One of the main reasons we are having a symposium involving extragalactic jets here is that jets are a commonplace phenomenon in active extragalactic radio sources.

Let's look quickly at evidence for this ~~from jet database I have kept from literature and many private communications from colleagues~~:

EXTRAGALACTIC JETS ARE COMMONPLACE

- A.H.B. "working list" of jets + jets?
  239 sources June 1985

⇓

136 "definite jets" in sources with KNOWN REDSHIFTS, spanning wide range:

Distances ($H=100$, $q_0=\frac{1}{2}$)	5 Mpc → 10,200 Mpc (Cen A) (QSO, $z=2.594$)
Total source powers at 1.4 GHz	$10^{21.6} \rightarrow 10^{28.4}$ W/Hz ($10^{31} \rightarrow 10^{38}$ watts, 10 MHz to 100 GHz)
Core powers at 5 GHz	$10^{20.4} \rightarrow 10^{28.2}$ W/Hz
Jet lengths	50 pc → 280 kpc

So - jets occur in sources with whole range of powers, sizes and distances characteristic of active extragalactic sources. Not confined to any one sub-type. This suggests they are part of basic physics of whatever makes the large scale sources

Also very important is rate of detection of jets in complete samples of different source types when observed with fairly homogeneous sensitivity, resolution + dynamic range.

Leader - collimated stream or flow

E/Ed - something looking like it might be the above - MORPHOLOGY ONLY except for VLBI!

DETECTION RATES OF JETS IN COMPLETE SOURCE SAMPLES

Weak radio galaxies

median $P_{tot}^{1.4} = 10^{24.43}$ W/Hz

65% - 80% in ($3CR^2$, $z < 0.05$)

(B2, $m_{pg} < 15.7$)

(E/S0, $m_{pg} < 14$)

Extended $3CR^2$ QSRs – median $P_{tot}^{1.4} = 10^{27.43}$ W/Hz

45% - 70%

Powerful $3CR^2$ radio galaxies ($z > 0.4$)

median $P_{tot}^{1.4} = 10^{27.36}$ W/Hz

< 10%

N.B. "jet" here = narrow feature running from core towards lobes

P_{tot} (10 MHz → 100 GHz) $\sim 10^{9.6} P_{tot}^{1.4}$ ($\alpha = 0.75$)

N.B. The galaxy - QSR difference at same total power can be interpreted as jet detection roughly correlating with core prominence in strong sources, as it is well known that QSR radio cores are more prominent than radio galaxy radio cores at same power.

Also, there are no strictly "coreless" or "disembodied" radio jets - if you detect the jet you also have detected the core in all but one case in the 136.

All explicable if core power + jet power x correlate

* ~~Burns (1985) has claimed core - jet power correlation~~ in strong sources. e.g. Burns ~~[illegible]~~

~~directly~~.

This suggests that jets are intimately related to ongoing activity in the innermost kpc, hence to energy TRANSFER from cores to lobes. Also suggests some other things about jet velocities that I hope to get to later.

hdc

Evidence for Outflow in Kpc-scale Extragalactic Jets

– VERY INDIRECT –

1. PROPER MOTIONS ON PARSEC SCALES AT BASES OF SOME KILOPARSEC-SCALE JETS

3C120, 3C179, 3C279

VLB → mainly OUTflows (expansion)

van Breugel (Tuesday)

2. EXTRANUCLEAR EMISSION LINES

(NLRs)

~8 radio galaxies, 1 QSR

Seyfert 2 or liner-like spectra

gas at EDGES of radio jets, outside bends, knots

gas pressure ≈ minimum pressure of synchrotron jet

$n_e T \sim 2\times10^6 - 2\times10^7 \, cm^{-3}$

line widths increase toward radio features

peculiar velocities few 100's of km/s

– all suggest –
INTERACTION of ISM with jets

BUT NO DIRECT MEASURES OF OUTFLOW VELOCITY (GAS NOT ENTRAINED IN FLOW)

3. "JETS" SEEN WHERE "BEAMS" PREDICTED

5 min

As I will be talking about correlations and trends involving jet data, we should look at some! I'm sure many detailed maps will be shown at this Symposium, so I will show just a few, rather typical objects, in an order which shows up some interesting trends — order of increasing core power.

Start with 3C31 – $P^{S}_{core} = 10^{22.45}$ W/Hz

note – jet starts out asymmetric ~5:1 (one-sided)

few kpc becomes symmetric (two-sided

smooth brightness decline as it expands rapidly

lack of clear termination, blends into edge-darkened plumelike meandering structure

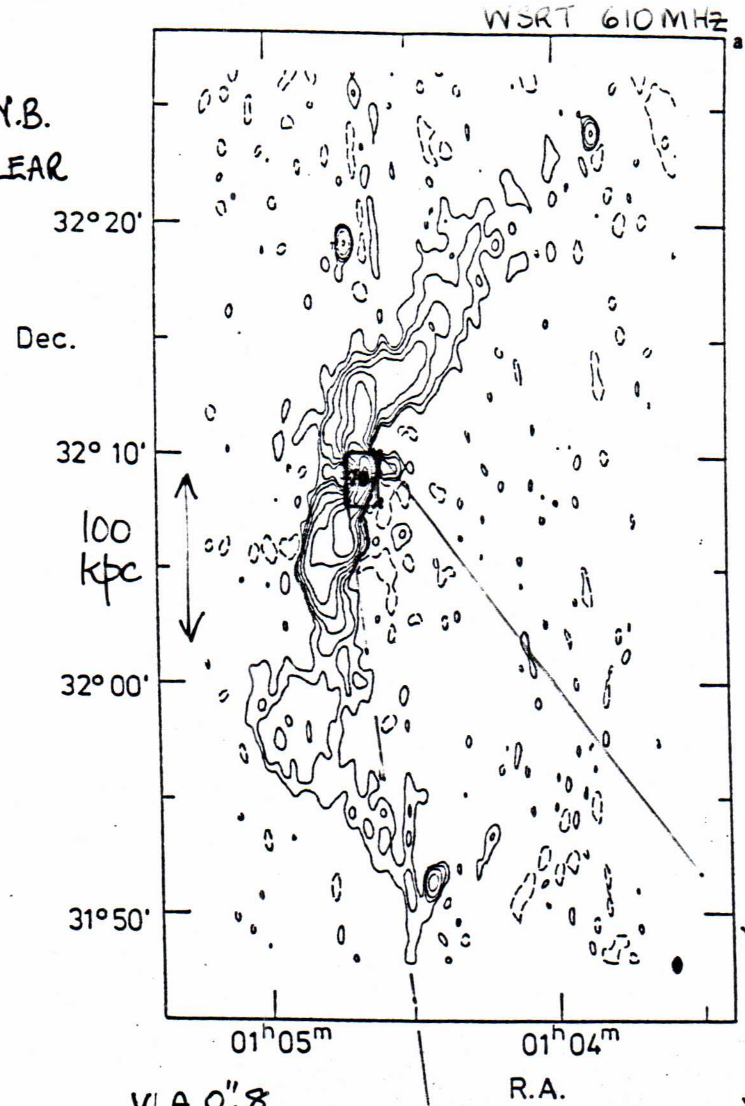
3C31

Radio galaxy

$P^{1.4}_{tot} = 10^{24.21}$ W/Hz

$P^{5}_{core} = 10^{22.45}$ W/Hz

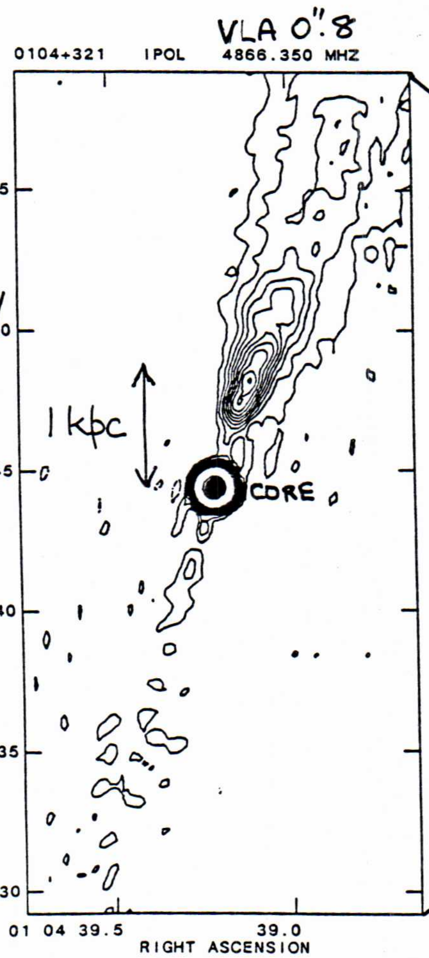
N.B.
NO CLEAR
END
OF
JET

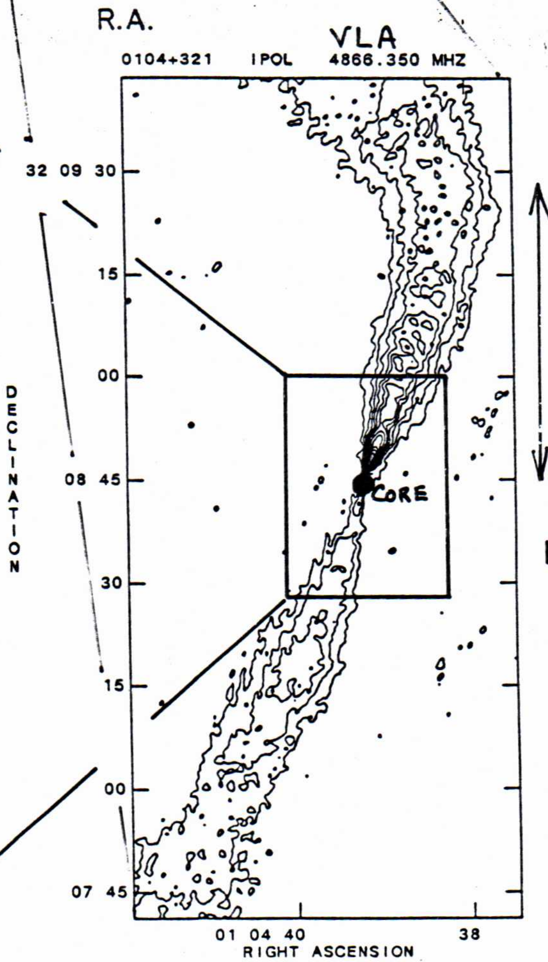


WSRT 610MHz
Strom et al.
AA, 122, 305 (1983)

VLA 4866 MHz
Bridle & Fomalont
(to be published)

N.B.
INITIAL
ASYMMETRY





N.B. DEVELOPING
SYMMETRY,
DEFLECTION,
EXPANSION,
SMOOTH
BRIGHTNESS
DECLINE

Next, montage of NGC6251

~ same total power as 3C31, but core is ~ 10× more powerful. $P^{5}_{core} = 10^{23.66}$

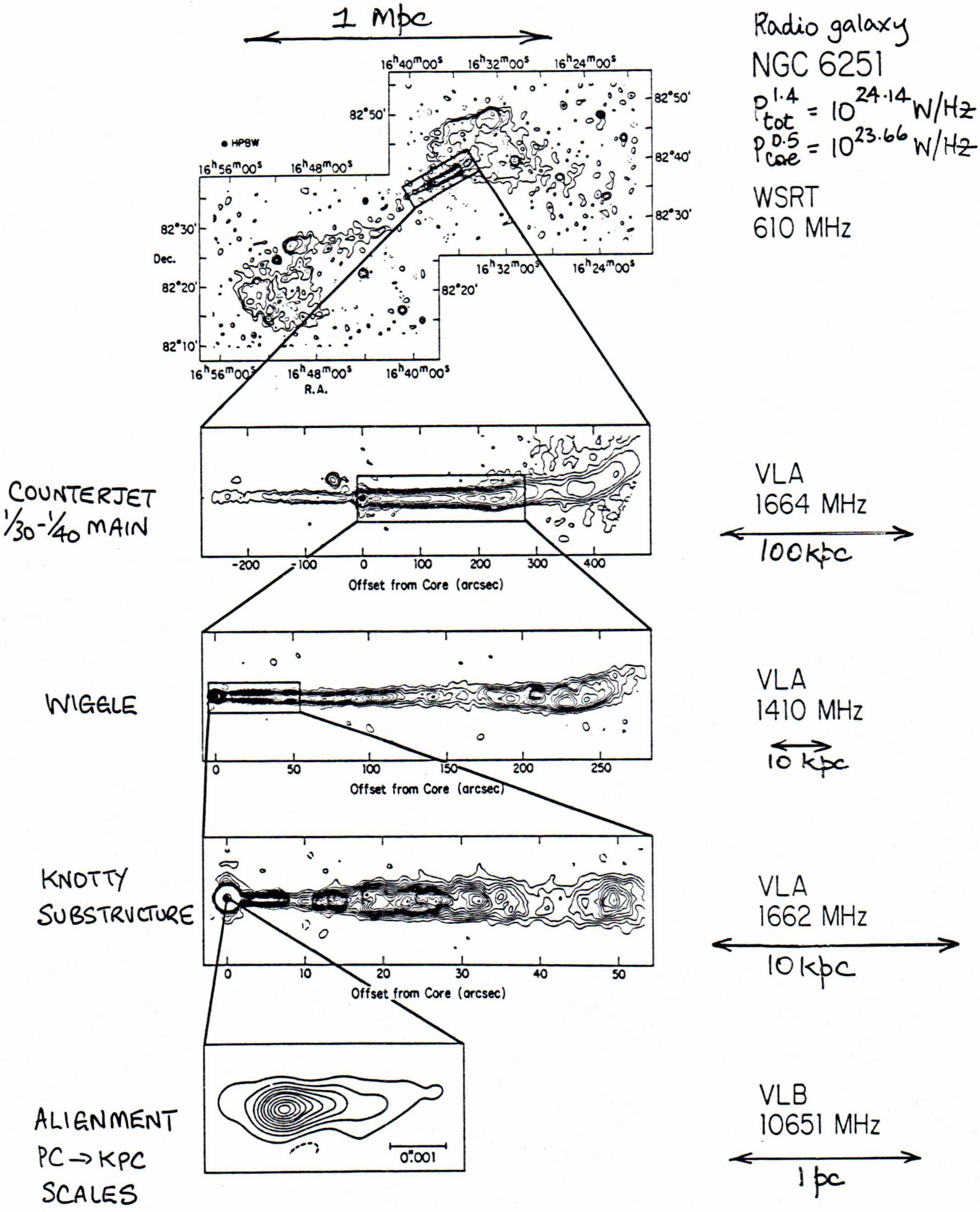
Now see jet/counterjet asymmetry larger. ~ 30:1

jet is blobbier/knottier

Also in this case we [redacted] know about VLBI pc-scale jet.

Note it is one sided on same ~~scale~~ side as 280-kpc scale jet. Also aligned with it to within a few degrees.

This is a lobe-dominated source still.



A.H.Bridle, R.A. Perley

Next up is 3C120

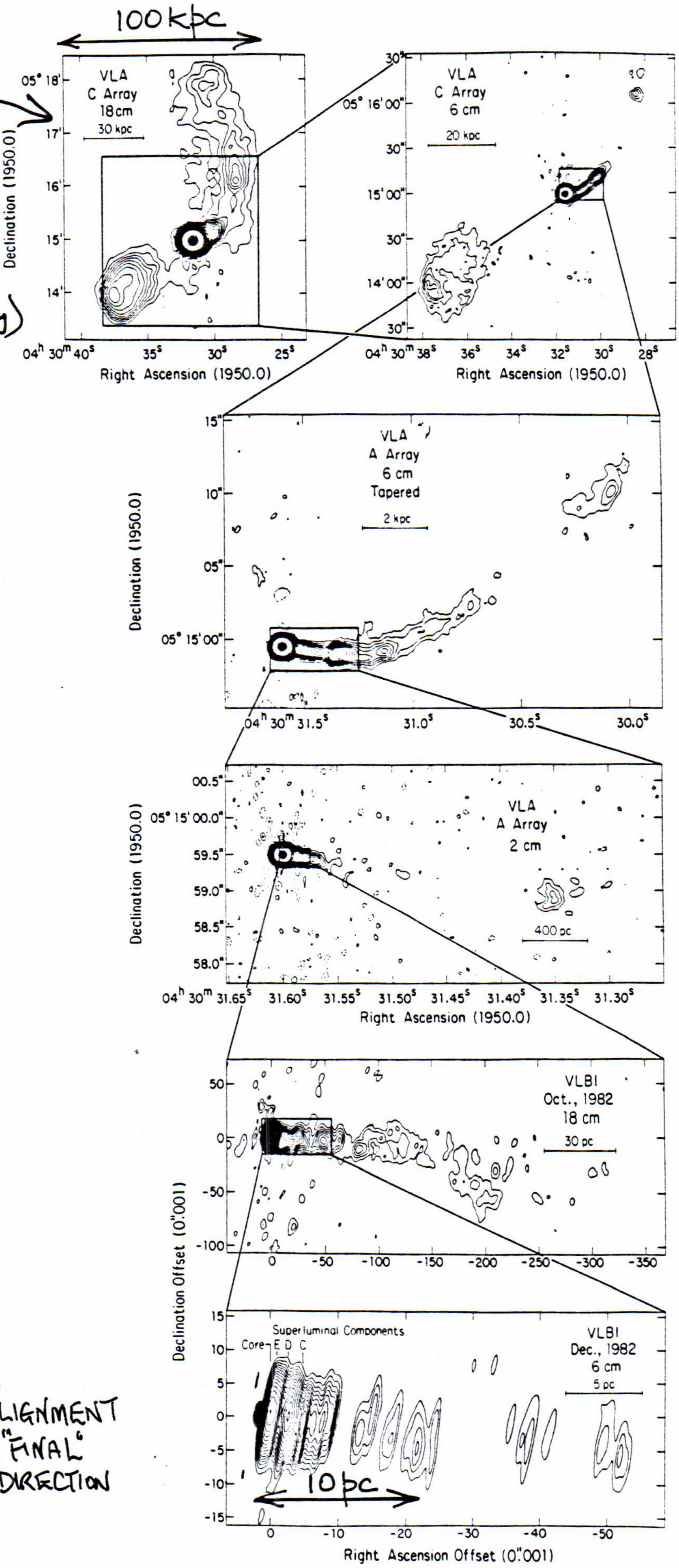
~ same extended source power, but core is ten times more powerful still ($P^{5}_{core} = 10^{24.9}$ W/Hz)

Again, one-sided structure over an enormous range of linear scales, pc → 100 kpc

Now no known converger, highly blobby "one-sided" jet

Initial jet direction is strongly misaligned with final (pc-kpc misalignment).

N.B. MORE TO COME! See C.Walker (Wednesday)



3C120

over a 10,000 : 1 range of scales (N.B.)

RADIO GALAXY (Core-dominated)

$P^{1.4}_{tot} = 10^{24.76}$ W/Hz

$P^{1.4}_{ext} = 10^{23.84}$ W/Hz

$P^{5}_{core} \sim 10^{24.9}$ W/Hz

Most sources with this extended ... have no clear hot spots at ends of their jets.

N.B. MISALIGNMENT WITH "FINAL" JET DIRECTION

R.C. Walker
J. Benson
G.A. Seielstad
S. Unwin

Now go up about a factor of 100 in core power

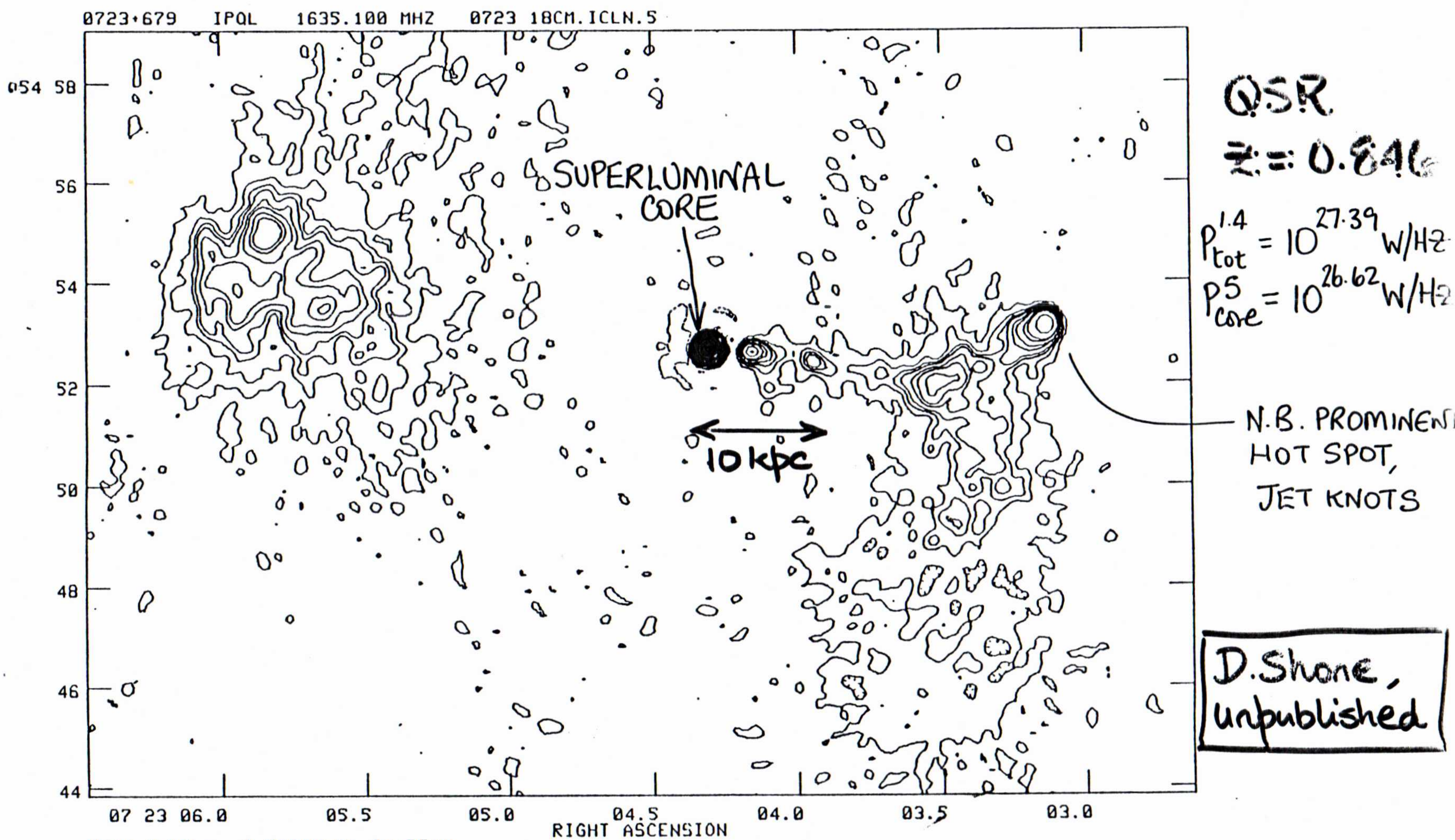
→ $P_{core} = 10^{26.6}$ W/Hz , but back to

lobe-dominated extended QSR (~65 kpc total)

— one-sided knotty jet, ending in prominent hot spot

— superluminal core, rel. little misalignment.

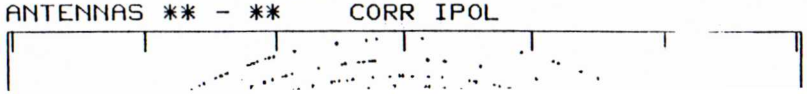
3C179 18cm 0″.28 resolution MERLIN + VLA "A"



PEAK FLUX = 3.5898E-01 JY/BEAM
LEVS = 0.1077E-02 * (-1.0, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 12.0, 16.0, 32.0, 64.0, 128.0, 256.0)

COMBINED MERLIN + 'A' ARRAY
Resolution 0″.28

V VS U FOR 0723 18CM.XY.1
ANTENNAS ** - ** CORR IPOL



The extreme case - 3C418

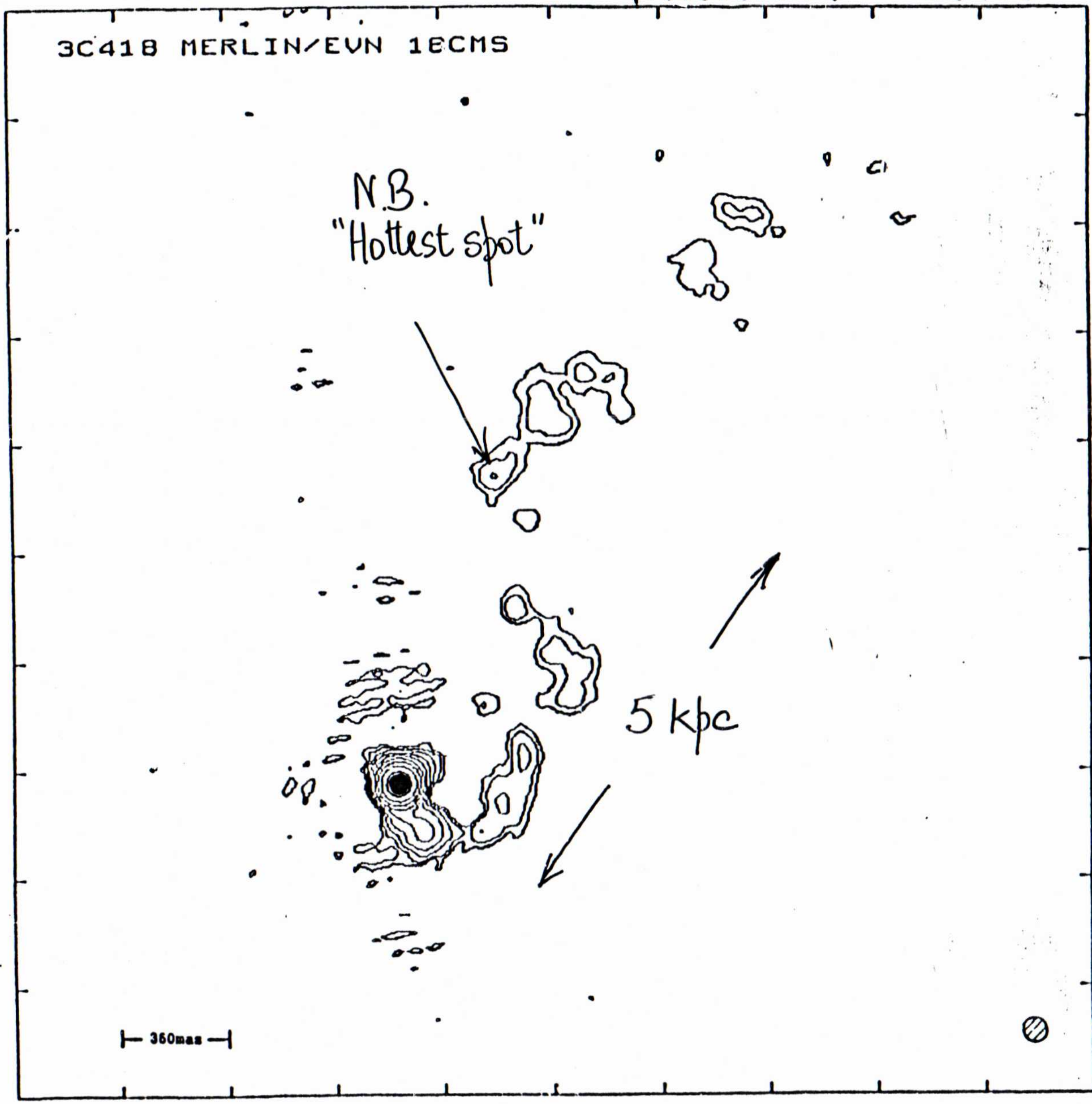
$P_{core} = 10^{28.24}$ W/Hz

strongly core-dominated

Huge twist in jet, which is one-sided, blobby

Hottest spot is at a deflection in jet.

MERLIN + EVN



QSO, $z = 1.686$
(Core-dominated)

$P^{1.4}_{tot} = 10^{28.41}$ W/Hz

$P^{1.4}_{ext} = 10^{27.79}$ W/Hz

$P^{5}_{core} = 10^{28.24}$ W/Hz

CONTOURS IN PERCENT:

0.2	0.4	0.8	1.[illegible]
3.2	6.4	12.8	25.6
51.2			

peak 4376mJy/beam
beam 80mas

4 TELESCOPE EVN
5 .. MERLI

λ18 MERLIN BEAM ~ 0″.23
λ18 EVN .. ~ 0″.0

RESTORING BEAM

Muxlow, Jullian, Linfiel
(1984)

Keep master slide to one side

Power-Related Properties of Extragalactic Radio Jets

Many jet properties change systematically with

– core power
– total power
– core prominence (ratio of above)

DETECTABILITY
– increases with core prominence in strong sources

SYMMETRY/SIDEDNESS
– "two-sided" in weak sources, "one-sided" in strong

TERMINAL HOT SPOTS
– absent in weak sources, prominent in strong

DOMINANT MAGNETIC FIELD (straight jets)
– perpendicular in weak sources, parallel in strong
– parallel B-field enhanced by bending (outer edges)
– bright knots may have B-field across I gradients

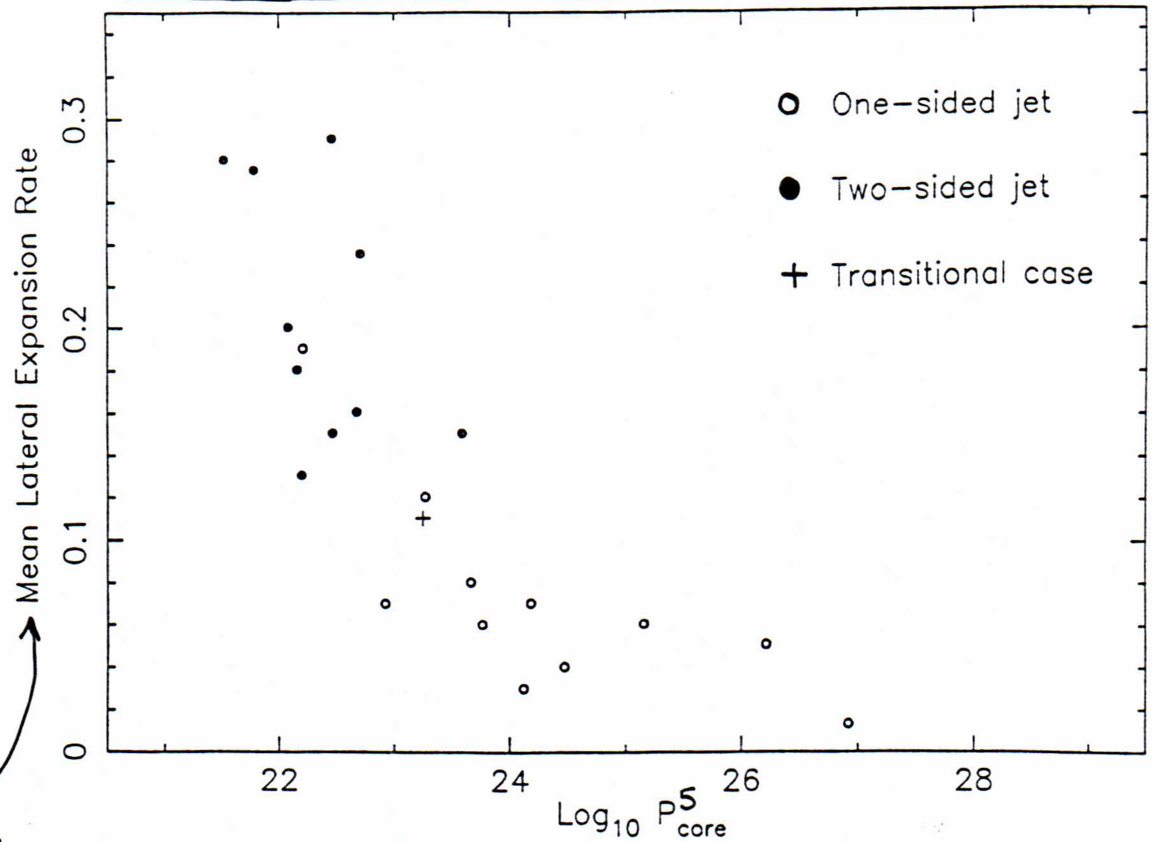
CLUMPINESS
– jets in weak sources smoother than in strong

COLLIMATION (SPREADING RATE)
– rapid spreading in weak sources, slow in strong

Show collimation trend using *updates* of curves I published last year of *mean spreading rate* vs. core and total powers.

Note that the trend involves *both* one-sided and two-sided jets — it's *not* a pure dichotomy between the two.

Jet Spreading Rate vs. Core Power

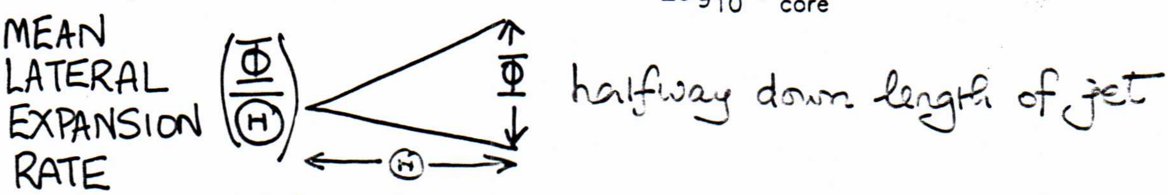


UPDATES

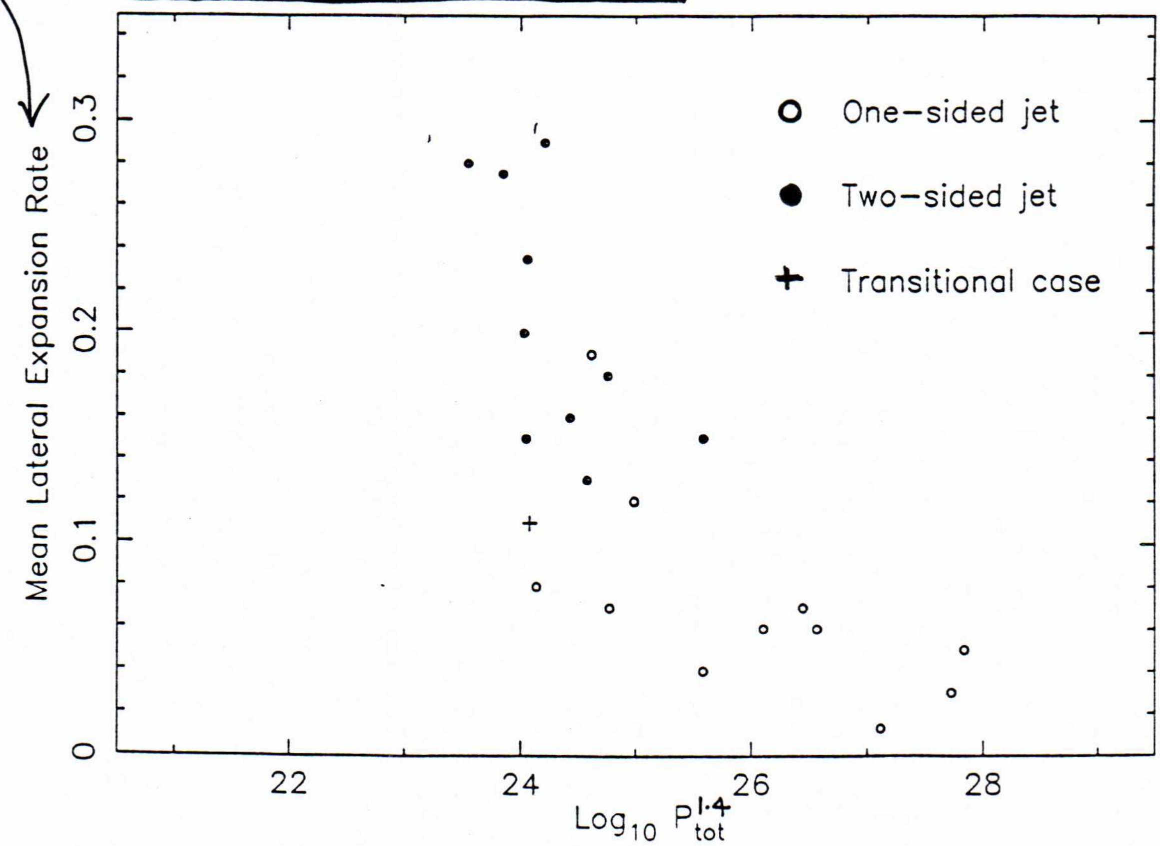
BRIDLE

AJ, 89, 979

(1984)



Jet Spreading Rate vs. Total Power



UPDATES

BRIDLE

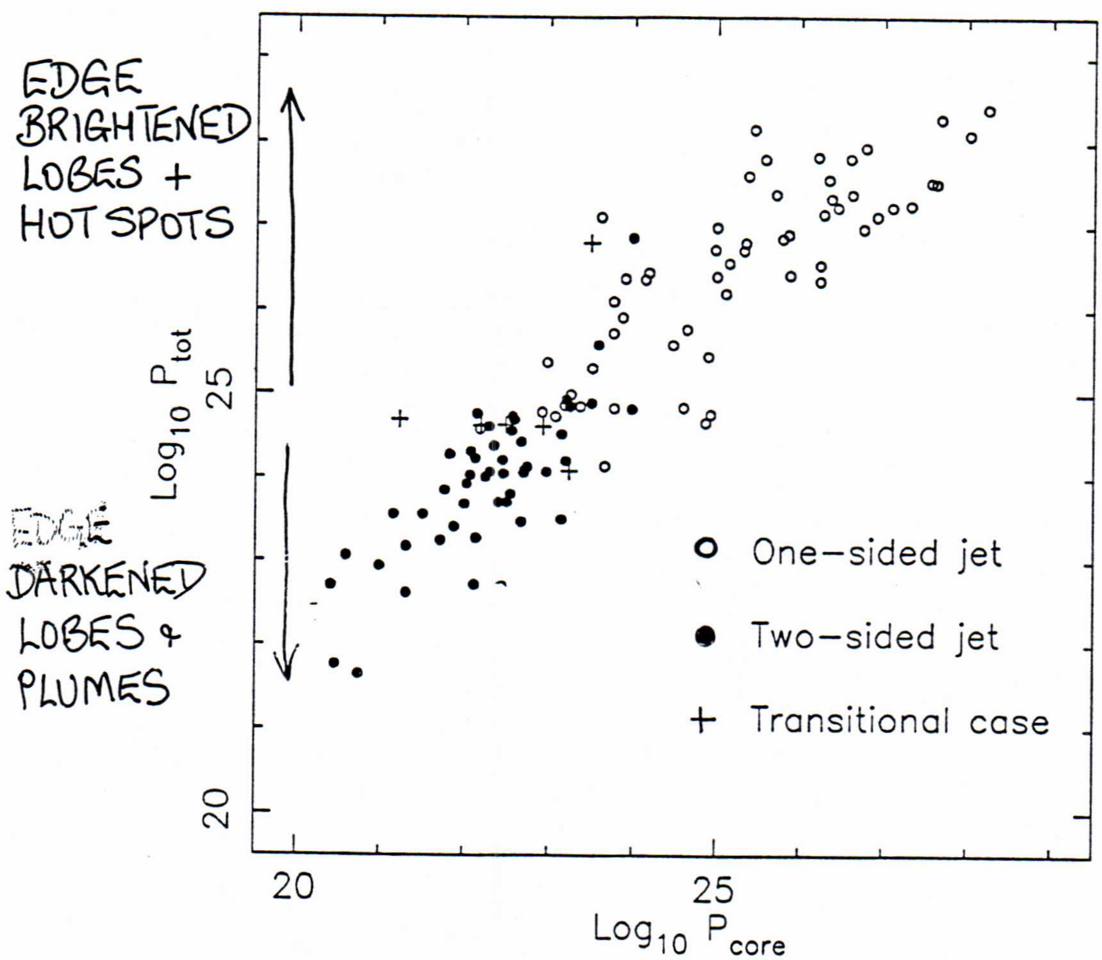
AJ, 89, 979

(1984)

110 jets with classifiable sidedness

June 1985
[updates Bridle (1984)
A.J., 89, 979]

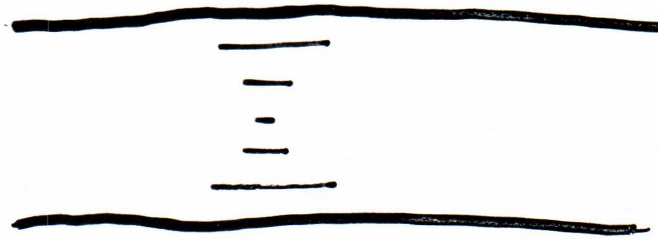
Distribution of jet sidedness vs. power



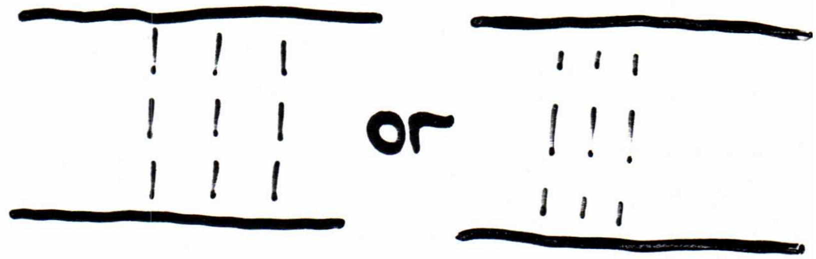
N.B. "One-sided" ≡ asymmetry > 4:1
"Two-sided" ≡ asymmetry < 4:1
"Transitional" ≡ $\gtrsim$ 4:1

COMMON JET PATTERNS OF $\underset{\sim}{B}_{app}$ (direction) AND DEGREE OF LIN. POL. (length)

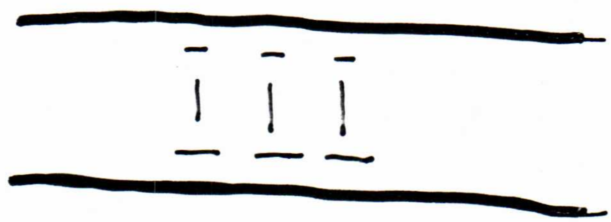
1) $B_{\parallel}$ JET
(strong sources, strongly curved week sources, bases of week jets)



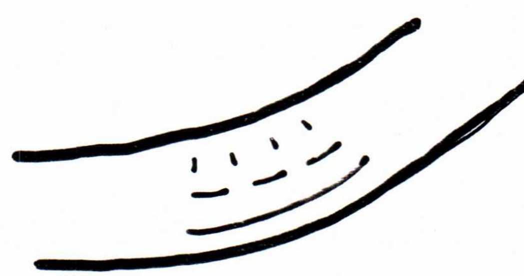
2) STRAIGHT $B_{\perp}$ JET
(outer jets, week sources)



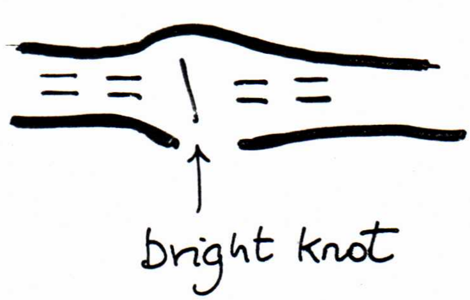
3) STRAIGHT $B_{\perp - \parallel}$ JET
(outer jets, week sources)



4) CURVED JET $B_{\parallel}$ ON OUTSIDE CURVE
(week sources)



5) BRIGHT KNOT IN $B_{\parallel}$ JET (sometimes)
(strong sources)



N.B. We do not know 3-D field configurations from these data — need FARADAY DEPTH also to distinguish helical from sheared/tangled fields.

Conclusions re correlations:

Jets come in two basic flavors.

TWO-SIDED
"SMOOTH"
$B_\perp$-DOMINATED
RAPIDLY SPREADING

} feeding edge-darkened structures

ONE-SIDED
CLUMPY
$B_\parallel$-DOMINATED
NARROW

} feeding lobes with well-defined edges + hotspots

At the base of many two-sided jets there lurks a short one-sided jet. (usually $\lesssim$10% total length)

$P^5_{core} < 10^{23}$ W/Hz → "two-sided" traits dominate

$P^5_{core} > 10^{24}$ W/Hz → "one-sided" traits dominate

$10^{23} < P_{core} < 10^{24}$ TRANSITION!

15 min

Questions about jets we'd like to answer.

1) Are they free or confined? Hydro or magnetohydro

2) ~~heavy or light?~~

3) fast or slow?

First: –

Freedom/confinement, we get clues from

detailed spreading data

I will show data on collimation (jet spreading)

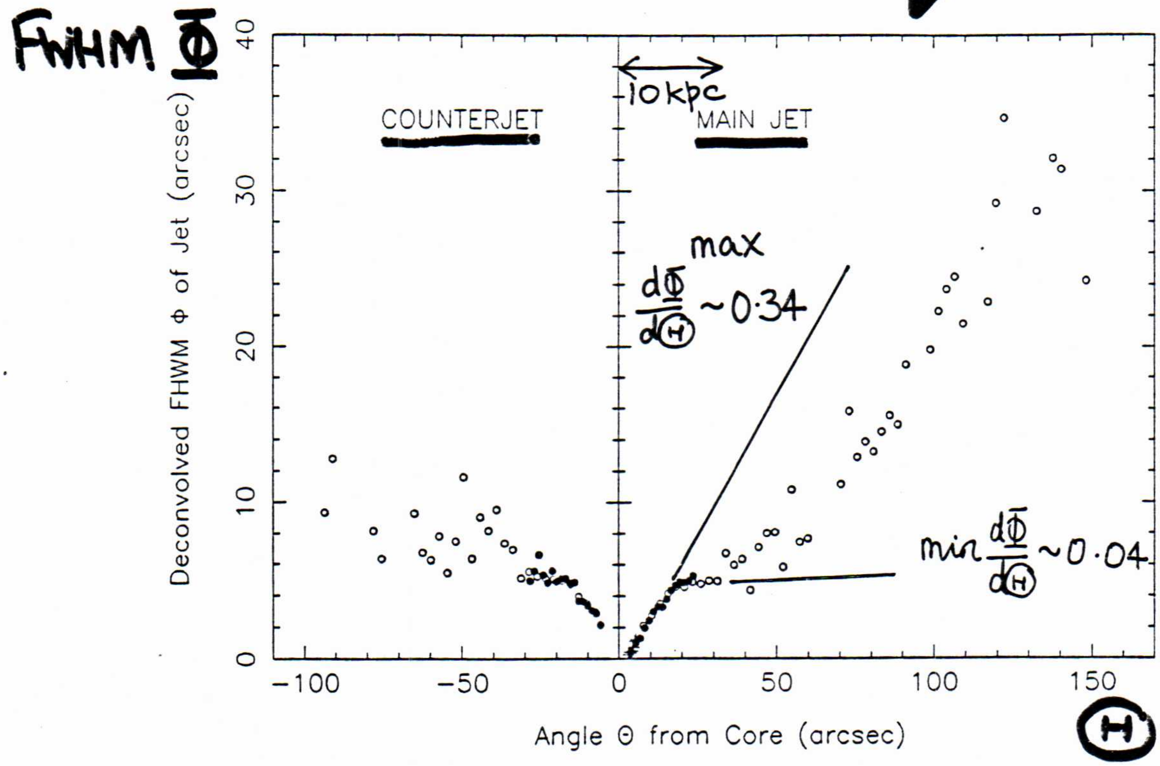
detail for two sources, chosen as one two-sided

weak, one one-sided powerful, each pretty

representative of its class.

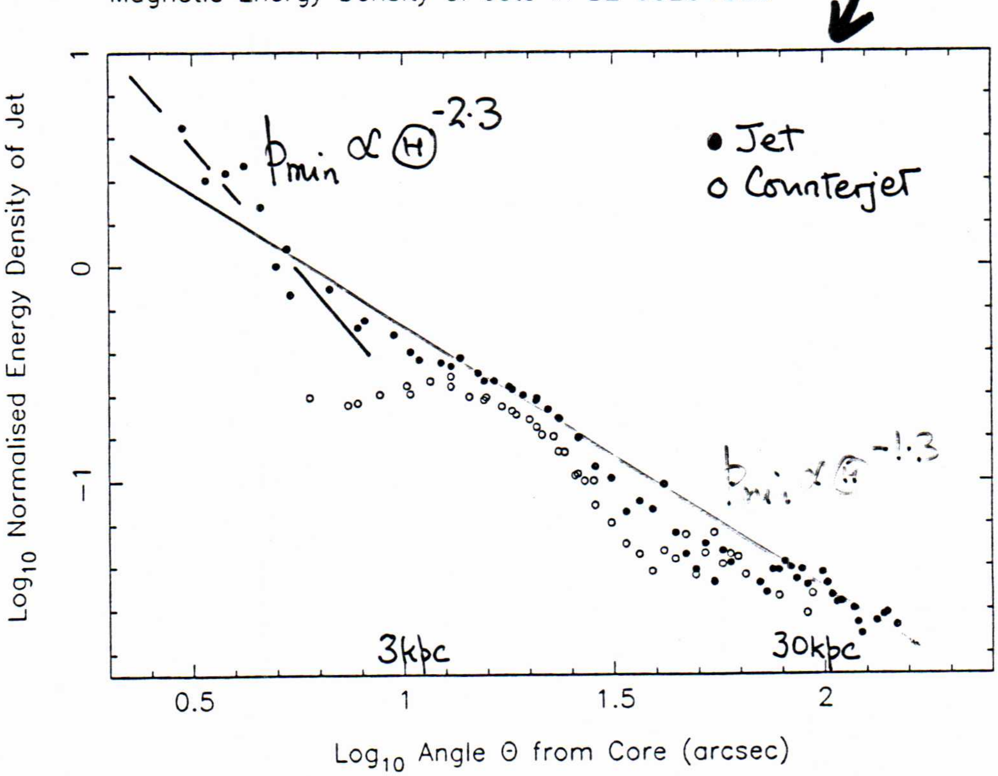
SPREADING DIAGRAM OF THE JETS IN A WEAK SOURCE ($P^{1.4}_{tot} = 10^{24.06}$ W/Hz)

Collimation of Jets in B2 0326+396

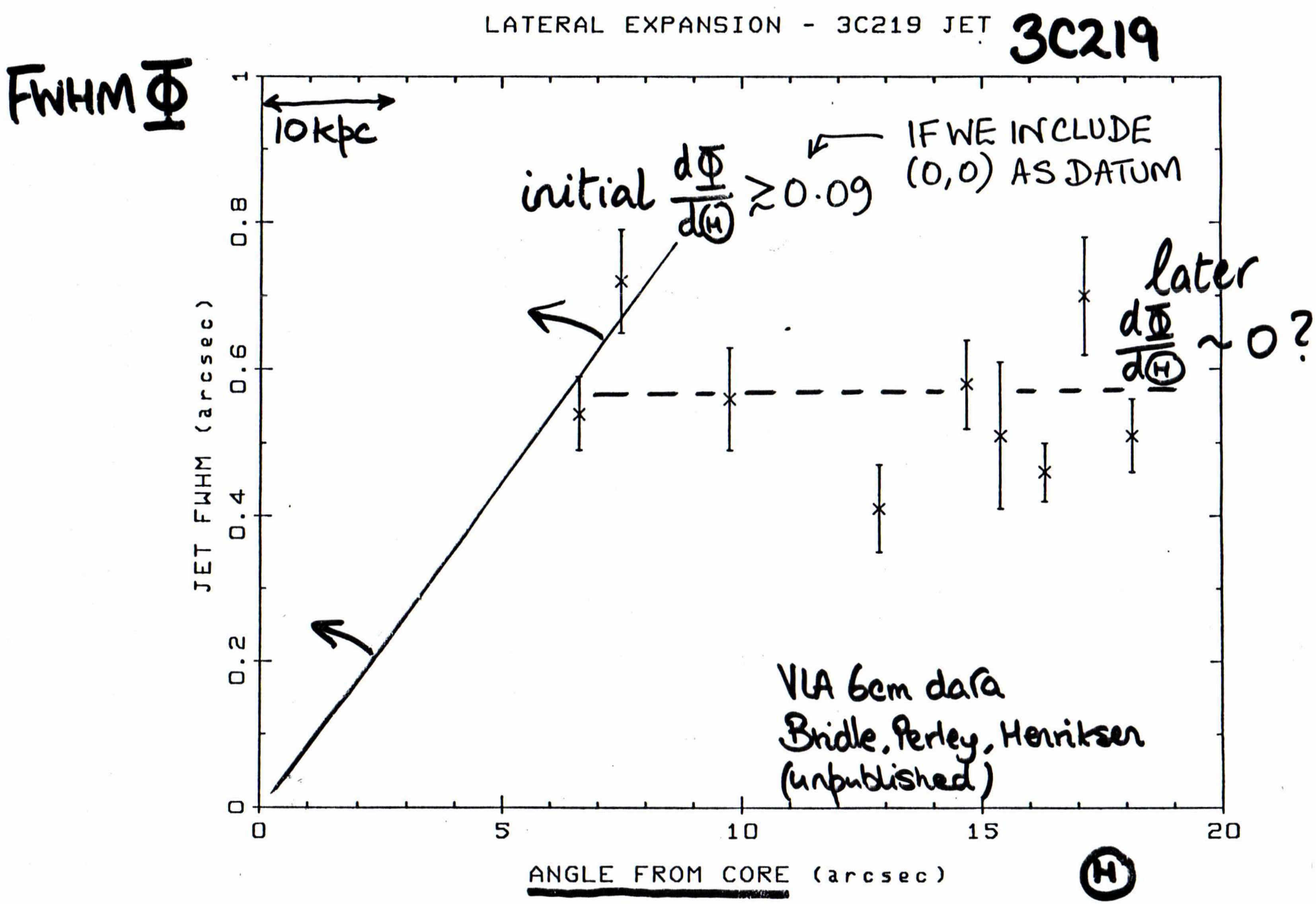


MINIMUM PRESSURE VARIATION

Magnetic Energy Density of Jets in B2 0326+396



P. Parma, R. Fanti, A. Bridle, S. Baum, R. Ekers, E. Fomalont (in preparation)



SPREADING DIAGRAM OF JET IN A STRONG SOURCE ($P^{1.4}_{tot} = 10^{26.45}$ W/Hz)

Where are Extragalactic Jets Collimated ?

VLBI →

INITIALLY, ON PARSEC SCALES

– but –

Many radio-galaxy jets spread rapidly a few kpc from the nucleus, but more slowly at 10–30 kpc from the nucleus **

– i.e. –

- THE JETS ARE NOT FREE ONCE AWAY FROM CORE

SOMETHING RECOLLIMATES MANY RADIO JETS ABOUT 10 KPC FROM THE PARENT NUCLEI — WHAT ?

**** in some cases they "flare" again further out**

Basic physical issue is – if both weak and strong source jets are recollimated on ~10kpc scales, what is the recollimating mechanism?

Most obvious candidate is thermal pressure of hot gaseous haloes known to exist around some nearby elliptical galaxies from X-ray data.

Are the thermal pressures in such haloes <u>on 10 kpc scales</u> of right magnitude and gradient to confine minimum pressures in synchrotron jets?

22
min

Can Jets be Thermally Collimated by X-ray Haloes of Galaxies/QSRs ?

- is minimum jet pressure p_{min} $\gtrless$ thermal pressure p^X_{th} ?
(from synchrotron data) (from X-ray data)

WEAK RADIO GALAXIES

$p^X_{th} \sim \theta^{-1 \text{ to } -2}$

Pressure laws of X-ray haloes have right form

Pressures of X-ray haloes have right magnitude $p_{min} < p^X_{th}$

$n_e T \sim 10^6 cm^{-3} K$, few kpc
$\sim 10^3 cm^{-3} K$, 100 kpc

STRONG RADIO GALAXIES

Pressure laws of X-ray haloes may have right form

Pressures of X-ray haloes are too low ? $p_{min} \sim 1\text{-}50\, p^X_{th}$

QUASARS

Total X-ray luminosities too low ? $p_{min} \gtrsim 10\, p^X_{th}$?

OBSERVERS MUST DISTINGUISH LOCAL OVERPRESSURES AT KNOTS FROM LARGE-SCALE OVERPRESSURES BETWEEN KNOTS

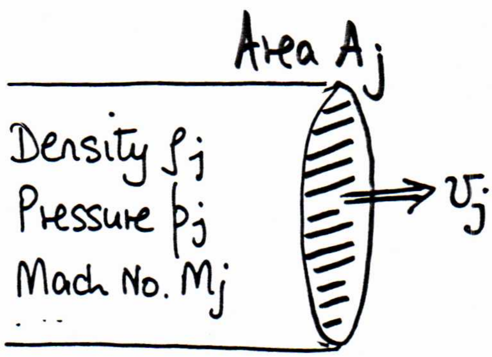
— before we are sure how bad the collimation problems are for strong radio galaxies/QSRs

N.B. All jets with $p_{min} > p^X_{th}$ are one-sided!

Slide 11 → 20 min here

John Wardle has also emphasised independently that the jets in strong QSR sources cannot be free, on grounds of thrust balance:

THRUST BALANCE FOR POWERFUL JETS



$$\text{Thrust} = \rho_j v_j^2 A_j$$
$$= \rho_j M_j^2 c_s^2 A_j$$
$$= M_j^2 \Gamma p_j A_j$$

$$\boxed{\text{THRUST} > M_j^2 \Gamma \underbrace{p_{min} A_j}}$$

<u>fixed</u> by observing synchrotron properties of jet

IF NARROW, POWERFUL JETS ARE <u>FREE</u>, $M_j \gtrsim 50$

$\Downarrow$

THRUSTS $\gtrsim 10^{39}$ dynes, <u>independent of unknown ρ_j</u>

PROBLEM – WHAT COULD STOP/DEFLECT SUCH THRUSTS?

e.g. if balanced by ram pressure $\rho_{IGM} v_{HS}^2 A_{HS}$ across a 1kpc-radius hot spot, <u>$v_{HS} = c$</u> requires $n_{IGM} \sim 0.025\,\text{cm}^{-3}$

TO ESCAPE PROBLEM, MUST <u>EITHER</u>

a) REDUCE M_j – JET IS <u>CONFINED</u>

b) REDUCE p_{min} ← Doppler boost? But not for many large sources!

Conclusions:
Freedom or Confinement for Extragalactic Radio Jets ?

1. NO DETECTED LARGE-SCALE JETS ARE EVERYWHERE FREE

- some rapidly-expanding parts of jets free ?
- fully free jets too dim to detect ?

2. CONFINEMENT MECHANISM UNCLEAR

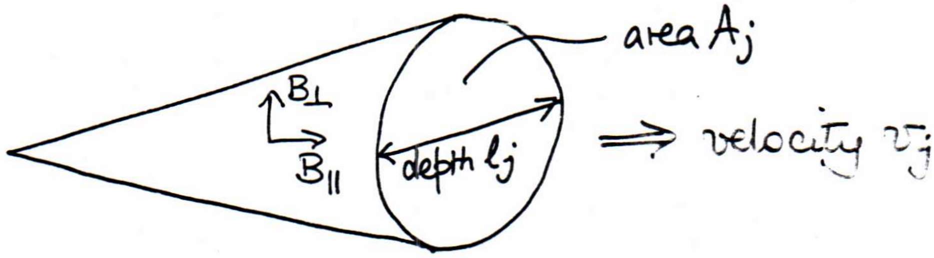
- especially for powerful QSR jets ?
- possible relation to one-sidedness ?
- magnetic collimation of current-carrying jets?
- thermal confinement possible for weak radio-galaxy jets, but are other mechanisms active ?

  ↑ e.g. magnetic viscous

- thermal confinement possible for all jets if synchrotron overpressures confined to shocked regions $\left(\frac{p_{max}}{p_{ambient}} \sim (\text{Mach No.})^2 \right)$

Now [redacted] consider why the jets we see stay so bright while they expand. Understanding this may help us understand their interactions with the ambient gas, + also their stability.

ADIABATIC "BENCHMARK" FOR DIMMING OF A SPREADING JET



IF JET FLOWS **CONSERVE MAGNETIC FLUX**

$$B_{\parallel} \propto \frac{1}{A_j} \qquad B_\perp \propto \frac{1}{l_j v_j}$$

AND **NO PARTICLE REACCELERATION**,

THEN **ADIABATIC SPREADING** →

SYNCHROTRON EMISSIVITY ε_ν $\propto$

↗ $A_j^{-\left(\frac{5\gamma+7}{6}\right)} v_j^{-\left(\frac{\gamma+2}{3}\right)}$ **($B_{\parallel}$)**

or

↘ $A_j^{-\left(\frac{\gamma+2}{3}\right)} l_j^{-\left(\frac{\gamma+1}{2}\right)} v_j^{-\left(\frac{5\gamma+7}{6}\right)}$ **($B_\perp$)**

Observers measure <u>either</u>:

luminosity per unit length $\mathcal{L}_\nu \propto \varepsilon_\nu A_j$ OR:

peak profile intensity $I_\nu \propto \varepsilon_\nu l_j$

"Typical" electron energy index $\gamma \sim 2.3$ ($\bar{\alpha} = 0.6$)

	CIRCULAR JET $A_j = \pi R_j^2$	SMITH/NORMAN ELLIPTICAL JET $A_j = \pi a_j b_j$
$B_{\parallel}$ dominates	$I_\nu \propto R_j^{-5.2} v_j^{-1.4}$	$I_\nu \propto R_j^{-2.9} v_j^{-1.4}$
$B_{\perp}$ dominates	$I_\nu \propto R_j^{-3.5} v_j^{-3.1}$	$I_\nu \propto R_j^{-2.2} v_j^{-3.1}$
	assuming ↓ $\gamma = 2.3$	assuming ↓ $\gamma = 2.3$ EXTERNAL PRESSURE $p_e \sim z^{-1.5}$ EQN. OF STATE $p_j \sim \rho_j^{5/3}$ GEOMETRY $R_j \propto a_j$

Note: VERY STRONG R-dependence if $B_{\parallel}$
SIGNIFICANT v- dependence if $B_{\perp}$
ELLIPTICAL JET may have weaker R- dependence

Departures from "Adiabatic" I-R_j Brightness Variations in Extragalactic Radio Jets

1. INITIAL "TURN-ON" AFTER "GAPS"
– $I \propto R_j^{+?}$ i.e. jet brightens as it expands

1-10 kpc out

2. GRADUAL DIMMING AFTER "TURN-ON"
– $I \propto R_j^{-1\pm0.5}$ initially to $I \propto R_j^{-4\pm1}$ far out

3. BRIGHT KNOTS
– especially jets in powerful sources

4. TERMINAL HOT SPOTS
– absent in weak sources, prominent in strong

5. FLARING
– rapid brightening and widening of trails/plumes
– often seen in weak sources

10's of kpc out

N.B. possible selection effect

– if jet does <u>not</u> exhibit one or more of these behaviors, we don't detect it ?

Proposed Mechanisms for "Sub-adiabatic" I vs. R_j Laws in Extragalactic Radio Jets

1. PARTICLE ACCELERATION AND/OR MAGNETIC FLUX AMPLIFICATION

- derived from bulk K.E. of jet
- mediated by shocks at high Mach number ?
- mediated by turbulence at low Mach number ?

2. PITCH ANGLE SCATTERING

- streaming parallel to $\underset{\sim}{B}$ until scattered ?

3. ADIABATIC SLOWDOWN

- longitudinal compression of slowing jet
- mediated by turbulent entrainment of ambient gas across boundary layer at low Mach number
- attractive for weak $B_\perp$ jets, due to strong v_j dependence in adiabats for $B_\perp$.

Tests of Mechanisms to Keep Extragalactic Jets Lit Up

1. OPTICAL to X-RAY IMAGING

- find particle reacceleration sites
  (short synchrotron lifetimes)
- full tests via detailed spectra (curvature !) plus
  model relating synchrotron emission to flow
- polarimetry (where possible) required to prove
  (a) emission mechanism is synchrotron
  (b) all of spectrum arises in same volume

2. EVIDENCE FOR SLOWDOWN

- bending radii of curved head-tail jets ? (O'Dea, later today)

3. EVIDENCE FOR ENTRAINMENT

- optical emission from entrained gas ?
- Faraday depth variations along jets

Faraday Depth Test for (Entrainment + Slowdown) keeping $B_\perp$ jet well lit up

length line of sight through jet

$$\text{Faraday depth} \propto \rho_j B_j l_j$$

$$\propto \frac{1}{A_j v_j^3}$$

(if $B_\perp$ + constant thrust)

an illustrative lower limit?

$B_\perp$ "adiabat" for circular jet ($\gamma = 2.3$)

$$I_\nu \propto R_j^{-3.5} v_j^{-3.1}$$

To make $I_\nu \propto R_j^{-0.5}$ to $R_j^{-1.5}$

we need $v_j \propto R_j^{-0.95}$ to $R_j^{-0.65}$

Faraday depth $\propto R_j^{0.85}$ to $R_j^{-0.05}$

compare $v_j = \text{constant}$

Faraday depth $\propto R_j^{-2}$

Compare: needs high resolution $\lesssim 1$ GHz!

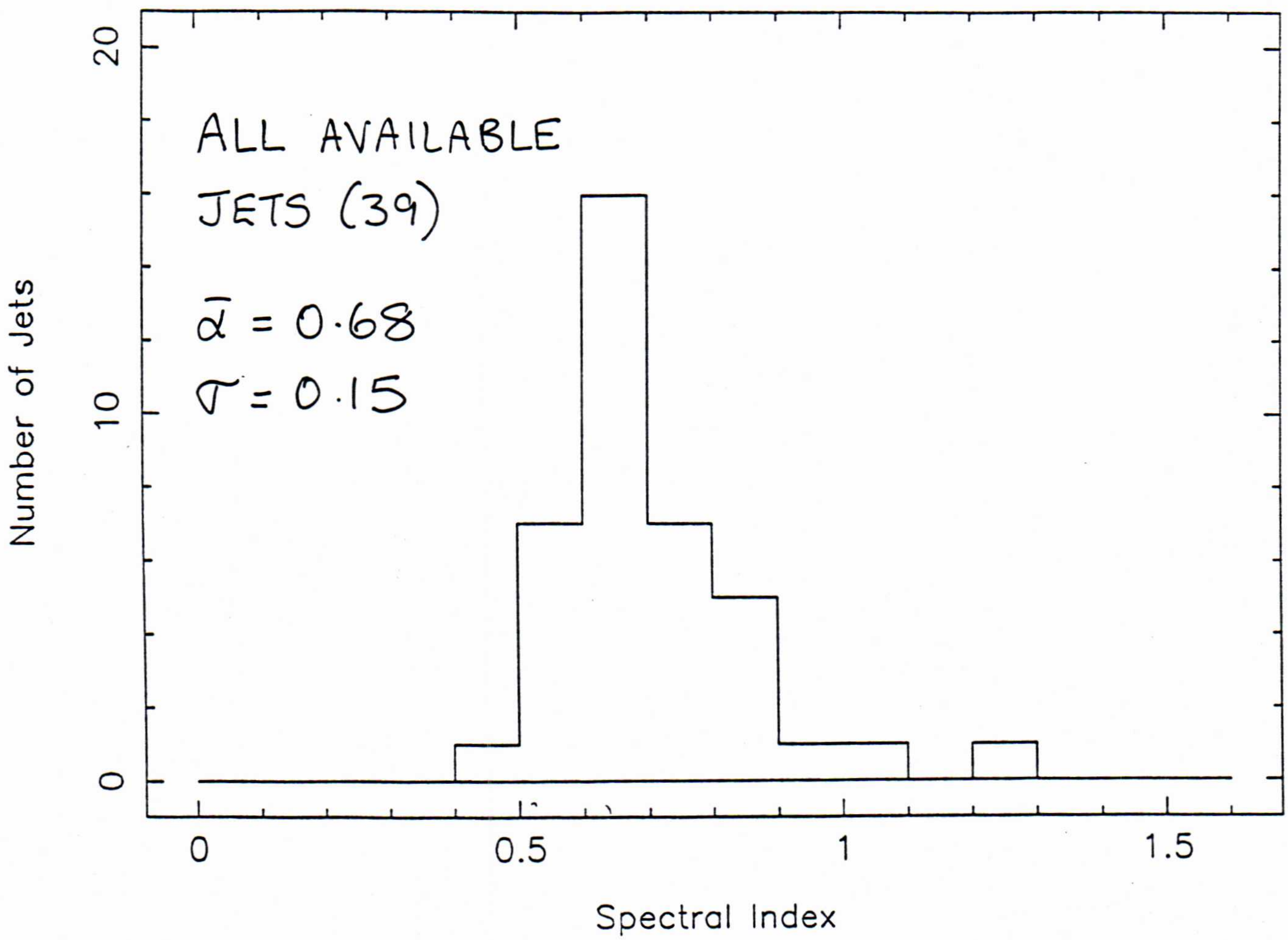
MERLIN, VLAX?

~~32~~ 32 min

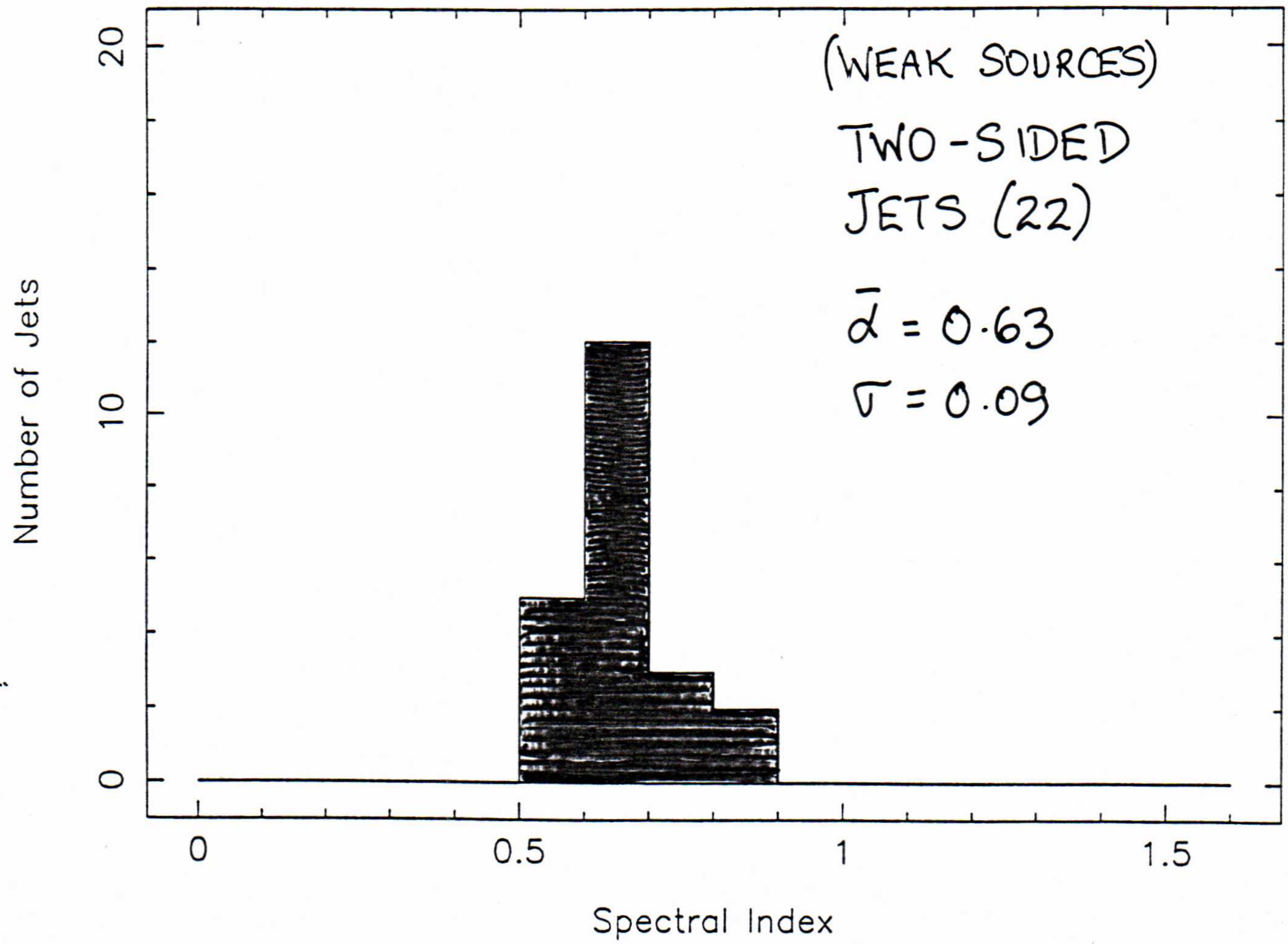
Ditch if > 32 min here

Possibly some rudimentary information also from jet radio spectra (hard to interpret at present as data are rather patchy) :-

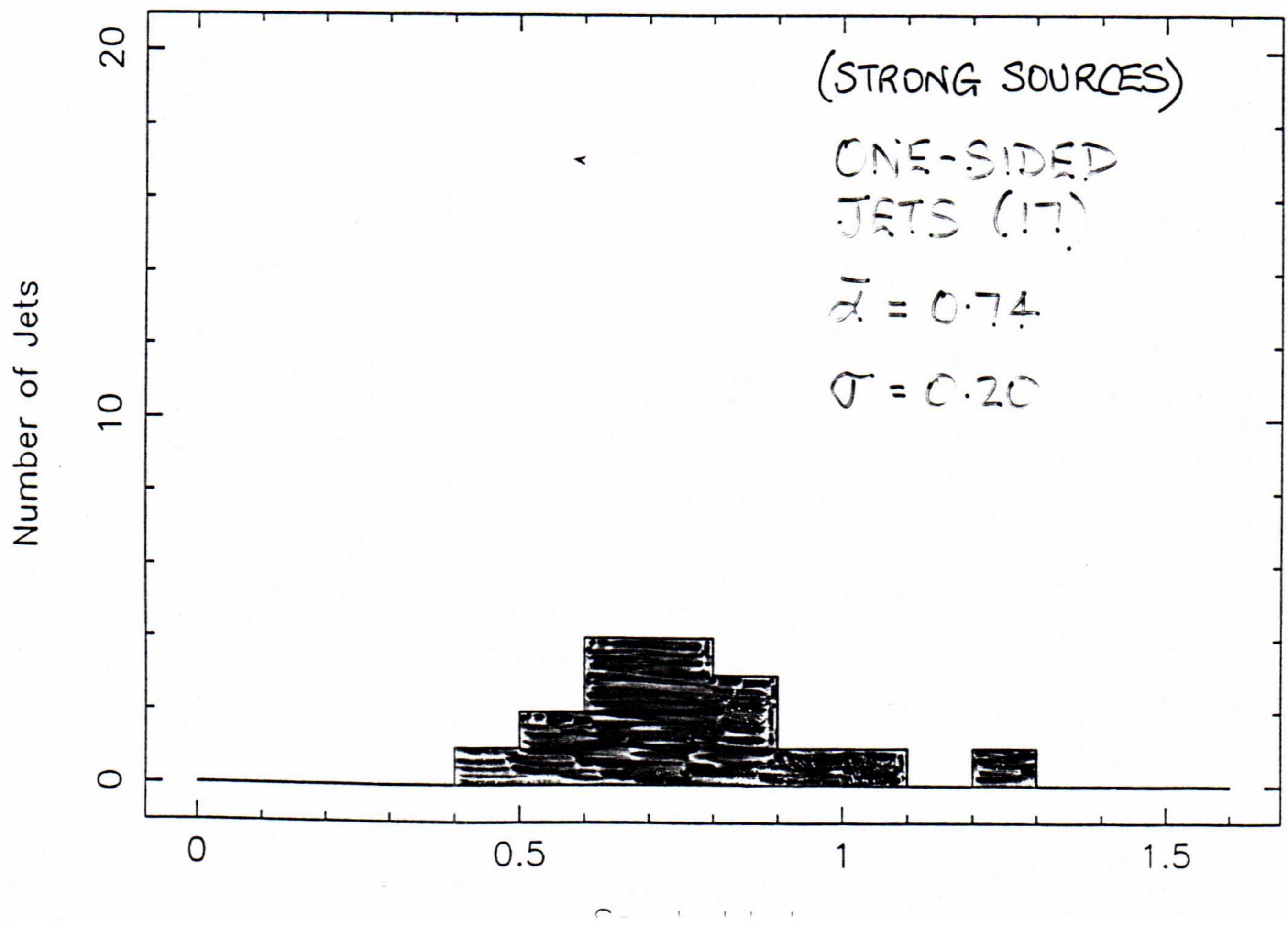
Mean Spectral Indices of 39 Jets near 20cm



A.H. Bridle, unpublished



(WEAK SOURCES)
TWO-SIDED JETS (22)
$\bar{\alpha} = 0.63$
$\sigma = 0.09$
Number of Jets
Spectral Index
0
10
20
0
0.5
1
1.5



(STRONG SOURCES)
ONE-SIDED JETS (17)
$\bar{\alpha} = 0.74$
$\sigma = 0.20$
Number of Jets
0
10
20
0
0.5
1
1.5

To understand these spectral differences, need spectral CURVATURE + B field variations also.

But observers might search for this trend in larger complete samples, in case it is telling us something about ~~differences~~ differences in particle accn. mechanisms between strong and weak sources.

Another clue may come from spectral gradients <u>along</u> jets. These are rarely strong at cm $\lambda\lambda$ but where they <u>have</u> been documented they are all of the same kind — <u>brighter</u> regions of jets tend to have <u>less steep</u> radio spectra.
(N.B. there are observational biases that can work in this direction, too — need to be <u>very</u> careful!)

Several cases where spectra simply steepen along a jet, as expected under synch losses. e.g. 3C31 Strom et al. 1983

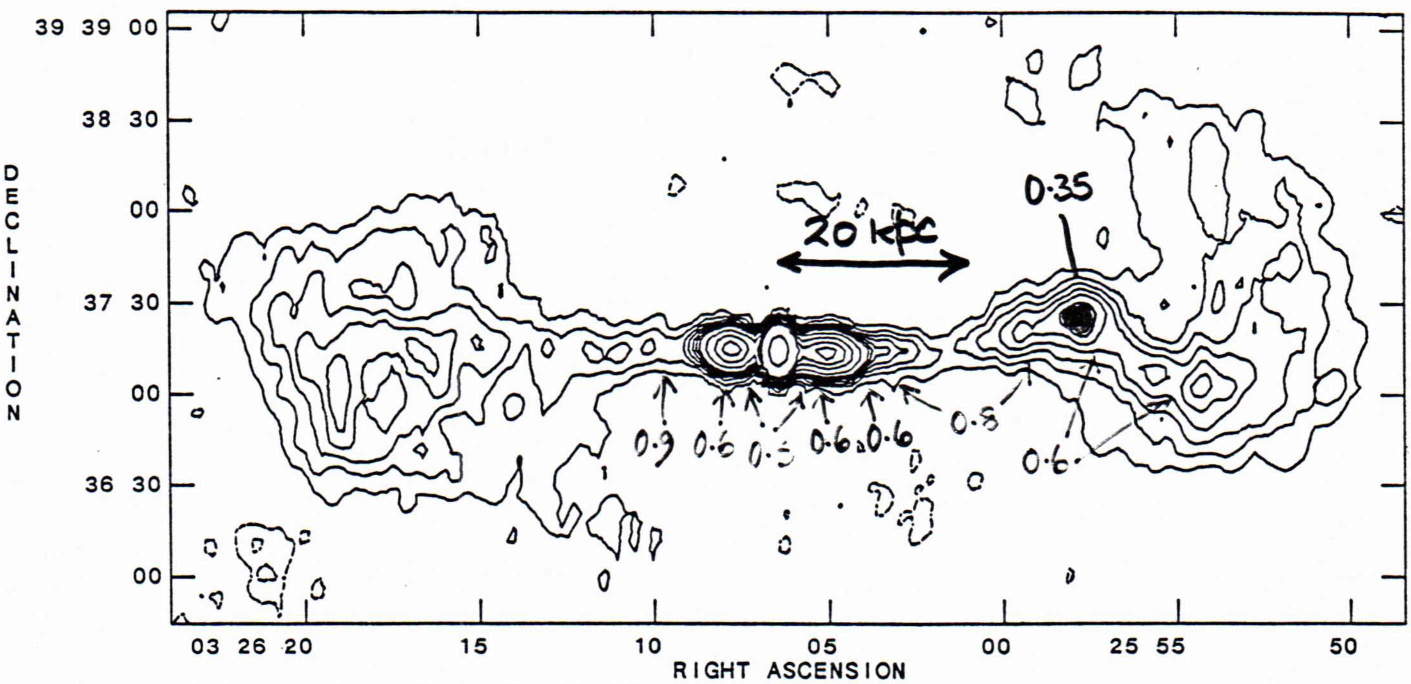
Also some cases of knots with flatter spectra than surrounding jet emission. (Me, O'Dea)

Weak steep-spectrum emission in "gaps" before bright "turn-ons" (Killeen) Poster

~~[illegible]~~.

REVERSAL OF SPECTRAL INDEX GRADIENT AT (RESOLVED) JET KNOT

0326+396 IPOL 4885.100 MHZ C326+396 6.ICLZPC.1



PEAK FLUX = 7.7624E-02 JY/BEAM
LEVS = 0.4000E-03 * (-2.00, -1.00, 1.000, 2.000, 3.000, 4.000, 5.000, 6.000, 7.000, 10.00, 15.00, 20.00, 25.00, 97.03)

α^{1415}_{4885}

Parma, Fanti, Bridle, Baum, Ekers, Fomalont
(in preparation)

35 min

Now let's look at a possible connection between jet brightness behavior and known instabilities of confined jets at different Mach numbers that may help to unify several of the correlations and also lead into my last topic, which will be the ~~jet~~ jet velocity ~~issue~~ question.

PRINCIPAL KELVIN-HELMHOLTZ INSTABILITY REGIMES OF CONFINED SUPERSONIC JETS

{ ANALYTIC (LINEAR) MODELING – e.g. Cohn, Ferrari et al., Hardee
{ NUMERICAL (NONLINEAR) MODELING – Norman et al. Woodward

both

⇓

1. ORDINARY MODE DOMINATED $\frac{\rho_j}{\rho_{ext}} > \left(\frac{M_j}{2}\right)^{3.3}$

"Heavy, mildly supersonic"

- rapidly growing mixing layer at jet boundary
- rapid deceleration via entrainment of ambient gas
- internal PLANAR shocks
- disruption via mass exchange with ambient gas

2. REFLECTION MODE DOMINATED $\frac{\rho_j}{\rho_{ext}} < \left(\frac{M_j}{2}\right)^{3.3}$

"Light, hypersonic"

- coupling of jet to external medium via SHOCKS
- instabilities saturate as BICONICAL shocks
- effects of mass exchange <u>minor</u>
- jet is not disrupted

UNMODELED COMPLICATIONS OF THE REAL WORLD

1) Real jets descend pressure gradients ($10^6 : 1$?) but most models don't!
   → parameter evolution in $(M, \rho_j/\rho_e)$

2) Non-axisymmetry, 3-D effects

3) Unsteady inputs from central engine

4) Electromagnetic effects - MHD needed ?

5) Synchrotron radiation as flow visualisation technique is poorly understood.

— BUT —

CITA Canadian Institute for Theoretical Astrophysics — Institut canadien d'astrophysique théorique ICAT

Typical Jet Mach Numbers May Increase with Source Power

JETS IN WEAK ($P_{10\,MHz}^{10\,GHz} \lesssim 10^{34}$ W) SOURCES RESEMBLE MILDLY SUPERSONIC FLOWS

1) They spread rapidly, hence – wide
2) are dominated by perpendicular magnetic field, $B_\perp$
3) so can stay bright as they expand by –
   (a) becoming turbulent — bright (smooth maybe?)
   (b) entraining gas and slowing down

and may thus become subsonic, so that they –

4) "poop out" without making hot spots — edge darkened, ext. structure

JETS IN STRONG ($P_{10\,MHz}^{10\,GHz} \gtrsim 10^{35}$ W) SOURCES RESEMBLE HYPERSONIC FLOWS ($M_j \gtrsim 3$)

1) They spread slowly, hence – narrow
2) are dominated by parallel magnetic field, but – $B_\parallel$

form strong X-shocks from boundary instabilities

3) so stay bright by shock acceleration at knots — knotty

and remain supersonic until they –

4) plow into undisturbed IGM, making hot spots — punch out hot spots

N.B. if light, hypersonic jet starts to thrash, it may also be ram-confined and brighter as internal shocks are driven in. Ext shocks also.

McLennan Physical Laboratories University of Toronto 60 St. George Street Toronto Ontario M5S 1A1

Jet Mach #'s increasing with power don't

tell us necessarily about jet <u>velocities</u> tho'.

How do sound speeds vary?

Let's look briefly at arguments relating to

jet <u>velocities</u>.

40 min

Arguments Favoring Bulk Relativistic Motions* in <u>Parsec</u>-Scale Jets

*typical Lorentz factors $\gamma_j \sim 5$

When such jets point near the line of sight, we may simultaneously explain:

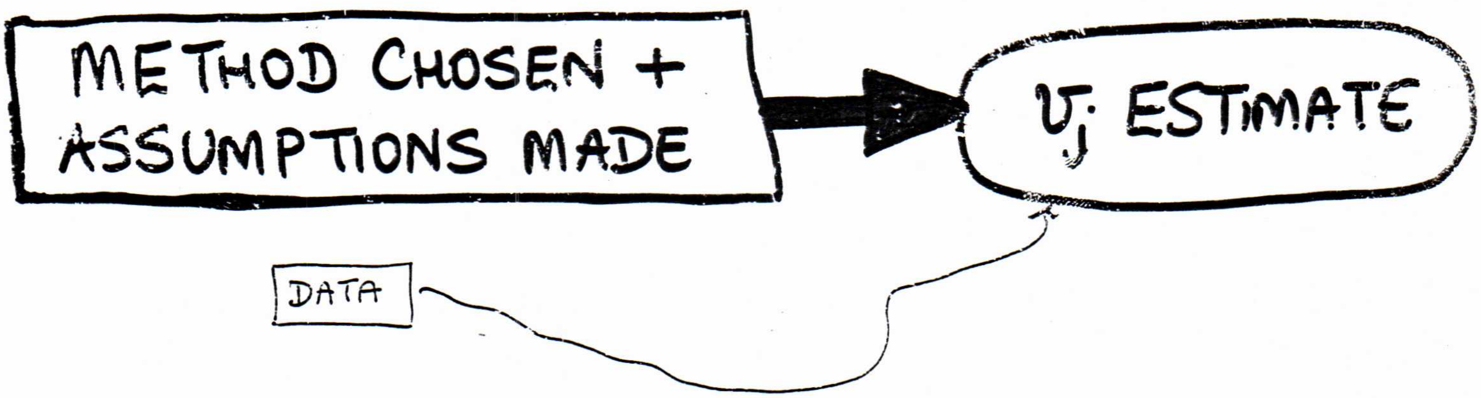
BY TIME DELAY EFFECTS:
Superluminal knot separations (VLBI data)

BY DOPPLER BEAMING/BOOSTING:
One-sidedness of core-jets
Low self-Compton X-ray fluxes of bright radio cores
"Excess" radio brightnesses of rapid variables

BY PROJECTION/ORIENTATION:
Large apparent jet curvatures/misalignments
in core-dominated sources

PROBLEMS WITH VELOCITY ESTIMATES FOR KPC-SCALE JETS

- JET DENSITIES POORLY CONSTRAINED
- assume
  - ENTHALPY / KE } FLUX DOMINANCE (≈ assume Mach # range)
  - STEADY STATE FLOWS
  - WIGGLE INTERPRETATION
  - PRESSURE BALANCE AT HOT SPOTS
  - EQUIPARTITION / EFFICIENCIES



What we can be **really sure of** on kpc scales:

1) $v_{escape} < v_j < c$

if there *is* outflow on these scales!

2) For 2-sided bent jets in C-shaped sources:

$v_j \lesssim 0.2c$ (O'Dea) from their brightness symmetries (unless *all* close to plane of sky!)

The Great Velocity Debate

From collimation/brightness arguments:

If jet MACH NUMBERS increase with increasing source power, do jet VELOCITIES increase also ?

From parsec-scale core-jet properties:

How far from the nucleus does bulk relativistic flow persist in the powerful sources ?

From symmetry/sidedness considerations:

Jet one-sidedness extends further from the core as core power increases – does this indicate increasing dominance of bulk relativistic effects with increasing power output ?

– and –

How much of the above is a geometrical effect ?

Very relevant to which of these statements is correct

are
~~is~~ the correlations between PC and KPC scale

jet properties.

Parsec/Kiloparsec Correlations

1. CORE – JET DETECTABILITY

Jets are found most easily in sources with prominent cores. There are no "disembodied" radio jets.

– thus –

A SIGNIFICANT PART OF THE CORE POWER IN MOST SOURCES IS NO MORE BEAMED THAN THE KPC-SCALE JET

BUT CORE = BASE OF JET IN MODELS OF PC SCALES

2. ONE-SIDEDNESS

One-sided pc-scale jets always point on the same side of the core as one-sided kpc-scale jets, when both are seen in the same source.

– thus –

THE PRIME CAUSE OF JET ONE-SIDEDNESS IS THE SAME ON BOTH PC AND KPC SCALES

3 Interpretations of Pc/Kpc Jet One-Sidedness Correlation

1. BOTH SCALES ARE APPROACHING SIDES OF SYMMETRIC (two-sided) BULK RELATIVISTIC ENERGY FLOWS

- why SO MANY one-sided jets in complete samples of big lobe-dominated QSRs ? ($\gamma \gg 1 \rightarrow$ most should not be seen)
- HOW one-sided are these QSR jets ?
- needs $\overline{\gamma}_j$ decreasing outwards ? $\gamma = 5$, pc scales ? $\gamma \sim 1$, 10kpc scales ?

2. BOTH SCALES HAVE SYMMETRIC ENERGY FLOWS BUT ONE SIDE DISSIPATES MORE

- why is dissipation coherent on pc/kpc scales ?
- why is asymmetry correlated with power ?

3. INTRINSIC ASYMMETRY ON BOTH SCALES

- needs $\overline{\gamma}_j$ decreasing with distance ? (to preserve $v > c$, etc)
- needs "flip flop" to build two lobes
- asymmetry and "flip time" increase with power ?

N.B. both non-Doppler interpretations should be taken seriously, because of:

Evidence for Non-Doppler Brightness Asymmetries in Low-Power Jets

BRIGHT ONE-SIDED JET BASES (first few kpc)
(a) on receding side in some dust lane galaxies
(b) close to plane of sky in others

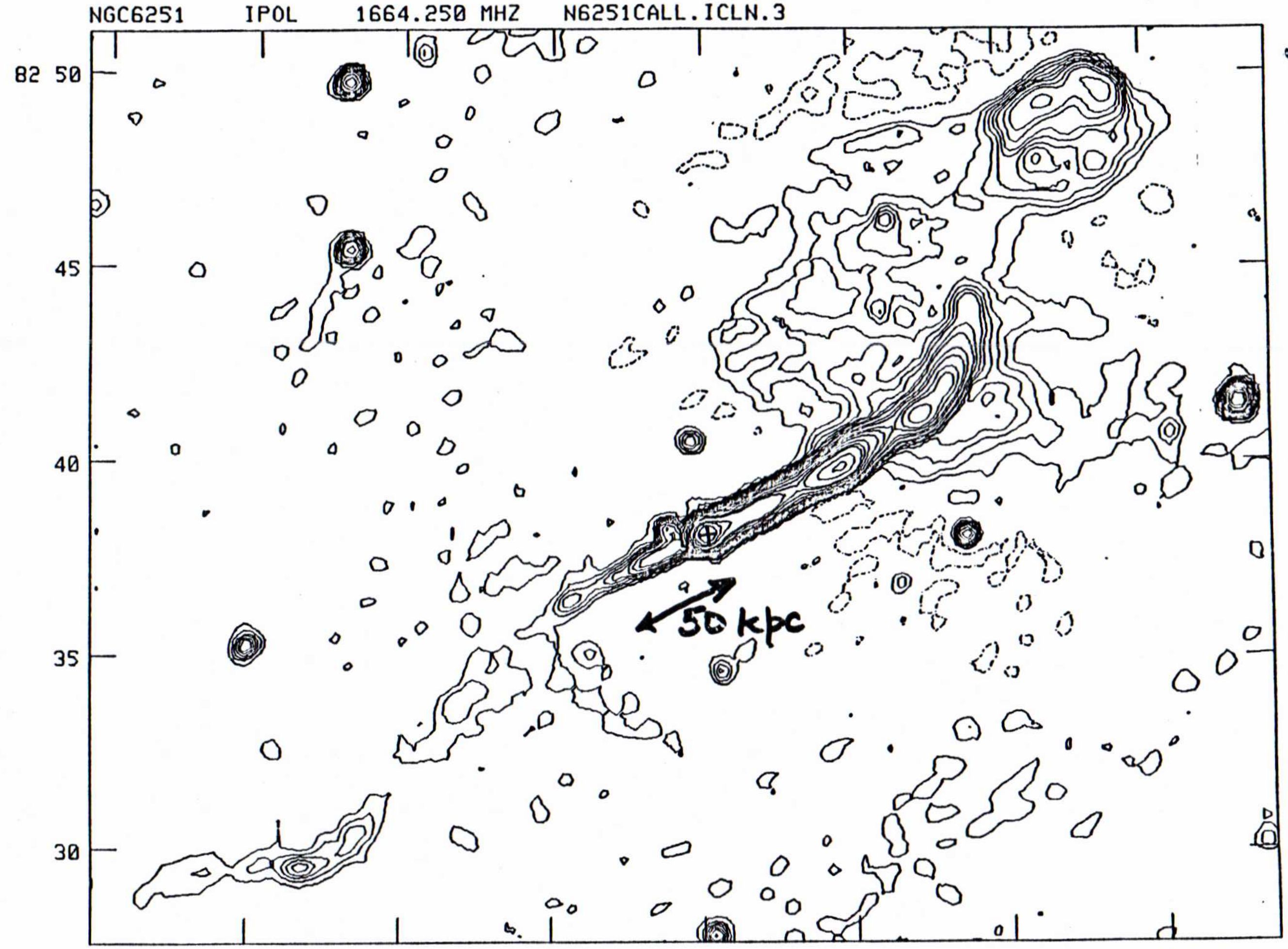
JETS IN "C"-SHAPED SOURCES
generally bend without showing the brightness changes expected if emission is Doppler-boosted

LOW-VELOCITY OPTICAL EMISSION LINES
share jet/knot asymmetries in most sources where both asymmetries and lines exist

SO – DOPPLER BOOSTING CANNOT EXPLAIN ALL ONE-SIDEDNESS NOW KNOWN IN EXTRAGALACTIC JETS

S SYMMETRY OF JET/COUNTERJET IN NGC6251

NGC6251 IPOL 1664.250 MHZ N6251CALL.ICLN.3



PEAK FLUX = 5.5324E-01 JY/BEAM
LEVS = 0.5532E-03 * (-0.5, 0.5, 1.0,
1.5, 2.0, 2.5, 3.0, 4.0, 5.0,
7.5, 10.0, 15.0, 20.0, 30.0, 50.0,
75.0, 100.0, 200.0, 300.0, 500.0)

VLA "C" array

28-hr ← N.B.
integration

+ = NUCLEUS OF NGC6251

681

Sidedness varies from 30:1 to 200:1

Perley Readhead
Bridle D.Jones

Conclusions about Jet Velocities

(as at June 1985)

1. **ALL** MODELS FOR PC/KPC SIDEDNESS CORRELATIONS HAVE **SOME** DIFFICULTY

   ALL-DOPPLER — statistics of big QSR sources with one-sided jets

   ONE-SIDED DISSIPATION — physics needed

   INTRINSIC/FLIP-FLOP — symmetric hot spots fed by one-sided jets (e.g. Cyg A)

2. EVIDENCE THAT $\gamma_j \gg 1$ IN JETS
   (a) decreases with distance from cores
   (b) decreases with decreasing power

3. SOME JETS ARE DEFINITELY SUBRELATIVISTIC, PERHAPS ALSO SUB**SONIC**? (Two-sided, wide jets in **weak** sources)

4. ALL STATEMENTS ABOUT JET VELOCITIES STARTING WITH "ALL" ARE LIKELY TO BE **WRONG**

Conclusions about Core-Jet Relationships

1. ($P^5_{core} = 10^{20.5}$ to 10^{24} W/Hz)

— core emission and jet emission CANNOT be significantly Doppler-boosted

VLB-ers: how many of <u>these</u> core-jets are one-sided, how many superluminal, etc?

2. ($P^5_{core} = 10^{24}$ to $10^{28.5}$ W/Hz)

— core-<u>dominated</u> sources → $\gamma_j \sim 5$ on parsec scales.

— lobe-dominated sources → roughly the same boosting factor on pc and kpc scales (N.B. "boost" could be = 1!)

- EASIEST TO UNDERSTAND IF CENTRAL ENGINES MAKE <u>BOTH</u> $\gamma_j \sim 5$ (optional?) <u>AND</u> $\gamma_j \sim 1$ (compulsory) OUTFLOWS.

+

- SOME ONE-SIDEDNESS <u>IS</u> NON-DOPPLER

Problems for Observers

1. DETECT COUNTERJETS (STRONG SOURCES) — VLA – e.g. NGC6251

– symmetries, sidedness, spectra, collimation

2. HOW MANY SUPERLUMINALS ? — VLBNets, VLBA

– complete samples of one-, two- and no-sided kpc-scale jets should be monitored for hard evidence of bulk relativistic motions at bases

3. TEST PC/KPC JET SIDEDNESS — VLA, MERLIN, VLBNets, VLBA

– are pc and kpc sidedness always the same ? i.e., same SYMMETRY ? same SIDE ?

4. MAP INTRINSIC FARADAY DEPTHS — VLAX, MERLIN

– constrain 3-D B field, jet density, entrainment

5. FIND PARTICLE REGENERATION SITES — HST, AXAF

– image optical, X-ray synchrotron emission

– polarimetry if you can !

6. IMAGE X-RAY HALOES — AXAF?

– test thermal collimation in detail for both galaxies and QSRs

Measure the Velocities

Problems for Theorists

1. RELATIVISTIC SLOWDOWN

– can it happen quietly about 10-100 pc out ?

2. ASYMMETRIC JET ENGINES

– can they have time scales or asymmetries that increase with increasing power output ?

3. JET "GAP AND PIECE" THEORY

– what do (a) unsteady, (b) flip-flop jets look like ? 3C219?

4. ASYMMETRIC DISSIPATION

– can it be coherent from pc to 100-kpc scales ?

5. SYNCHROTRON FLOW VISUALISATION M.Norman (Wednesday)

– how do the synchrotron parameters "visualise" (a) collimation, (b) pressure ? – predict I,Q,U !

6. FLOW IN PRESSURE GRADIENTS

– can parameter evolution in haloes stabilize jets ?

P.Wiita (Wednesday)