PHENOMENOLOGY OF EXTRAGALACTIC RADIO JETS

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ABSTRACT. The use of the term "jet" is critically reviewed. "Jets" occur often, in a wide variety of extragalactic radio sources, and with properties well correlated both with the total luminosities of the sources and with the relative prominence of their compact radio cores. The one sided jets in powerful sources with symmetrical double lobes pose some acute problems. We need to understand why they break the symmetry of the lobes. Also, though these jets appear not to be free, it is not clear what confines them. The evidence bearing on particle acceleration and on the 3-D magnetic field structures in radio jets is briefly summarized.

1. INTRODUCTION

The observations which tell us about energy transport in extragalactic radio sources are in an exciting phase. Advances in image processing and improvements in array hardware are providing radio images of complex sources with unprecedented combinations of sub-arcsecond resolution, good sensitivity and high dynamic range. Sources we thought we knew well, such as Cygnus A, M87, NGC1265, 3C219 and 3C449, are showing new internal complexity (wisps, rings, sharp-edged jet knots and hot spots, cocoons, and hitherto undetected segments of jets). From 140 to 220 extragalactic "jets" have now been detected, depending on the rigor of your definition of a "jet". This talk updates what we know of the systematic properties of extragalactic jets – most trends suggested by early observations (e.g., Fomalont 1981, Willis 1981, Bridle 1982) have been confirmed, and several new ones have emerged. To counteract the impression that all jets are well-behaved conformists, I mention some "maverick" sources which fight the main trends.

2. WHY "JETS" ?

We left the word "jet" out of the title of this Workshop to show that heretical views of energy transport are welcome here ! But as extragalactic astronomers have described elongated luminous features as "jets" for 30 years now, and "jet language" permeates the optical, radio and X-ray literature, I expect that much of our discussion will simply *assume* that these elongated radio features map the paths of fluid outflows from active nuclei to extended radio lobes. The evidence supporting this assumption is indirect, and flimsier than we might wish, however.

The large sizes of powerful extragalactic sources show that active galaxies and QSRs eject *something* that can supply energy to relativistic particles and magnetic fields. The optical and radio cores also remain active long after the initial ejection has taken place, though we cannot prove that the activity has been continuous. VLBI shows radio emission that has been collimated on parsec scales. But we lack direct evidence that

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the link between the parsec and many-kiloparsec scales is a "jet" in the fluid mechanical sense, i.e., a continuous, forced (momentum-dominated) collimated outflow. Why then do we use the word so liberally ?

The term "jet" appeared on a hunch by Baade and Minkowski (1954) that there is outflow through the optical knots in M87. This hunch has still not been directly verified. There are no emission lines from the knots – the evidence for outflow in M87 is the velocity profile of [OII] lines *in the nucleus.* The radio nucleus has yet to reveal significant proper motions – this is not evidence *against* outflow in it (radio features may, for example, mark a slowly moving shock pattern in a rapidly moving flow), but the radio data give no direct evidence *for* flow.

In the early 1970's, the existence of elongated kiloparsec-scale optical and radio features in a few bright sources encouraged continuous flow, or "beam", models of energy transport. These models have attractive aspects which have ensured their longevity. The bulk kinetic energy in a beam exerts no pressure, so is not lost adiabatically. Supersonic beams terminate at shocks near their interface with ambient gas. Shocks can transform beamed kinetic energy into relativistic particle and field energy, thus providing a framework for explaining the locations, brightness distributions, and short radiative timescales of hot spots in radio lobes. These attractions of the "beam" models have rolled the "jet" bandwagon in reverse – observers now use the word "jet" as a synonym for "elongated feature" mainly because they find such features in places where beam models postulate continuous collimated outflow, not because they have direct evidence for the outflow itself.

Stellar jets, or "bipolar flows", have a much better pedigree than this, as outflow velocities have been directly measured in many cases. In SS433, the radio proper motions and optical spectroscopic data both show a mean velocity of $0.26c$, and the flow geometry is known in detail. The ~ 100 light-day scale and typical 1.4 GHz luminosity of SS433 ($P_{tot}^{1.4} = 10^{15.8}$ W/Hz) are much less than those of extragalactic jets, however. There is also good evidence for collimated outflow from recently formed stars – velocities of tens to hundreds of km/s are known from Doppler shifted molecular emission lines at mm wavelengths, from optical spectroscopy of nearby Herbig-Haro objects (some of which are linked to the stars by sinuous filaments), and from the 2.12 μm line of H_2. It is not clear, however, that the processes which produce these galactic jets scale to the extragalactic case[1]. They nevertheless add to the momentum of the extragalactic jet bandwagon, by showing that supersonic jets can arise in astrophysical situations where accretion flows and disk geometries may be relevant.

As we have now reached a stage where most extragalactic observers automatically use "jet language" when presenting their primary data, we must be careful to distinguish evidence from prejudice when discussing energy transport. Are we sure that there is steady outflow, rather than intermittent ejection ? Could some "jets" be inflow (splashbacks, backflow ?), or a mixture of inflow and outflow ? Could some be radiation

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[1] They may however allow us to study the propagation and stability of supersonic jets in a background medium with measurable properties, thus becoming a "laboratory test" of models of jet dynamics (though possibly not in the same regimes of Mach number, density contrast, or Reynolds number as in the extragalactic case).

from static, or slowly-moving, dissipative sheaths around faster primary flows, i.e. does the energy transport occur throughout the radio emitting volume ? Finally, *where's the beef ?* – can we find *hard evidence* for continuous outflow on kiloparsec scales ?

3. EVIDENCE SUGGESTING OUTFLOW

Two lines of evidence would have suggested that there is outflow in extragalactic radio sources, independent of our reasoning about the origin of radio lobes and their hot spots.

(a) Extranuclear Optical Emission Lines.

When Hα, Hβ, [OII], [OIII], [NII], [SII] and other emission lines were first found near radio jets in galaxies (see the references in Bridle and Perley 1984), there were hopes that their peculiar velocities might indicate jet velocities directly. These hopes have faded.

The extranuclear line emission is generally found *beside* the jets, particularly on the outer edges of bends. The lines are often brightest near, but not at, bright knots or hot spots. The line widths (typically 300 to 500 km/s) increase towards the radio features. The line emitting gas typically has densities $\approx 10^2$ to 10^3 cm^{-3}, and temperatures $\approx$ 20,000 K, so its pressure is near the lower limits to the pressures of radiating particles and fields in adjacent radio features. Typical peculiar velocities are a few hundred km/s.[2] These data suggest that the lines are formed when radio jets interact with ambient ISM, but the spatial displacements between the line emission and the radio features argue that the peculiar line velocities are not those of gas that is now entrained in the flow. The gas may instead be clouds which have been heated, ionized and accelerated by encountering the jets, perhaps deflecting them in the process. The detailed dynamics of the cloud/jet encounters are uncertain, however, so that while the emission line data are *consistent* with outflow along radio jets, they do not measure the flow velocities directly. They may however give lower limits to the flow velocities, similar to those obtained by saying that jets must be able to escape from their galaxies.

In some sources, e.g. 3C277.3 (Miley 1983), extranuclear line emission shares the side-to-side brightness asymmetry of a one-sided radio jet, showing that the radio asymmetry is not due primarily to Doppler favoritism in a relativistic flow. The radio asymmetries in such sources must be due either to differential dissipation in a two sided flow (e.g., by obliquely shocking and deflecting the flow at an encounter with an interstellar cloud on one side of the source but not on the other), or to intrinsic one-sidedness of the flow.

(b) Proper motions.

There is evidence for outflow in the first few parsecs of some extragalactic radio "jets" from VLBI proper motion studies of knots on these scales. In all but 4C39.25

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[2] An optical continuum and emission line feature in the radio galaxy DA240 has been described as an "optical jet" blueshifted relative to the galactic nucleus by 3400 km/s (Burbidge *et al.* 1975, 1978) and the velocity discrepancy has been invoked as direct evidence for a jet velocity of 3400 km/s (Burbidge *et al.* 1978; Strom and Willis 1981). The feature has not been detected at the VLA, however, and there is now circumstantial evidence (van Breugel *et al.* 1983) that it is a foreground galaxy. Its nature is still not completely clear, but it is certainly premature to use its peculiar optical velocity as a constraint on the flow velocity in an extragalactic radio source.

(Shaffer 1984), the knots separate with time, but only in 3C345 has it been shown in an external reference frame ("NRAO 512 = fixed", Bartel *et al.* 1984) that the compact flat-spectrum "core" is stationary while a "jet knot" feature moves outward. Equally careful VLBI astrometry of knots in other sources with compact neighbors (to act as references) could reinforce the case for outflow.

To study proper motions by VLBI we must recognise patterns of knots at several epochs – we cannot track motions in continuous elongated emission. The proper motion studies must therefore relate to patterns of *dis*continuity (shocks, or turbulent "bursts") in the flow. Shock pattern speeds and flow velocities need not be the same (or even have the same sign !), but the preponderance of expansions among the knot proper motions makes it very likely that there *is* outflow, at least on the 1 to 10 parsec scales over which the motions can presently be tracked by VLBI.

Composites of VLBI, MERLIN and VLA data can "propagate the guilt" of outflow to larger scales if they demonstrate *continuity* of emission between moving parsec-scale 'jets" and the larger-scale features. The study of 3C120 by Craig Walker and colleagues (this Workshop) is an excellent example, tracing a radio connection from a superluminally expanding parsec-scale pattern to a kiloparsec-scale jet in a larger lobe-like structure. 3C179 may be the best available example combining superluminal motion, a kiloparsec-scale jet and *symmetrical* double lobes, but the continuity of the connections is less obvious in this source. Such data do not prove there is outflow in the large-scale features, but they add transverse velocities and directional alignments to the justification used by Baade and Minkowski for invoking outflow in M87 !

4. DEFINING A "RADIO JET"

The useful but prejudicial term "radio jet" should be employed like a useful but hazardous chemical – sparingly and carefully. If form and location will guide our view of energy transport physics, we need clear morphological criteria for jethood. I use here three criteria I have employed before (Bridle 1982; Bridle and Perley 1984), namely that be termed a "jet" a radio feature must be:

(a) at least four times as long as it is wide (after deconvolving the instrumental beam from the data),

(b) separable at high resolution from other extended structure (if any) either by brightness contrast or spatially (e.g. it should be a narrow ridge running through more diffuse emission, or a narrow feature in the inner part of a source entering more extended emission in the outer part),

(c) aligned with the radio core where it is closest to it. This is to distinguish *jets* from misaligned ridges near the hot spots in radio lobes.[3]

Even these three seemingly simple criteria are not always easy to apply. For example, if observed with lower sensitivity to smooth emission, the jet in NGC6251 (Perley *et al.* 1984a) would be a train of discrete knots, not all of which are elongated along it. I call such trains of knots *jets* only if some knots are elongated along the length of

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[3] These lobe features may be closely related to jets if there is redirected outflow beyond, or backflow from, the hot spots (e.g., Robert Laing, this Workshop), but no interpretation of misaligned ridges in the lobes is yet obligatory and it is still useful to make empirical distinctions based on their alignment.

the train, or if it comprises more than two knots, as in 3C219 (Figure 1). This may exclude some real blobby jets, but rather than use prejudicial language too liberally, I prefer to hold some jet candidates in abeyance until better data convince me they are legitimate. Criterion (b) can be ambiguous in edge-darkened sources such as 3C31 or 3C449. The outer structures of such sources can equally plausibly be termed "broad jets" or "elongated lobes", as they fade away without clear terminations or hot spots. They resemble the meanderings of *subsonic* laboratory jets. I doubt that total intensity imaging alone can distinguish forced *jets* from buoyant *plumes* in the outer parts of such sources, but I ask that a bright "spine" of emission meets criterion (b) at some resolution before saying that such sources contain a *jet.*

There is a further complication in sources like M84 and 3C341 (Figure 2) which have faint emission "cocoons" around their jets. Other examples are NGC1265 (O'Dea and Owen, this Workshop), 3C147, 0938+39, 1321+31, 4C32.69 and 2354+47. Should we distinguish faint "cocoons" from brighter "jets" when discussing jet properties ? The collimation properties of the cocoons in M84 and 3C341 are quite different from those of the jets, so the distinction is not merely semantic. We need to diagnose the relationship of cocoons to the brighter structure[4] – are they faint "outer jets", static sheaths, leakage from the jets or emission from the backflows predicted by numerical simulations of hypersonic jet propagation in confining media ?

5. RATES OF DETECTION OF EXTRAGALACTIC RADIO JETS

Bridle and Perley (1984, BP) listed data on 125 sources with jets satisfying the above three criteria. Although the BP list is not statistically complete, the statistics of jets in several complete samples can be derived from it. It exhibits several trends that are unlikely to reflect statistical incompletenesses or biases.

Jets occur in extragalactic sources of all luminosities, sizes and structure types, justifying the assumption that they are associated with processes common to all extragalactic radio sources. Every jet in the BP list is accompanied by a detectable radio "core" in the inner kpc of the parent object, though in a some sources the cores are fainter than the brightest parts of the jet at cm wavelengths by factors ~ 2 to 4. This broadens the case for relating jets to continuing activity in the parent objects, supported further in some sources by the presence of VLBI jets. The fact that jets are neither rare nor confined to any one type of extragalactic source is strong support for the now-conventional assumption that they result from inefficiencies in the basic process of energy transport from the cores to the lobes. This conclusion is independent of whether the dissipation occurs in the primary flow itself, or in a static sheath or backflow around it.

As BP relate in some detail, jets or possible jets are detected in 65 to 80% of nearby (weak) radio galaxies, and in 40 to 70% of the extended QSRs mapped at the VLA with good dynamic range. It is much harder to detect jets in distant radio galaxies with similar powers, flux densities, and angular sizes to these QSRs – only 5% of a sample of powerful 3CR[2] galaxies mapped at the VLA have definite jets, and only $< 10\%$

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[4] The cocoons may not all be the same class of phenomenon; for example, the cocoon in 3C341 has a very different brightness distribution from that in M84.

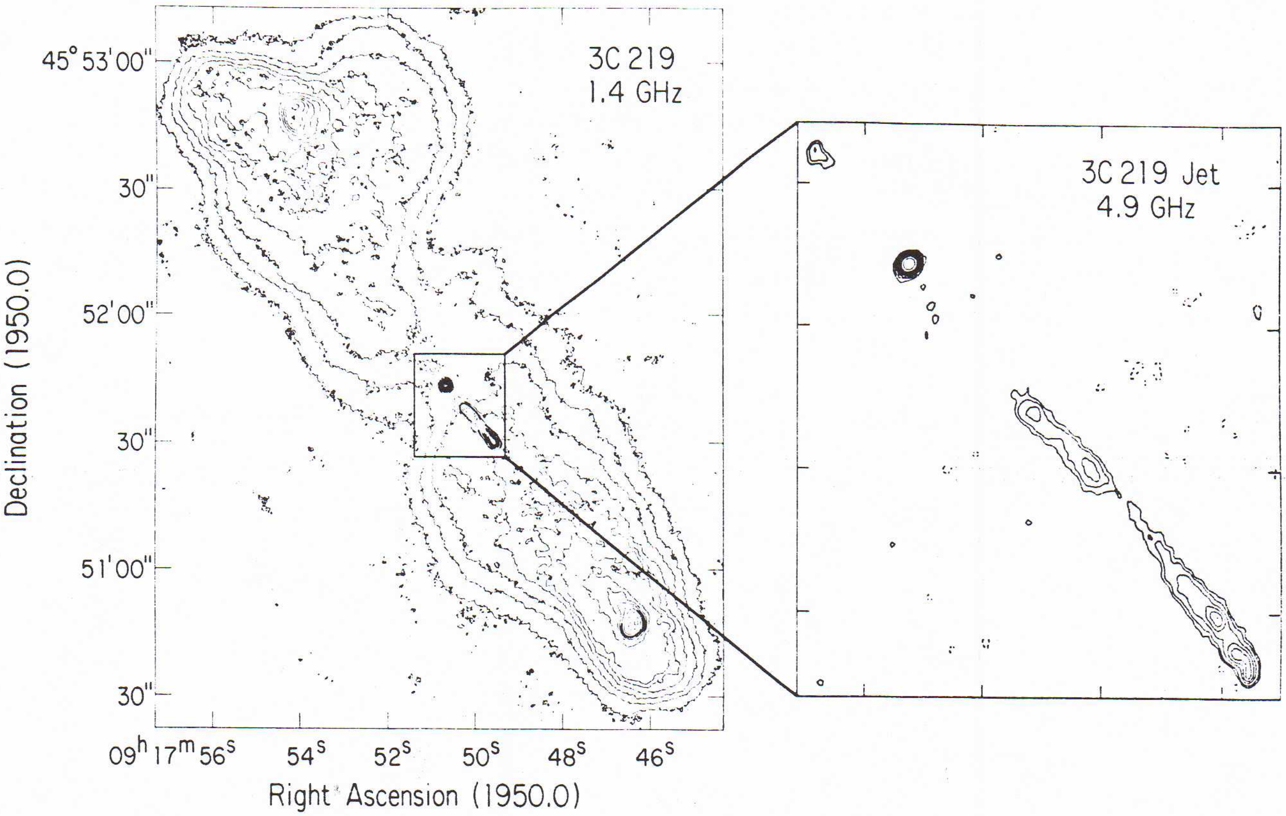

Figure 1.
(Left panel) VLA 1465 MHz map of 3C219 with 1.7 arcsec resolution (circular Gaussian restoring beam). Contours are plotted at -1, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 20, 30, 40 and 50 times 2 mJy per beam.
(Right panel) VLA 4885 MHz map of a ~ 20 arcsec region near the nucleus of 3C219 (box in left panel) at ~ 0.35 arcsec resolution. The brightest feature is the radio core. The contours on the jet are plotted at -1, 1, 2, 4, 6 and 8 times 0.2 mJy per beam. Note the elongated knot to the north-east of the core – presumably the brightest part of the counterjet, as it is elongated along the jet axis. Note also that this knot is opposite the end of the initial "gap" in the main jet.

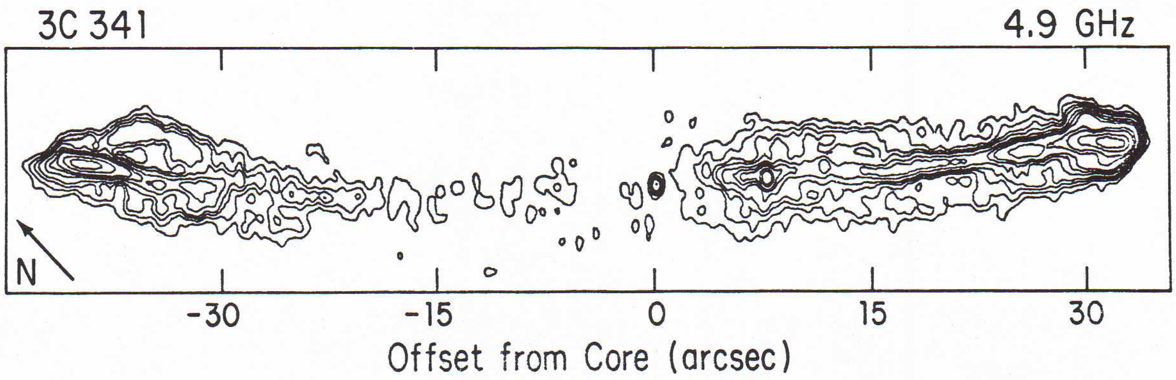

Figure 2. VLA 4885 MHz map of 3C341 with 1.0 by 0.6 arcsec resolution. The contours are plotted at -1, 1, 2, 3, 4, 6, 8, 10, 15, 20, 30, 40 and 50 times 0.237 mJy per beam. Note the cocoon around the jet(s).

have structure resembling jets. This relative faintness of jets in powerful radio galaxies is not an instrumental bias. The powerful $3CR^2$ galaxies were observed at the VLA with roughly similar sensitivities, dynamic ranges and numbers of beamwidths across their lobe structures as the extended $3CR^2$ QSRs. The jets in luminous radio galaxies must typically emit a smaller fraction of the total flux density than those in weak radio galaxies or extended QSRs[5].

These statistics pose an intriguing question for jet models – what is it that varies with radio luminosity among galaxies, and with the prominence of the optical nucleus among powerful radio sources generally, that affects the relative luminosities of the jets and the lobes ?

The detectability of the jets in the powerful sources may be related to the relative prominence of their cores – among the extended $3CR^2$ QSRs mapped at the VLA, the detection rate of jets increases with the relative prominence $f_C = S^5_{core}/S^{1.4}_{tot}$ of the radio core, apparently regardless of redshift. All six extended $3CR^2$ QSRs with $f_C > 0.03$, but only two of the six with $f_C < 0.005$, have jets or features resembling the brightest parts of jets. Saikia (1984) finds a similar correlation in a sample of 59 QSRs observed at the VLA. The lack of detectable jets in distant $3CR^2$ galaxies may therefore be connected with the faintness of their radio cores relative to those of the QSRs (the median value of f_C in the distant $3CR^2$ galaxy sample is only 0.0005).

Jack Burns (this Workshop) suggests a direct correlation between core and jet powers over a wide range of powers, which is consistent with these correlations between jet and core prominence and with the lack of totally "coreless" jets referred to above. A false power-power correlation might arise from z^2 bias in flux-limited samples, but the effect should clearly be tested for in volume-limited samples.

6. TRENDS WITH LUMINOSITY

(a) Sidedness.

The symmetry of the lobes of the powerful doubles is strongly broken by their jets. Most of the powerful extended sources have lobes of roughly similar powers and sizes on each side of the parent object, but only in the weaker sources ($P^5_{core} \leq 10^{23.2}$ W/Hz or $P^{1.4}_{tot} \leq 10^{24.5}$ W/Hz) do the kiloparsec scale jets have counterjets with more than 1/4 their brightness per unit length.

Most *straight* kiloparsec scale jets are one-sided (by more than a 4:1 intensity ratio) close to their parent object, but those in weak radio galaxies become two-sided after a few kiloparsecs. The one-sided bases of the jets in these weak sources typically occupy $< 10\%$ of their length, and the jet with the one-sided base is generally somewhat brighter on the large scale.[6] Most kiloparsec-scale jets in powerful sources, whether radio galaxies or QSRs, are one-sided (more than 4:1 in brightness) for their entire lengths. All the

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[5] The recent detection of a large-scale jet in Cygnus A (Perley *et al.* 1984b) is consistent with this, as this jet contains only about 0.25% of the total luminosity of the source at 1.4 GHz, and became apparent only in VLA maps of much higher quality than those available for most other powerful sources.

[6] Frazer Owen and Chris O'Dea tell me that the initial one sided regime is rare in the C-shaped trails, though some (e.g., IC708 – Vallée *et al.* 1981; 3C129 – Burns 1983) show it clearly. It will be interesting to examine this difference quantitatively in sources of different luminosities, as it might be a hint of extrinsic (environmentally induced) sidedness relationships.

large scale QSR jets are one-sided, but radio galaxy jets may be either one- or two-sided, depending on the radio power – there are 14 radio galaxies in the BP list with one-sided jets > 10 kpc long. The range $P^{1.4}_{tot} = 10^{24.5-25}$ W/Hz which marks the transition between large-scale two-sidedness and large-scale one-sidedness (at the 4:1 brightness ratio level) also marks the transition between morphological classes I (edge darkened) and II (edge brightened) of Fanaroff and Riley (1974 – FR). There is a clear trend for the jets in weak, edge darkened sources to be much more symmetric on the large scale than those in powerful, edge brightened sources.

Further details on these trends are given in Bridle (1984); now for some sources which buck them. 3C438, an FR II radio galaxy with $P^{1.4}_{tot} = 10^{26.86}$ W/Hz, has a relatively weak ($P^{5}_{core} = 10^{23.99}$ W/Hz) core and a two-sided jet. Its total radio power exceeds that of many extended double QSRs, all of which have stronger cores and one-sided jets. This could indicate that core power, rather than total power, is better correlated with jet sidedness, but this should be tested with further examples. The two weakest cores associated with clear one-sided jets are those in Cen A ($P^{5}_{core} = 10^{22.20}$ W/Hz) and M87 ($P^{5}_{core} = 10^{22.92}$ W/Hz). Both jets are short (M87 – 1.8 kpc; Cen A – 5.2 kpc); their lengths are comparable to, or shorter than, those of the one-sided bases of two-sided jets in other sources with similar total powers. The "unusual" feature of the M87 and Cen A jets may therefore not be their brightness asymmetry, but the fact that they end in two-sided "inner lobes" rather than two-sided "outer jets" extending 10 to 50 kpc beyond them. NGC3078 and NGC6146 (Wrobel and Heeschen 1984) may be further examples of this effect in nearby weak sources, so the effect might be common in *volume-limited* samples of extragalactic sources.

3C219 (Figure 1), NGC1265 (O'Dea and Owen, this Workshop) and 3C445 (Wil van Breugel, private communication) have features with >4:1 brightness asymmetries on *both* sides of their cores. 3C219 and 3C445 both have isolated knots on one side of the core opposite *gaps* in the jets on the other side. Although these knots do not by themselves meet my criteria for being termed "counterjets", they *are* elongated along the axes of the main jets. The sidedness of such discontinuous "pieces of jets" is difficult to quantify; but, at least with present resolutions, there are not enough of them to cast the overall trend into doubt. They do, however, prompt questions about the origin of "avoidance" effects, and about intermittent or "flip-flop" outflow (Rudnick and Edgar 1984; Bridle, this Workshop).

(b) 2-D Magnetic Configuration.

Three configurations of the "apparent magnetic field" $\mathbf{B_a}$ (Laing 1981) are common:

1. $B_{||}$, i.e. $\mathbf{B_a}$ is predominantly parallel to the jet axis all across the jet.
2. $B_{\perp}$, i.e. $\mathbf{B_a}$ is predominantly perpendicular to the jet axis all across it.
3. $B_{\perp-||}$, i.e. $\mathbf{B_a}$ is predominantly perpendicular to the jet axis at the center of the jet, but becomes parallel to the axis near one or both of its edges.

Most two-sided regions of straight jets have either the $B_{\perp}$ or the $B_{\perp-||}$ configuration, while most one-sided regions of jets have the $B_{||}$ configuration. In straight jets emanating from weak cores, $\mathbf{B_a}$ usually turns from $B_{||}$ to $B_{\perp}$ or $B_{\perp-||}$ in the first 10% of their lengths, while jets associated with powerful cores are generally $B_{||}$–dominated for their entire length (Bridle 1984). This transition in magnetic properties occurs at

$P^5_{core} = 10^{23-24}$ W/Hz (roughly corresponding to $P^{1.4}_{tot} = 10^{24-25}$ W/Hz). Combining this with the sidedness trend, the FR effect, and the occurrence of hot spots, we can identify two primary types of (straight) radio jet – two-sided, $B_\perp$– or $B_{\perp-\parallel}$–dominated jets (with short one-sided bases) in weak sources with edge-darkened structures and no hot spots (FR I sources), and one-sided $B_\parallel$–dominated jets in powerful sources with edge-brightened structures and strong hot spots (FR II).

Two departures from these basic trends may be traceable to perturbations of the jet flows:

(a) Two-sided jets often have the $B_{\perp-\parallel}$ configuration where they bend. The $B_\parallel$ edge is often deeper (and more strongly polarized) on the outside of the bend (3C31, NGC6251, M84) as if $B_\parallel$ is amplified there by stretching and shearing. The bent jets in the C–shaped head-tail source NGC1265 are $B_\parallel$–dominated even though they are two-sided (O'Dea and Owen, this Workshop). The fields in such sources may be extreme examples of the $B_{\perp-\parallel}$ type resulting from viscous interaction with ambient gas.

(b) Some knots in one-sided jets have $B_\perp$, or oblique, apparent fields although fainter emission near them is $B_\parallel$–dominated – e.g. Knot A in M87, the knot $50''$ from the core in NGC6251 and Knot A2 in Cen A. These "magnetic anomalies" at bright knots may be due to oblique shocks which accelerate relativistic particles and amplify the component of $\mathbf{B}_\mathrm{j}$ parallel to the shock. $B_\perp$ fields also appear where one-sided $B_\parallel$ jets terminate at bright hot spots, and the physics there may be similar.

(c) Size, Curvature and Misalignments.

Jets in weak radio galaxies and in strong core-dominated sources are generally short – < 10% of all jets in BP sources with $P^5_{core} < 10^{22.5}$ W/Hz, and only 13% of those in BP sources with $P^5_{core} > 10^{26.5}$ W/Hz, are longer than 40 kpc but ≈50% of those in sources of intermediate powers exceed this length. The jets in core-dominated sources may be shortened by projection effects if cores are Doppler boosted small-scale jets, but the jets in weak radio galaxies are mainly two-sided, so are probably short intrinsically. Strong jet curvature is also common in two distinct regimes – (a) the C-shaped two-sided jets in weak "head-tail" cluster galaxies and (b) the one-sided jets in core-dominated sources. Curvature may be due to bending of a confined jet by an external pressure (as in models for head-tail sources) or to wandering of the central collimator.

The misalignments between parsec and kiloparsec-scale jets increase with increasing core prominence. Several lobe-dominated double radio galaxies with kiloparsec-scale jets have cores with one-sided parsec-scale jetlike extensions on the same side as the large jets and aligning with them to $\leq 10°$. In powerful core-dominated sources however, the misalignments between parsec and kiloparsec-scale structures are often $> 20°$, and in 3C345 (John Biretta, this Workshop) and 3C418 they exceed 90°. These trends are consistent with the short jets in core-dominated sources being close to the line of sight.

(d) Collimation.

The jets in over a dozen radio galaxies, but in few QSRs, have been resolved transversely well enough to show their lateral expansion (spreading) directly. The transverse brightness profiles are generally center brightened, so their FWHMs Φ (corrected for the instrumental resolution) can be used to characterise how the synchrotron emission widens with angle Θ from the radio core. Bridle (1984) shows that the resolved jets in powerful sources tend to expand more slowly than those in weak radio galaxies. The jets in the powerful sources have been observed with about as many beamwidths along their lengths as those in the weaker sources, so this trend is unlikely to be merely a resolution effect. The small median angle ($< 1^\circ$) subtended at the radio cores by hot spots in powerful doubles is consistent with the trend, if the sizes of the hot spots indicate (roughly) the diameters of the (still to be detected) jets at these distances from the cores.

7. FREEDOM AND CONFINEMENT

The fact that radio jets are generally center brightened supports the view that they are radiative losses in the energy transport region itself, not from a static cocoon around it. $\Phi(\Theta)$ may therefore show, at least qualitatively, how the flow radius R_j varies with distance z from the core. If the jet magnetic fields $\mathbf{B_j}$ are dominated by large scale organised components whose configuration changes with distance down the jet, some features of the $\Phi(\Theta)$ evolution may also reflect changes in field organization. Except in a few very highly polarized jets, there is not much evidence for this so far (an observation which may itself constrain the 3-D form of $\mathbf{B_j}$, see §9).

If we suppose that the observable parameter $d\Phi/d\Theta \propto 2\,(dR_j/dz)\sec i$, where i is the angle of the jet to the plane of the sky, then *decreases* in $d\Phi/d\Theta$ signify that the jet pressure p_j is being balanced by a *slowly* decreasing external pressure $p_e(z)$. The $\Phi(\Theta)$ data for many well resolved jets indeed show collimation "shoulders" at which $d\Phi/d\Theta \rightarrow 0$, at projected distances $z \approx 10$ kpc. This implies that they are not free jets whose spreading rates were decided forever on parsec scales, even though VLBI data show that many jets are *first* collimated on such small scales. This property of the resolved jets raises a major question for models of energy transport – what process recollimates the jets on the kpc, or 10 kpc, scales ?

(a) Weak Radio Galaxies ($P_{tot}^{1.4} < 10^{25}$ W/Hz).

Both sides of the jets in the radio galaxies 3C449, NGC315 and 1321+31 recollimate at similar distances from their cores. Those in 2354+47 decollimate as they descend intensity gradients in its soft X-ray halo. The synchrotron properties of the jets set lower limits p_{min} to the jet pressure that typically range from $\approx 10^{-10}$ dyne/cm^2 in the inner few kpc to $\approx 10^{-13}$ dyne/cm^2 $\sim$ 100 kpc from the galactic nuclei, scaling with jet radius R_j roughly as R_j^{-1} to R_j^{-2}. These data suggest, but by no means insist, that low-power jets can be collimated by the thermal pressures in the X-ray halos, which typically decline with z as z^{-1} to z^{-2} over the appropriate ($\sim$ 10 kpc) scales.

The *average* run of $p_{min}(z)$ from the jet synchrotron calculations sets a lower limit to the required $n_e(z)T$ in a halo if the jet is thermally confined – local overpressures at knots of order M_j^2 times the mean may be tolerable (Norman *et al.* 1984). Assuming a value for T, we can estimate the minimum X-ray luminosity of a hypothetical isothermal confining halo between energies E_1 and E_2 as:

$$L_X(E_1, E_2) = 1.995 \times 10^{-34} \bar{g}_{E_1,E_2} \sqrt{T} \left(\exp\left(\frac{-E_1}{kT}\right) - \exp\left(\frac{-E_2}{kT}\right)\right) \int n_e^2 dV \ \mathrm{W}$$

where $\bar{g}$ is the mean Gaunt factor in the appropriate energy range. The emission measure integral $\int n_e^2 dV$ can be evaluated from $n_e(z)$ by assuming the gas distribution to have spherical symmetry. For a fixed $p_{min}(z)$, the predicted $L_X \propto T^{-1.5}$, apart from the variation of the exponential factor. The minimum L_X required if a jet *of given flux density, angular size and redshift* is confined at a given temperature is also quite sensitive to the assumed H_0 – $L_X \propto H_0^{-13/7}$ with these constraints.

For NGC315, 3C66B, IC4296, Cen A and NGC6251, such calculations show that confinement by gas at $T \approx 1$ to 3×10^7 K (c.f. the M87 halo) is (just) compatible with the *Einstein* IPC detections or upper limits for extended soft X-ray sources around the galaxies. Confinement by intracluster gas at $T \approx 7 \times 10^7$ K is even more compatible with the X-ray data. The contribution of compact nuclear X-ray sources to the IPC data is unclear in some cases, however, so sensitive X-ray imaging and temperature determinations of the regions 1-50 kpc from the galactic nuclei are needed to clarify the situation. For M87, the *Einstein* and VLA data show that p_{min} in the knots (in this case a few times 10^{-9} dyne/cm^2) exceeds the thermal pressure in the X-ray halo at their projected distances by factors > 10 (Biretta *et al.* 1983). Nevertheless, although the first kiloparsec of this jet expands at a constant rate, the lateral expansion slows after Knot A, suggesting that the outer parts of the jet are not free. Whether these discordancies in M87 should be interpreted as local shock-related overpressures in a jet with Mach number $M_j > 3$, or as a problem requiring nonthermal (magnetic ?) collimation is not completely clear.

If the longer, rapidly-expanding segments of these recollimating jets are free, then the observed $d\Phi/d\Theta \ll 1$ implies that they are supersonic. The data suggest the jets are collimated initially, and become transonic, < 1 kpc from the nuclei then escape into regions where the external pressure p_e drops rapidly. If $p_e \propto z^{-n}$ and $p_j \propto \rho_j^x$, the sound speed in the jet $c_S = \sqrt{\Gamma p_j/\rho_j} \propto p_j^{(x-1)/2x}$. If the jet stays *confined*, $p_e = p_j \propto z^{-n}$, so $c_S \propto z^{(n/2x)-n/2}$ while $v_r = v_j(dR_j/dz) \propto z^{(n/2x)-1}$. Comparing the exponents of the z dependence of these two velocities shows that continued confinement of a supersonic jet eventually requires $v_r > c_S$ if $n > 2$. If the external pressure falls faster than z^{-2}, the jet must then "detach" from p_e, i.e. become free. If p_e begins to fall slower than z^{-2} (as in the X-ray halo of M87) after a jet has become free, the jet may be reconfined. Conical shocks would propagate into it from its surface (where it first "feels" the declining gradient of p_e (Sanders 1983), reheating the jet and possibly (re)accelerating relativistic particles in it (Jean Eilek, this Workshop). The shock structure downstream from the reconfinement may be quasi-periodic, leading (a) to oscillations in the jet's expansion rate and (b) to regularly spaced bright knots along it. These phenomena may have been observed in NGC315 (Willis *et al.* 1981) and particularly in NGC6251 (Bridle and Perley 1983, PBW) whose jet is limb-brightened near its first reconfinement (consistent with particle acceleration in the conical shocks). Sanders (1983) argued that jets which stay bright enough to be observed may be just those which do oscillate between freedom and confinement in this way.

(b) Powerful Radio Galaxies and QSRs ($P_{tot}^{1.4} > 10^{25}$ W/Hz).

The narrower collimation of the jets in stronger sources, coupled with their greater distances, means that the expansion properties $\Phi(\Theta)$ of many of them are but crudely known. The data (Bridle 1984) are adequate to show however that jets in some powerful sources must be:

(a) free with Mach numbers $M_j \geq 50$,

(b) confined by much larger $p_e(z)$ than that in nearby radio galaxies, or

(c) the approaching sides of relativistic twin jets, whose minimum p_j is overestimated by the conventional calculation due to Doppler boosting.

Several of the jets in powerful sources show little or no systematic expansion with increasing distance from their cores (e.g. 3C33.1, 3C111, 3C219), though they are resolved at all distances. This suggests that the jets in these powerful sources "flare" on small scales, then recollimate some tens of kiloparsecs from the cores. As in the weaker radio galaxies, this is evidence that the powerful jets are not free at all distances, and, in particular, are confined by a mechanism that takes effect tens of kiloparsecs from the central engine.

Potash and Wardle (1980) have argued that freedom for these jets is also inconsistent with thrust balance. The thrust of a nonrelativistic jet is given by $T_j = \rho_j v_j^2 A_j$ where ρ_j is its density, v_j its velocity and A_j its cross-sectional area. But $v_j^2 = M_j^2 c_S^2$ and $c_S^2 = \Gamma p_j / \rho_j$, so we can write $T_j = M_j^2 \Gamma p_j A_j \geq M_j^2 \Gamma p_{min} A_j$ where p_{min} follows from the synchrotron calculations. If the jets in powerful extended QSRs have the high Mach numbers M_j derived by presuming them to be free, T_j so estimated becomes so large that the jets could not be stopped or deflected by the IGM. In these cases, either M_j or p_{min} must have been over-estimated.

Thermal confinement of the pc-scale jets in several powerful radio galaxies (but not in Cygnus A) is compatible with the X-ray data but for several large-scale QSR jets, the *Einstein* data rule out pure thermal confinement at temperatures $\approx 1-3\times10^7$ K unless the jets are Doppler-boosted. Boosting with a Doppler factor $\mathcal{D} = \gamma_j^{-1}(1-\beta_j \sin i)^{-1}$ could mean that p_{min} is over-estimated by a factor $\mathcal{D}^{(8+4\alpha)/7}(\sec i)^{4/7}$, which can be larger than the relativistic correction γ_j^2 to the thrust, (thus relieving the thrust balance problem) if the flow comes close to the line of sight. Reducing p_{min} also reduces the external pressure required to confine the jet thermally. Although all the jets which have these thrust balance and/or confinement problems are one-sided, as expected if Doppler boosting is occurring, the Doppler solution has unpalatable aspects. Both the thrust balance problem and the X-ray luminosity required for thermal confinement respond only very slowly to the Doppler fix. In the thermal confinement case, the projection required for the Doppler boosting increases the *linear scale* of the radio source by $\sec i$, and thus increases the volume to be filled with the confining gas by $\sec^3 i$. This increase must be more than compensated by the reduction in n_e^2 attending the reduction in p_{et} for the confinement problem to be solved at all. Unless the beaming cone is much wider than $1/\gamma_j$, very small angles to the line of sight are required to cope with both the thrust and confinement problems, and would make it difficult to account for the high fraction of jets now being detected in the extended $3CR^2$ QSRs.

For these reasons, magnetic confinement is frequently, and increasingly, invoked for jets in the powerful sources. There is no direct evidence for the required toroidal magnetic fields but neither is magnetic collimation excluded by the available polarimetry (see §9). Another possibility would be that some jets in powerful sources *are* thermally confined, but at temperatures $\geq 10^8$ K. A new generation of measurements of the X-ray temperatures and scale sizes around the powerful jet sources is required to test this possibility observationally, but even in clusters there are theoretical difficulties with heating and confining such hot gas.

It therefore appears that the jets in the powerful sources are not free, yet we do not know of a convincing way to confine them. In this sense the question "what collimates the energy transport in the most powerful sources ?" is no better answered in 1984 than it was in 1954, though the question can be *posed* with greater sophistication now than then !

(c) Complications at Knots and Cocoons.

The interpretation of jet collimation is also complicated by knots in the jets and by the sources with faint cocoons around brighter jets. For example, Φ decreases at each of the outer knots in NGC6251 while the lower contours of the jet expand smoothly (Perley *et al.* 1984a). The collimation properties of cocoons can differ from those of their jet "spines" – the cocoon in M84 expands much faster than the jets $> 5''$ from the core. At what level of brightness (if any) in such sources does the synchrotron expansion rate $d\Phi/d\Theta$ indicate the spreading rate of an underlying flow ? Are these sources a warning that we may be misleading ourselves about the collimation properties of jets whose radio emission happens to look simpler ?

8. INTENSITY EVOLUTION AND DISSIPATION

This Section reviews aspects of jet data relating to particle acceleration in the flows.

(a) Spectral Indices.

The most common spectral index near 1.4 GHz in extragalactic jets is $\alpha \approx 0.65$ ($S_\nu \propto \nu^{-\alpha}$), but some jets, and some knots in jets, have indices >0.8. Spectral gradients in jets are difficult to measure, as jets may be confused with the lobes at low resolution, and maps with unscaled arrays at different frequencies may not be equally sensitive to all scales. Spectral gradients along most jets are small. Those which do exist are mainly in the sense of α increasing with distance from the cores (e.g. 3C31, For A, M87, 3C279, Cen A, 4C32.69), consistent with depletion of the higher energy particles by synchrotron losses in the outer parts of these jets. Jets also generally have slightly flatter spectra than the lobes they feed (Cen A may be an exception).

Possible exceptions to this trend occur where the the brighter jets in NGC315 (Bridle, Fomalont and Henriksen, in preparation), and IC 4296 (Bicknell *et al.*, this Workshop) initially "turn on". The weak emission between the cores and the bright bases of these jets (i.e. in the regions formerly called the "gaps") has $\alpha \geq 0.8$ near 1.4 GHz, while the jets have $\alpha \approx 0.6$ to 0.65. This suggests that local flattening of the electron energy spectrum (relatively more high-energy particles) accompanies the initial increase in jet emissivity at the ends of such "gaps".

Optical continuum emission coincides with bright knots in the radio jets of 3C31, 3C66B, M87, 3C273, 3C277.3, and Cen A. The 4500Å to 6 cm spectral index is generally within 0.1 of 0.7. The optical continuum is up to 20% linearly polarized in M87 and

$\approx 14\%$ linearly polarized in 3C277.3. This polarization, the positional coincidence with the radio knots, and the connected optical-radio spectrum in M87, provide evidence that the optical continuum emission is synchrotron radiation from the same region as the radio. If the magnetic field strengths are near the equipartition values (inferred from the optical-radio spectrum and the radio knot sizes), the knots are several synchrotron lifetimes from the radio cores, showing that the knots are sites of relativistic particle reacceleration (or possibly of pitch angle scattering). Imaging of the optical continuum knots in jets with the *Space Telescope* should determine how discrete, or continuous, the conversion regimes are.

The region near the M87 jet has a luminosity $\approx 10^{41}$ erg/s in the *Einstein* HRI band. Individual knots are not resolved, but this integrated X-ray luminosity is consistent with extrapolating the steep spectrum of the knots above 6000Åto the X-ray regime. Schreier *et al.* (1982) conclude that the entire spectrum is probably synchrotron emission – too much gas is required for thermal emission, and drastic departures from equipartition are required for inverse Compton emission. If the synchrotron interpretation is correct, electrons with Lorentz factors $\sim 10^{7.3}$ are required to produce the observed X-rays in the equipartition magnetic field of the knots, providing a severe test for particle acceleration models. The radiative lifetimes of such particles would be $\lesssim$200 yr, comparable to the light crossing time in the knots, but much less than the light travel time to the knots from the nucleus of M87. The X-ray and radio structures of the jet in Cen A are also very similar, suggesting that this is also synchrotron emission, and raising similar demands for local particle acceleration.

(b) "Adiabats" for circular and elliptical jets.

Both the magnetic field strengths B_j and the relativistic particle energies E will decrease along an expanding laminar jet in which there is no magnetic flux amplification or particle reacceleration. If magnetic flux is conserved, $B_{\|} \propto A_j^{-1}$ and $B_{\perp} \propto (\ell_j v_j)^{-1}$, where A_j is the cross-sectional area of the jet and ℓ_j is the depth of the jet in the line of sight. Assuming relativistic particle conservation and adiabatic expansion then gives the synchrotron emissivity ϵ_ν as a function of jet area A_j and velocity v_j. For $B_{\|}$-dominated fields:

$$\epsilon_\nu \propto A_j^{-(5\gamma+7)/6} v_j^{-(\gamma+2)/3} \qquad (B_{\|})$$

From this, the luminosity per unit length (the quantity most readily measured for a jet that is *unresolved* transverse to its width) is $\mathcal{L}_\nu \propto \epsilon_\nu A_j$, i.e.:

$$\mathcal{L}_\nu \propto A_j^{-(5\gamma+1)/6} v_j^{-(\gamma+2)/3} \qquad (B_{\|})$$

For well resolved jets we can also determine the variation of central intensity I_ν with FWHM (Φ) along the jet ridge line. In an optically thin jet, this will be related to the adiabat for $I_\nu \propto \epsilon_\nu \ell_j$:

$$I_\nu \propto A_j^{-(5\gamma+7)/6} \ell_j v_j^{-(\gamma+2)/3}. \qquad (B_{\|})$$

For $B_{\perp}$-dominated fields, these adiabats become:

$$\epsilon_\nu \propto A_j^{-(\gamma+2)/3} \ell_j^{-(\gamma+1)/2} v_j^{-(5\gamma+7)/6}, \qquad (B_{\perp})$$

$$\mathcal{L}_\nu \propto A_j^{-(\gamma-1)/3} \ell_j^{-(\gamma+1)/2} v_j^{-(5\gamma+7)/6}, \qquad (B_\perp)$$

and

$$I_\nu \propto A_j^{-(\gamma+2)/3} \ell_j^{-(\gamma-1)/2} v_j^{-(5\gamma+7)/6}. \qquad (B_\perp)$$

The results for the circular jet (Fanti *et al.* 1982; Perley *et al.* 1984a) follow by putting $A_j = \pi R_j^2$ and $\ell_j = R_j$ in these general forms, whereon

$$I_\nu \propto R_j^{-(5\gamma+4)/3} v_j^{-(\gamma+2)/3} \quad (B_{||}) \text{ or } \quad I_\nu \propto R_j^{-(7\gamma+5)/6} v_j^{-(5\gamma+7)/6} \quad (B_\perp)$$

In a laminar circular jet with the typical $\gamma = 2.3$, $I_\nu \propto R_j^{-5.2} v_j^{-1.4}$ if $B_{||}$ dominates, or $I_\nu \propto R_j^{-3.5} v_j^{-3.1}$ if $B_\perp$ dominates.

For the more general case of an elliptical jet with $A_j = \pi a_j b_j$, the adiabats for $\mathcal{L}_\nu$ and I_ν depend on the orientation of the jet cross-section relative to the observer. For a pressure matched jet with $p_e \propto z^{-n}$ and $p_j \propto \rho_j^x$ with $n < 2x$, the circular cross section is unstable, and the major axis $a_j \propto z$ and the minor axis $b_j \propto z^{(n/x)-1}$ (Smith and Norman 1981). If the jet is viewed from a direction near the minor axis of its cross section (the most probable case),

$$\mathcal{L}_\nu \propto R_j^{-(5n\gamma+n)/6x} v_j^{-(\gamma+2)/3} \quad \text{and} \quad I_\nu \propto R_j^{-(5n\gamma+n+6x)/6x)} v_j^{-(\gamma+2)/3} \quad (B_{||})$$

or

$$\mathcal{L}_\nu \propto R_j^{(3x+3x\gamma-5n\gamma-n)/6x} v_j^{-(5\gamma+7)/6} \quad \text{and} \quad I_\nu \propto R_j^{(n+7n\gamma+3x-3x\gamma)/6x} v_j^{-(5\gamma+7)/6} \quad (B_\perp)$$

These adiabats are sensitive to n and x, as these determine how the *shape* of the jet varies with distance z from the core. As $R_j \propto a_j \propto z$ for this viewing direction, the jet would appear to be "free" but would dim at rate generally quite different from that of the circular jet. For example, if we set $\gamma = 2.3, n = 1.5$ and $x = 5/3$ to represent a cold (nonrelativistic) jet propagating in a typical X-ray halo, $I_\nu \propto R_j^{-2.9} v_j^{-1.4}$ for $B_{||}$ dominant, or $\propto R_j^{-2.2} v_j^{-3.1}$ for $B_\perp$ dominant. As Smith (1984) has emphasized, a laminar elliptical jet viewed along its minor axis *may* dim less rapidly than a circular jet with the same apparent radius, due to its slow expansion in the hidden direction.

(c) The $I_\nu(\Phi)$ data.

The actual variations of I_ν with jet FWHM Φ (assumed proportional to R_j) are slower than most of these "adiabats" over long regions of many jets. Nearest to the core, I_ν often increases with increasing Φ – the jets "turn on" following regions of diminished emission, or "gaps". The "turn-on" is often followed by regimes many kpc long in which I_ν typically declines as Φ^{-n} with $n = 1.2$ to 1.6. In 3C31, NGC315 and NGC6251, the value of n reaches ≈ 4 far from the core, as expected for the adiabatic $B_\perp$-dominated circular jet, but in NGC6251 (PBW) the "adiabatic" decline ≥ 100 kpc from the core is repeatedly interrupted by the "turning on" of bright knots.

Dissipation and particle acceleration in jets are extensively explored later in this Workshop (see the papers by Jean Eilek, Geoff Bicknell and Dick Henriksen), so suffice it here to note that the highly subadiabatic $I_\nu(\Phi)$ behavior of $B_{||}$-dominated jets makes it likely that some of their bulk kinetic energy (which is not lost by adiabatic expansion) is dissipated to magnetic flux and relativistic particles through shocks or turbulence. If B_j is near equipartition on the kiloparsec scales, $B_{||}$ must be amplified locally (instead of falling as R_j^{-2}) or else long $B_{||}$-dominated jets would have unreasonably high fields on parsec scales.

These mechanisms for particle reacceleration may also be effective in $B_\perp$-dominated regions, but another process can also work well there – deceleration of the jet by entraining surrounding material. The "typical" $I_\nu \propto R_j^{-1.4}$ dimming law can be reached by adiabatic compression with $v_j \propto R_j^{-0.68}$ in a circular jet with electron energy index $\gamma = 2.3$, or $v_j \propto R_j^{-0.26}$ in an elliptical jet with $\gamma = 2.3$ and $x = 5/3$ propagating in an atmosphere with $n = 1.5$. The hypothesis that adiabatic deceleration is solely responsible for the slow dimming of such jets can be tested quite simply at low frequencies. The Faraday depth through a jet is roughly proportional to $\rho_j B_j R_j$, which in a circular $\mathrm{B}_\perp$-dominated jet entraining at constant thrust T_j is proportional to $R_j^{-2} v_j^{-3}$. The Faraday depth in such a jet would therefore be nearly constant if it decelerated with $v_j \propto R_j^{-0.68}$, whereas it would decrease as R_j^{-2} in a constant-velocity flow. The low-frequency Faraday depth variations of resolved jets in weak radio galaxies should therefore be a good diagnostic of whether their slow dimming is due to adiabatic deceleration by entrainment[7].

Detailed understanding of what keeps large scale jets lit up requires self-consistent modeling of their collimation $\Phi(\Theta)$, intensity evolution, and apparent magnetic field configurations. Abrupt changes in $\mathbf{B_a}$ from $\mathrm{B}_{||}$ to $\mathrm{B}_\perp$ at bright knots may indicate particle acceleration at oblique shocks, particularly if the knots have their sharpest brightness gradients on their coreward sides, as in M87 and NGC6251. The degrees of linear polarization in, and the depths of, the $\mathrm{B}_{||}$ edges on $\mathrm{B}_\perp$–dominated jets may indicate the extent of viscous interactions with the surrounding ISM/IGM. The observations provide copious constraints for the models – jet spreading rates $d\Phi/d\Theta$, "turn-on" heights, transverse intensity profiles, field orderliness and orientation, as well as in the $I_\nu(\Phi)$ evolution. Models of jet propagation are not yet sufficiently versatile to confront the data at all of these points self-consistently, however, but the prospects for the future are discussed elsewhere in this Workshop.

9. 3-D MAGNETIC FIELD CONFIGURATIONS

The jet magnetic fields $\mathbf{B_j}$ must be at least partially ordered, (a) because of the high degrees of linear polarization in the jets and (b) because of the organization seen on the available well resolved maps of the "apparent" magnetic fields. The 3-D configuration of the ordered fields is important for models of the jet dynamics, but cannot yet be

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[7] It was the *appearance* of constant Faraday depth in NGC315 (Willis *et al.* 1981) and NGC5127 (Fanti *et al.* 1982) that first made me aware of the possible significance of adiabatic slowdown for keeping jets lit up. The depolarizations observed in these two jets are only marginally different from unity, however, so the published Faraday depth estimates for them should probably be treated as upper limits rather than secure measurements. Multifrequency polarimetry at arc-second resolution below 1 GHz is required to carry out this test properly.

found unambiguously from the radio data.

The intrinsic degree of polarization $p_i(\gamma) = (3\gamma{+}3)/(3\gamma{+}7)$ would be about 71% for particles with $\gamma = 2.3$ moving in a uniform field. Observed polarizations up to 40% are common in radio jets at 6 cm and shorter and local values $> 50\%$ are known. Such high polarizations imply significant spatial ordering through the jet of $\mathbf{k} \times (\mathbf{k} \times \mathbf{B_j})$, where $\mathbf{k}$ is the unit vector towards the observer. This ordering need not imply full 3-D ordering of $\mathbf{B_j}$, however, as emphasized by Laing (1981). Suppression of one spatial component of $\mathbf{B_j}$, leaving the others randomized is sufficient to explain the high polarizations, though not to explain the variation of p_ν *across* a jet. Jets with $< 5\%$ linear polarization at short wavelengths (e.g. 3C277.3, 3C388) are exceptional.

Relating the distribution of $\mathbf{B_a}(\alpha, \delta)$ over the face of a jet to that of $\mathbf{B_j}(r, \phi, z)$ throughout it is non-trivial. $\mathbf{B_a}$ lies along the dominant ordered component of $\mathbf{B_j}$ perpendicular to the line of sight $\mathbf{k}$, in a synchrotron emissivity weighted vector average. If $\mathbf{B_j}, N_0$ and γ are *axisymmetric* functions of radius r in the jet and distance z along it, and the divergence of the jet is small, $\mathbf{B_a}$ must be either parallel to, or perpendicular to, the jet axis. All three of the common configurations, $\mathrm{B}_{\|}$, $\mathrm{B}_{\perp}$ and $\mathrm{B}_{\perp-\|}$, can thus be synthesized from axisymmetric $\mathbf{B_j}$ distributions. The fact that these three configurations are common probably indicates that the organized components of $\mathbf{B_j}$ are axisymmetrically distributed.

To get further, we need the information provided by the distribution of the degree of linear polarization p_ν transverse to the jet. p_ν is generally highest at the edges of the jet in $\mathrm{B}_{\|}$ regions, but near the center of the jet in $\mathrm{B}_{\perp}$ regions. $\mathrm{B}_{\perp-\|}$ regions have polarization minima at each of the field transitions across the jet. Ideally, we could combine observed transverse profiles of I_ν and p_ν with the distribution of the apparent field $\mathbf{B_a}$ to infer the 3-D field configurations $\mathbf{B_j}(r, \phi, z)$. The relation of the data to $\mathbf{B_j}$ is not unique, however, especially if the data do not extend to the Faraday thick (long-wavelength) regime.

Laing (1981) gives analytic expressions and graphs of transverse profiles of I and p for several axisymmetric $\mathbf{B_j}$ distributions, assuming $\gamma = 3$ (for which many of the integrals have analytic forms) and $n_e = 0$, to eliminate Faraday effects. It is clear from Laing's results, and from more general cases that I have examined numerically, that two broad classes of 3-D field configurations generally fit the distributions of p_ν at high frequencies for which the Faraday depths should be negligible. These are (a) tangled field loops confined to a plane perpendicular to the jet axis near the center of the jet but stretched along the axis towards its edges or (b) "flux ropes" with organized helical fields of variable pitch, i.e. with ϕ and z components $B_\phi = B_0(r/R_j)\cos\psi_R, \quad B_z = B_0 \sin\psi_R$ (where ψ_R is the pitch angle of the field at the jet boundary $r = R_j$, Chan and Henriksen 1980) *plus* a random field component B_{rand}. Such calculations also show that $\mathrm{B}_{\|}$ can dominate $\mathbf{B_a}$ across much of the transverse profile of a jet with a helically-wound field if the jet is not in the plane of the sky (e.g. Laing 1981); thus merely searching for $\mathrm{B}_{\perp}$ is inadequate as test for helical field geometries.

Observations of jets in their Faraday thick regime are required to distinguish these alternative 3-D field configurations, which have very different implications for the possible influence of the fields on jet dynamics and collimation. At frequencies where the jet

Faraday depth is finite but typically < 1 radian, the flux rope fields produce transverse Faraday rotation gradients across a jet. At these wavelengths the degree of polarization at a given location and resolution will also decrease with frequency on one side of the jet but increase on the other, until the Faraday depth becomes large. The "sheared tangled" fields would not produce such systematic transverse asymmetries in the apparent Faraday rotation or depolarization. Several beamwidths are needed across the jet to detect and distinguish these cases. As the Faraday thick regime appears to be below 1.3 GHz in most jets, this will require polarimetry with MERLIN or a composite VLA/VLBA array. Note from §8 that such observations would also test adiabatic deceleration as the prime mechanism for keeping a $B_\perp$-dominated jet lit up.

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