NRAO Summer Students 1983

Extragalactic Sources

References.

Miley, G.K. "The Structure of Extended Extragalactic Radio Sources"
- Ann. Rev. Astron. Astrophys., 18, 165 (1980).

Fomalont, E.B. "Extended Radio Sources", Proc. I.A.U. Symp. #94,
- "The Origin of Cosmic Rays", p. 111 (1981)

Kellermann, K.I. and Pauliny-Toth, "Compact Radio Sources",
- Ann. Rev. Astron. Astrophys., 19, 373 (1981)

van der Hulst, J.M. "Radio Continuum Emission from the Nuclei of Normal Galaxies", Highlights of Astronomy, 5, 177 (1980)

I.A.U. Symposium No. 97 - "Extragalactic Radio Sources"
ed. D.S. Heeschen and C.M. Wade

— especially reviews by

	Oort, p. 1	general
	Feigelson, p. 107	Cen A
	Bridle, p. 121	Jets
	Wilkinson, p. 149	kpc-scale sources
	Wilson, p. 179	Seyferts
	Rees, p. 211	Jet mechanisms
	Thorne & Blandford, p. 255	Black hole models
	Readhead & Pearson, p. 279	VLBI structures
	Cohen & Unwin, p. 345	Superluminal sources

Extragalactic Radio Sources.

— distinguish "normal" and "active" systems

"Normal" systems.

35mm slides - M51, M82

Radio emission is trickle-down from stellar processes.

- cosmic ray electrons from SNR's
- HII regions
- active stars, etc.

} → $L_{radio} \sim 10^{-6} L_{optical}$.

+ nuclear radio sources (nonthermal) — slide - M31

- 10^{18-20} W/Hz in Scd at 6cm
- $10^{18.5} - 10^{21}$ W/Hz in Sab - - - -
- $10^{19} - 10^{22}$ W/Hz in S0

} mechanisms arguable (multiple SNRs, supermassive stars, BH models, etc).

(notes-p3)

"Active systems"

Spirals — Seyfert activity (~1% of all spirals)
bright nuclei, emission lines, uv excess, Xray

Ellipticals — "radio galaxies" (few% of all ellipticals)
nuclear sources $10^{22} - 10^{25}$ W/Hz at 6cm
extended emission ~100 × brighter, outside galaxy
(10kpc → several Mpc)
radio luminosity function - Auriemma et. al., A.&A., 57,41 (1977)

QSOs — radio quiet, like Seyfert 1 galaxies only more luminous

QSRS — radio loud (~10% of QSO's). Cores $10^{23} - 10^{28}$ W/Hz at 6cm
can be core-dominated or lobe-dominated. No FeII

Properties of Nuclear Sources in Bright Galaxies

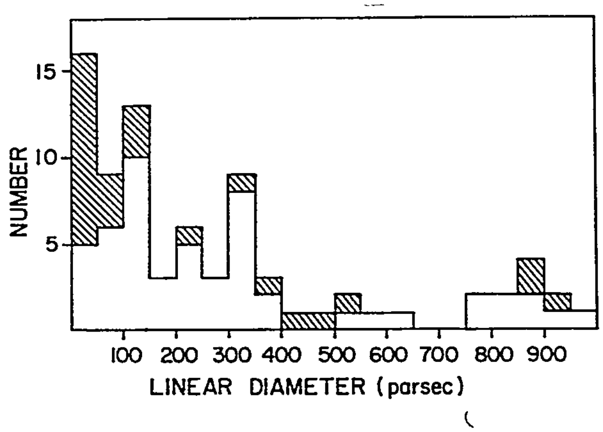


Fig. 2 Distribution of sizes of nuclear sources in spiral galaxies.

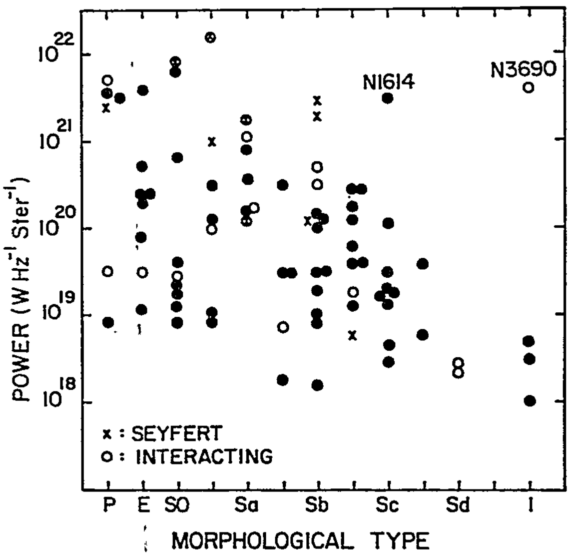


Fig. 3 Monochromatic power (6cm) of nuclei as a function of Hubble type.

from van der Hulst (1980)

QSO's and Type 1 Seyferts

- bright nuclei, faint diffuse envelopes
- high and low luminosity ends of continuous range in optical powers?

  $10^{43} - 10^{47}$ erg/s.

- permitted emission lines $\Delta v \sim 10{,}000$ km/s "broad"
- forbidden emission lines $\Delta v \lesssim 1{,}000$ km/s "narrow"
- not rapidly variable
- uv excesses, ~ black-body at 20,000 – 30,000 K.
- FeII emission common
- Xray sources
- nonthermal power-law emission dominates in visual/IR.

Type II Seyferts — weak "broad" lines $\Delta v \sim 10{,}000$ km/s
strong "narrow" lines $\Delta v \lesssim 1{,}000$ km/s
starlight and IR source at 200K dominate.

QSR's — ~ 10% of QSO's
- optically and Xray similar to QSO's, but lack FeII

radio sources always contain cores

Core dominance increases with radio luminosity (assuming isotropic)

$\gtrsim 50\%$ have jets, all <u>one</u>-sided.

<5% of all Seyferts are elliptical galaxies → QSO's a spiral-galaxy phenomenon.

But lobe-dominated QSR's resemble radio galaxies
- are <u>these</u> the "Seyfert ellipticals"?

35mm slides

1. Known for almost 25 yrs that sources have basic double structure

   - e.g. Cyg A (20cm VLA)

     Double structure ~ 90 kpc across

     Hot spots ~ kpc

     Faint central core in optical object

     Optical galaxy (35mm)

     Dusty elliptical with strong high-excitation emission lines

     Cen A galaxy

     Example of nearest RG known.

Optical nature of radio gals.

Typically ellipticals with unusual dustlines and bright nuclei + evidence of high-excitation gas (strong emission lines) (like Seyferts)

Emission line spectra resemble high-ionization planetary nebulae + strong forbidden lines. Unusually strong lines of once-ionized ions and neutral atoms.

Apart from abundance differences, resemble Crab Nebula spectrum.

Possibly photoionised by power law spectrum in continuum?

<u>Models</u> – Hot gas at 2×10^6 K, $n_e\sim10^2\,cm^{-3}$, Mass $\sim10^{8.5}M_\odot$

+ clouds at 10^4 K filling $\sim10^{-6}$ of volume, $\sim10^7 M_\odot$
$n_e\sim10^4\,cm^{-3}$

~ 1 field galaxy in 10^5 is a radio gal.

Long suspected that activity in nuclei fuels the radio lobes.

Synchrotron lifetimes in hot spots << light travel time if hot spots are in equipartition, + evidence for continuing activity in cores.

Reinforced continuous-activity models with discovery of long thin radio structures linking cores to lobes in many sources — "radio jets"

— e.g. VLA maps of (color)
3C449
M84
NGC315
NGC6251

N.B. "Jet" here means "long thin thing" so far
– no <u>direct</u> evidence for <u>flow</u> of material.

- 35mm slide sequence showing trends
  - Some active radio gals. order of lum

M84 - (1)
M84 - (2)
IC4296 -
NGC315 -
NGC1265 - (1)
- (2)

NGC6251 - (1)
- (2)

Some transparencies copied in notes p. 9-12

3C388

3C390.3 - (1)
- (2)

3C405

two feeds hotspot

- then QSR o/heads

MAIN COMPONENTS OF RADIO GALAXIES

CORES

LINEAR SIZES $\ll 10$ PC

RADIO SPECTRA $\nu^{0.0}$

EQUIPARTITION MAGNETIC FIELDS 10^{-3} GAUSS

LINEAR POLARIZATION $\lesssim 2\%$

JETS

LINEAR SIZES 1 TO 300,000 PC

RADIO SPECTRA $\nu^{-0.6}$

EQUIPARTITION MAGNETIC FIELDS 10^{-4} TO 10^{-6} GAUSS

LINEAR POLARIZATION 0 TO 65%

HOT SPOTS

LINEAR SIZES 1,000 TO 5000 PC

RADIO SPECTRA $\nu^{-0.6}$

EQUIPARTITION MAGNETIC FIELDS 10^{-5} GAUSS

LINEAR POLARIZATION $\sim 15\%$

LOBES

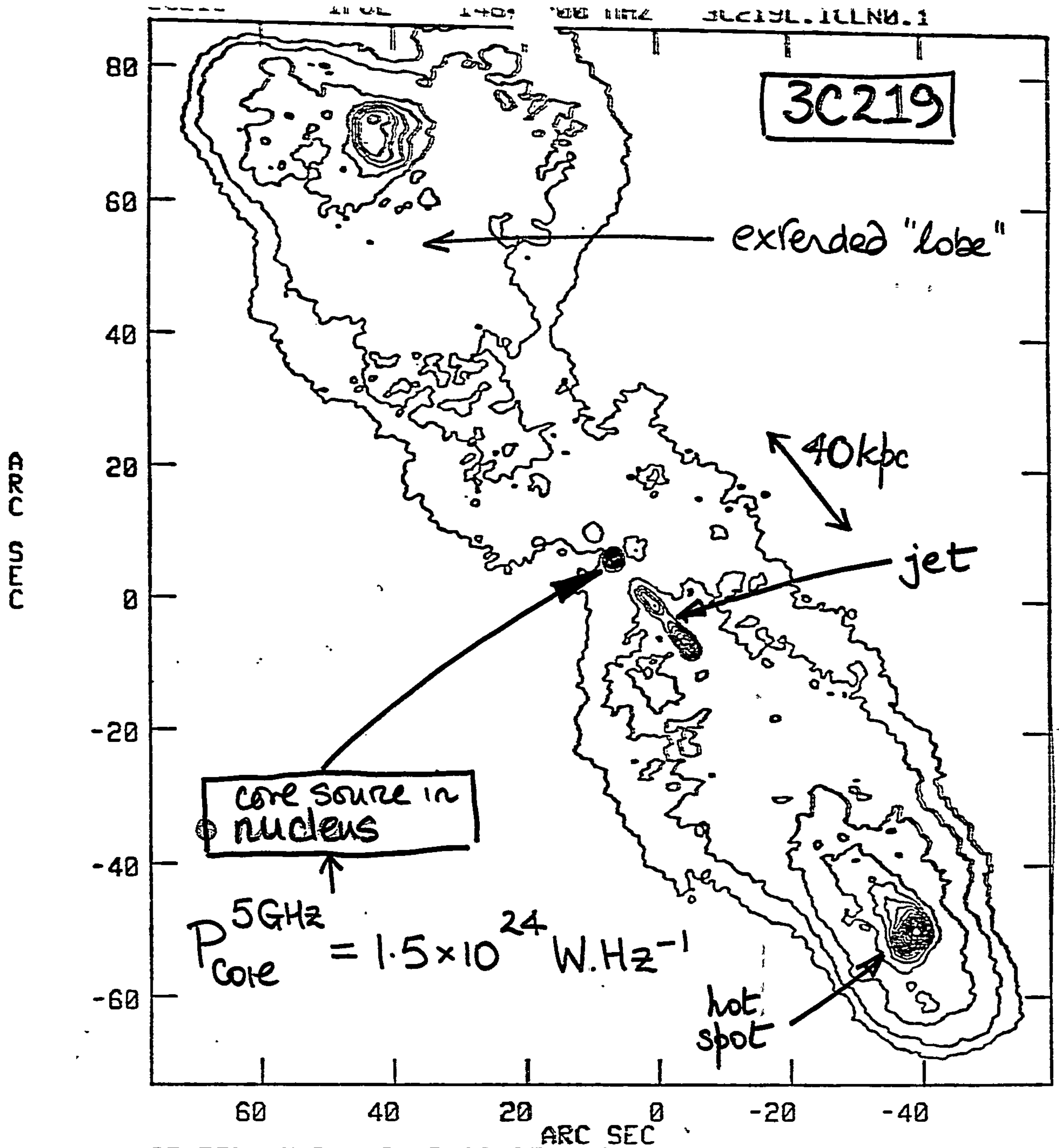
LINEAR SIZES 50,000 TO 1,000,000 PC

RADIO SPECTRA $\nu^{-0.8}$ TO $\nu^{-1.3}$

EQUIPARTITION MAGNETIC FIELDS 3×10^{-6} TO 10^{-5}

LINEAR POLARIZATION 0% TO 60%

Parts of a typical powerful radio galaxy

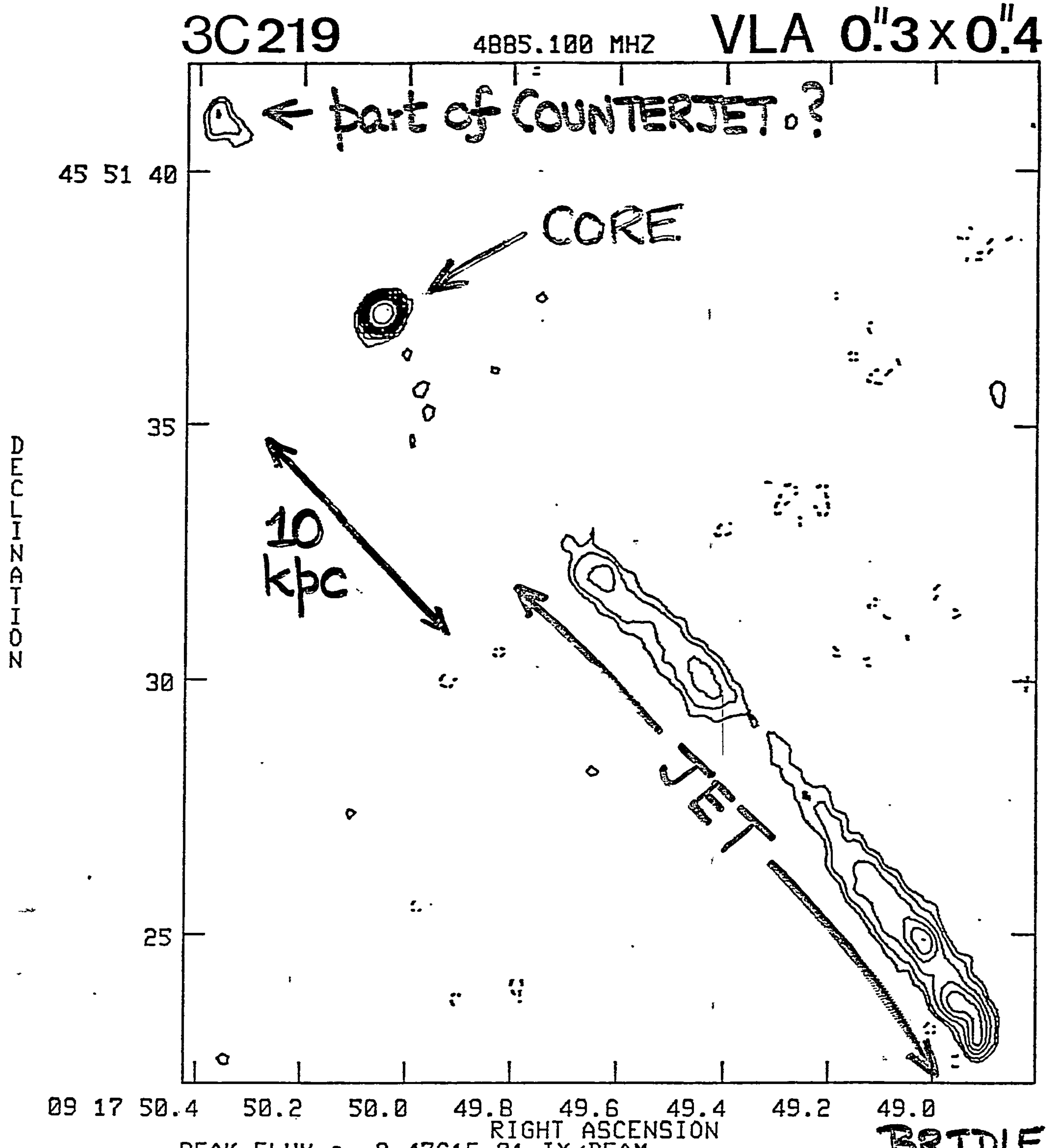


CENTER AT RA 09 17 50.05 DEC 45 51 37.2
PEAK FLUX = 0.7354E-01 JY/BEAM
LEVS = 0.7354E-03 * (-2.5, 2.5, 5.0,
10.0, 15.0, 20.0, 25.0, 30.0, 35.0,
40.0, 45.0, 50.0, 55.0, 60.0, 65.0,
70.0, 75.0, 80.0, 85.0, 90.0)

Rog. (

Bridle
Perley
Henrike
in pre[p]

Detail of central region of p. 6



PEAK FLUX = 0.4761E-01 JY/BEAM
LEVS = 0.2000E-03 * (-1.0 1.0 2.0 4.0 6.0 8.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 50.0 100.0)

BRIDLE
PERLEY
HENRIKSEN
in preparation

$P_{core}^{5GHz} = 1.5 \times 10^{24}$ W.Hz^{-1}

Some Systematic Trends in extragalactic sources

SOURCES WITH LOW CORE POWERS ($P_{core}^{5GHz} \lesssim 10^{23}$ W/Hz)

- large scale jets are "two-sided" ($\lesssim 4:1$) –
  $B_{\perp}$ – dominated
  p_{min} confinable by Xray halo [but not M87]
- brighter large scale jet has short one-sided $B_{\parallel}$ base
- VLB "jet" (if any) aligns with brighter large scale jet
- jets merge gradually with lobes

SOURCES WITH HIGH CORE POWERS ($P_{core}^{5GHz} \gtrsim 10^{23}$ W/Hz)

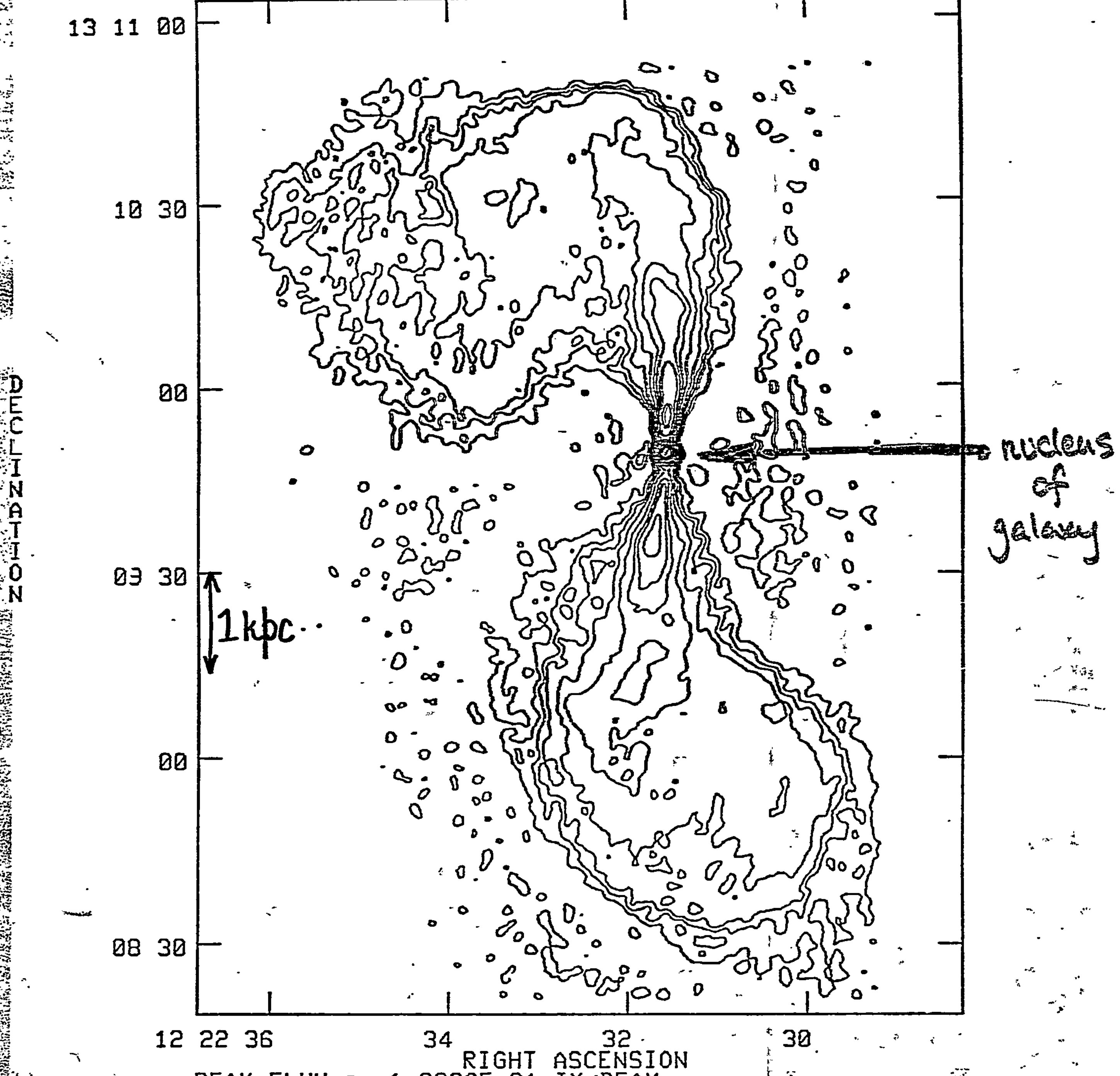
- large scale jets are "one-sided" ($\gtrsim 4:1$)
  $B_{\parallel}$-dominated
  p_{min} hard to confine by Xray halo
- jets terminate in bright spots
- VLB "jet" (if any) <u>on same side</u> as brighter large scale jet, <u>alignment</u> better if core does not <u>dominate</u>.

Occurrence rates in "complete" samples

Nearby radio galaxies	70 – 80%	($z<0.05$)
Distant radio galaxies	$\lesssim 10\%$	($z>0.4$)
3CR QSRs	$> 50\%$	

VLA 1".3

M84 IPOL 4885.100 MHZ M84 6BC V3.ICLN.1



PEAK FLUX = 1.8026E-01 JY/BEAM
LEVS = 0.1803E-03 * (-2.0, -1.0, 1.0, 2.0, 3.0, 5.0, 10.0, 20.0, 30.0, 50.0, 100.0, 200.0, 300.0, 500.0, 1000.0)

$P_{core}^{5GHz} = 5.5 \times 10^{21}$ W.Hz^{-1}

R.A. LAING
A.H. BRIDLE
in preparation

E galaxy in Virgo Cluster
Typical week radio galaxy

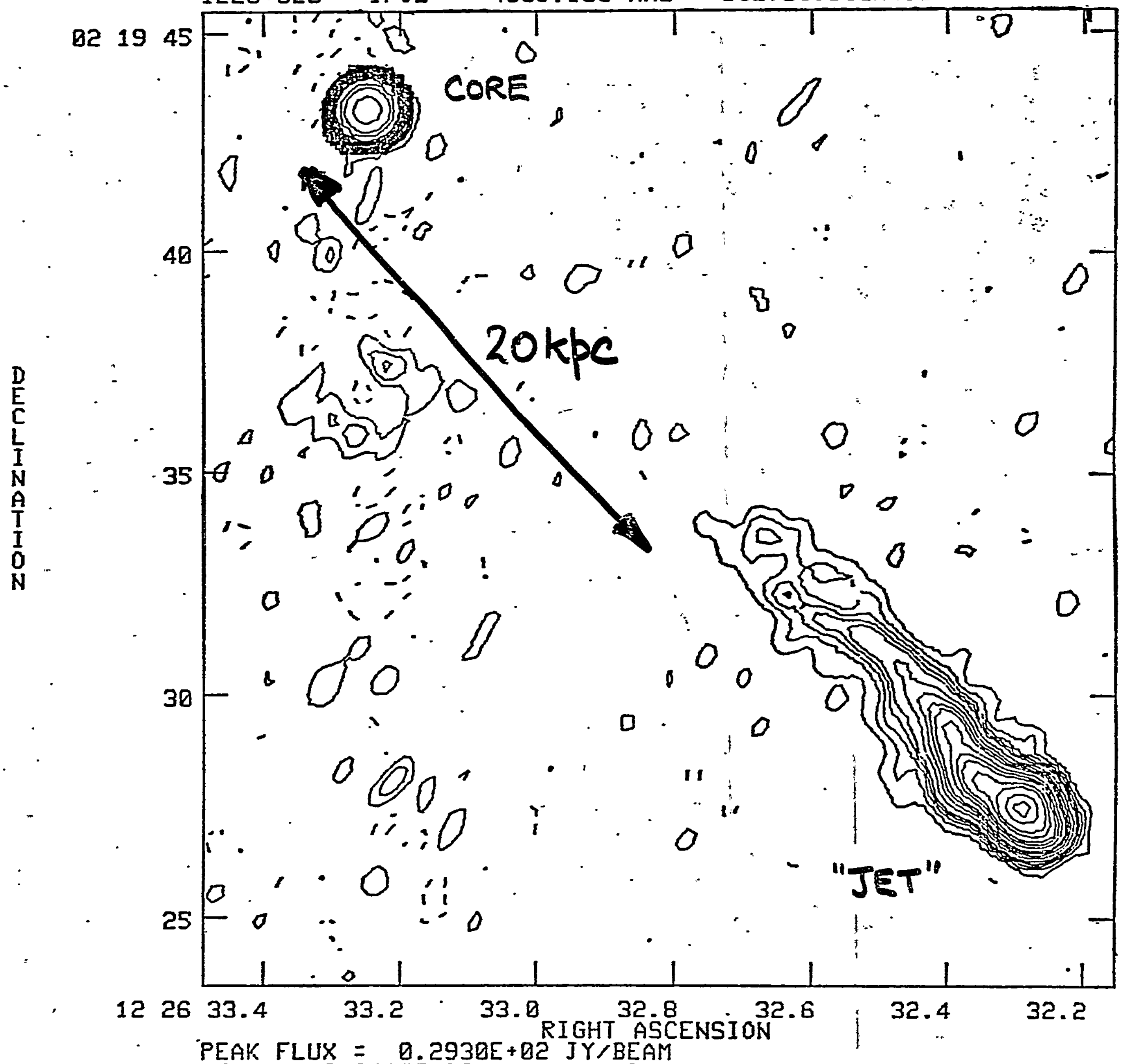
Perley
Fomalont
Johnston

(10)

QSO

3C273 $z = 0.158$ VLA 0".6

1226+023 IPOL 4885.100 MHZ 3C273C.ICLN4.1



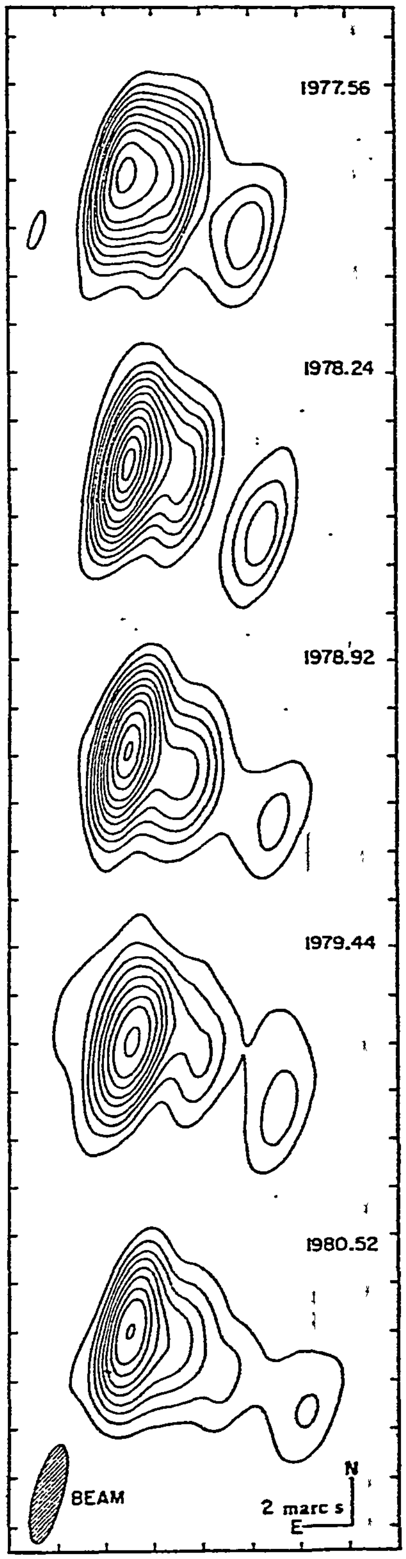
PEAK FLUX = 0.2930E+02 JY/BEAM
LEVS = 0.9757E-02 * (-1.0 1.0 2.0
3.0 4.0 5.0 7.5 10.0 12.5 15.0
20.0 25.0 30.0 40.0 50.0 75.0 100.0
250.0 500.01501.5)

$P^{5}_{core} = 8.4 \times 10^{26}$ W/Hz

Typical core-dominated quasar source

Perley, Fomalont, Johnston

10pc ⟷ 3C273 CORE

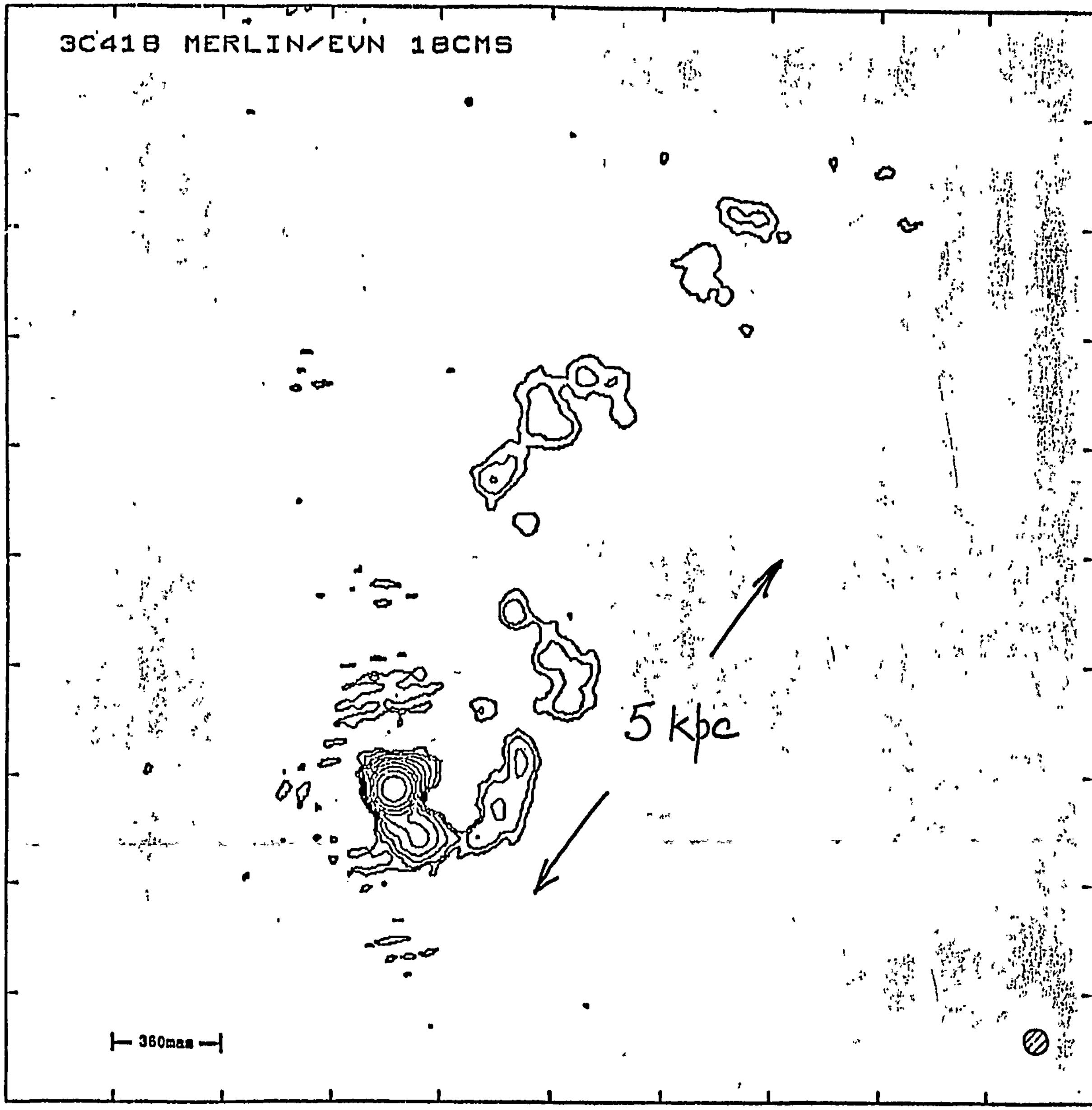


v_{exp} $(H=100,\ q_0=\frac{1}{2})$
$= (5.3 \pm 0.3)c$

"Superluminal expansion" in Core-dominated quasar

Pearson et al.
Nature,
290, 365
(1981)

extreme case of core-dominated source → note bent structure



QSO, $z = 1.686$

$P^{5GHz}_{core} = 1.7 \times 10^{28}$ W.Hz

CONTOURS IN PERCENT:
0.2 0.4 0.8 1.6
3.2 6.4 12.8 25.6
51.2

peak 4376mJy/beam
beam 80mas

4 TELESCOPE EVN
5 " MERL

λ18 MERLIN BEAM ~ 0.2
λ18 EVN " ~ 0''.

RESTORING BEAM

Muxlow, unpublished

(A FEW OF THE) PROBLEMS POSED BY RADIO GALAXIES and QSRS

1. **ENERGY BUDGET**

-- MINIMUM (EQUIPARTITION) ENERGY RESERVOIRS OF EXTENDED LOBES ARE OF ORDER 10^5 TO 10^7 $M_\odot c^2$

2. **COLLIMATION/CONFINEMENT**

-- FREE RELATIVISTIC PLASMOIDS EXPAND AT SOUND SPEED $\sim c/\sqrt{3}$ BUT SEPARATE FROM GALAXY AT VELOCITIES $< c$

-- SHOULD THEREFORE SUBTEND ANGLES $> 2 \tan^{-1}(1/\sqrt{3})$ AT GALAXY $> 60^0$

-- MOST RADIO GALAXY LOBES SUBTEND ANGLES $\ll 60^0$ AT GALAXY

-- MEDIAN ANGLE SUBTENDED BY HOT SPOTS $\sim 0.6^0$ AT GALAXY

-- HENCE MOST LOBES NOT FREELY EXPANDING BUT CONFINED
MUST BE ENERGY LOSSES WORKING AGAINST CONFINEMENT

3. **ADIABATIC EXPANSION LOSSES**

-- IF MAGNETIC FLUX CONSERVED $B \propto R^{-2}$ (R = PLASMOID SCALE)
PARTICLES WORK AGAINST CONFINEMENT $E \propto R^{-1}$

-- SYNCHROTRON EMISSIVITY DECLINES AS R^{-2x} $[N(E) \propto E^{-x}]$
FOR OBSERVED $x \sim 2.5$, R^{-5} DECLINE IN SYNCHROTRON EMISSIVITY

-- OBSERVED LOBE STRUCTURES REQUIRE SUPERLUMINOUS "EVENTS"

4. LIFETIMES OF RADIATING PARTICLES

-- SYNCHROTRON LIFETIMES OF PARTICLES IN HOT SPOTS (IN EQUIPARTITION) ARE LESS THAN $\frac{\text{SEPARATION FROM GALAXY}}{c}$

-- NEED CONTINUOUS SUPPLY OF FRESH PARTICLES AT HOT SPOTS

PRIMARY INGREDIENTS OF "BEAM" MODELS

ENERGY GENERATION

$>10^{36}$ Watts - powerful RG
$>10^{38}$ Watts - powerful QSO

- * WELL WITHIN OBSERVED RADIO CORES
- * INFALL OF MATTER, ANGULAR MOMENTUM, INTO DEEP GRAVITATIONAL POTENTIAL WELL AT CENTER OF GALAXY
- * CONVERSION OF GRAVITATIONAL, ROTATIONAL ENERGY INTO BULK KINETIC ENERGY

ENERGY TRANSPORT

- * PATHWAY SHOWN BY RADIO JETS
- * COLLIMATION OF KINETIC ENERGY OUTFLOW BY (A) NOZZLES
  (B) DONUT HOLES (THICK DISKS)
  (C) VORTEX FUNNELS
- * DIRECTED OUTFLOW (AT WHAT VELOCITY ??) OF ENERGY, MOMENTUM IN TWO STREAMS

ENERGY CONVERSION

- * SITE INDICATED BY RADIO HOT SPOTS
- * SUPERSONIC FLOWS END AT SHOCKED INTERFACE WITH CIRCUMGALACTIC GAS
- * RANDOMIZATION OF DIRECTED KINETIC ENERGY, PARTICLE ACCELERATION, ETC.

ENERGY DISSIPATION

- * DIFFUSION THROUGHOUT RADIO LOBES
- * WASTE HEAT ?

IMPLICATIONS OF RADIO JETS FOR PHYSICS OF ENERGY TRANSPORT IN RADIO GALAXIES AND QUASARS

1. EXISTENCE OF JETS

-- FLOWS OF RADIATING PARTICLES AND FIELDS FROM ACTIVE NUCLEI TO THE DISTANT RADIO LOBES, COLLIMATED AT OBSERVABLE DISTANCES (SEVERAL KPC) FROM THE ACTIVE NUCLEI

2. WIDTH EVOLUTION OF JETS (COLLIMATION)

-- CONSTRAINTS ON MECHANISMS FOR CONFINEMENT

-- EVIDENCE FOR LARGE-SCALE HIGH-PRESSURE ATMOSPHERES ?

3. LINEAR POLARIZATION DISTRIBUTIONS

-- ORGANISED MAGNETIC FIELD STRUCTURES, PARALLEL → PERPENDICULAR

-- CORRELATIONS WITH RADIO CORE LUMINOSITY

4. INTENSITY AND SPECTRAL DISTRIBUTIONS

-- EVIDENCE FOR PARTICLE REACCELERATION ALONG THE JETS

JET BENDING

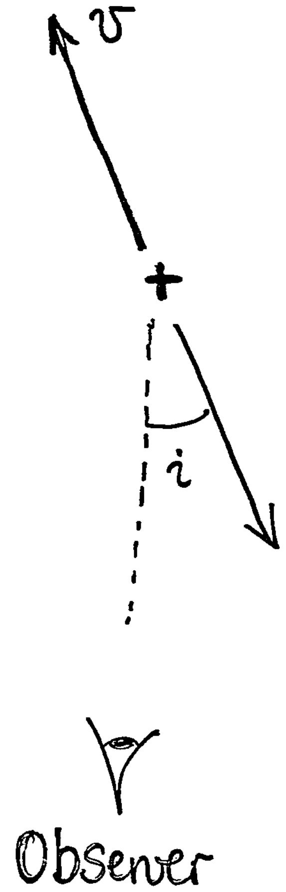
-- EVIDENCE FOR JET STABILITY

-- CONSTRAINTS ON (MAGNETO)FLUID DYNAMICAL MODELS

5. SIDE-TO-SIDE ASYMMETRIES

-- ?? (STRONG UNEXPLAINED CORRELATION WITH LUMINOSITY)

"Doppler favouritism" of relativistic jets



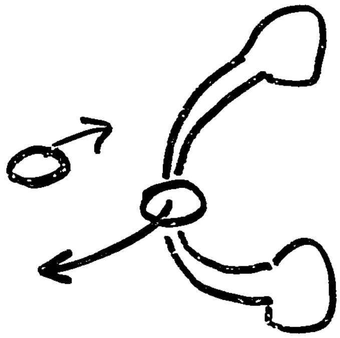
intrinsic emission spectrum $\propto \nu^{-\alpha}$

$$\frac{S_{\text{approaching}}}{S_{\text{receding}}} = \left(\frac{1 + \frac{v}{c} \cos i}{1 - \frac{v}{c} \cos i} \right)^{2+\alpha}$$

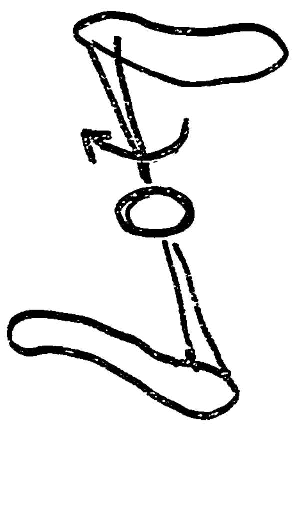
Apparent separation velocity $v' = \dfrac{v \sin i}{1 - \frac{v}{c} \cos i}$

can be $> c$

UNPERTURBED TWO-SIDED JET



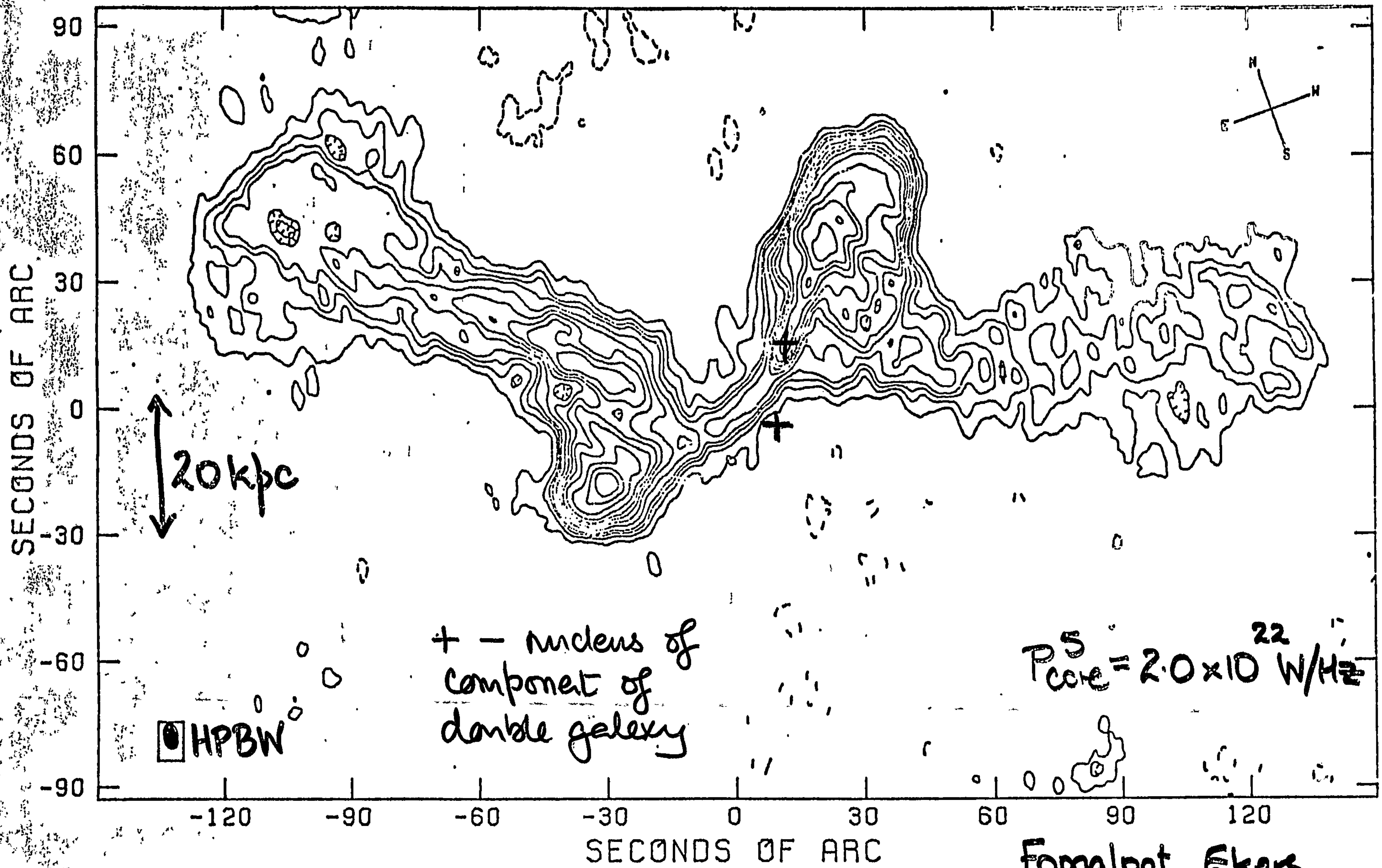
PERTURBATION BY TRANSLATION THROUGH CIRCUMGALACTIC MEDIUM



PERTURBATION BY PRECESSION (WOBBLE) OF PRIMARY COLLIMATOR (BLACK BOX)

Possible Exotic Source Shapes Derivable from Basic Jet-Lobe Structure

NGC326 IPOL 1465 MHZ CLEAN MAPNO= 700 VLA



Fomalont, Ekers, Fanti, Lari, Parma unpublished

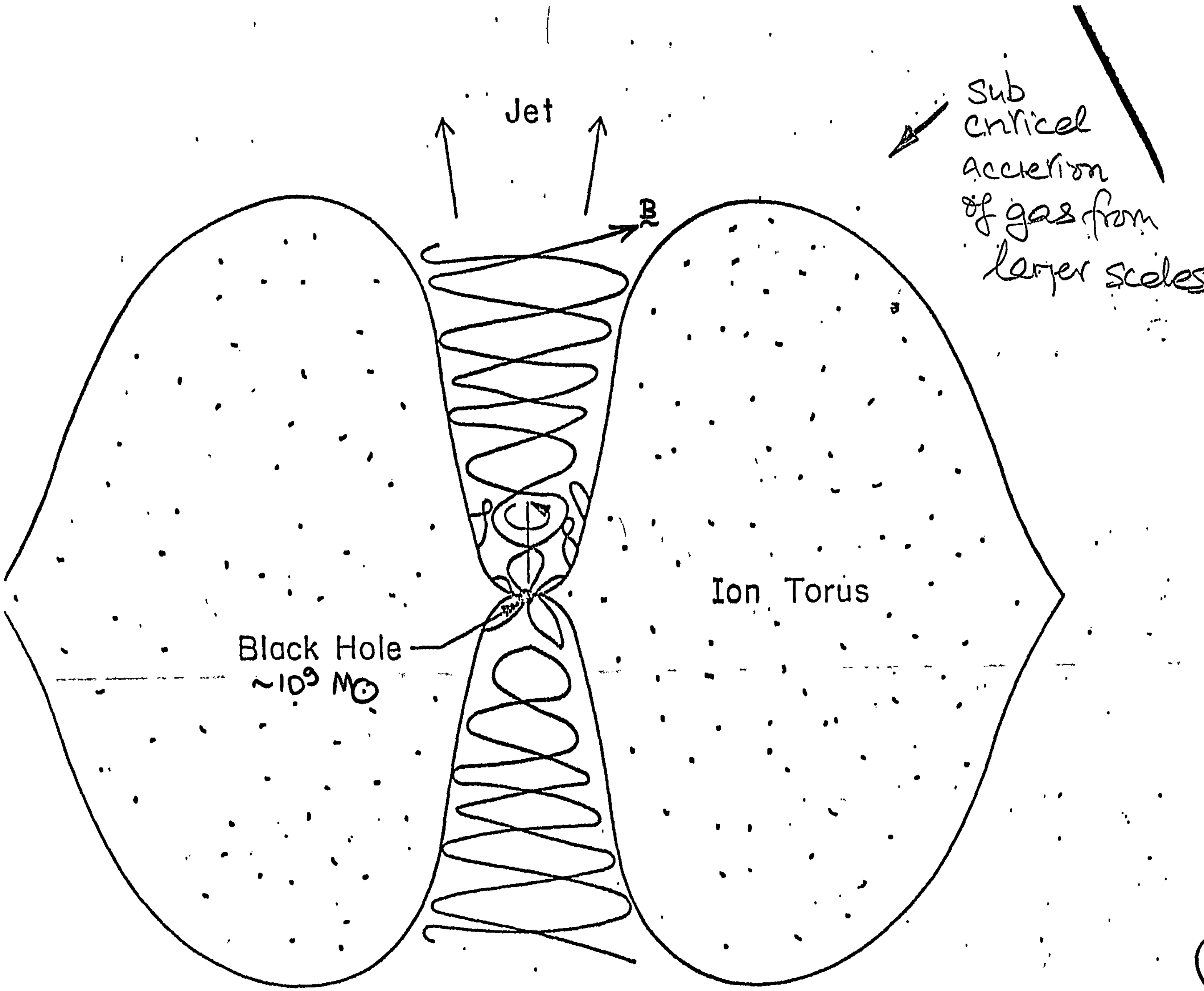
PEAK FLUX = 27.8 MJY

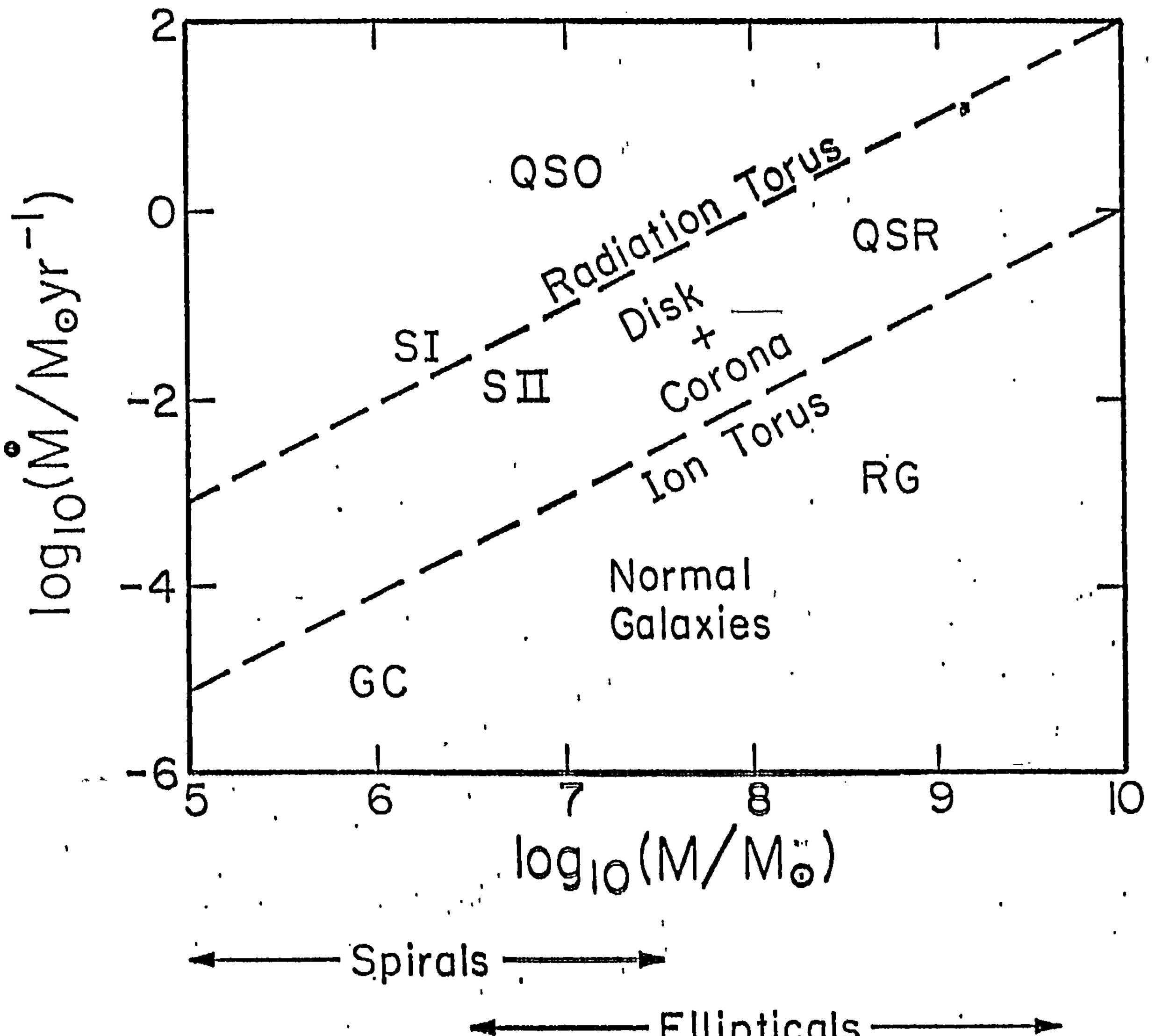
LEVS = 0.60 × (40 30 25 20 15 12 10 8 6 4 3 2 1 -1)

CLEAN BEAM: MAJ, MIN, PA 6.00 3.50 -12.0 NITER = 2710

CENTER POSITION 00 55 42.060 , 26 35 33.40

Ingredients of a typical central engine model
(Blandford)





Blandford "unified scheme" for active objects
(Texas Symposium, 1983)

6