	4/13; $\sigma \geq 3$	Homan & Wardle ApJ, 118, 1942, 1999

Surveys of flat spectrum (variable) objects typically find that 25-50% of the sources emit detectable Stokes V at cm band.

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Example: Magnetic helicity and CP handedness



Geometry of a jet source with rotation illustrating magnetic twist
(Ensslin, A&A, 2003)

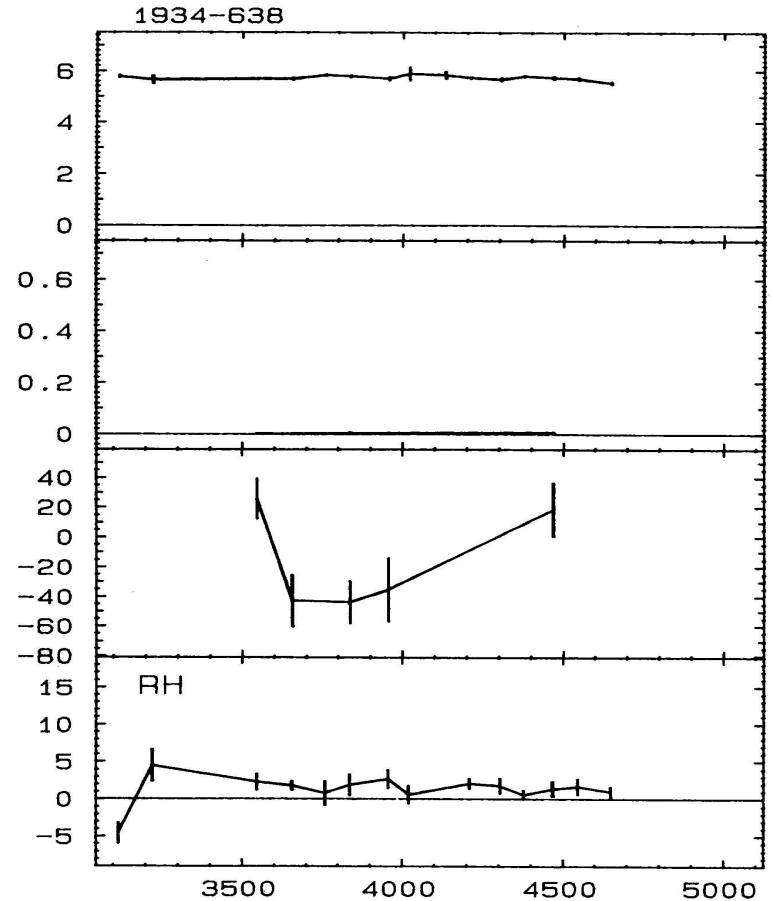
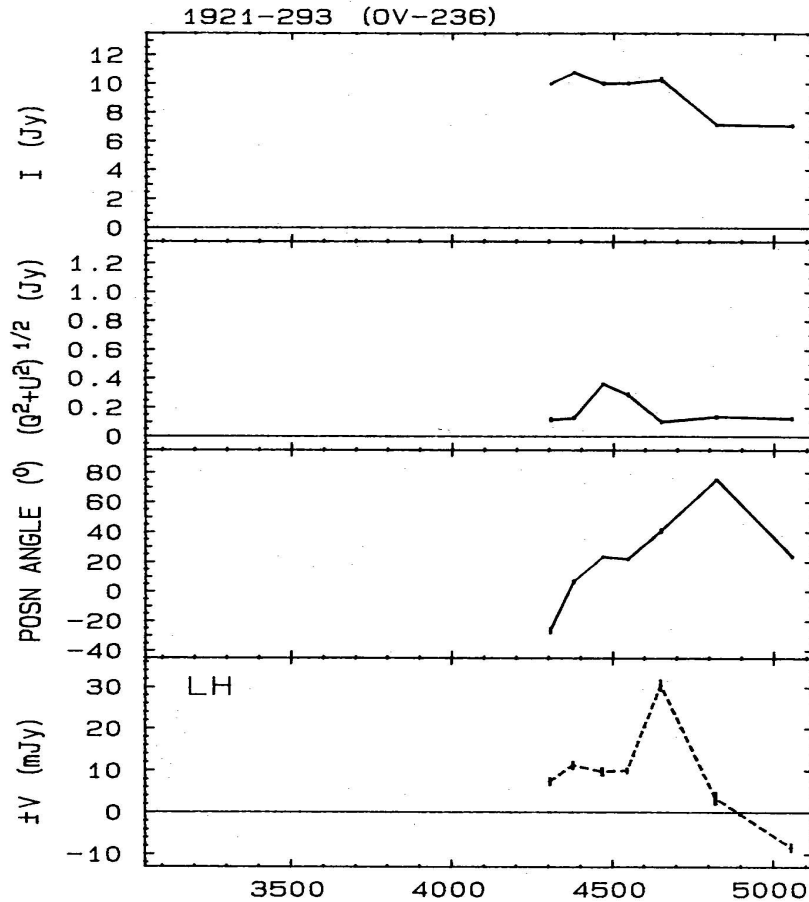
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Challenges Provided by the Data: acquisition/interpretation

- The emission is weak yielding low S/N measurements (typically tenths of a percent of Stokes I and an order of magnitude weaker than LP) and near the detection limit of many instruments.
- Many telescopes are not optimized to observe CP (e.g. the VLBA uses circularly polarized feeds).
- Southern instruments (Parkes, ATCA) well-suited for CP studies and used effectively for past studies provide minimal overlap with sources studied with high resolution VLBA imaging.
- Overlapping multi frequency data are sparse (few epochs of VLBA data exist); single dish monitoring windows are often not matched to variability time scales, i.e. too short and/or generally at only one frequency.

An Example: Parkes Monitoring



- The time window is short relative to the variability time scale (12/76-03/82)
- The data are at 1 frequency only (5 GHz)
- Several sources are not/not easily observable with the VLBA (note $\delta > -25$)

UMRAO CP PROGRAM

Aller, Aller, Hughes, Latimer (Hodge & Plotkin)

Resumption of observations at 8, 4.8 GHz; addition of a new polarimeter at 14.5 GHz in late 2003

TIME SPAN of DATA:

T1: 1978-1983 (4.8, 8.0 GHz)

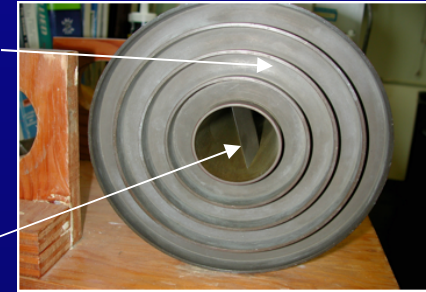
T2: 2001-2006 (4.8, 8.0, 14.5 GHz)

SAMPLING during T2:

- ♣ initially 25% of telescope time
- ♣ increased to 50% in fall 2005

Scalar feed

Quarter Wave Plate



4.8 GHz Circular Polarimeter

UMRAO 26-m paraboloid



Source selection

Initial sample: 36 sources (positive/suspected detections)

0059+581	3C 120	0743-006	3C 279	1741-038	OX 161
DA 55	0420-014	OJ 287	1308+326	OT 081	2145+067
0235+164	0607-157	4C 39.25	1335-127	1800+440	BL Lac
3C 84	0642+449	1055+018	1510-089	OV-236	3C 446
NRAO 150	0716+714	1150+497	1519-273	1928+738	CTA 102
3C 111	0736+017	3C 273	3C 345	2134+004	3C 454.3

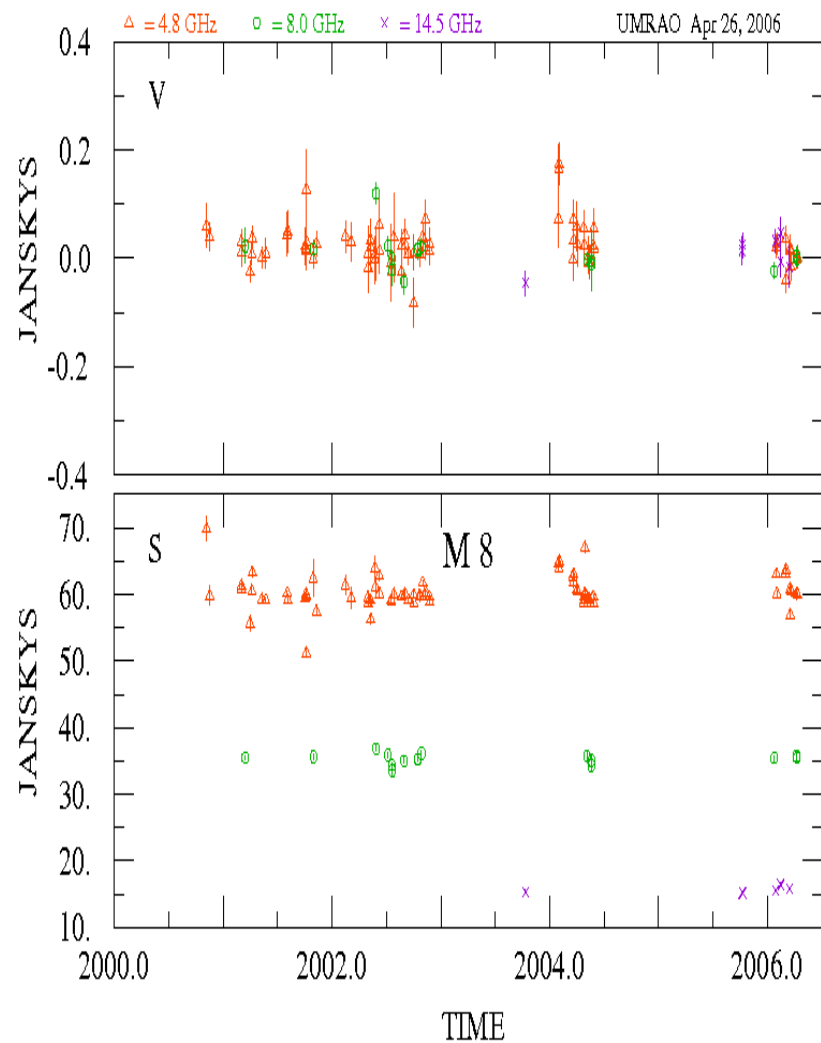
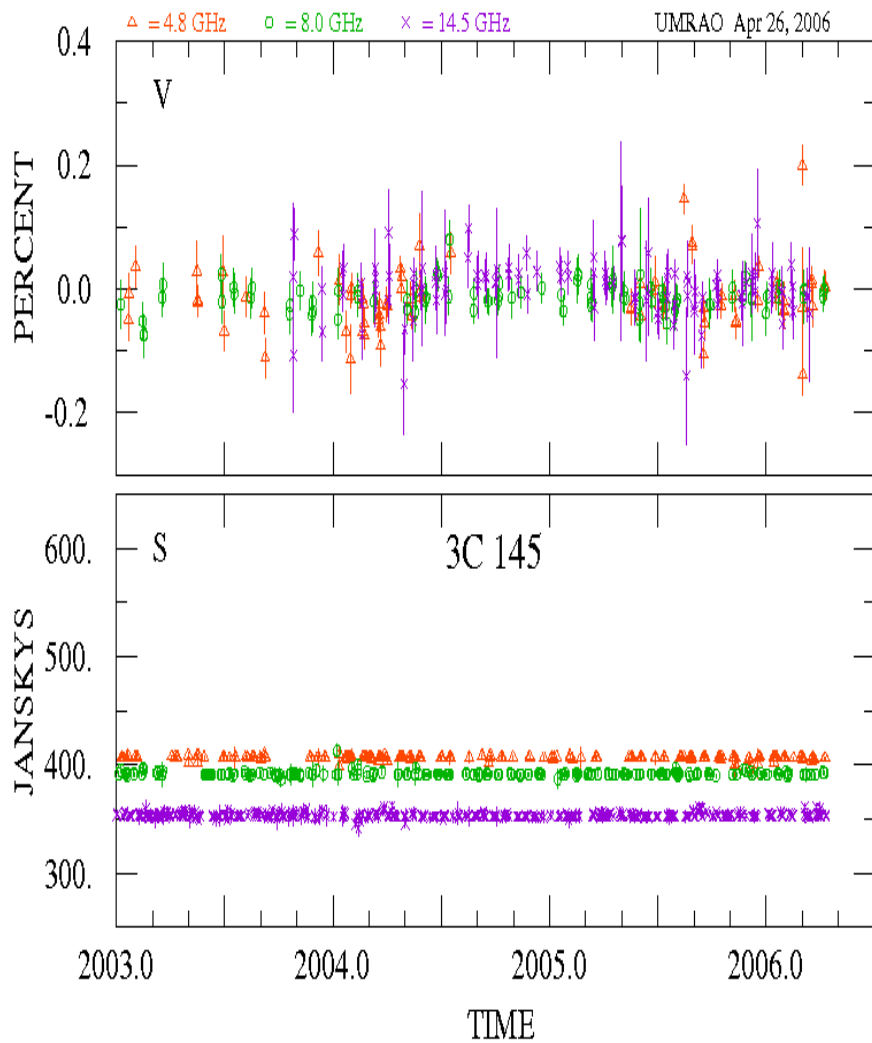
Sample comprised primarily of flat spectrum objects and includes radio galaxies, BL Lacs and QSOs. Objects in magenta were selected for intensive monitoring based on average CP strength and current total flux density.

Observing Procedure/Limitations

- Prime focus polarimeters simultaneously measure all 4 Stokes parameters. This is useful for identifying the variability and spectral state during each CP epoch.
- Observations require a minimum on-source integration time of 1.5 hours, and several observations must be averaged to obtain 3 sigma detections. Only variability with timescales of several weeks to months can be identified.
- Source observations are interleaved with both flux and polarization calibrators (H II regions). Detections of CP are set by the instrumental polarization. These required observations restrict the number of program sources observed per day to 12-14.

IP level $< 0.1\%$ from (unpolarized) HII regions

daily averages for a strong and for a weak calibrator



Goals of the UMRAO Observational Program

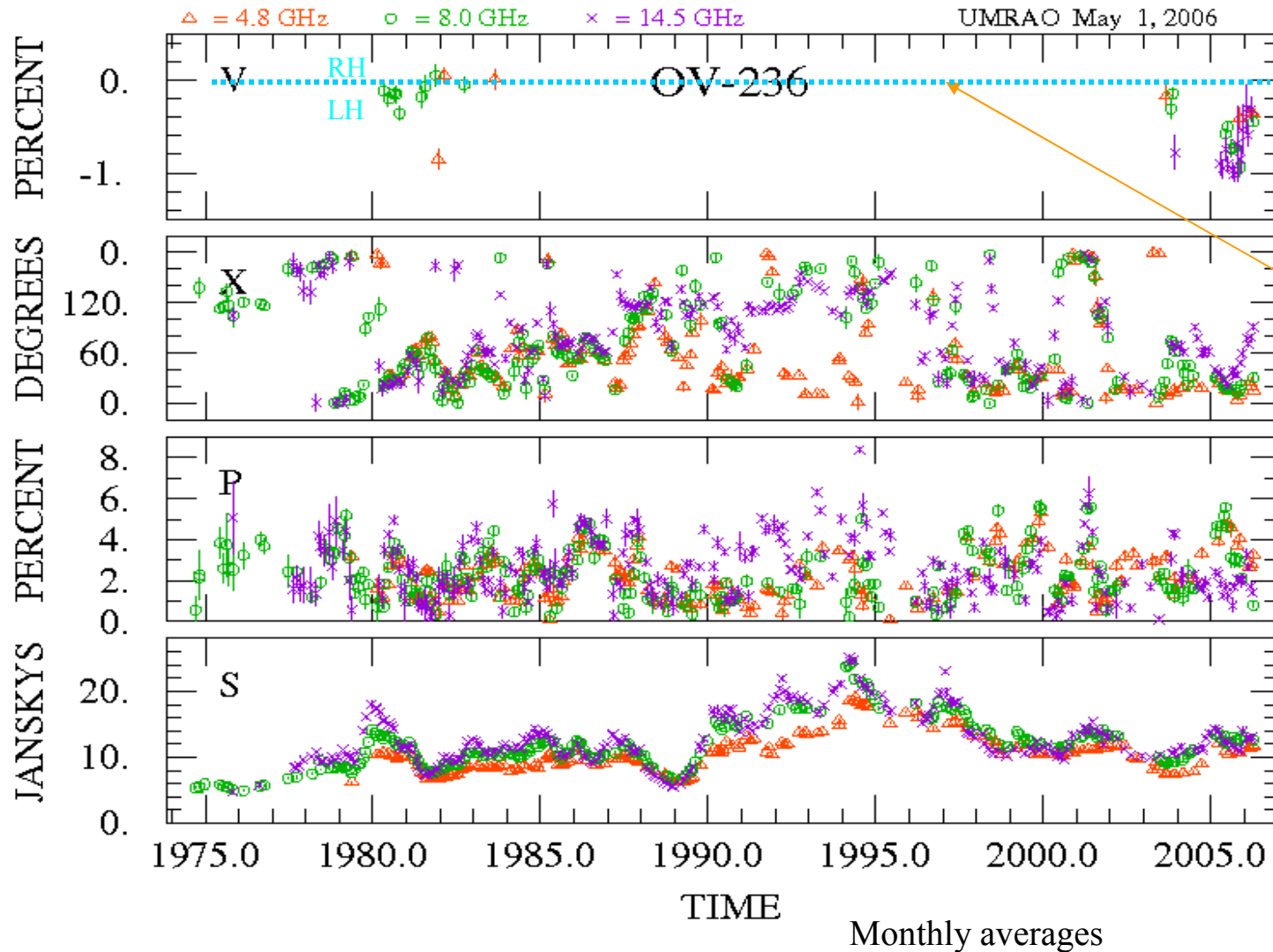
IN COMBINATION WITH MODELING, to set limits on:

- 1) the low energy particle cut-off from the limit on Faraday rotation (assuming an electron-proton gas)
- 2) the fraction of energy in an ordered component of the magnetic field from the amplitude of Stokes V
- 3) the direction of the global B field from the polarity of Stokes V if a preferred value persists

Requirements of the data:

- 1) Long term observations (preferably from the same instrument).
- 2) Data at 2 or more frequencies (to discriminate between models).

Evidence for Constant Polarity

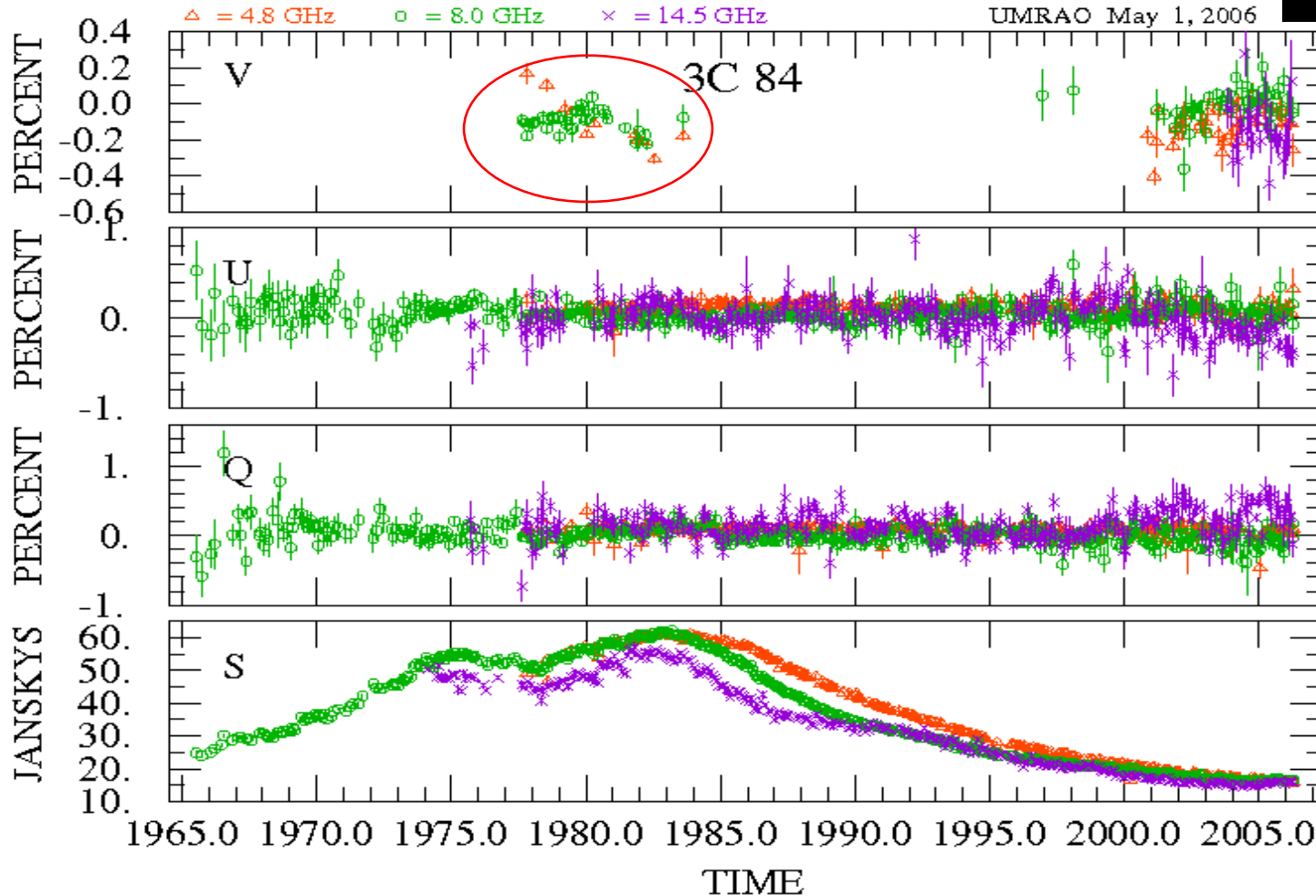
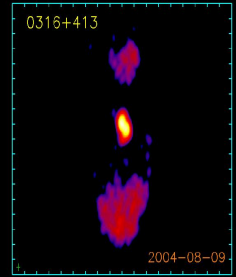


UMRAO:
Negative sign
persists for
decades

VLBA:
12/96 5 GHz
sign negative

Parkes: 80-82
5 GHz mostly
neg.

3C 84: constant polarity?



MOJAVE I image

Drift at 4.8
GHz with
sign change

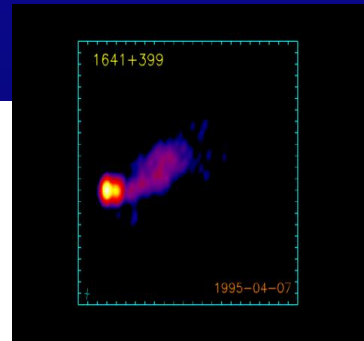
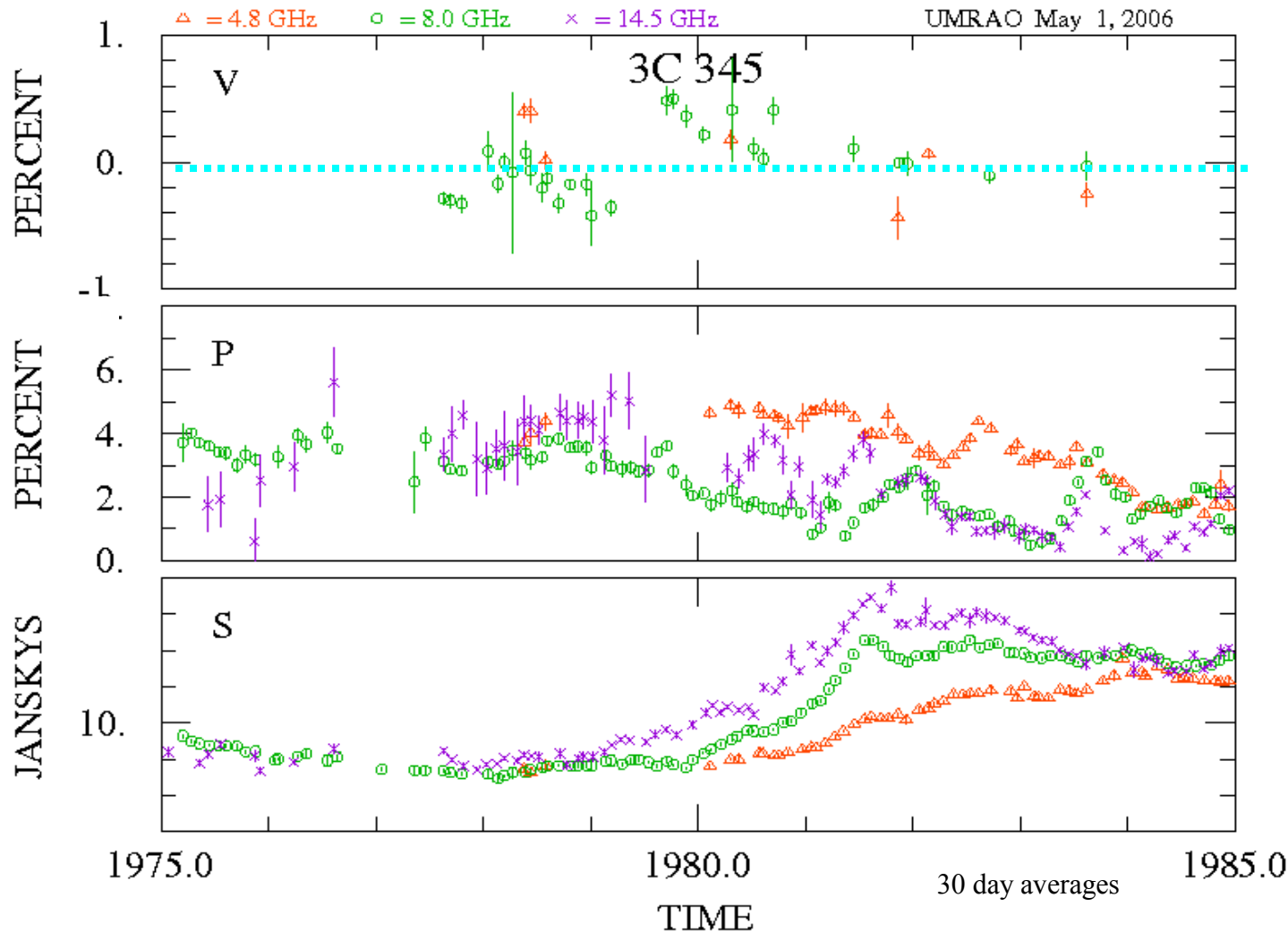
Q & U
shown:

P% low

Simple light
curve with 2-3
long term
events

30 day averages

Systematic polarity changes at 2 freqs which track: 3C 345 (8 & 4.8 GHz) during T1

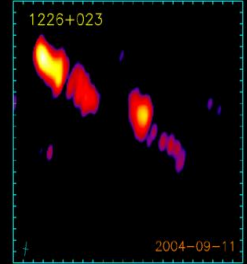
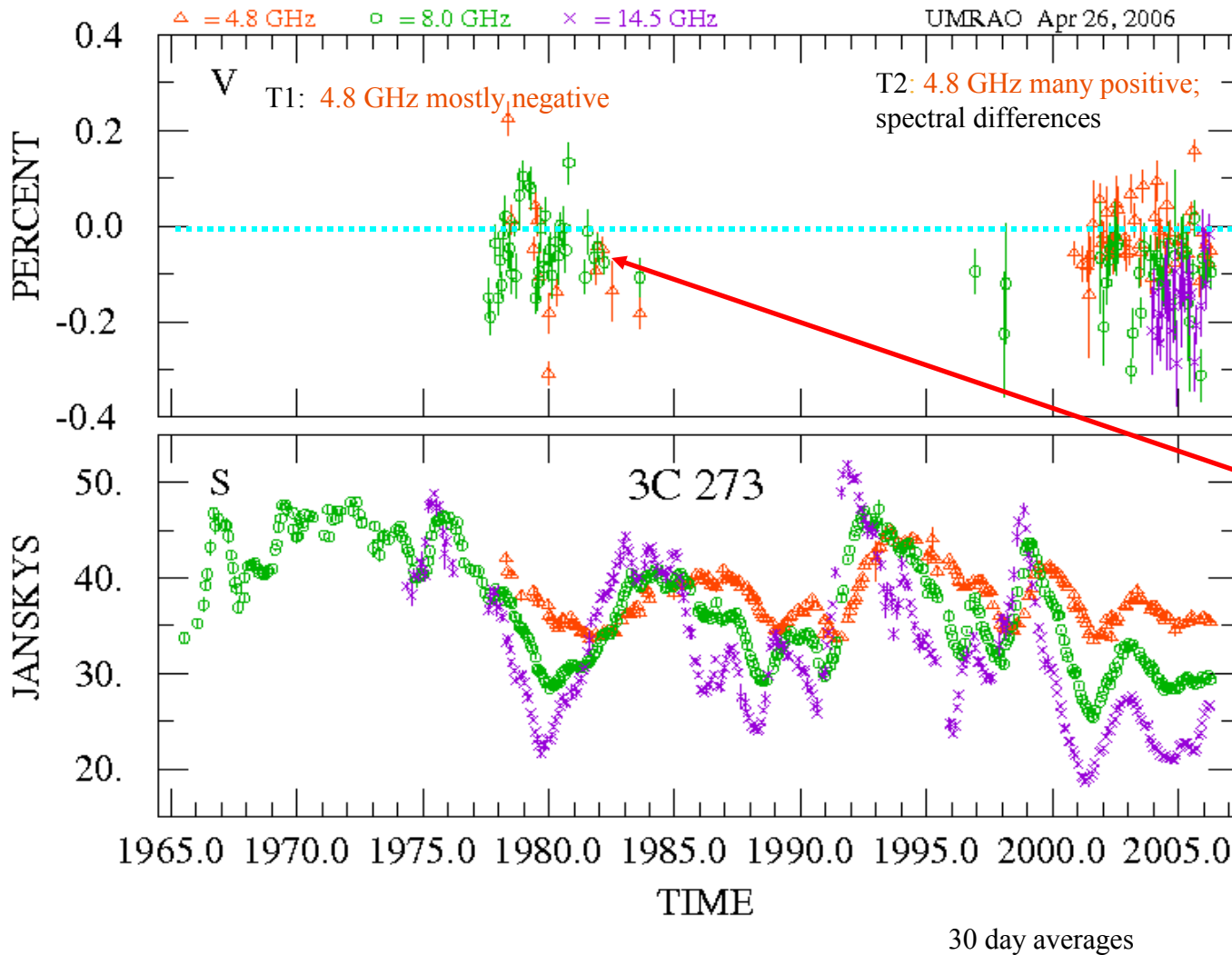


MOJAVE image

LP: Complex,
multi-component
source

S: Self-absorbed
source

Long-term Frequency-dependent Differences in Polarity

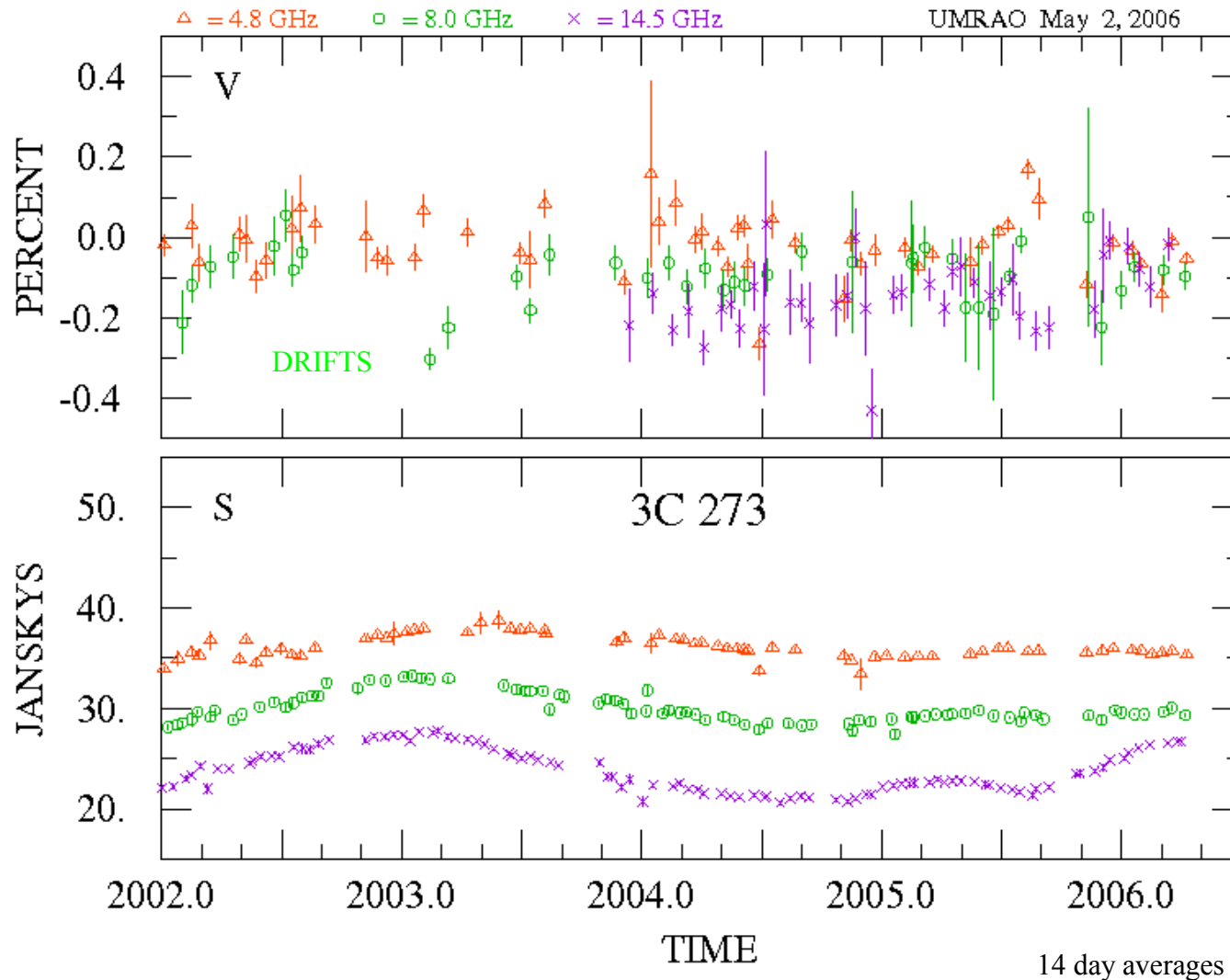


MOJAVE I image

Parkes 5 GHz:
1977-82 negative

Multi-decade data show variability in BOTH amplitude AND polarity

3C273: Frequency-dependent Changes in Amplitude (shorter term variations during T2)



BEHAVIOR:

amplitude:

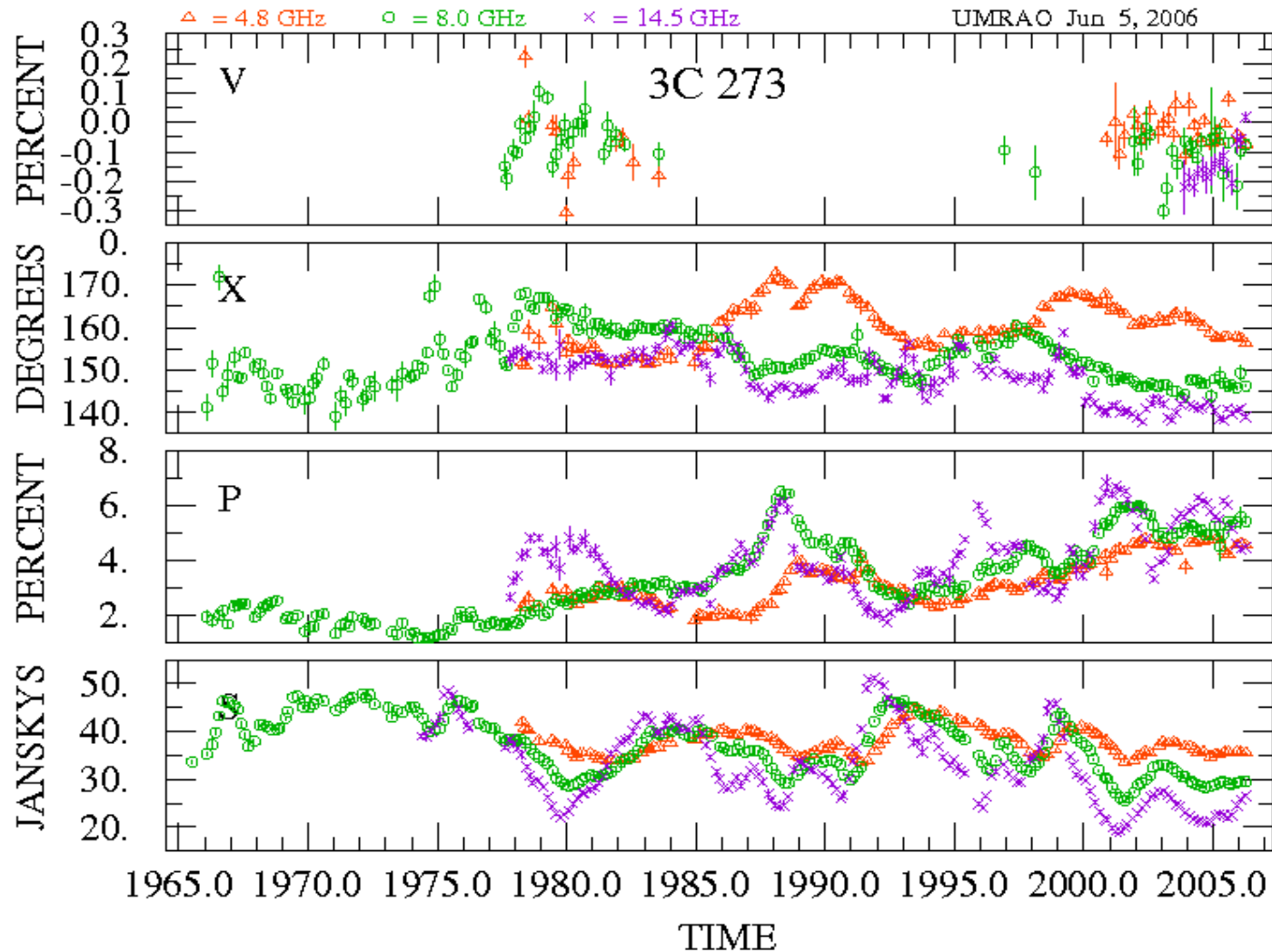
generally near 0
with systematic
drifts of order 1 yr

polarity:

negative (mostly)

variations: do not
track at each
frequency

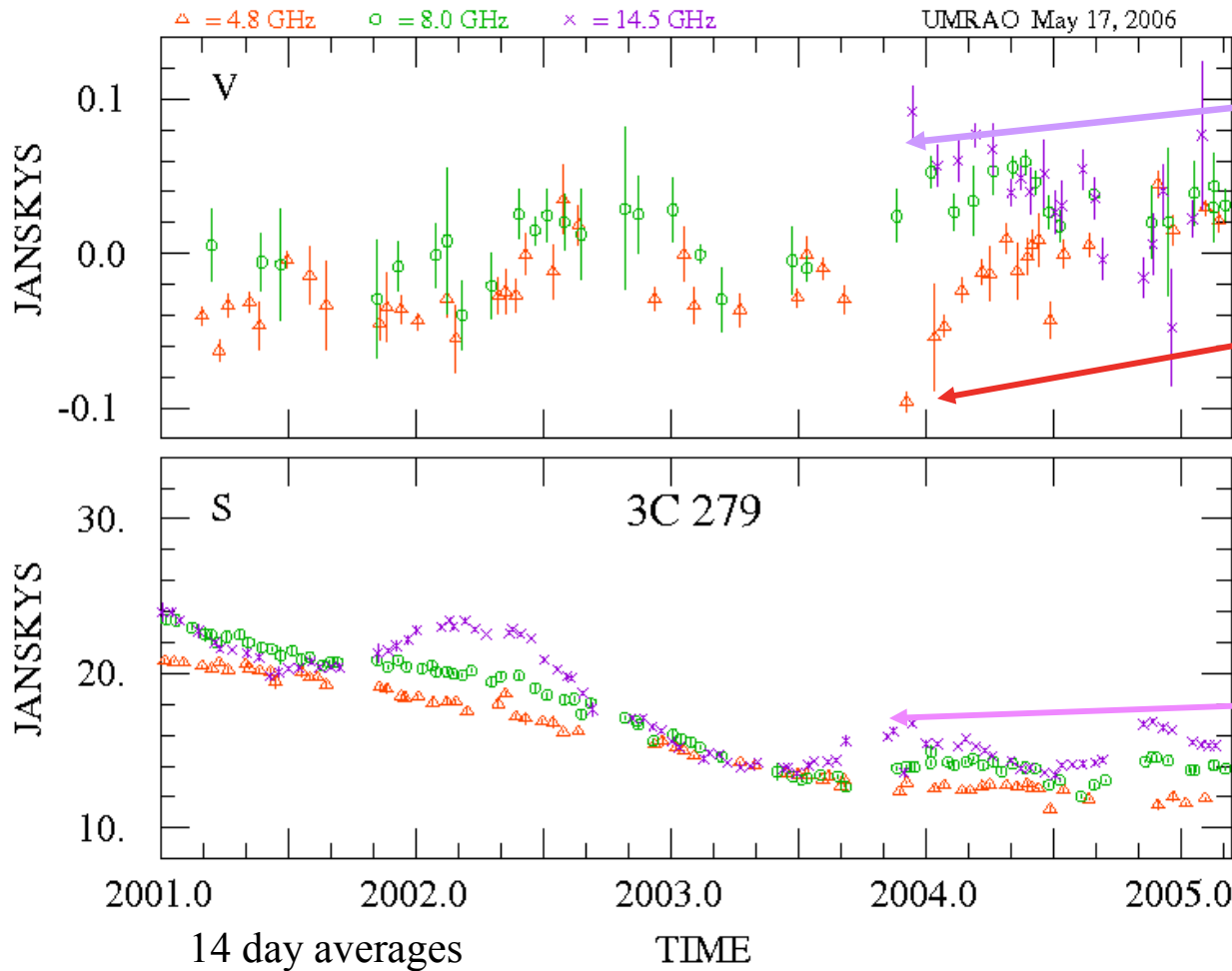
Evidence for self-absorption from LP data



Opacity effects shown by spectral behavior of LP

60 day averages

A Dramatic Spectral Change in 3C 279

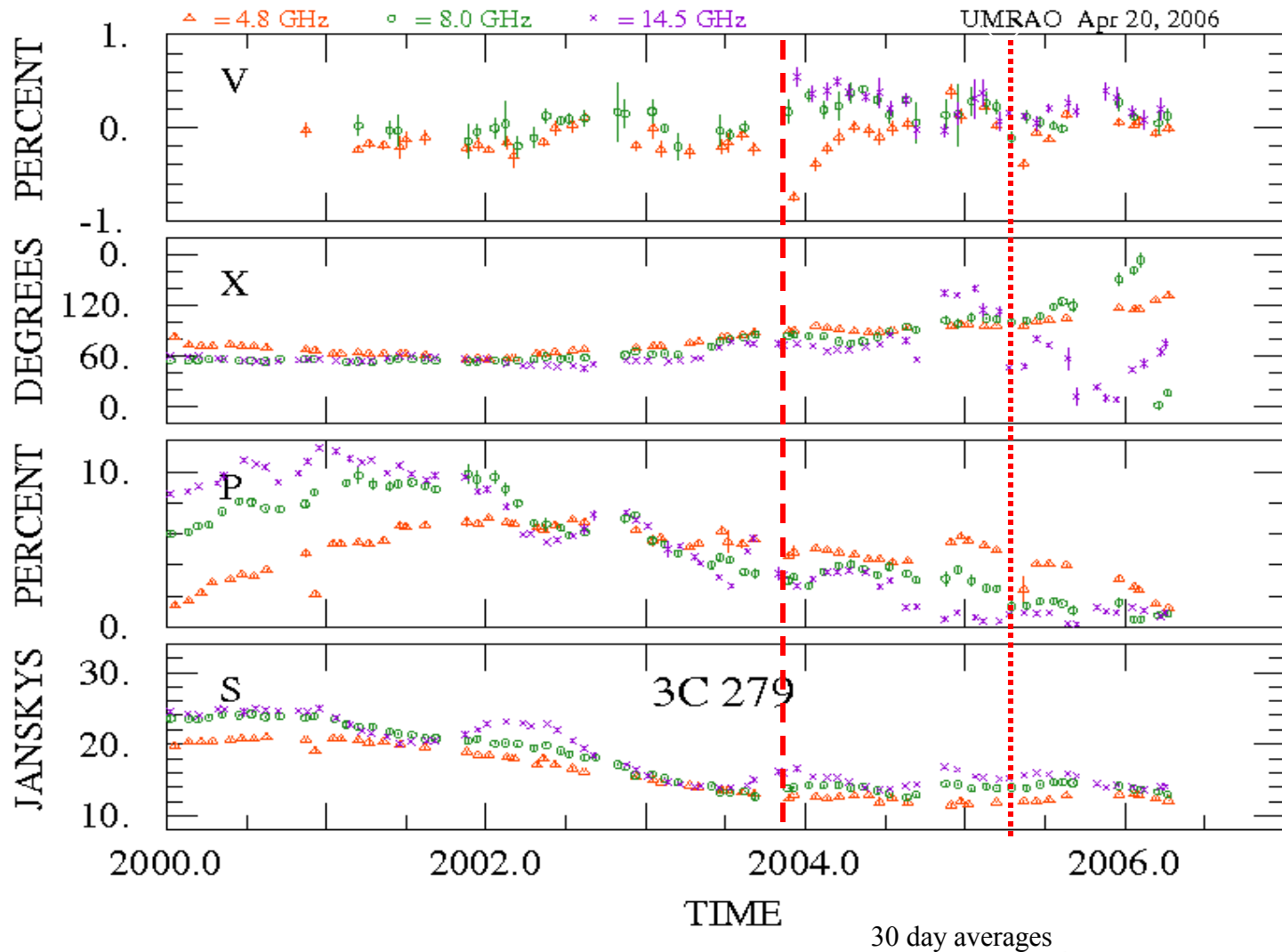


First 14.5 GHz data
in Stokes V

Stokes V near 1%

Small outburst in
total flux density;
inverted spectrum

Repeated Patterns in Stokes V: 3C 279



Summary of Trends in the Data

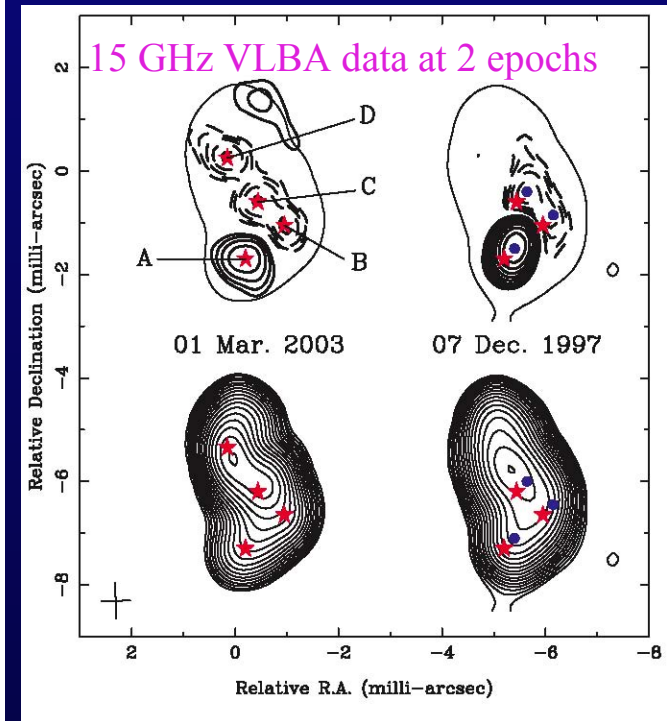
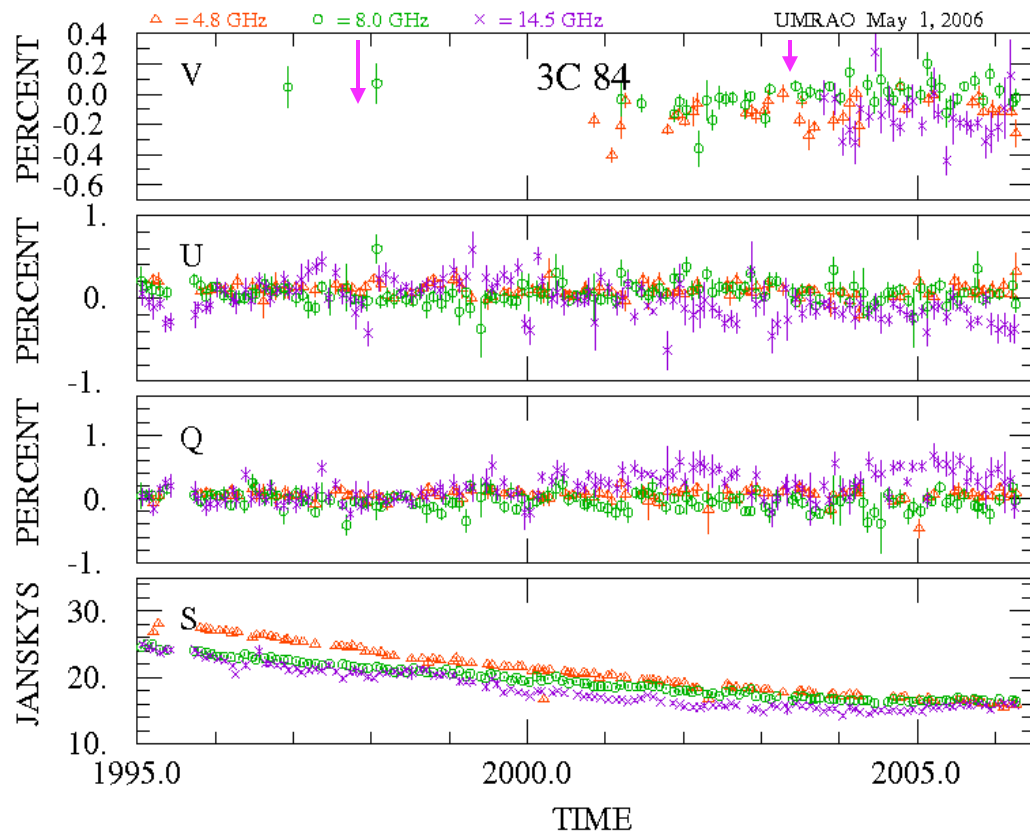
- There is evidence for changes in polarity on both long (decades) and shorter (multi-month drifts) time scales.
- Changes in amplitude and polarity occur when there is evidence for self-absorption from the total flux and/or linear polarization spectra.
- The largest amplitude changes in V/I occur at the lowest frequencies (Faraday effects). In contrast, during outbursts in Stokes I, the variations are highest at 14.5 GHz (opacity effects).
- During some events, polarity changes (flips in handedness) occur at 4.8 and/or 8 GHz. None yet are observed at 14.5 GHz (data noisier, shorter time span?).

Where/how is the emission produced?

- VLBA imaging shows that CP is generated at or near the core ($\tau=1$ surface) with additional very weak emission from jet components in a few sources (e.g. Homan & Lister 2006).
- The data are consistent with a stationary emission region based on limited VLBA imaging data at more than one epoch. (3C 84 result**)
- The CP emission arises in self-absorbed regions as indicated by the total flux density spectrum or by the LP spectral behavior.
- Linear-to-circular mode conversion is a plausible mechanism (e.g. Jones & O'Dell 1977 paper II) consistent with the UMRAO monitoring data.
- A spatially varying B field serves as the catalyst in the mode conversion. Plausibly this is a turbulent B field comprised of cells with random orientations (e.g. Jones 1988); alternatively a helical magnetic field might produce the conversion. A likely scenario includes a combination of both a turbulent and a global helical magnetic field (Beckert and Falcke 2002).

Evidence for spatially-invariant CP emission region over a 5 year time span

Note: VLBA data at 14.5 GHz precedes commencement of UMRAO program at 14.5 GHz



Homan & Lister 2006

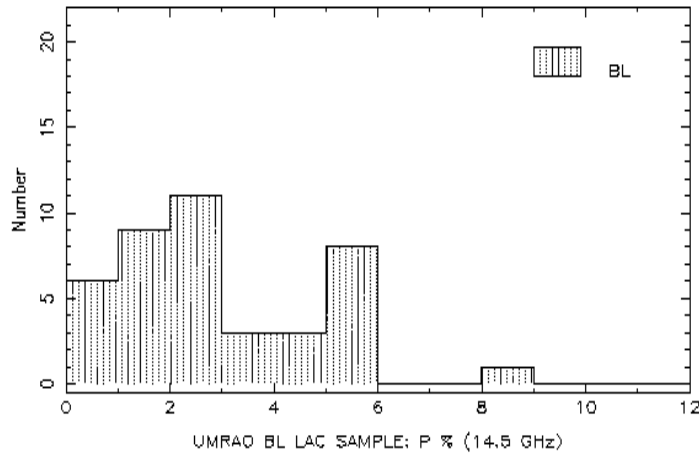
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Evidence for Turbulent Magnetic Fields: Low P%

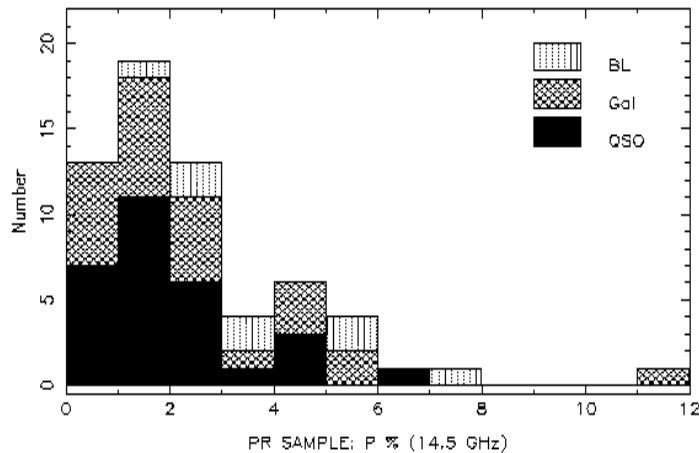
Histograms of $\langle P \rangle$ from time-averaged Q and U for two flux-limited samples

Fractional Polarization Distributions: 14.5 GHz



UMRAO BL Lac Sample

0 < P < 9%: 41 objects observed since 1979



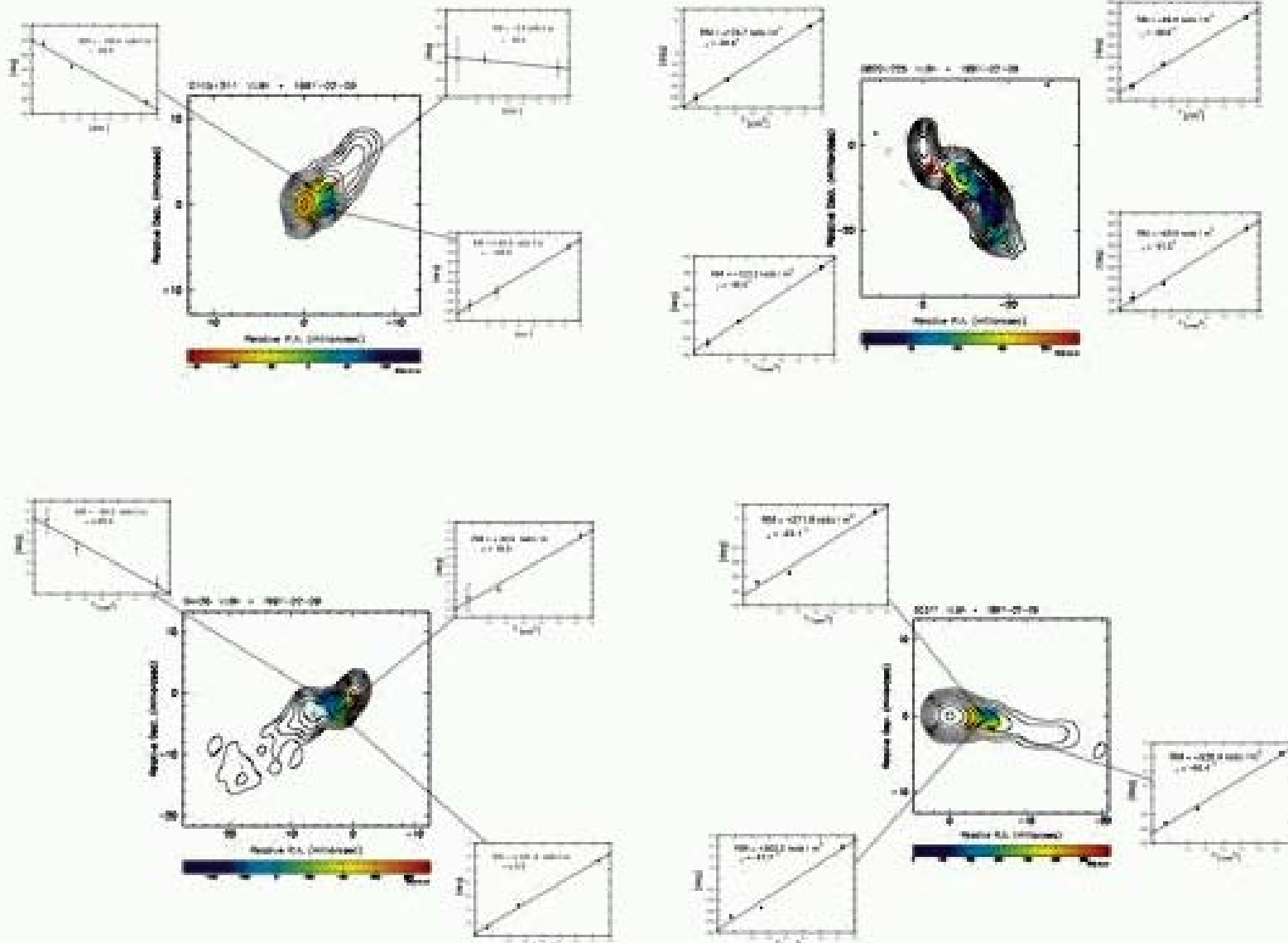
Pearson Readhead Sample

Primarily Q, G classes

0 < P < 12%: 62 sample members monitored since 1984

Evidence for Helical/Toroidal Magnetic Fields

Rotation Measure Mapping



from Gabuzda, Murray, & Cronin 2004

CP as a tool to set limits on the structure of the B field and jet energetics

Adopted model:

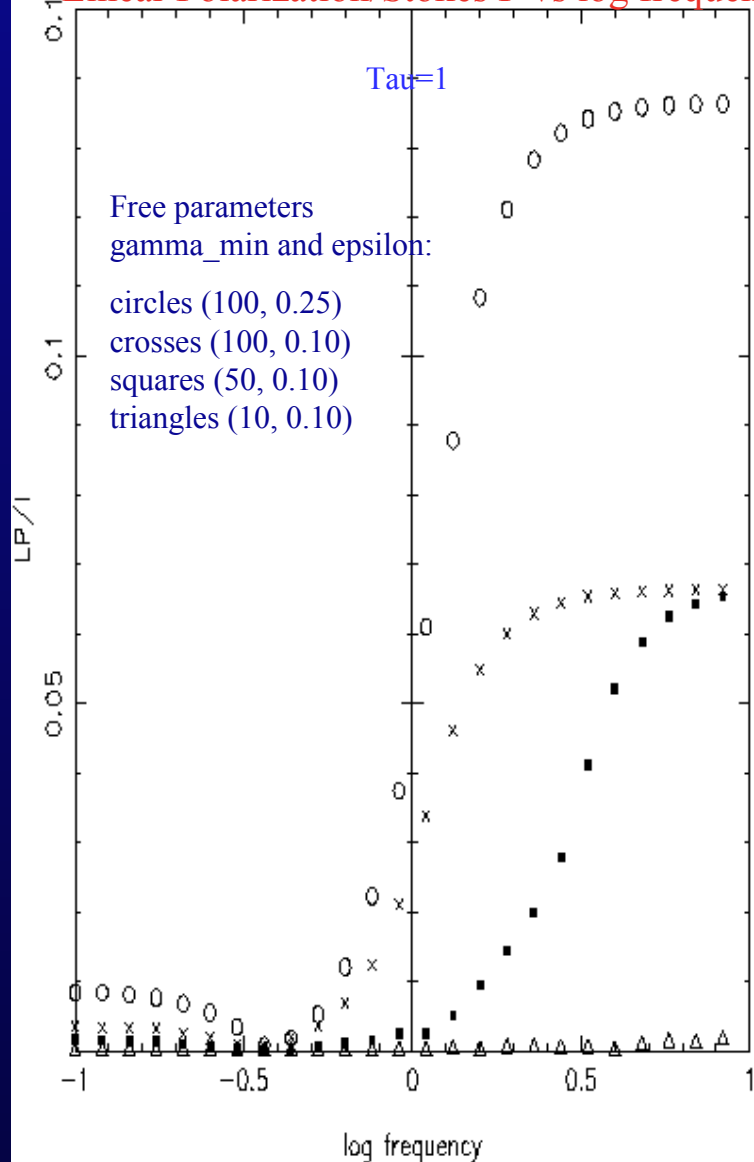
- CP is produced by mode conversion in a process driven by Faraday effects (birefringence).
- Radiative transfer calculations follow the formulation of Jones (1988). The emission is due to relativistic electrons.
- The B field is characterized by two components: an ordered mean component, and a turbulent field with a specified coherence length. This turbulent field is the origin of the Faraday rotation.

Free parameters to be constrained by comparison with the data are:
gamma min (the minimum Lorentz factor) & epsilon (the fraction of energy in an ordered B field)

Exploratory Radiative Transfer Calculations

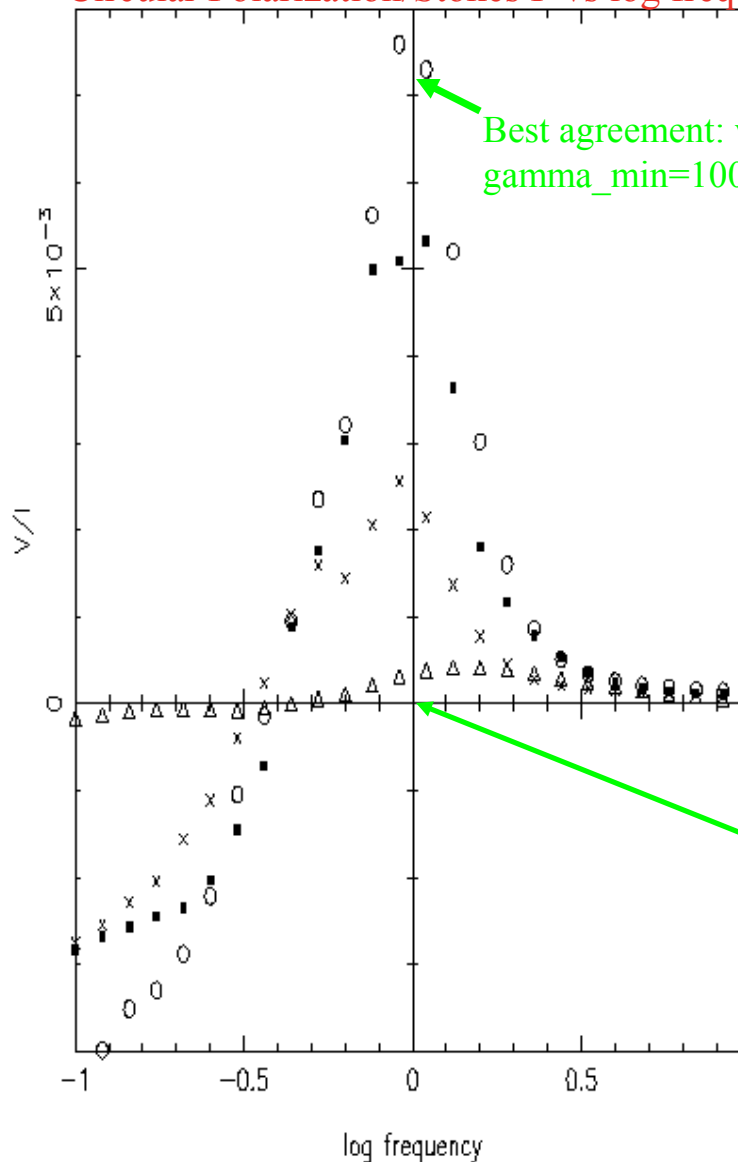
Linear Pol.

Linear Polarization/Stokes I vs log frequency



Circular Pol.

Circular Polarization/Stokes I vs log frequency



Results from Comparing Model and Data

- A straightforward model with mode conversion during outbursts reproduces the observed LP and CP spectra. The predicted levels of CP and LP are very sensitive to the choice of values for the free parameters: a moderate level of LP is needed to seed the conversion to CP.
- The relative values of LP and CP require that a substantial fraction of the energy be in an ordered magnetic field.
- The observed sign change in Stokes V is predicted by the model.
- For the case of an electron/proton gas, constraints on the low energy particle distribution are obtained. Low energy cutoffs below 50 are inconsistent with the data: Faraday depolarization by the low energy electrons then suppresses both LP and CP.

N.b. An electron/positron gas would not produce internal Faraday rotation.

Interpretation: Some Possible Problems

- There is not universal agreement on the emission mechanism itself: does the same mechanism dominate in all Blazars? Intrinsic synchrotron emission in the jet? Magnetic helicity in the accretion disk? [Need high quality spectral data in V/I as a discriminator]
- Is there an underlying field direction which is masked during large outbursts from a localized region of the flow? [Need observations during quiescent states]

Future Directions

1. Improve the 14.5 GHz detector system to improve the signal/noise.
2. Continue to look for more events in these and other flaring objects using UMRAO.
3. Study CP in non-flare state using telescopes with larger collecting area: is there an underlying B field direction during quiescent phase?
4. Obtain simultaneous multi frequency VLBI and single dish observations (Nov 2005 first epoch of program).
5. Carry out detailed simulations which follow the source evolution in all 4 Stokes parameters with time.

