GSU 29 Oct 87

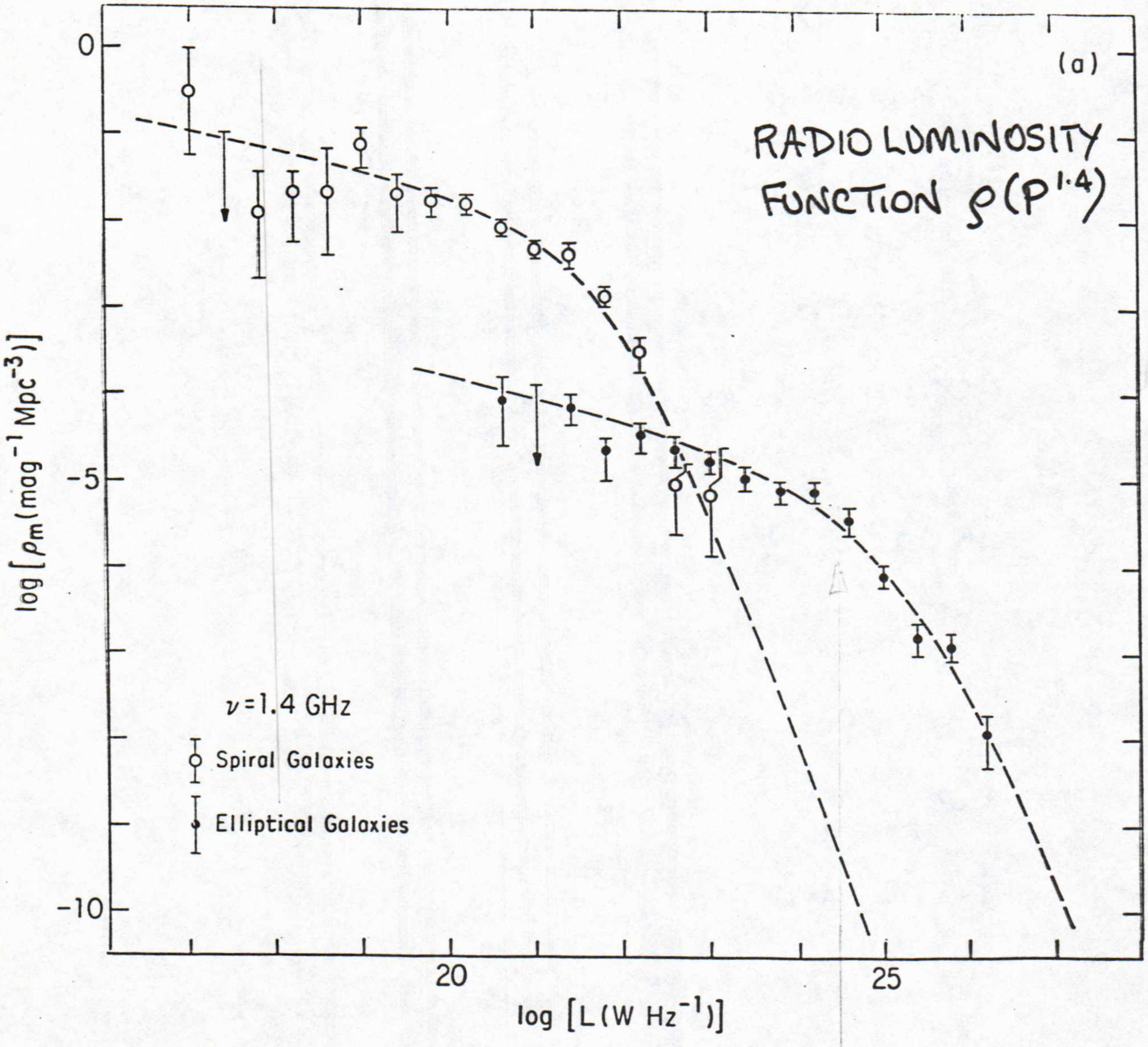
My agenda for this talk.

1. Review properties of the kpc-scale radio structures that seem to be generic (i.e. shared by many of the sources)

2. Summarize how these get described in today's popular models.

3. Wonder if we're really so smart after all.

4. Look at some observations that bear on the large-scale jet asymmetry question (i.e. could one-sidedness on 1–100 kpc scales be due to bulk relativistic motions?)



$P^{1.4} = 10^{24.5}$ W.Hz^{-1}

Many Radio Galaxy Properties Change Near $P_{extended} \sim 10^{24.5}$ W.Hz^{-1} at 1.4 GHz

Below this power: (generic trends)

- Most extended structures are edge-*darkened*
- Steepest spectra are in *outer* extended regions
- Jets are *prominent* and mostly *two*-sided
- Jets *widen rapidly*, are soon $\mathbf{B}_{\perp}$-dominated
- Jets *merge smoothly* into plumes, trails (**C**,**S** shapes)
- Hosts tend to be "big, round, pink and friendly"
- Hosts tend to have weak emission lines

Above this power: (generic trends)

- Most extended structures are edge-*brightened*
- Steepest spectra are in *inner* extended regions
- Jets are *less prominent* and mostly *one*-sided
- Jets *widen slowly*, stay $\mathbf{B}_{||}$-dominated
- Jets end *near* bright emission, *hot spots* at high P
- Hosts tend to be "disturbed and lonely"
- Hosts tend to have strong emission lines (e.g. Caganoff et al. poster yesterday)

At about this power:

- *"Break"* in galaxy radio luminosity function
- Many "transitional" cases, e.g. WAT's, and giants

Illustrate *some* of the key effects with 35mm slides.

① 3C449 Twin jets + fading plumes no clear *end*

② 3C83.1 (NGC1265) Bending low-P jets into C's in clusters

③ 3C31 To show ~~[illegible]~~ expansion

⑤ Cyg A Edge-*brightened*

Filaments

Jet *much* less prominent

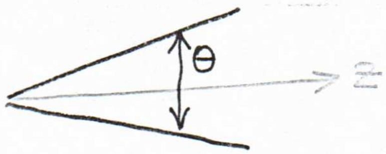
⑥ Cyg A overexposed to show 0.1% jet + CJ neck

⑦ Cyg A α distrib^n — old particles at center as if being left behind by advancing jets (or even *backflow*).

(8A) 3C219 Bi-lobed structure with hot spots.

(8B) 3C219 α distrib^n — outflow *from* hs?

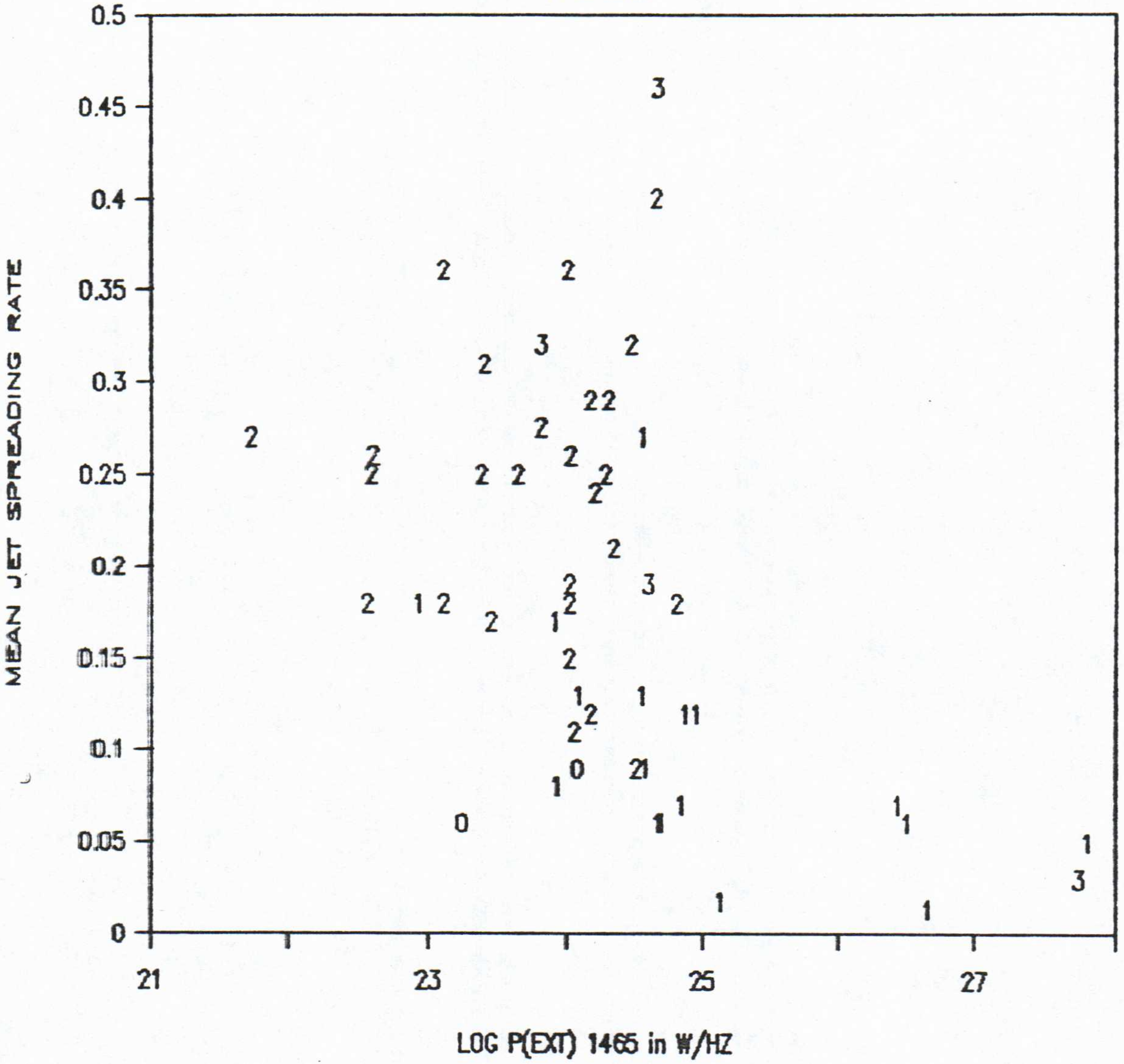
{Hcused}



$$\text{Spreading Rate} = \frac{d\theta}{dz}$$

Spreading Rate vs Extended Power

1465 MHZ

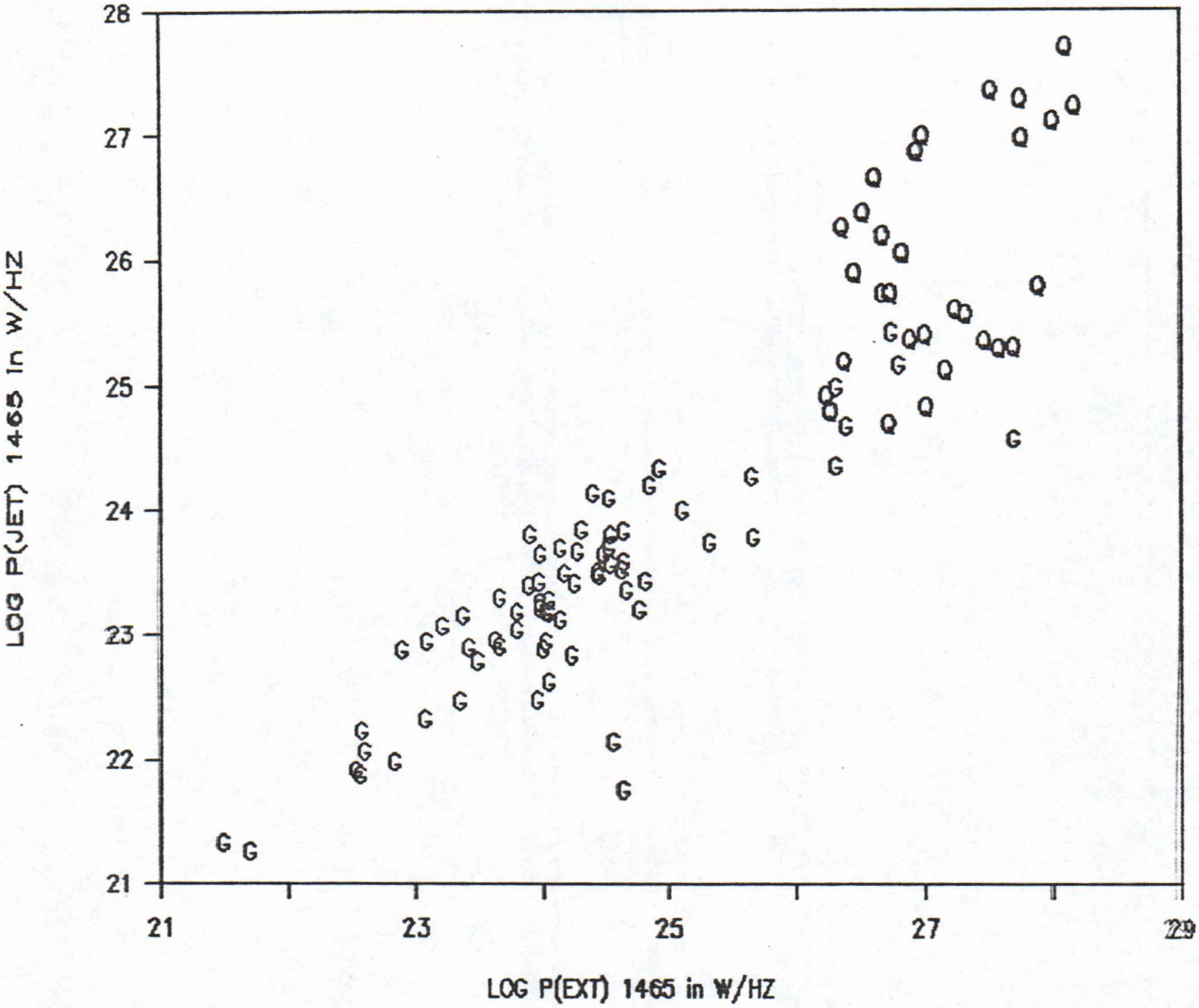


1 = "one-sided" jet (>4:1 brightness ratio)
2 = "two-sided" jet (<4:1 brightness ratio)
3 = sidedness varies with distance from core
0 = sidedness indeterminate

An upper envelope to . . . . . .

LOG(Jet Power) vs LOG(Extended Power)

1465 MHZ



G = radio galaxy

Q = quasar

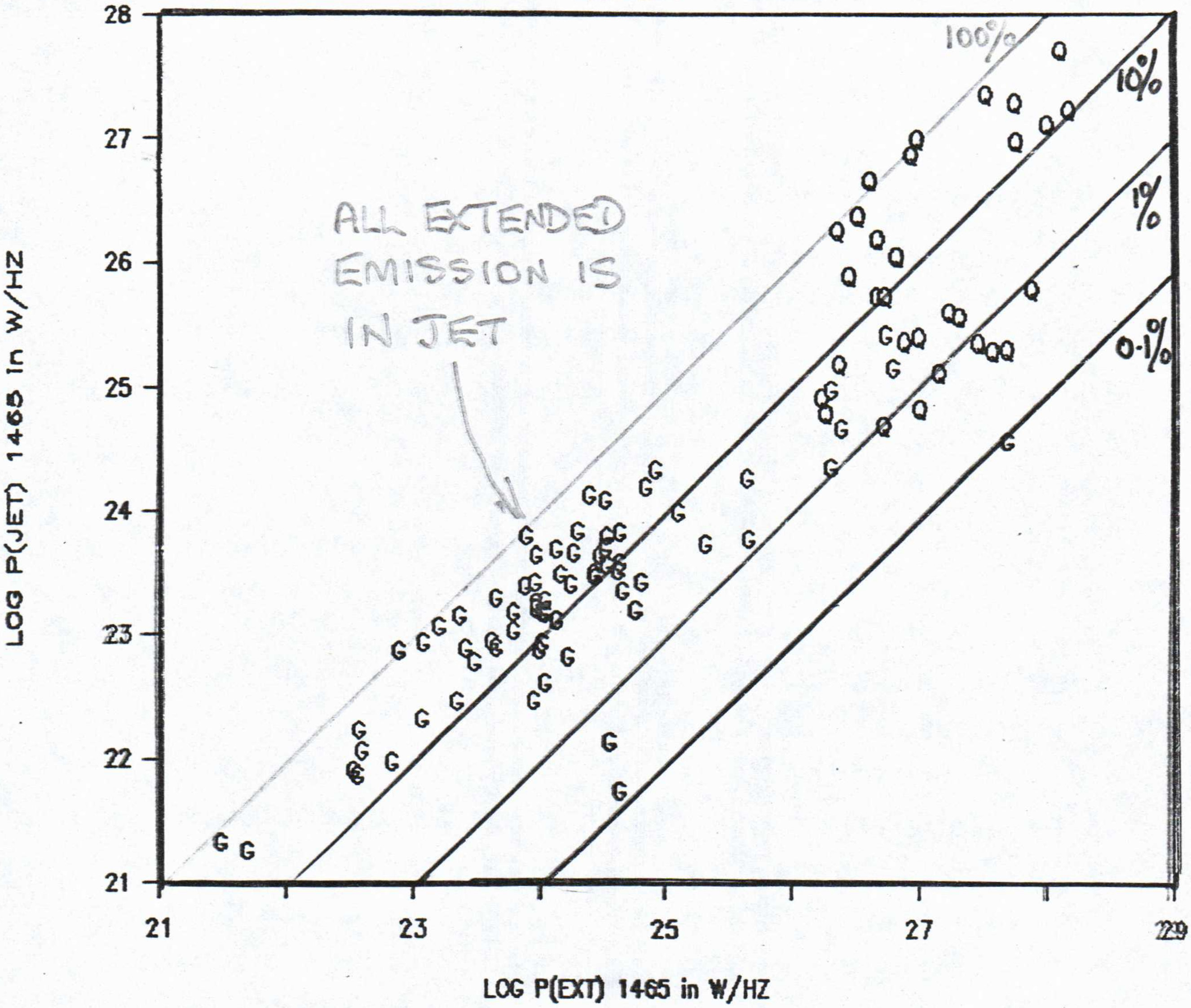
(98 sources for which integrated jet flux densities and redshifts known)

(sources with no detected jets will lie below these detections.)

An upper envelope to......

LOG(Jet Power) vs LOG(Extended Power)

1465 MHZ



G = radio galaxy

Q = quasar

(98 sources for which integrated jet flux densities and redshifts known)

(Sources with no detected jets will lie below these detections.)

Bicknell
Williams
Norman et al.
etc.

(Plausible) Outflow Dynamics

Below $P_{ext} \sim 10^{24.5}$ W.Hz^{-1}:

- Jets transonic, turbulent, mass-entraining
- Low Mach numbers, rapid spreading → $\mathbf{B}_{\parallel}$ dominates
- Adiabatic deceleration helps to keep jets "lit up"
- Density $\rho_J \rightarrow \rho_{IGM}, \rho_{ISM}$ as jets propagate, until:
- Jets "poop out" as subsonic plumes, trails

Above $P_{ext} \sim 10^{24.5}$ W.Hz^{-1}:

- Jets stay light ($\rho_J \ll \rho_{IGM}$) and hypersonic until:
- Jets end at *complex* shock structures → hot spots
- Slow advance velocity → *wide* lobes
- Flows *beyond* the jets ?
  - — Nonaxisymmetry → oblique first shock
  - — jets deflect → "splatter spots"
  - — qualitatively like observed "multiple hot spots"
  - — light jets can self-cocoon in *hot* backlow ?
  - — jet-cocoon instabilities → X-shocks → knots ?
  - — deflected backflows → **L** and **X** shaped lobes ?

→ Reduces most of observed radio properties to evolution of jets in HD models in the MACH NUMBER, DENSITY CONTRAST parameter space. But what sets $P^{1.4}_{crit} = 10^{24.5}$ W/Hz?

Why <u>multiple</u> hot spots in some sources

— Where we can <u>see</u> jets, associated with some jet deviation from major symmetry axis — e.g. thrashing

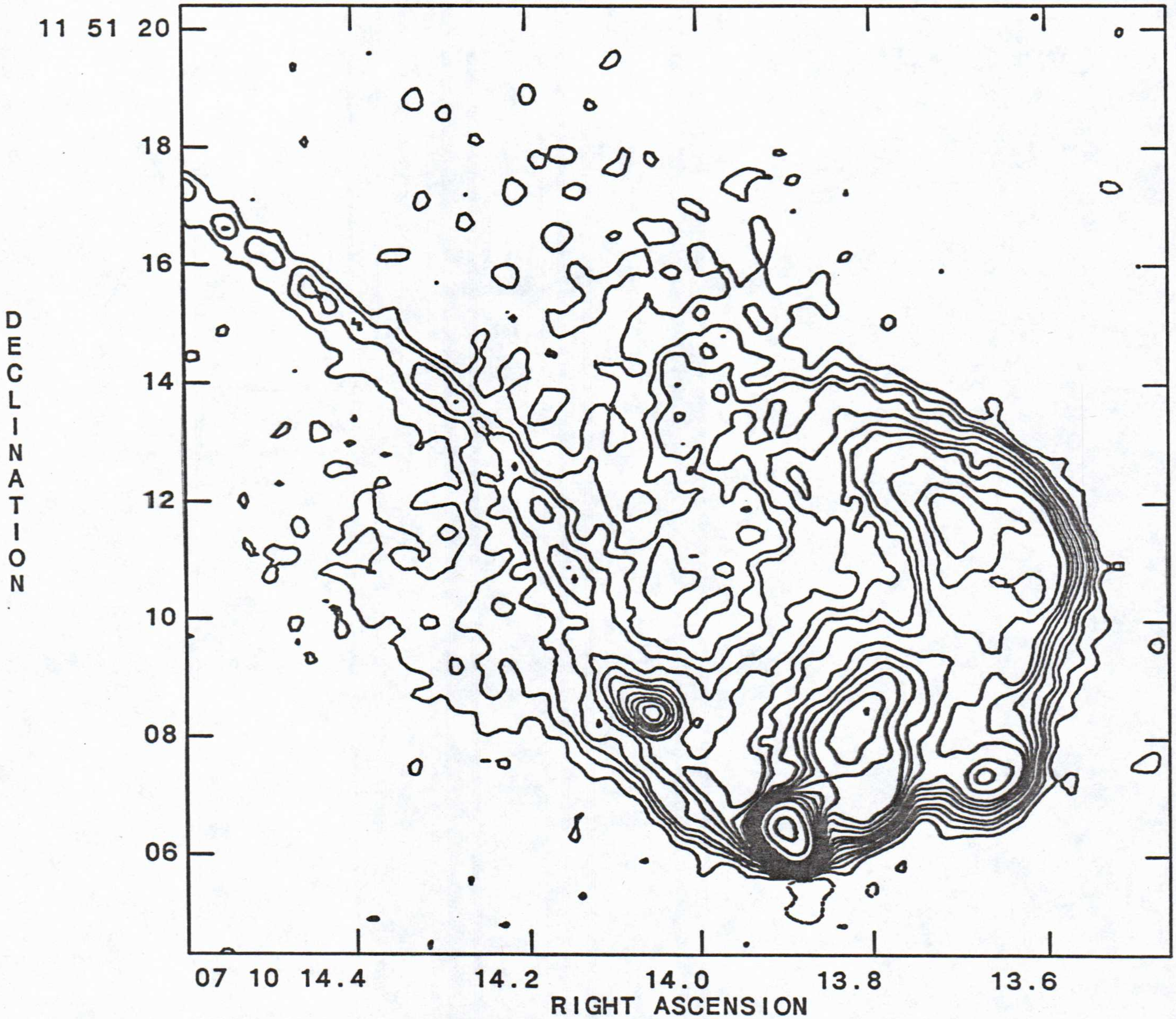
or ~~[illegible]~~ realignment of primary engine.

E.g. <u>3C175.</u> (35mm slide) [COLOR]

Jet enters lobe off-axis (N.B. bend appears mainly towards end).

3C175 South preceding lobe detail   Bridle et al. in prep.

PLOT FILE VERSION 2 CREATED 10-SEP-1986 21:07:48
3C175 IPOL 4885.100 MHZ 3C175 AB SUM.ICLNSU.1



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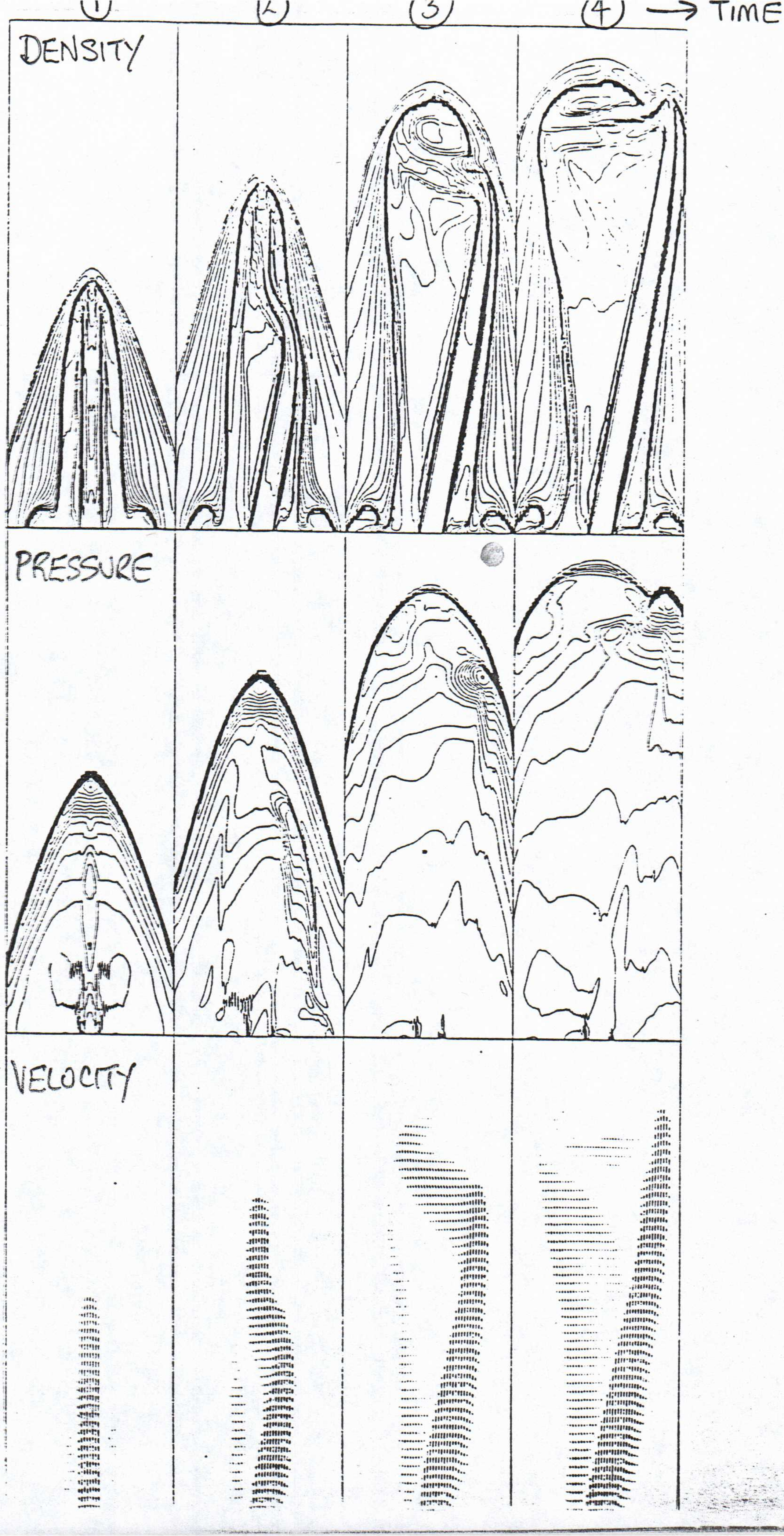
LEVS = 5.0000E-05 * (-1.00, 1.000, 2.000,
3.000, 4.000, 6.000, 8.000, 10.00, 12.00,
16.00, 20.00, 24.00, 30.00, 40.00, 50.00,
70.00, 100.0, 200.0, 400.0, 800.0)

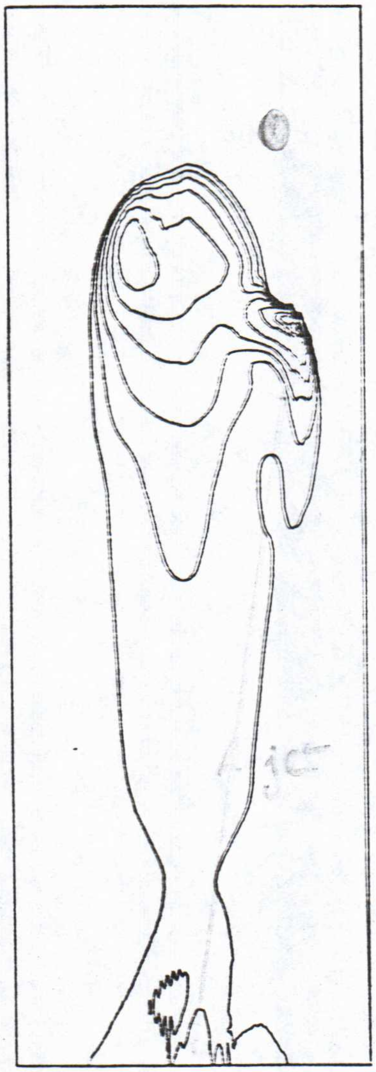
43, 12
10,173



WILLIAMS and GULL (1985)

NATURE 313, 34

IF RADIO EMISSIVITY ∝ p
INSIDE CONTACT DISCONTINUITY
(where relativistic particles are):

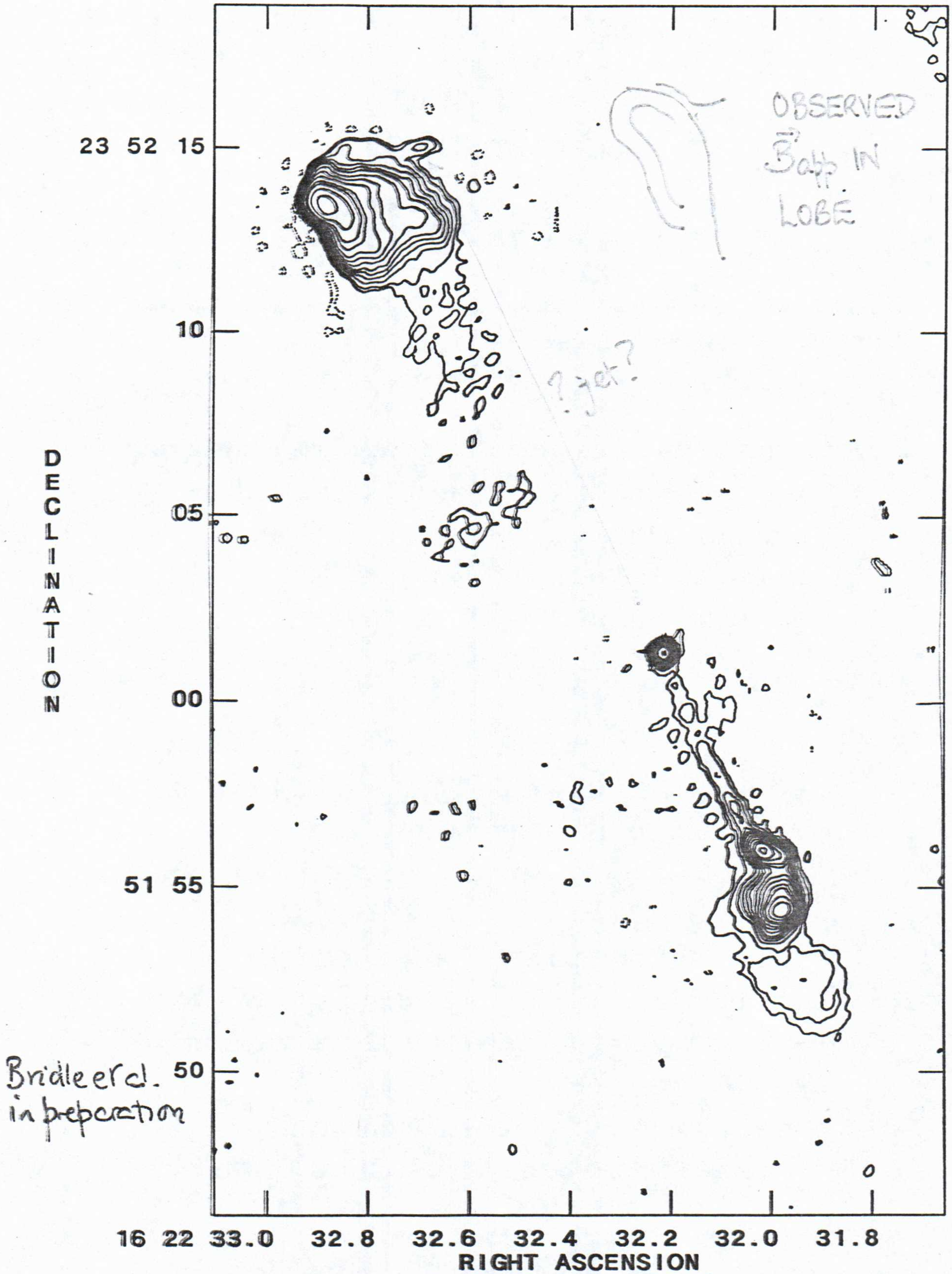


Williams and Gull, Nature 313, 34 (1985)

Figure 5.4 An indication of the location of radio emission for the 10^{o} simulation at $t = 27.7$, calculated by integrating the pressure, inside the contact surface, along a line of sight through the source. The contour levels are equally spaced.

PLOT FILE VERSION 1 CREATED 14-JUL-1987 22:42:01

3C336 IPOL 4835.100 MHZ 3C336 A BDU.ICLN.1



PEAK FLUX = 5.1909E-02 JY/BEAM

LEVS = 1.5000E-04 * (-1.00, 1.000, 2.000, 4.000, 6.000, 8.000, 10.00, 14.00, 20.00, 30.00, 50.00, 70.00, 120.0, 200.0)

σ=45μJy

IS WHAT WE THINK WE SEE

(via synchrotron radiation)

WHAT'S REALLY GOING ON ?

- What flow properties are "visualized" by radio images ?
  - — where are particles and fields energized ?
  - — and how efficiently ?
  - — do the energy and mass flow paths always radiate ?
  - — are there "invisible" jets, cocoons ?
  - — do *radio* shapes map *flow* shapes ?

- How much of what we "see" is *relativistically* moving ?
  - — do brightness, time delay, aberration distort kpc-scale sources significantly ?
  - — how randomly oriented are flux-selected samples ?

- How important are classical projection effects ?
  - — are filling factors = 1 and depths = widths ?
  - — how many large angles in 2-D are small in 3-D ?

- Does centimeter-decimeter chauvinism matter ?
  - — do sidedness, sizes, shapes vary with wavelength ?

<u>Hardee</u>

Jet filamentation + substructure.

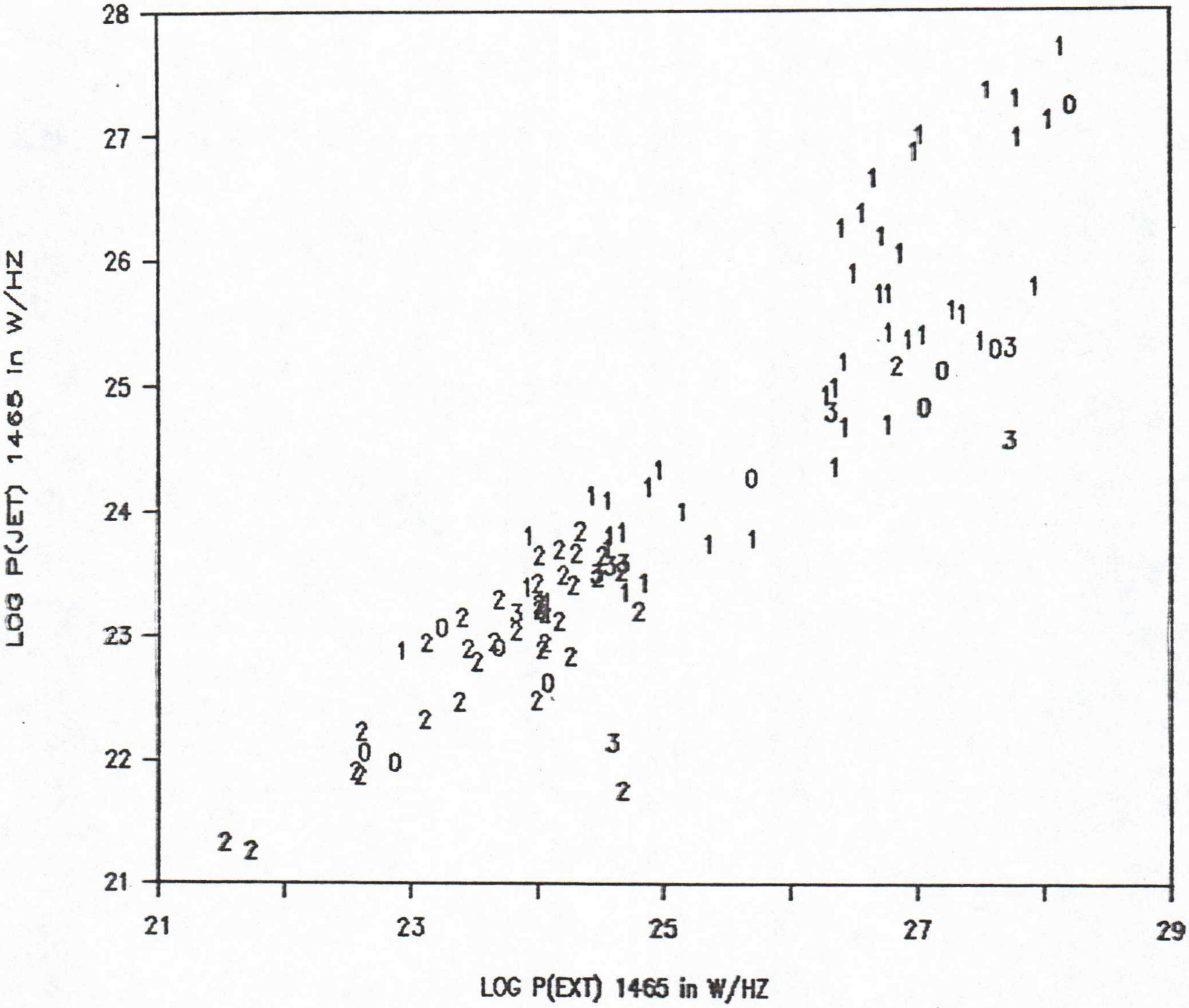
What are we <u>seeing</u>?

Jet or boundary layer?

<u>HD shocks</u> or <u>MHD flux ropes</u>?

LOG(Jet Power) vs LOG(Extended Power)

1465 MHZ



1 = one-sided jets (>4:1)
2 = two-sided jets (<4:1)
3 = variable sidedness
0 = not known from best data

HOW ONE-SIDED ARE THEY?

Tales from the Dark Side
or, Counter-jets in Powerful Sources

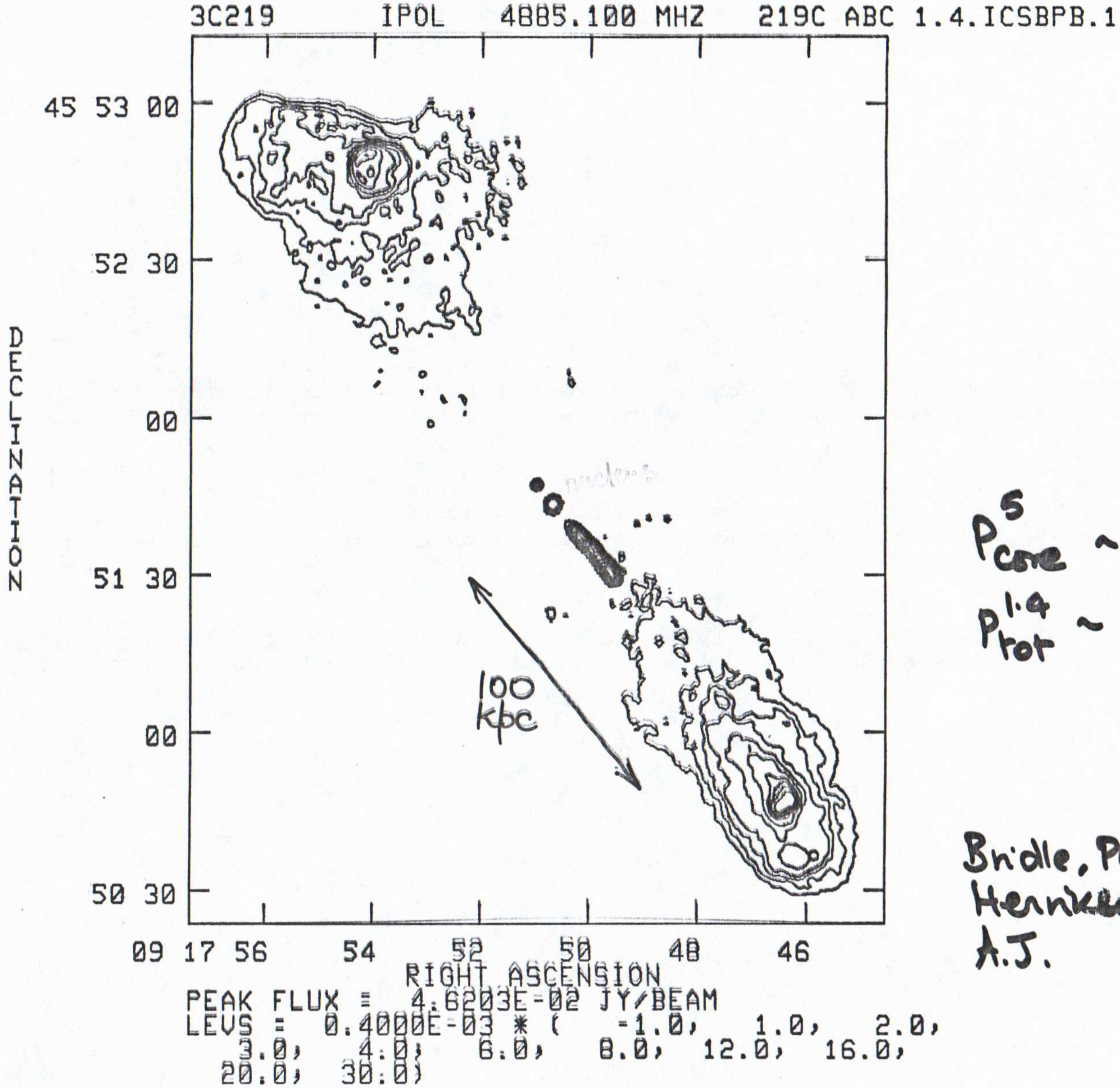
- In powerful radio galaxies:
  - — 3C 219, log $P_{ext} = 26.44$, log $P_{cj} = 23.22$
  - — 3C 288, log $P_{ext} = 26.36$, log $P_{cj} = 23.68$
  - — both " interrupted" jets ?
  - — counterjets bright tips, closer to core than jet
  - — 3C288 counterjet steep-spectrum ?
  - — all properties of "born-again" relativistic jets ?

  - — 3C 341, log $P_{ext} = 26.78$, log $P_{cj} \approx 25.1$
  - — 3C 438, log $P_{ext} = 26.84$, log $P_{cj} \approx 25.0$
  - — Cyg A, log $P_{ext} = 27.74$, log $P_{cj} \approx 24.2$
  - — all extended, but confused with lobe emission

- In 3CR QSRs LAS >10 arcsec (systematic study at VLA):
  - — no clear continuous counterjets cores→lobes
  - — but "bits and pieces" in 30% to 50% of cases:
  - — 3C 68.1, log $P_{ext} = 27.74$, log $P_{cj} \approx 24.5$
  - — 3C 334, log $P_{ext} = 26.93$, log $P_{cj} \approx 24.5$
  - — 3C 9, log $P_{ext} = 28.15$, log $P_{cj} > 24.3$

- Conclude:
  - — there *is* something for VLA, MERLIN etc. to see !
  - — frequency dependence may be important (3C288) ?
  - — no clear pattern vs. LLS, core prominence, yet.

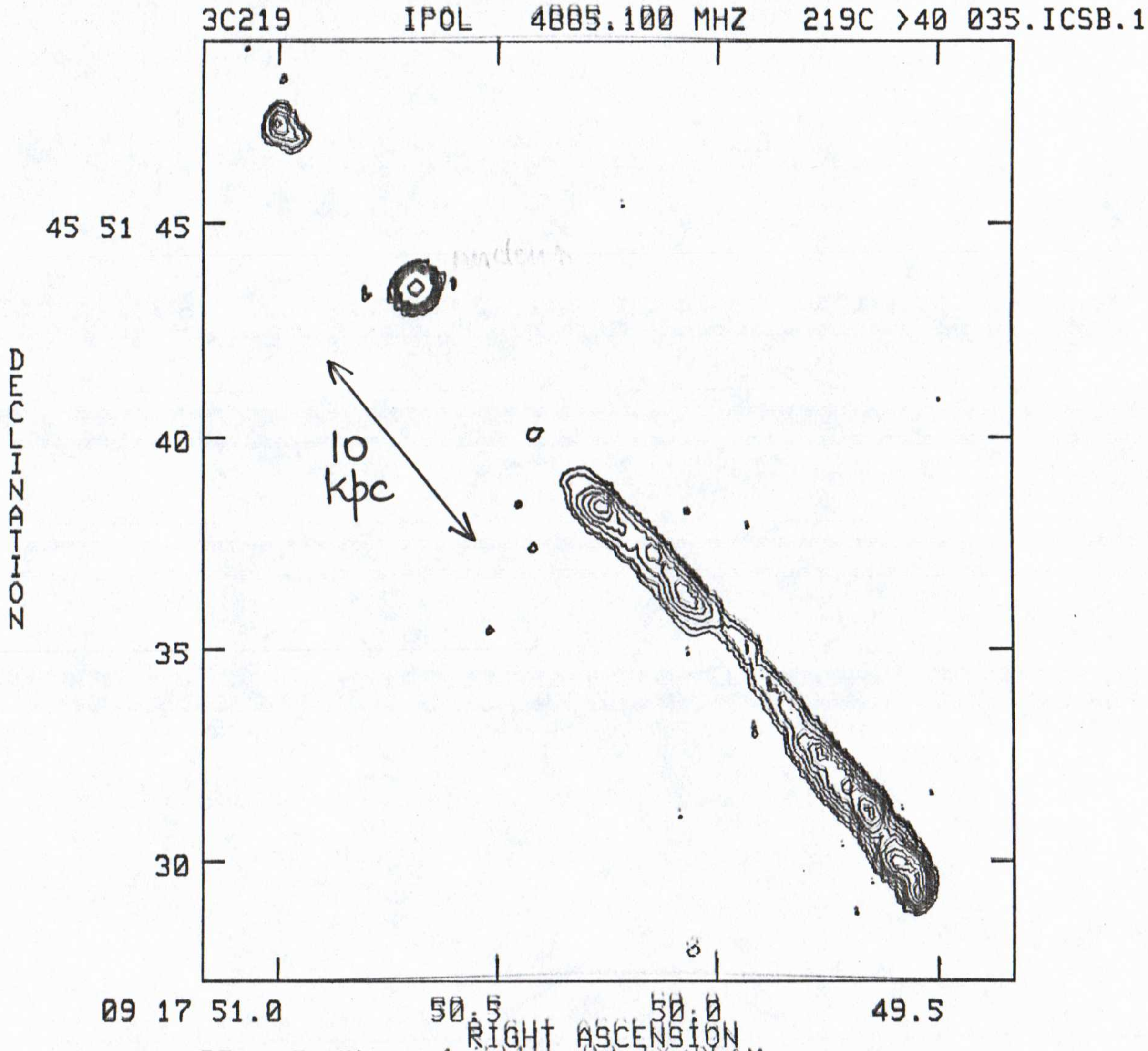
Also, counterjet in core-dominated superluminal QSR
— 1928+73, log $P_{ext} = 26.32$, log $P_{cj} \sim 24.5$
(4C73.18)



$P^{5}_{core} \sim 10^{24.2}$ W/Hz

$P^{1.4}_{tot} \sim 10^{26.5}$ W/Hz

Bridle, Perley & Henriksen 1986 A.J.



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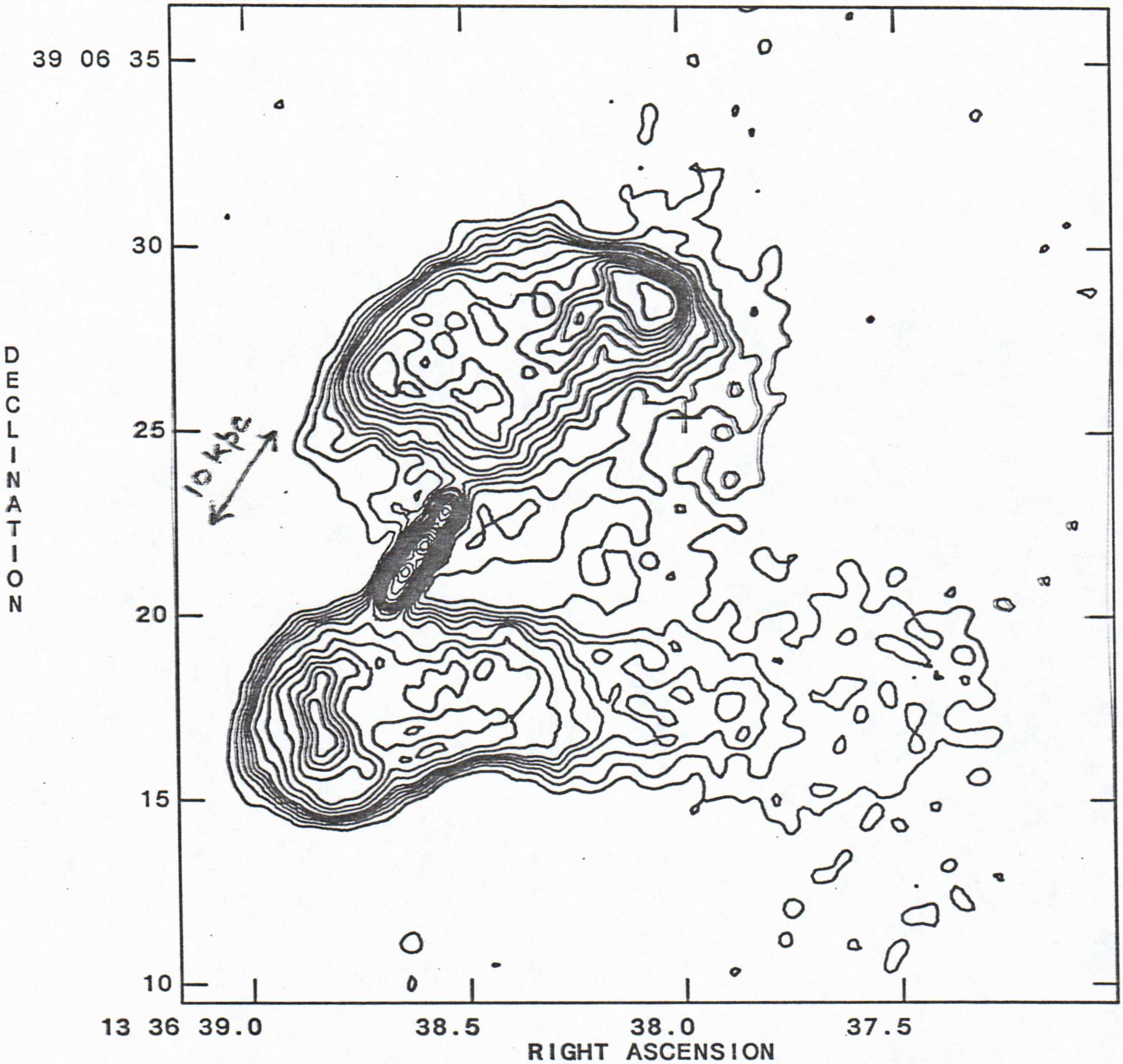
LEVS = 0.1000E-03 * (-1.0, 1.0, 2.0,
4.0, 6.0, 8.0, 10.0, 14.0, 18.0,
22.0, 236.5)

PLOT FILE VERSION 5 CREATED 09-APR-1987 17:41:19

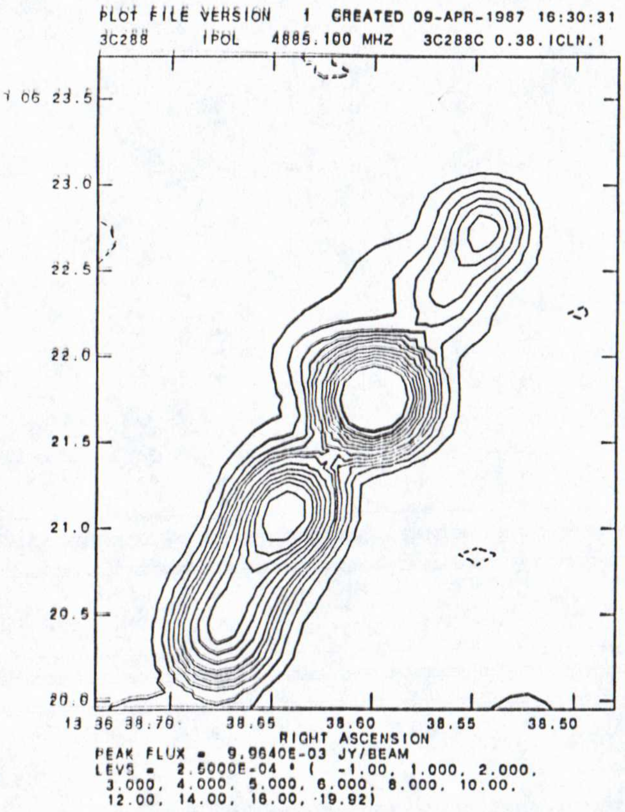
3C288 IPOL 4885.100 MHZ 3C288C0.6.ICLN.1



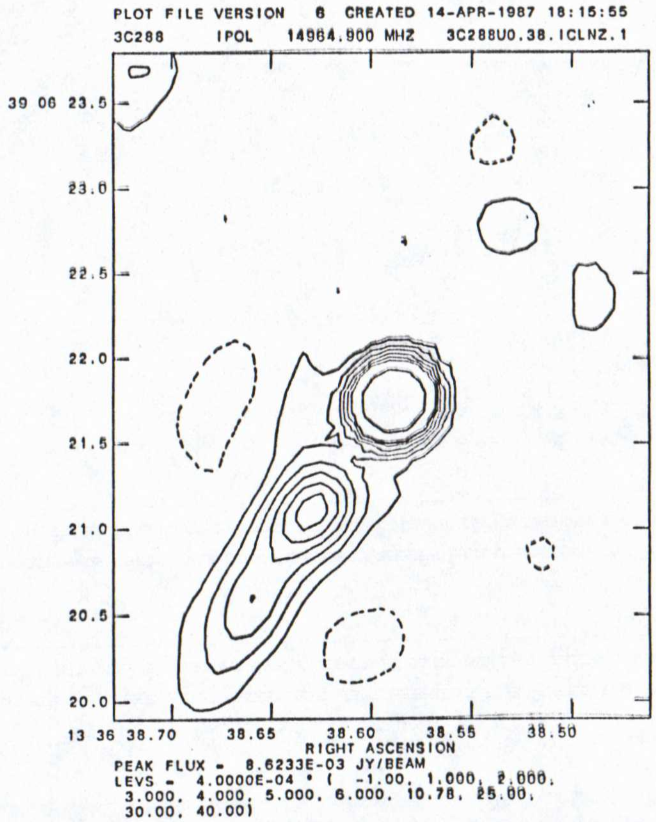
PEAK FLUX = 1.2830E-02 JY/BEAM

LEVS = 2.7500E-04 * (-1.00, 1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 8.000, 10.00, 12.00, 14.00, 16.00, 18.00, 20.00, 24.00, 30.00, 36.00, 42.00, 50.00, 58.00)

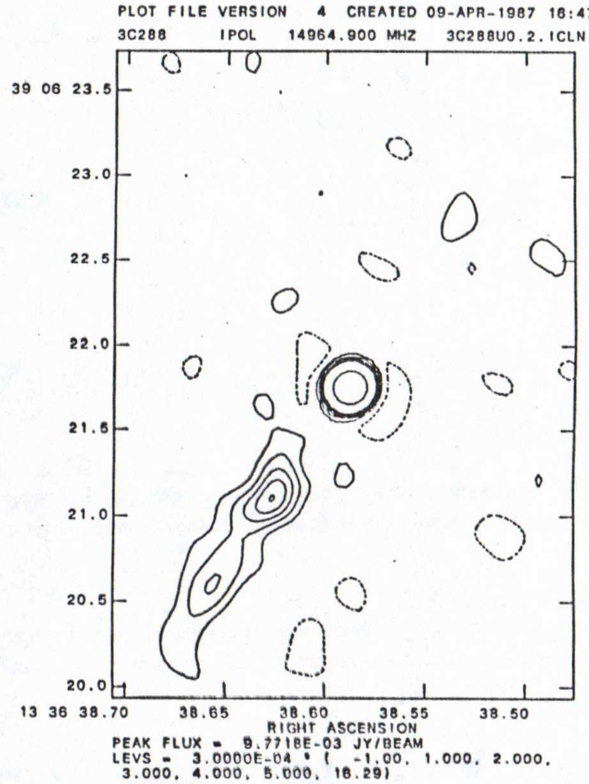
Byrd, G.G. et al. in preparation



6cm, 0".38 res



2cm, 0".38 res



2cm, 0".2 res

Jet spectral index ($\nu^{-\alpha}$) $\alpha = 0.72 \pm 0.04$

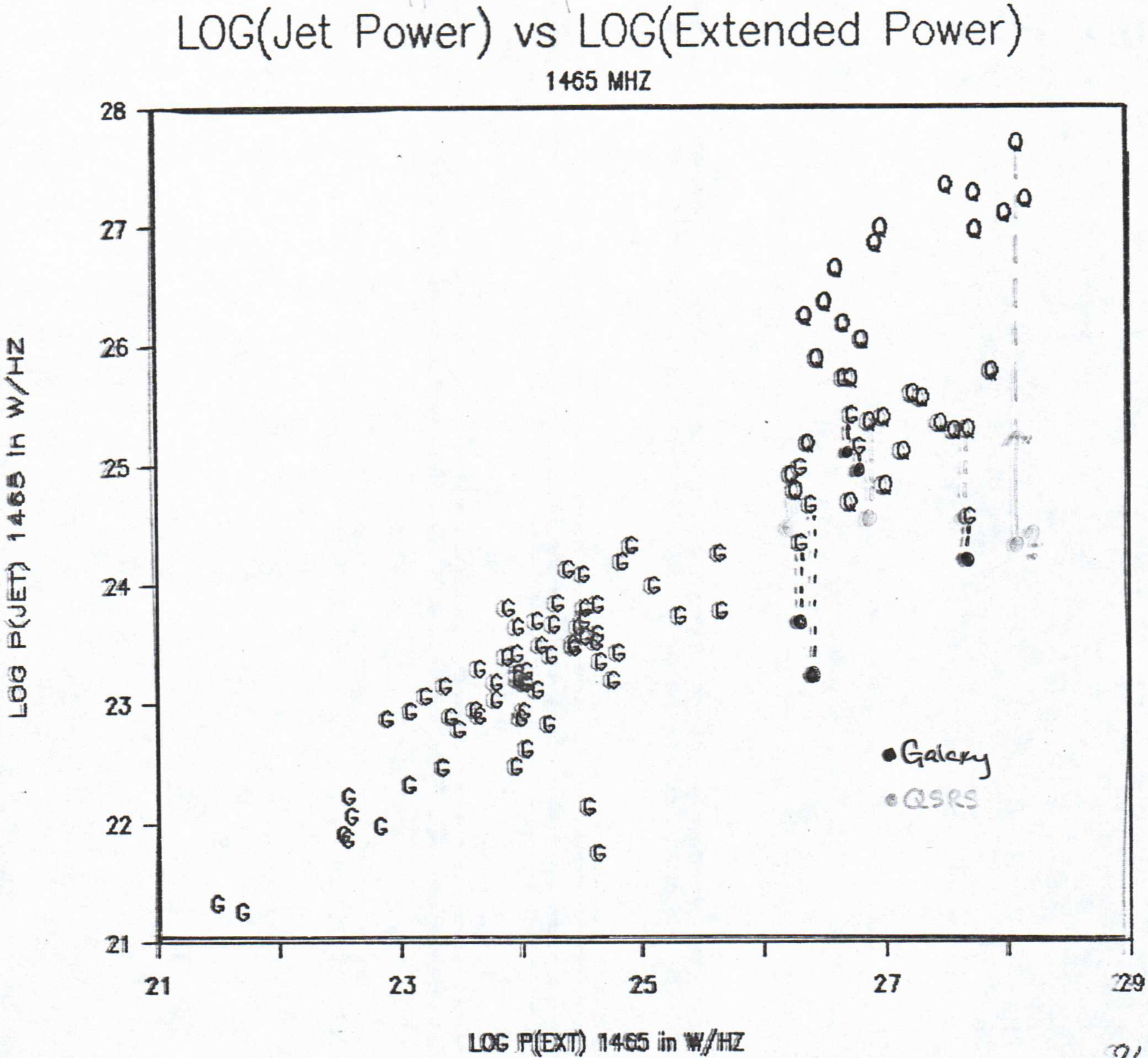
Counterjet $\alpha = 1.30 \pm 0.17$

Jet

Counterjet

Byrd, G.G. et al.
in preparation

An upper envelope to . . . . . .



Counter-jet detections in sources at $P_{ext} > 10^{26}$

G = radio galaxy ●

Q = quasar ●

(98 sources for which integrated jet flux densities and redshifts known)

(Sources with no detected jets will lie below these detections.)

① Integrated sidedness ratios for <u>detected</u> counterjets range from $\frac{1}{2}$ to $\frac{1}{\text{few }100}$ × main jet. DO NOT NEED $\gamma = 5$ OR SMALL ANGLES TO LINE OF SIGHT TO → THESE!

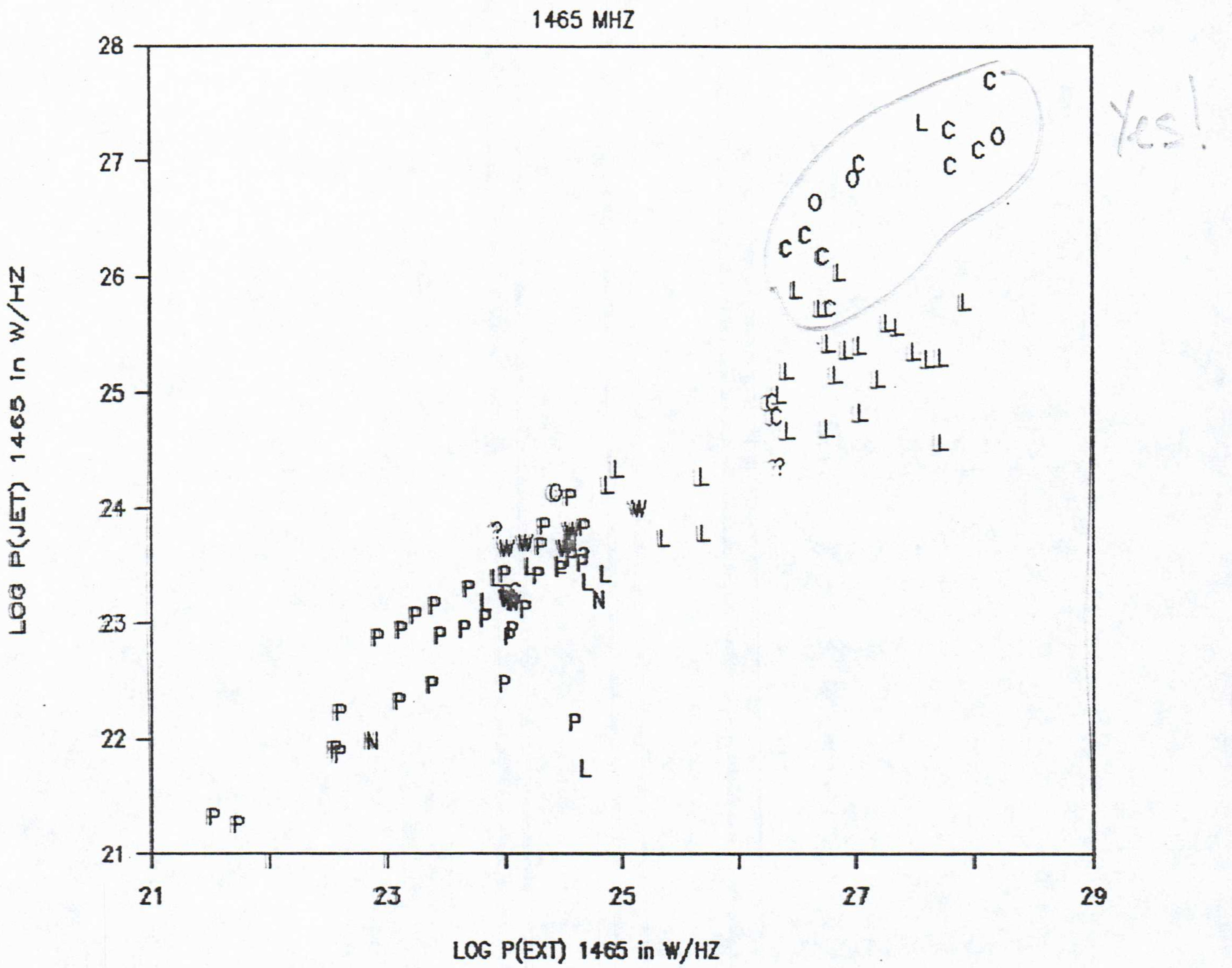
(Jets could have decelerated to $\approx \frac{3}{4}c$)

② <u>Counterjets</u> in stronger sources are more powerful than brightest 2-sided jets in weaker sources.

→ must be <u>some</u> intrinsic increase in jet powers at high <u>total</u> powers for the classical doubles.

DOES JET PROMINENCE CORRELATE WITH LOBE MORPHOLOGY IN STRONG SOURCES?

LOG(Jet Power) vs LOG(Extended Power)



P = Plumed (edge-darkened) double (FR I)
L = Lobed (edge-brightened) double (FR II)
N = Narrow Trail (NAT)
W = Wide-angle trail (WAT)
C = Complex, confused, not obviously FR II
O = one-sided jet/lobe structure

The Small, Bright, Kpc-scale Jet Show

- Barthel, Lonsdale, Miley, Schilizzi sample:
  - — jets in steep-spectrum QSRs at $z > 1.5$
  - — many prominent, bent jets
  - — jet-to-lobe ratio increases with *curvature*
  - — but not with core-to-lobe ratio
  - → epoch dependence at $z > 1.5$ (if ID's "normal")

- All jets, $P_{extended} > 10^{26}$ W.Hz^{-1}, $0.25 < z < 1.5$
  - — classical doubles show few trends, but:
  - — if lobes are ***not clearly*** classical doubles,
  - — kpc-scale jet-to-lobe ratios increase at small LLS
  - — kpc-scale jet-to-lobe ratio increases with core ratio

- Conclude:
  - — if small LLS, morphology together → projection, some *kpc-scale* jets at $z < 1.5$ may be beamed
  - — if not, "some small sources have bright jets" !
  - — young sources, all redshifts ?

- Work needed:
  - — samples small when selection effects minimized
  - — need larger samples with integrated jet fluxes *
  - — need better maps of weak, small *lobes*
  - — need still more diagnostics for orientation

* helpful if radio observers document the integrated flux densities of jets they publish!

Increased
Bending of Sources With
$P_{1.4} > 10^{27}$ W.Hz^{-1} at $z > 1.5$
(Miley 1986)

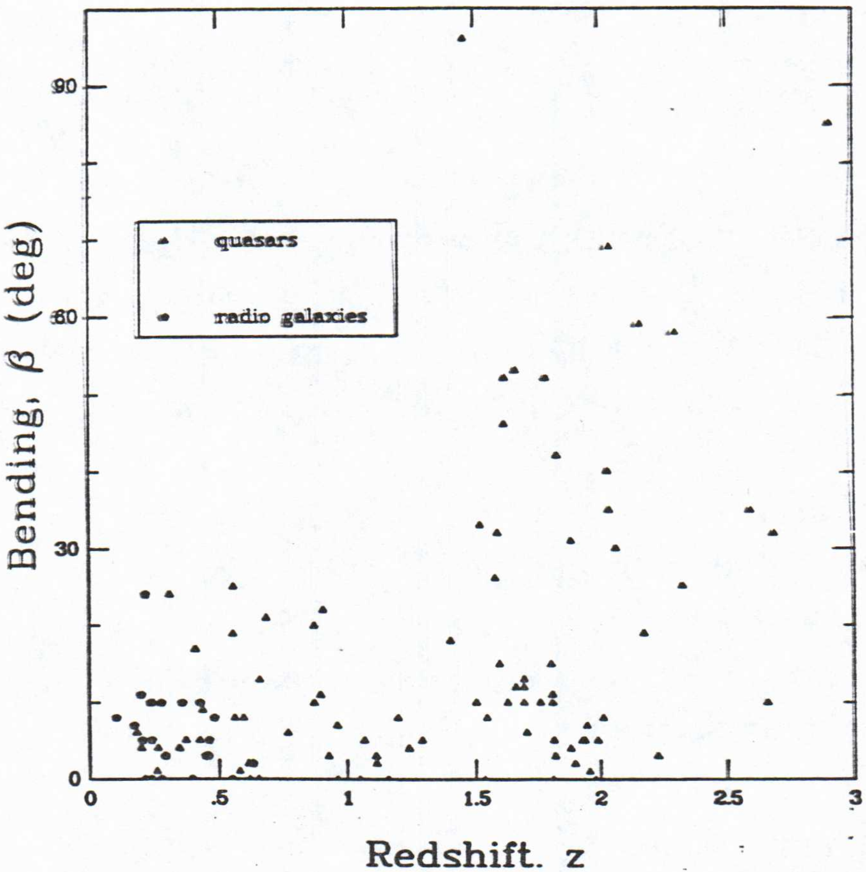
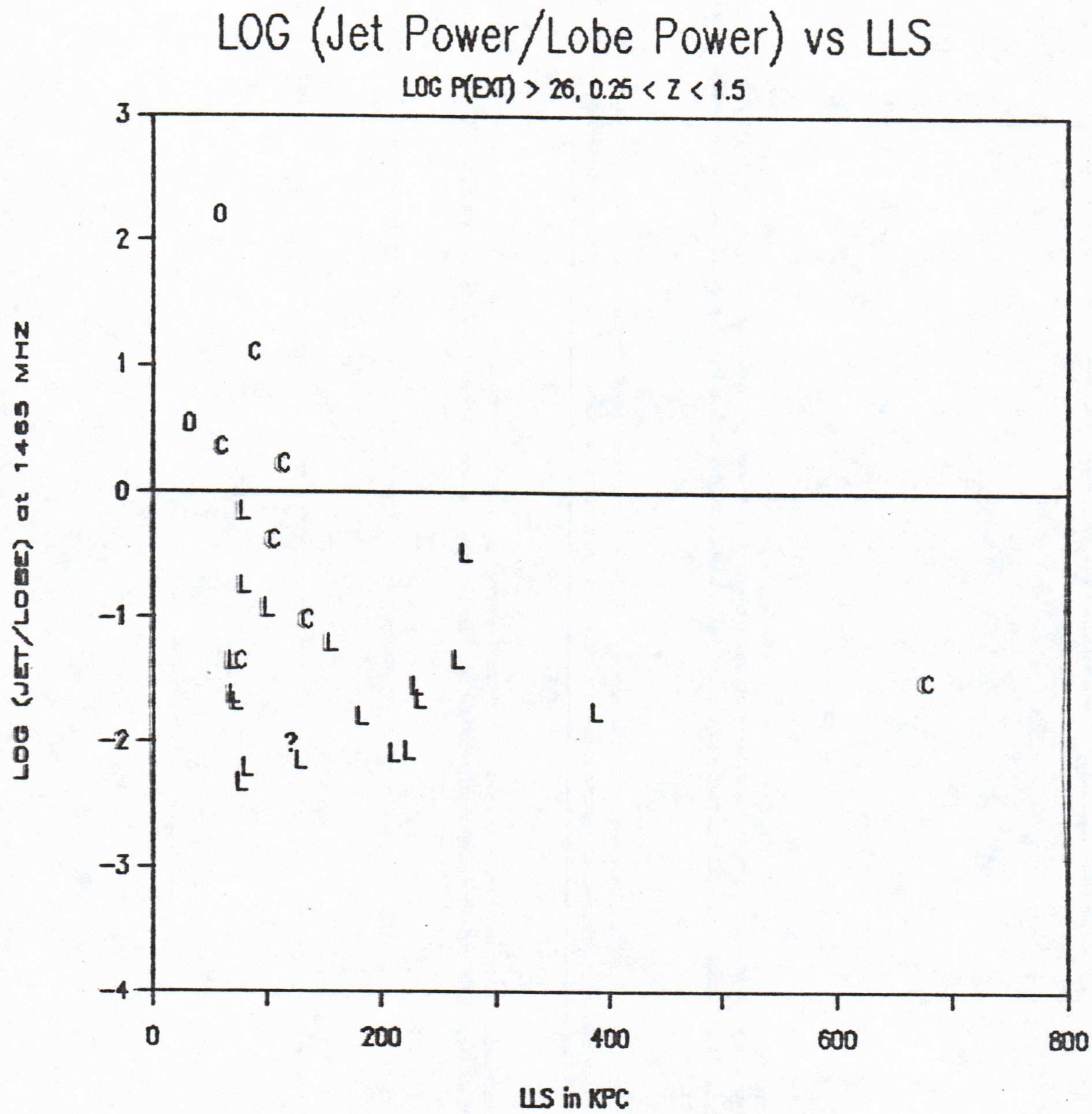
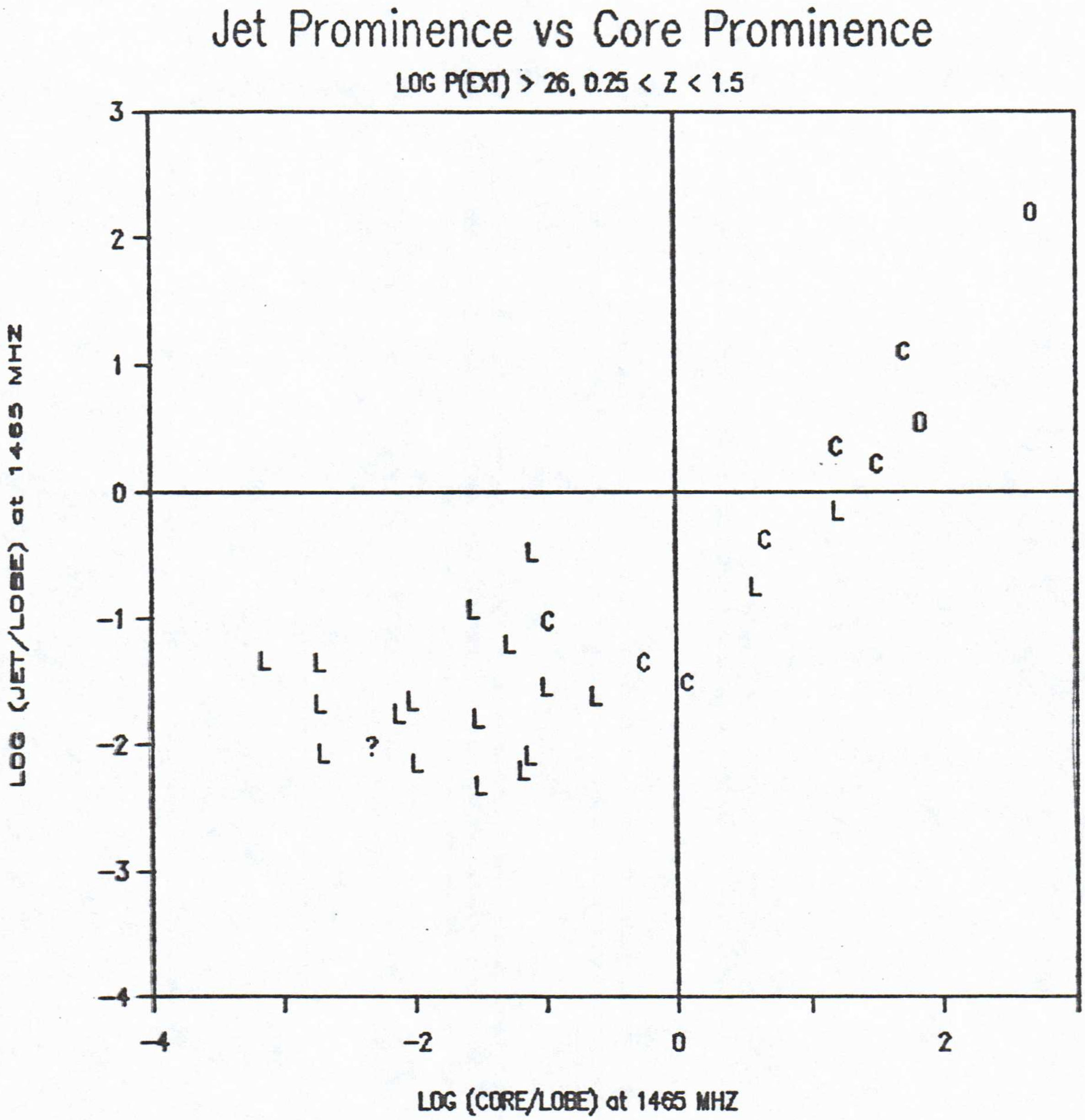


Figure 1. Bending of quasar radio sources as a fuction of redshift. $\beta = 0$ refers to a straight source. All sources have steep spectra ($\alpha < -0.6$: $S \propto \nu^{\alpha}$) and high luminosity ($P_{1.4GHz} > 10^{27}$ W Hz^{-1}).



Plot is for all jets satisfying criteria, for which A.H.B. has integrated jet flux densities.

N.B. MANY SOURCES WITH NO DETECTED JETS MUST LIE BELOW THIS REGION OF DIAGRAM



Jet Prominence vs Core Prominence
LOG P(EXT) > 26, 0.25 < Z < 1.5
LOG (JET/LOBE) at 1465 MHZ
LOG (CORE/LOBE) at 1465 MHZ
3
2
1
0
−1
−2
−3
−4
−4
−2
0
2

There is a possible orientation clue emerging: from an unexpected direction.

Faraday screens around Radio Sources

(possibly related to the zero-displaced BAL QSR features) Ray Weymann described

Evidence for Structured Faraday Screens Around Radio Galaxies

1. EVIDENCE FROM ROTATION MEASURE DATA

- Extreme rotation measures (1000's rad.m^{-2})
  - — Cyg A RM mapped at VLA (Dreher, Carilli, Perley)
  - — RMs from -4000 rad.m^{-2} to $+3000$ rad.m^{-2}
  - — ∇RM up to 400 rad.m^{-2}.kpc^{-1}
  - — no internal depolarization of lobes, jets
  - → screen *outside* source (sheath or ICM)

  - — others with *net* RMs >1000: M87, 3C295, 3C218
  - — cluster (cooling flow) related ?

- Modest rotation measures (10's to 100's rad.m^{-2})
  - — M84, NGC1265, NGC6251, 3C449, 3C66B
  - — linear scales 1 to 100 kpc if in host galaxy
  - — symmetries → *host galaxy related*
  - — no *internal* depolarization of lobes, jets
  - → screens *outside* sources (sheath or ISM)
  - — Faraday depths *not smooth*
  - — kpc-scale substructure
  - — ∇RM typically 10 to 20 rad.m^{-2}.kpc^{-1}
  - → depolarize across radio beams at decimeter $\lambda\lambda$

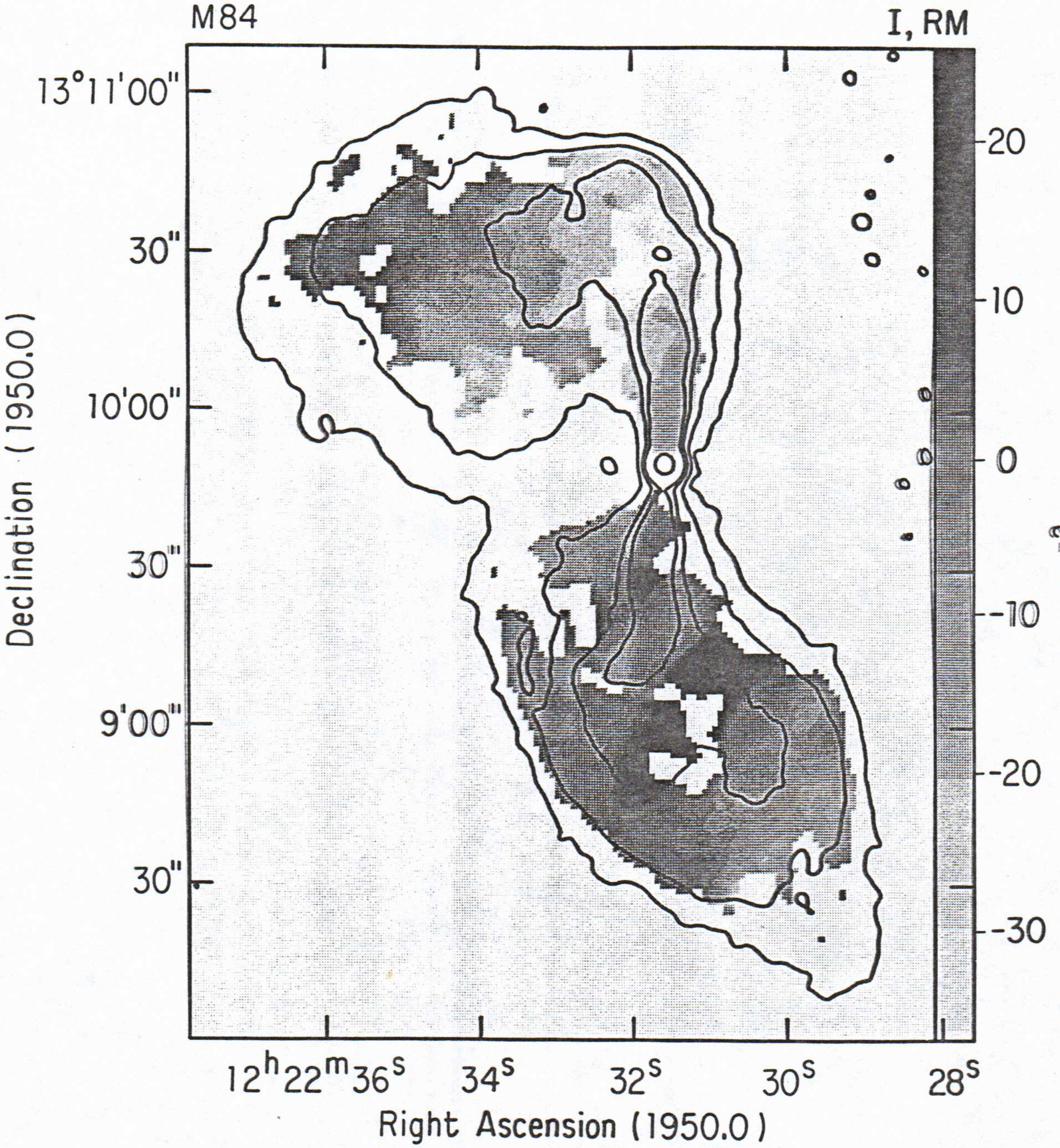
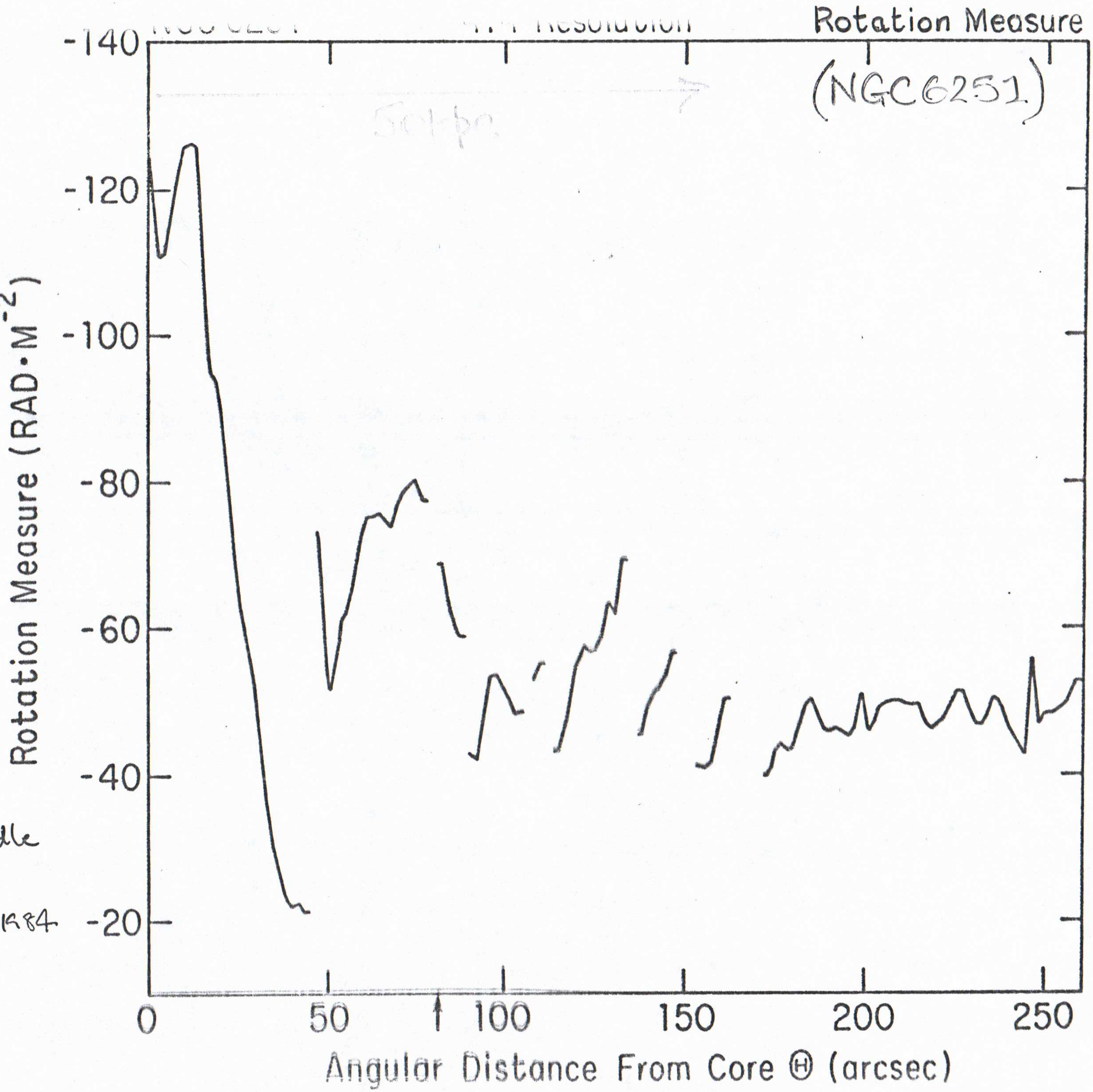

M84
I, RM
13°11'00"
30"
10'00"
30"
9'00"
30"
Declination (1950.0)
20
10
0
-10
-20
-30
RAD: M^-2
12h22m36s
34s
32s
30s
28s
Right Ascension (1950.0)

fig 21



Perley, Bridle & Willis ApJ Suppl 1984

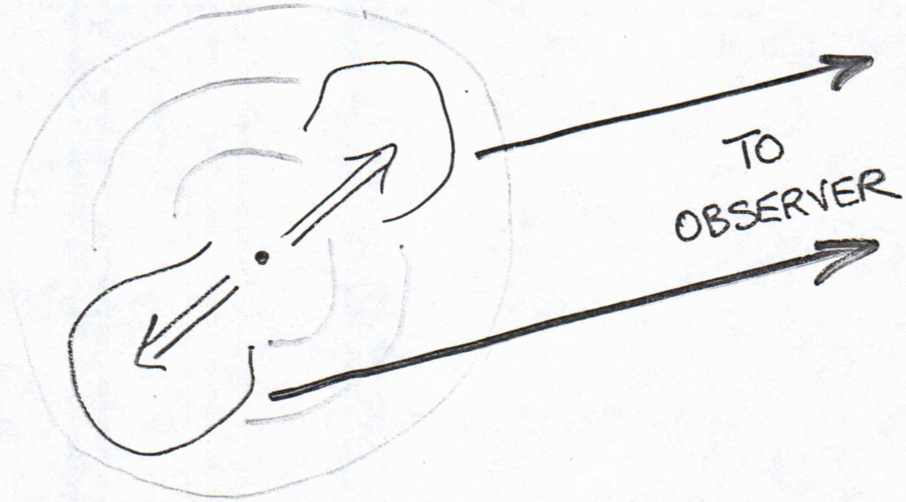
Evidence for Structured Faraday Screens Around Radio Galaxies

2. EVIDENCE FROM DEPOLARIZATION DATA

- Systematic depolarization gradients at 49cm
  - — Jägers Ph.D. thesis, Leiden (1986)
  - — Strom and Jägers preprint (1987)
  - — p_{49cm} systematically $<$ p_{21cm} in *inner* parts of radio galaxies
  - — p_{49cm}/p_{21cm} increases away from galactic nuclei

- Conclude:
  - — *structured* Faraday screens round *many* radio galaxies
  - — if screens are symmetric, depolarization data can distinguish *front* side of source from *back*

e.g. —



"FRONT" (APPROACHING JET SIDE) HAS LESS PATH LENGTH THROUGH SCREEN

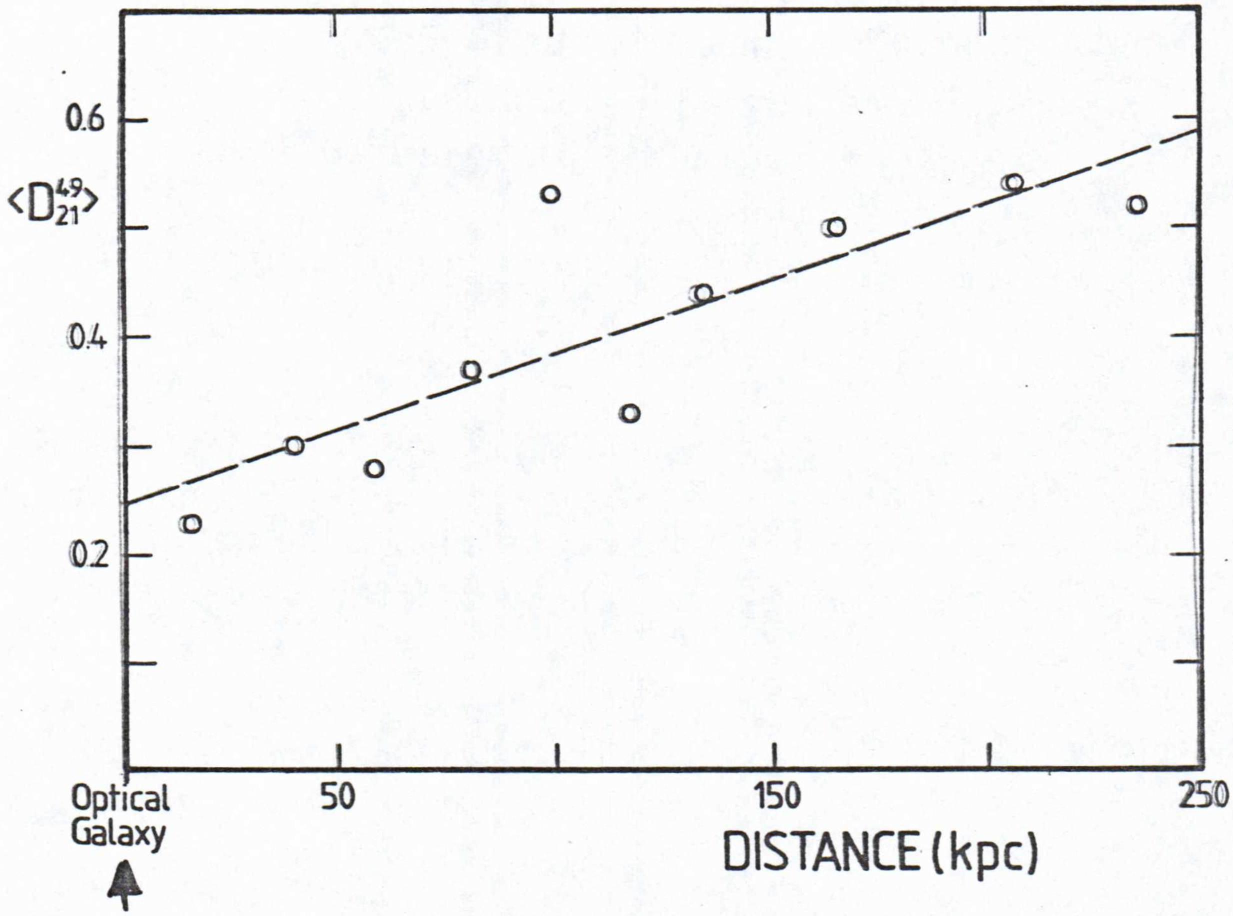
Average depolarization $D^{49cm}_{21cm} = \frac{p(49)}{p(21)}$

vs

Distance from Parent Galaxy

for 7 extended radio galaxies

(W.J. Jägers, Ph.D thesis)



→ evidence for <u>structured</u> Faraday screens on 100-kpc scales in <u>MANY</u> radio galaxies ?

Depolarization Asymmetry

- Laing (1987), *Nature*, in press:
  — 10 powerful 3CR radio galaxies synthesized
  — 1.4, 2,7 and 4.9 GHz data
  — 9 of 10 depolarize faster on counterjet side
  — also, integrated data (Strom and Conway 1985)
  — 8 of 12 jetted sources show same effect
  — one "counter-example" disagrees with VLA data

- Garrington, Leahy, Conway and Laing (1987) also *Nature*, in press:
  — VLA images of 25 sources with one-sided jets
  — 1.4 and 4.9 GHz
  — 23 depolarize faster on counterjet side
  — one has *no* polarization on counterjet side
  — one "wrong way round", but small depolarization

- Conclude, for sources with one-sided jets:
  — jetted sides usually depolarize less than unjetted
  — (statistics about 33 out of 35)
  — if screens *symmetric*, one-sided jets are *toward* us
  — comforting result for Doppler-boost model
  — intrinsic-asymmetry models will soon follow !

- Work needed:
  — map ∇RM, test location, symmetry of screens
  — study depolarization gradients of twin-jet sources

CONCLUSIONS

jet props
hot spots
plumes

(1) Picture of large-scale source dynamics looks promising, with Mach no. of outflows a key variable.

(2) But some evidence ~~for relativistic jet~~ that one-sided kpc-scale jets may be ~~boosted~~ brighter in small, distorted sources and on side facing us — looking as if they were relativistic?

Hence may need to add relativity to models.

(3) ~~No clue from any of this~~ Need to understand better why $P = 10^{24.5}$ is the magic luminosity, or what the specific connections ~~to~~ between environment and jet / lobe properties are. We have strongly correlated symptoms of something ~~affecting~~ produced by AGN's, but not yet explicit connections between environment + fuelling params. and observable radio params.