Extragalactic jets: trends and correlations[1]

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The systematic properties of jets from active extragalactic objects are reviewed and related to models of confined jet propagation. The debate about jet velocities and the origin of one-sidedness is outlined, and some important future observations are listed.

On présente une revue des propriétés systématiques des jets provenant d'objets extragalactiques et ces propriétés sont reliées aux modèles de propagation confinée des jets. On expose les grandes lignes du débat concernant les vitesses des jets et l'origine de l'unilatéralité, et on donne une liste de certaines observations futures importantes.

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1. Introduction

I have been asked to review the observed properties of jets emanating from active galactic nuclei (AGNs), which I shall take to mean radio galaxies and quasi-stellar objects (QSOs). In his review on outflows from star-forming regions, Lada defined a jet as "a collimated stream or flow." I wish that those of us studying AGNs could do the same. Most of our statements about flow velocities in our putative jets rest not on the bedrock of Doppler-shifted emission lines and proper motions but on rickety piles of assumptions and model-building. For us, a jet is a feature that *looks* as if it *might* be a collimated stream or flow emanating from the center of an AGN. Still, active galaxies form a large part of the agenda of this "Jets" meeting because *so many* of them contain long, narrow radio features. Section 2 discusses this ubiquity of jetlike features from AGNs. Section 3 outlines how their properties correlate with power and identifies two basic "flavors" of extragalactic jet. Section 4 considers their collimation and Sect. 5 their brightness properties. Section 6 argues that the two jet flavors parallel the two principal instability regimes of confined supersonic jet propagation. Section 7 reviews the current debate about jet velocities and sidedness, and Sect. 8 lists some problems to challenge jet observers at all wavelengths. More detailed reviews of extragalactic jet data and models can be found in refs. 1–3.

2. The ubiquity of extragalactic jets

I know of 136 extragalactic sources with measured red shifts and radio features that meet my three empirical criteria for jethood; namely, the feature is

(i) at least four times as long as it is wide (after deconvolving the instrumental response from the image),

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

(iii) aligned with the nucleus of the parent object where it is closest to it. (The nuclei of sources with clear radio jets are always marked by compact radio "cores," so I use core and nucleus interchangeably here in practice. My criterion does, however, admit the *possibility* of a so-far unobserved class—coreless radio jets.)

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The 136 sources with clear morphological jets and known red shifts are at distances ranging from 5 Mpc (Cen A) to 10.2 Gpc (a quasi-stellar radio source (QSR) with $z = 2.594$; I assume $H_0 = 100\,\mathrm{km\cdot s^{-1}\cdot Mpc^{-1}}$ and $q_0 = 0.5$ in this paper). Their total powers $P_{\mathrm{tot}}^{1.4}$ at 1.4 GHz range from $10^{21.6}$ to $10^{28.4}$ $\mathrm{W\cdot Hz^{-1}}$, and their core powers P_{core}^{5} at 5 GHz range from $10^{20.4}$ to $10^{28.2}\,\mathrm{W\cdot Hz^{-1}}$. The total jet lengths range from a few tens of parsec (those detected only by very long baseline interferometry (VLBI) jets) to several hundred kiloparsec (jets in giant radio galaxies and QSRs). Jets from AGNs are evidently not confined to any subrange of red shifts, powers, or size scales.

Jets are also found in large *fractions* of complete samples of both weak radio galaxies and extended QSRs imaged at the Very Large Array (VLA) with good sensitivity, dynamic range, and relative resolution (many beam widths across the extended lobes). Definite jets are detected in at least 12 of the 22 radio galaxies with $z < 0.05$ in the rerevised 3C sample ($3CR^2$ (4)), whose median $P_{\mathrm{tot}}^{1.4} = 10^{24.43}\,\mathrm{W\cdot Hz^{-1}}$. Definite jets are also detected in 11 (and possible jets in 4 more) of the 21 *lobe-dominated* $3CR^2$ QSRs with angular diameters $\geq 10''$ that have been imaged by self-calibrated 20- or 6-cm observations $\geq$ 30 min long with the VLA's highest resolution. The median 1.4-GHz total power of these 21 QSRs is $P_{\mathrm{tot}}^{1.4} = 10^{27.39}\,\mathrm{W\cdot Hz^{-1}}$.

In contrast, definite jets are detected in only two of a complete sample of 42 $3CR^2$ radio galaxies with $z \geq 0.4$. The median power ($P_{\mathrm{tot}}^{1.4} = 10^{27.36}\,\mathrm{W\cdot Hz^{-1}}$), angular size, and brightness of these strong $3CR^2$ galaxies are all similar to those of the extended $3CR^2$ QSRs, and both groups have been imaged at the VLA with similar sensitivities, dynamic ranges, and relative resolution. The differing jet-detection rates are thus not merely an instrumental bias; the jets in most strong $3CR^2$ galaxies emit smaller fractions of the total radio flux density than those in the extended $3CR^2$ QSRs. (The large-scale jet in Cyg A emits only about 0.25% of the total luminosity at 1.4 GHz and was found only in VLA images of much higher quality than those available for most other strong radio galaxies.) The differing prominence of the jets in strong radio galaxies and QSRs may also be related to the differing prominence of their nuclear regions at both radio and optical wavelengths. The median value of $f_C = S_{\mathrm{core}}^{5}/S_{\mathrm{tot}}^{1.4}$ for the 21 extended $3CR^2$ QSRs observed at the VLA is 0.017, while for the strong $3CR^2$ galaxies, it is only 0.0005. The two $3CR^2$ radio galaxies with $z > 0.4$ and definite radio jets are 3C200 (with an unusually high f_C = 0.018) and 3C341 (f_C = 0.0005).

The ubiquity of radio jets in extragalactic sources and the morphological and statistical connections between jets and cores suggest that jet production is a universal aspect of AGNs.

Jet radio emission presumably arises from dissipation in the energy transfer from the nuclei to the more extended structures. The sources, or sides of double sources, without detectable jets are therefore often assumed to have invisible (i.e., efficient?) "beams," which might be revealed as jets by more sensitive observations.

This view of jets from AGNs has evolved without direct evidence for outflow in *most* of them. Very long baseline interferometer imaging shows an overwhelming excess of outward-moving knots in parsec-scale jets, some of which point towards larger scale jets. Travelling shocks in parsec-scale jets can account for this, but there is no direct evidence for similar phenomena on scales >10 pc. The properties of the extranuclear optical narrow-line emission systems in some nearby radio galaxies, which van Breugel reviews here (5), also suggest that the lines in these galaxies are excited by kiloparsec-scale outflows interacting with the interstellar medium (or with other galaxies). These emission-line systems do not tell us jet velocities directly, however. The line-emitting gas is usually adjacent to, not entrained in, the synchrotron emission, and the dynamics of its excitation by the outflow are uncertain. Since we lack direct velocity measures, emphasis has been given to the theoretical evidence that AGN jets are outflows. "The jets occur where beam models postulated collimated outflow from AGNs, so if they are not dissipation from the beams, what are they?" We must remain critical of such "evidence," lest we emulate Broderick's s(t)imulated Buffalo Herd (6).

3. Power-related properties of jets

Many properties of the jets change systematically with core power, total power, and the ratio between these.

3.1. Detectability

As noted above, the detectability of radio jets in radio galaxies decreases with increasing P_{tot}; while amongst all strong sources (radio galaxies and QSRs), it appears to increase with core prominence f_C.

3.2. Sidedness

Jets break the symmetry of the lobes in powerful edge-brightened double sources; only in the weaker, edge-darkened sources do the jets generally have detectable counterjets. For reasons described in detail elsewhere (7), I classify jets as one-sided or two-sided by whether $\mathcal{S}$, the ratio of intensities per synthesized beam between the brighter and fainter jet measured at the same separation from the core at low transverse resolution, is >4 or <4. I take $\mathcal{S} = 4$ as the break point solely because this allows me to classify the sidedness of ~75% of known jets from the available imagery, while a break at a higher ratio does not. $\mathcal{S} = 4$ has no a priori physical significance.

In these terms, most kiloparsec-scale jets are one-sided close to the nucleus, but those in weak radio galaxies become two-sided after a few kiloparsecs. The one-sided bases of the two-sided jets in weak sources typically occupy <10% of their total lengths; the jet with the one-sided base is usually the brighter of the two on the large scale. Figure 1 shows how the sidedness of the outer ~90% of the lengths of 110 jets varies with P^5_{core} and $P^{1.4}_{tot}$, updating the corresponding plot in ref. 7. The jets in sources with $P^5_{core} \leq 10^{23}$ W · Hz^{-1} or $P^{1.4}_{tot} \leq 10^{24.5}$ W · Hz^{-1} are mostly two-sided, while most jets in sources with $P^5_{core} > 10^{24}$ W · Hz^{-1} or $P^{1.4}_{tot} > 10^{25.5}$ W · Hz^{-1}, whether radio galaxies or QSRs, are entirely one-sided. This transition is sharper as a function of P_{core} than of P_{tot}, but a small number of sources determines this. The range $P^{1.4}_{tot} = 10^{24.5-25.5}$ W · Hz^{-1}

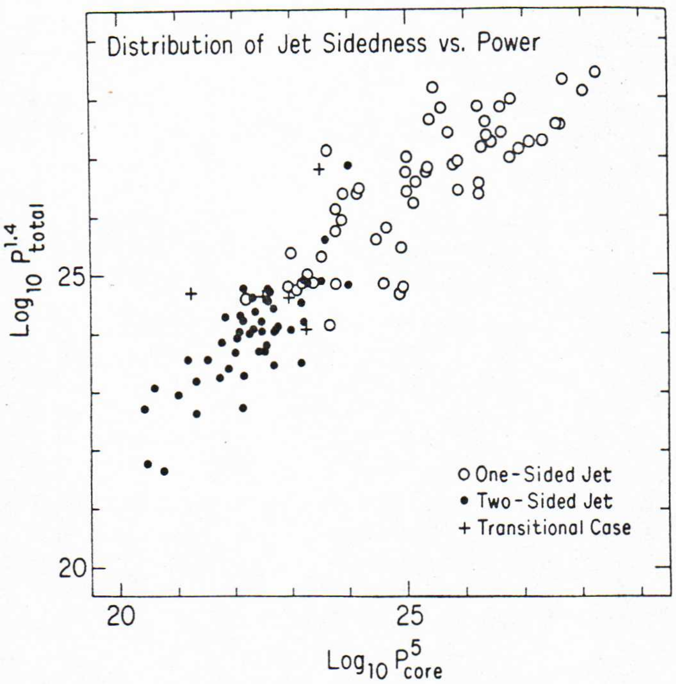

FIG. 1. Distribution of jet sidedness (brightness asymmetry greater than or less than 4 : 1) in the plane of log P^5_{core} and log $P^{1.4}_{tot}$ for the outer ~90% of the lengths of 110 jets associated with radio galaxies and QSRs.

also marks the transition between weak sources with edge-darkened plumelike large-scale structures without clear hot spots and powerful sources with edge-brightened lobes containing strong hot spots.

The two weakest cores associated with one-sided jets are those in Cen A ($P^5_{core} = 10^{22.20}$ W · Hz^{-1}) and M87 ($P^5_{core} = 10^{22.92}$ W · Hz^{-1}). Their jets are short (M87, 1.8 kpc; Cen A, 5.2 kpc), comparable in length to the one-sided bases of the two-sided jets in other sources with similar total powers. The deviant feature of the M87 and Cen A jets may, therefore, not be their one-sidedness but the fact that they turn into two-sided inner lobes instead of into two-sided outer jets extending tens of kiloparsecs further from the nuclei.

3.3. Magnetic configuration

Degrees of linear polarization $p = \sqrt{(Q^2 + U^2)}/I$ up to 40% are common in radio jets at wavelengths ≤6 cm, and local values $p > 50\%$ are not unusual. Jets with $p < 5\%$ at short wavelengths are exceptional. High p implies significant spatial ordering through a jet of the component of the jet magnetic field $\boldsymbol{B}_j$ perpendicular to the line of sight, but this need not imply three-dimensional (3-D) ordering of $\boldsymbol{B}_j$ (8, 9). Suppression of one spatial component of $\boldsymbol{B}_j$, leaving the others randomized, is sufficient to explain high p.

Three apparent magnetic configurations $\boldsymbol{B}_a$ are common in the 40 straight jets for which adequate polarimetry exists ($\boldsymbol{B}_a$ lies along the dominant ordered component of $\boldsymbol{B}_j$ perpendicular to the line of sight, in a synchrotron emissivity-weighted vector sum):

(i) $B_{\parallel}$, i.e., $\boldsymbol{B}_a$ is predominantly parallel to the jet axis all across the jet. In such cases p is usually a minimum at the center of the jet at high frequencies.

(ii) $B_{\perp}$, i.e., $\boldsymbol{B}_a$ is predominantly perpendicular to the jet axis all across it. In such cases p usually reaches a maximum at the center of the jet or is roughly constant across it.

(iii) $B_{\perp-\parallel}$, i.e., $\boldsymbol{B}_a$ 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. In such cases p is usually a maximum near the center of the jet.

Most two-sided regions of straight jets have either the $B_\perp$ or the $B_{\perp-\parallel}$ configuration, while most one-sided regions of jets have the $B_\parallel$ configuration. In straight jets emanating from weak cores, $\boldsymbol{B}_a$ usually turns from $B_\parallel$ to $B_\perp$ or $B_{\perp-\parallel}$ in the first 10% of their lengths. Jets emanating from powerful cores are generally $B_\parallel$-dominated everywhere (7).

Two departures from these basic patterns of $\boldsymbol{B}_a$ may arise from perturbations of jets:

(i) Curved jets often develop a deep, strongly polarized $B_\parallel$ edge on the outside of a bend, as if $B_\parallel$ is amplified there by stretching and shearing of the flow. $B_\parallel$ can extend all across very bent jets in C-shaped head–tail sources, even though they are two-sided. These fields may be extreme examples of the $B_{\perp-\parallel}$ configuration resulting from viscous interaction with the ambient medium, though helically wound fields can also show such asymmetry purely geometrically (9).

(ii) Some bright knots in one-sided jets have $\boldsymbol{B}_a$ perpendicular to the steepest brightness gradient in the knot, although fainter emission near it is $B_\parallel$-dominated. These magnetic anomalies at bright knots may be due to oblique shocks accelerating relativistic particles and (or) compressing the component of $\boldsymbol{B}_j$ parallel to the shock front. One-sided $B_\parallel$ jets may also terminate at $B_\perp$ hot spots, perhaps for similar reasons.

The relation between the patterns of $\boldsymbol{B}_a$ and p over the face of a jet to the 3-D distribution of $\boldsymbol{B}_j$ throughout it is not unique, especially if the data do not extend to the Faraday thick (long-wavelength) regime. Two broad classes of 3-D fields fit the $(\boldsymbol{B}_a, p)$ data at short wavelengths, where the Faraday depths $\mathcal{F}$ are small. These are (i) tangled loops confined to a plane perpendicular to the jet axis near the center of the jet (8, 9), but stretched along the axis towards its edges (10, 11), or (ii) "flux ropes" with partially randomized helical fields whose pitch angle varies with radius (11–13). At longer wavelengths where $\mathcal{F}$ is significant but <1 rad, flux-rope fields must produce transverse Faraday-rotation gradients across a jet, and p at a given pixel and resolution should decrease with increasing wavelength on one side of the jet but increase on the other (until $\mathcal{F}$ becomes large). The "tangled-loop" fields would not produce such systematic transverse asymmetries in the apparent Faraday rotation or depolarization. Observations of intrinsic Faraday rotation and depolarization of jets at $\approx 1''$ resolution may be able to distinguish these cases. As the $\mathcal{F} \rightarrow 1$ regime appears to be at $\lambda > 20$ cm in most jets, this is a job for the multi-element radio-linked interferometer network (MERLIN) or for a composite VLA–VLBA array at 327 MHz.

3.4. Size, curvature, and misalignments

Jets in weak radio galaxies and in powerful core-dominated sources are generally short, at least in projection (1). The jets in core-dominated sources may be foreshortened by projection if their cores are really the Doppler-boosted bases of bulk relativistic jets. The jets in the weak radio galaxies are two-sided, however, so they are probably short intrinsically.

Strong jet curvature is also common in two distinct regimes: (i) C-shaped, two-sided jets in weak "head–tail" cluster galaxies and (ii) one-sided jets in core-dominated sources. Curvature may be due to bending of a confined jet by an external pressure (as in most models for narrow head–tail sources), by interaction with clouds in the ISM or intergalactic medium (IGM), by wandering of the axis of the central collimator, or, in distant sources, by gravitational distortion due to intervening matter (14).

The misalignments between parsec- and kiloparsec-scale jets increase with increasing core prominence (15). Several lobe-dominated double radio galaxies with kiloparsec-scale jets have one-sided parsec-scale jets on the same side as the large jets and aligned with them to $\leq 10°$. In powerful core-dominated sources, the misalignments between parsec- and kiloparsec-scale structures are often much larger than this.

3.5. Collimation

Jet spreading rates decrease with increasing source power. Figure 2 shows the mean spreading rates of the resolved jets in 22 extragalactic sources as functions of both $\log_{10} P^5_{\mathrm{core}}$ and $\log_{10} P^{1.4}_{\mathrm{tot}}$, updating the data in ref. 7. These plots smooth fine detail of each jet to show the general trend; the mean jet spreading rates are measured by the ratio of the full width half maximum (FWHM) Φ to the angle Θ from the core halfway along each jet, and the data for jets and their counterjets in the same source have been averaged. Most of the jets in the powerful sources in Fig. 2 have been observed with as many beam widths along their lengths as those in the weaker sources, so the trend is unlikely to be a resolution bias. The small median angle ($<1°$) subtended at the radio cores by hot spots in the lobes of powerful doubles (16) is consistent with the trend, if the sizes of the hot spots indicate (roughly) the diameters of shock structures near the ends of (often invisible) jets in such sources.

3.6. Clumpiness

The brightness distributions of the one-sided jets in many powerful sources, and of the initial one-sided segments of jets in weak sources, are clumpier than those of the two-sided outer regions of the jets in low-power sources (17), though there are few quantitative measures of this in the current literature.

3.7. Summary

To generalize, straight extragalactic jets come in two basic flavors: two-sided, smooth, $B_\perp$-dominated, rapidly spreading jets that feed edge-darkened extended structures, and one-sided, clumpy, $B_\parallel$-dominated narrow jets that feed edge-brightened lobes containing hot spots. At the base of many two-sided jets there lurks a short one-sided jet, but the two-sided traits dominate in sources with $P^5_{\mathrm{core}} < 10^{23}\ \mathrm{W \cdot Hz^{-1}}$ and the one-sided ones dominate in sources with $P^5_{\mathrm{core}} > 10^{24}\ \mathrm{W \cdot Hz^{-1}}$. The transition between these extremes is rapid in P^5_{core}, relative to the $\sim 10^8 : 1$ range of this parameter in jetted AGNs.

4. Where and how are the jets collimated?

A steady free jet (internal pressure $p_j \gg p_e$, the sum of all external pressures) would spread with a constant lateral velocity $v_r = c_S$, its internal sound speed where it first became free. Its radius R_j would, therefore, grow with distance z from the core at a constant rate $\mathrm{d}R_j/\mathrm{d}z = v_r/v_j$, unless v_j is slowed by gravity, in which case $\mathrm{d}R_j/\mathrm{d}z$ might increase with z near the core. The transverse brightness profiles of well-resolved jets are generally center brightened, so their FWHMs Φ (corrected for the instrumental resolution) can be used to characterize how the synchrotron emission spreads with angle Θ from the radio core. Center brightening supports the view that jet radio emission is generated in the energy-transport region itself, not in a static cocoon around it, so $\Phi(\Theta)$ may track the form of $R_j(z)$. If the jet magnetic fields $\boldsymbol{B}_j$ are dominated by large-scale organized components whose configuration changes with z, parts of the $\Phi(\Theta)$ evolution may also reflect $\boldsymbol{B}_j$ evolution.

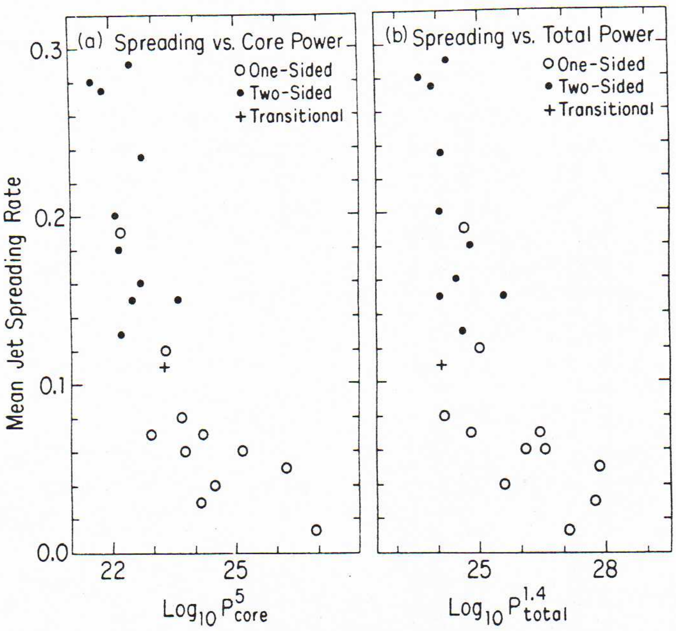

FIG. 2. Decrease in mean spreading rates of transverse-resolved jets in 22 radio galaxies and QSRs with increasing log $P^2_{\rm core}$ (*a*) and increasing log $P^{1.4}_{\rm tot}$ (*b*). Jet sidedness (brightness asymmetry greater than or less than 4 : 1) is indicated by the same symbols as in Fig. 1; note the overlap between one-sided, two-sided, and transitional cases at intermediate powers.

If $d\Phi/d\Theta \propto 2(dR_j/dz)$ 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 p_j is being balanced by a slowly decreasing $p_e(z)$. The first kiloparsec or so of well-resolved jets in weak radio galaxies typically have $d\Phi/d\Theta \le 0.1$. Between 1 and 10 kpc, such jets usually "flare," $d\Phi/d\Theta$ reaching $\approx$0.15–0.5. Many then recollimate on scales of 10–30 kpc, $d\Phi/d\Theta$ oscillating near zero at these distances; some, e.g., ref. 11, re-expand rapidly still further from their cores. Both sides of two-sided jets in weak radio galaxies recollimate at similar distances from the core. The recollimation shows that the jets are not free flows whose spreading rates are fixed on parsec scales, even though VLBI data show that many jets are first collimated on such scales. Instead, we must have $p_j \approx p_e$ over many kiloparsecs of these jets. It is still unclear, however, what physical mechanism causes the recollimation that occurs on 10- to 30-kpc scales, i.e., what term dominates p_e at these distances.

The observed synchrotron properties set lower limits $p_{\rm min}$ for the total jet pressures p_j in nearby radio galaxies that typically range from $\approx 10^{-10}$ dyn · cm^{-2} in the inner few kiloparsecs to $\approx 10^{-13}$ dyn · cm^{-2} ~ 100 kpc from the galactic nuclei. $p_{\rm min}$ usually scales as $\sim z^{-1}$ to $\sim z^{-2}$. The Einstein Observatory detected extended soft X-ray emission at $\sim(1-3) \times 10^7$ K around several nearby elliptical galaxies. The Einstein data are consistent with such galaxies having gaseous haloes in which the thermal pressures are similar to $p_{\rm min}$ in the jets of weak radio galaxies and vary similarly with radius z. The thermal pressures of these gaseous haloes could, therefore, (just) confine typical, weak, radio galaxy jets. Jet confinement by intracluster gas at $\sim 7 \times 10^7$ K is even more compatible with the X-ray data in some cases. However, the contribution of compact X-ray sources to the Einstein data is often unclear. Sensitive X-ray imaging and temperature determinations of the regions 1–50 kpc from AGNs are needed to check whether the jets in weak sources are actually collimated by galactic halo gas.

In the case of M87, the Einstein and VLA data (18, 19) show that $p_{\rm min}$ in the radio knots (a few times 10^{-9} dyn · cm^{-2} here) exceeds the thermal pressure at their projected distances in the X-ray halo by >10 : 1. Biretta *et al.* (19) conclude that only the first few hundred parsecs of this jet can be thermally confined by the halo gas, unless the jet has a bulk Lorentz factor $\gamma_j \ge 50$ and points within about 1° of the line of sight. The jet does not, however, appear to be free; its first kiloparsec spreads at a constant rate, but the spreading rate slows beyond the brightest knot ("A").

The $\Phi(\Theta)$ evolution is but crudely known for most of the kiloparsec-scale jets in more powerful sources. They spread slowly (Sect. 3.5) and are observed with relatively poor linear resolution because they are distant. The data are good enough to show in some cases that $d\Phi/d\Theta \approx 0$ on 10-kpc scales; but to reach the measured widths Φ in the first place, they must spread rapidly near the cores, i.e., these jets also appear to be confined by a mechanism that takes effect some tens of kiloparsecs out. An argument based on thrust balance (20) also suggests that some of these jets are not free. A nonrelativistic jet has a thrust

$$T_j \ge \rho_j v_j^2 A_j$$

where ρ_j is its density; v_j is its velocity; and A_j is its cross-sectional area. However,

$$v_j^2 = M_j^2 \Gamma p_j / \rho_j$$

so

$$T_j \ge M_j^2 \Gamma p_j A_j > M_j^2 \Gamma p_{\rm min} A_j$$

where $p_{\rm min}$ and A_j can be estimated from the radio data. If the jets in powerful extended QSRs were free, their spreading rates would imply $M_j \approx 50$, making T_j so large that the jets could not be stopped or deflected by the IGM. Either M_j or $p_{\rm min}$ must have been overestimated, i.e., either these jets are confined or they are Doppler-boosted.

Both thermal confinement and the Doppler mechanism have difficulties with other data on these QSRs, however. The X-ray luminosities of the regions around several QSRs with kiloparsec-scale radio jets (21) are too low to confine the mean jet pressures unless the halo gas has temperatures well above 10^8 K. Heating and confinement of the gas are then nontrivial problems in their own right. Doppler boosting of a jet with bulk Lorentz factor γ_j could mean that $p_{\rm min}$ is overestimated by a factor γ_j^2 (relieving the thrust problem) if the jet is very close to the line of sight. Although all the jets that have thrust-balance and (or) thermal-confinement problems are one-sided, as expected if Doppler boosting is important, the Doppler solution has unpalatable aspects; both the thrust-balance and thermal-confinement problems respond only very slowly to the Doppler remedy. The projection required for the Doppler boosting increases the inferred linear size of the radio source by sec i and thus increases the volume to be filled by any thermally confining gas by sec^3 i. To avoid continuing conflict with the X-ray-luminosity data, this increase in the volume must be more than compensated for by the reduction in the square of the confining density n_e^2 obtained by lowering $p_{\rm min}$. In practice, the jets must lie very near the line of sight to eliminate both the thrust and confinement problems, making it hard to explain why so many are detected in samples of large lobe-dominated QSRs (which should not be oriented preferentially towards the observer).

For these reasons, magnetically assisted confinement is frequently (e.g., refs. 3, 13, and 22) invoked for jets in powerful sources. It requires that currents $\approx 10^{17}$–10^{18} A flow along the jets if B_j is near equipartition. Such currents could be driven at reasonable mass fluxes with very small drift velocities ($\approx 10^{-12} v_j$) between positive and negative charges in the jet plasma. The magnetic stresses in toroidal fields around the current can then "buffer" a high value of p_{min} near the jet axis to a lower value of the thermal pressure further from the axis.[3] The return currents required to prevent space-charge accumulation must lie outside the observed radio-emission regions. As $\boldsymbol{B}_a$ in the QSR jets is $B_\parallel$ dominated, there is no direct evidence for the toroidal components of $\boldsymbol{B}_j$ required by this mechanism. This does not exclude magnetically assisted collimation, however, as $B_\parallel$ can dominate $\boldsymbol{B}_a$ across most of a jet with a helically wound field if the jet is not in the plane of the sky (9). The synchrotron-radiating particles may also be confined to the $B_\parallel$-dominated core of a jet that is confined by this means. It may, therefore, be difficult to use radio polarimetry to test whether this mechanism is operating. Jet observers must also distinguish local overpressures at knots from large-scale overpressures *between* knots before we can be sure how widespread the collimation problems are. The jet pressure p_j could rise to $\sim M_j^2 p_e$ in shocked regions without requiring additional global confining mechanisms such as magnetic effects.

To summarize, the jets in all sources appear not to be free on scales of order 10 kpc, but we are not yet sure what confines those in the powerful sources. Thermal collimation is possible in the weaker sources, but if electromagnetic effects help to confine jets in powerful sources, they may also be active in weak ones.

5. What keeps jets lit?

Both the magnetic-field strengths B_j and the relativistic particle energies E decrease along an expanding laminar jet without magnetic-flux amplification or particle re-acceleration. If (i) magnetic flux is conserved, (ii) the radiating particles do work as an optically thin jet both expands laterally and responds to variations in its flow velocity v_j, (iii) there is no particle re-acceleration, and (iv) the relativistic electron energy spectrum is a power law of index γ from energies E_{min} to $E_{max} \gg E_{min}$, then the synchrotron emissivity ε_ν varies with jet area A_j and velocity v_j as

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

in a region of the jet where B_j is dominated by $B_\parallel$ (23). For well-resolved jets, we can measure the variation of the peak intensity I_ν with FWHM Φ ($\propto R_j$) along the jet ridgeline. In an optically thin jet $I_\nu \propto \varepsilon_\nu l_j$, where l_j is the depth of the jet along the line of sight, so

$$I_\nu \propto A_j^{-(5\gamma+7)/6} l_j v_j^{-(\gamma+2)/3}$$

if $B_\parallel$ dominates. For $B_\perp$-dominated fields, these relations are

$$\varepsilon_\nu \propto A_j^{-(\gamma+2)/3} l_j^{-(\gamma+1)/2} v_j^{-(5\gamma+7)/6}$$

and

$$I_\nu \propto A_j^{-(\gamma+2)/3} l_j^{-(\gamma-1)/2} v_j^{-(5\gamma+7)/6}$$

The adiabats for circular jets (11) follow by putting $A_j = \pi R_j^2$ and $l_j = R_j$ in these general forms, whereon

$$I_\nu \propto R_j^{-(5\gamma+4)/3} v_j^{-(\gamma+2)/3}$$

for $B_\parallel$ dominant and

$$I_\nu \propto R_j^{-(7\gamma+5)/6} v_j^{-(5\gamma+7)/6}$$

for $B_\perp$ dominant. In a laminar circular jet with the typical $\gamma = 2.3$,

$$I_\nu \propto R_j^{-5.2} v_j^{-1.4}\ (B_\parallel)$$

or

$$I_\nu \propto R_j^{-3.5} v_j^{-3.1}\ (B_\perp)$$

Note that neither of the flux-conserving expansions $B_\parallel \propto R_j^{-2}$ or $B_\perp \propto (l_j v_j)^{-1}$ is compatible with equipartition of energy between the radiating electrons and the magnetic fields in a confined jet if the radiating particles do work and are not re-accelerated. Equipartition, adiabatic expansion of the particles, and flux conservation are mutually inconsistent in an expanding circular jet.

The adiabats for I_ν in elliptical jets with $A_j = \pi a_j b_j$ depend on the orientation of the jet cross section relative to the observer. For a pressure-matched elliptical jet with $p_e \propto z^{-n}$ and $p_j \propto \rho_j^x$ with $n < 2x$, the major axis $a_j \propto z$ and the minor axis $b_j \propto z^{(n/x)-1}$ (24). If the jet is viewed from a direction near the minor axis of its cross section (the most probable case), then the observer measures $R_j \approx a_j$ and $l_j \approx b_j \approx R_j^{(n/x)-1}$. Then

$$I_\nu \propto R_j^{-(5n\gamma+n+6x)/6x} v_j^{-(\gamma+2)/3}$$

for $B_\parallel$ dominant, and

$$I_\nu \propto R_j^{-(n+7n\gamma+3x-3x\gamma)/6x} v_j^{-(5\gamma+7)/6}$$

for $B_\perp$ dominant. n and x enter these expressions because they determine how the jet shape varies with z. As $R_j \propto a_j \propto z$ for this viewing direction, the jet would appear to be "free." Taking $\gamma = 2.3$, $n = 1.5$, and $x = 5/3$, i.e., a nonrelativistic jet propagating in a typical X-ray halo, we then have $I_\nu \propto R_j^{-2.9} v_j^{-1.4}$ ($B_\parallel$) or $I_\nu \propto R_j^{-2.2} v_j^{-3.1}$ ($B_\perp$). Adiabatic elliptical jets viewed along their minor axes could, therefore, dim less rapidly than circular jets, owing to their slow spreading in the hidden direction. This presentation to the observer is favored both by geometry and by selection; jets that dim rapidly may not be recognized by observers (25).

We see that I_ν should depend strongly on R_j, and significantly on v_j if $B_\perp$ dominates, in adiabatic jets of either cross section. The observed $I_\nu(\Phi)$ variations are often much slower than any of these $I_\nu(R_j)$ adiabats over long regions of the kiloparsec-scale jets. Five types of subadiabatic behavior occur.

(i) In the first 1–10 kpc, I_ν often increases with increasing Φ. The jets "turn on" following regions of diminished emission (sometimes called gaps).

(ii) The turn on is often followed by regimes many kiloparsecs long in which I_ν declines as Φ^{-n} with $n = (1 \pm 0.5)$. In 3C31, NGC315, and NGC6251, the value of n reaches (4 ± 1) far from the core.

(iii) In many jets, the general brightness decline $I_\nu(\Phi)$ is interrupted by the turning on of bright knots, at which I_ν becomes uncorrelated with Φ.

(iv) The jets in powerful sources may terminate at bright hot spots where I_ν and Φ are again uncorrelated, as at jet knots.

(v) In weak sources, the outermost parts of jets or "trails" often brighten and widen simultaneously. This flaring may re-

[3] I call this magnetically *assisted* confinement as no magnetic-field configuration is intrinsically confining; the field can always achieve a lower total energy by expanding, so it must be held in place by something else.

sult from processes similar to the intial turn on but which occur some tens of kiloparsecs farther from the parent object.

Mechanisms suggested to account for such subadiabatic behavior include (a) conversion of some of the bulk kinetic energy of the jet (which is not lost by adiabatic expansion) to magnetic flux and relativistic particles through dissipative interactions with the surrounding ISM, (b) adiabatic slowdown due to entrainment of ambient gas across the turbulent jet boundary, and (c) streaming of the particles along field lines until they are scattered to large pitch angles by magnetic irregularities.

Particle re-acceleration could be mediated either by shocks or by turbulence. If B_j is near equipartition on the kiloparsec scales, $B_\parallel$ must be amplified locally (instead of falling as R_j^{-2}) or else long $B_\parallel$-dominated jets would have unreasonably high fields on parsec scales. Turbulent flows are an attractive model for the subadiabatic behavior of jets in low-power sources as turbulence can explain why the most rapidly spreading parts of such jets are often those of their most subadiabatic intensity evolution (26, 27). The gaps at the bases of some jets can be attributed either to the distance travelled by initially laminar flows before becoming turbulent or to the distance needed for material ejected with different outflow velocities v_j to interact and produce shocks in a jet.

The best way to test different models of particle acceleration in jets will be to image them at optical and X-ray wavelengths, where the synchrotron lifetimes of the particles are short and the shapes and locations of the acceleration regions may, therefore, be seen directly. Data on spectral curvature from radio to X-ray energies as a function of position along a jet would be especially valuable. Polarimetry should be attempted at as many wavelengths as possible to check (i) that the emission being imaged is indeed synchrotron radiation and (ii) that all of any spectrum whose curvature is analyzed arises in the same volume. Abrupt changes in $\boldsymbol{B}_a$ at bright knots may also signify particle acceleration at shocks, particularly if the sharpest brightness gradients at such knots are on their coreward sides.

Adiabatic slowdown is an attractive alternative to particle re-acceleration in jets with Mach numbers ≤ 2, for which entrainment of ambient gas may be very important. Entrainment may make v_j decrease along a jet sufficiently to compensate for the dimming by lateral expansion if $B_\perp$ dominates. Evidence for adiabatic slowdown could be sought in curved jets (by modeling changes in their bending radii). Entrainment might be detected by searches for optical emission lines from entrained gas or by measuring the intrinsic Faraday-depth variations across parts of jets that are not "contaminated" by foreground magnetoionic screens. The Faraday depth $\mathcal{F} \propto \rho_j B_j l_j$, which in a $B_\perp$-dominated jet entraining at constant thrust, is $\propto A_j^{-1} v_j^{-3}$. To make the $B_\perp$-dominated circular-jet adiabat $I_\nu \propto R_j^{-3.5} v_j^{-3.1}$ ($\gamma = 2.3$) appear to be $I_\nu \propto R_j^{-1\pm0.5}$, as typically observed, would require $v_j \propto R_j^{-0.8\pm0.15}$, hence $\mathcal{F} \propto R_j^{0.45\pm0.4}$; whereas in a constant-velocity jet, $\mathcal{F} \propto R_j^{-2}$. This constant-thrust case is an idealization but illustrates that $\mathcal{F}$ will not drop rapidly, and may indeed grow, along a spreading jet that stays as bright as observed by entrainment and adiabatic slowdown. Long-wavelength polarimetry with MERLIN and the composite VLA–VLBA may, therefore, be able to test this mechanism.

To decide in detail what keeps jets lit up, we should require jet-brightness models to describe self-consistently many of the observables: jet spreading rates, turn-on heights, transverse intensity profiles, field orderliness and orientation, $I_\nu(\Phi)$ evolution, spectral curvature, and Faraday depths.

6. The two jet flavors and propagation regimes

Both analytic and numerical modeling of the effects of boundary-layer instabilities on the propagation of pressure-confined supersonic jets identify two main regimes of jet propagation in the parameter plane, representing the initial density contrast $\eta = \rho_j/\rho_{ext}$ between the jet and the external medium and the jet's internal Mach number M_j (22, 28, 29). The heavy or mildly supersonic regime $\eta > (M_j - 1)^2$ is that of "ordinary mode" (OM) dominated propagation characterized by a rapidly growing mixing layer at the jet boundary, rapid deceleration of the jet via entrainment of ambient gas, and ultimate disruption of the jet by mass exchange with the surrounding medium. In contrast, the light, hypersonic regime $\eta < (M_j - 1)^2$ is that of "reflection mode" (RM) dominated propagation wherein the jet couples to the external medium mainly via shocks. The effects of mass exchange in this regime are relatively minor, and the jets develop internal patterns of biconical shocks that do not immediately disrupt them, though they do extract kinetic energy from the flow and convert it into internal energy.

Real jets must undergo parameter evolution in the (η, M_j) plane as they descend pressure gradients in galactic haloes, and they may also oscillate between freedom and confinement. We also do not know in detail how the brightness of synchrotron emission visualizes different details of the model flows. Despite these caveats, I believe that the two basic extragalactic jet flavors may parallel the two basic jet-propagation regimes.

The jets in the weak sources resemble the mildly supersonic (OM-dominated) case. Their rapid spreading resembles that of round, turbulent laboratory jets with $1 \leq M_j \leq 2$ (30) and may account for the rapid dominance of $B_\perp$. Such jets can stay bright as they spread by (i) becoming turbulent and (ii) entraining gas and slowing down. Mass exchange with the surrounding medium may eventually make them subsonic so that they ultimately "poop out" as meandering plumes without making radio hot spots, i.e., forming edge-darkened large-scale structures. They do not form extensive backflow cocoons.

The jets in the strong sources resemble the light, hypersonic (RM-dominated) case. Such jets spread more slowly so it is easier for $B_\parallel$ to remain dominant through surface shear. They develop cellular patterns of internal X-shocks that may manifest themselves as the observed clumpy brightness distributions through particle reacceleration and field amplification at the shocks. Parameter evolution and spreading geometry can expand the scale of the shock cells as the jets descend pressure gradients. Such jets may, therefore, remain supersonic and thus punch their way out to form shock structures near an interface with the IGM far from the parent object. Nonaxisymmetry in such light hypersonic jets may lead to two-stage oblique shocking before the jet finally decollimates, producing pairs of hot spots and "splatter spots" near the outer edges of the lobes, in agreement with observation (31). Backflow from the ends of jets with $\eta \ll (M_j - 1)^2$ can accumulate around them to form cocoons, which may correspond to the broad interlobe bridges of classical double sources (32).

7. The great velocity–sidedness debate

There is some evidence for, and little evidence against, bulk relativistic motion on parsec scales in at least some jets. If some outflows in AGNs have components with bulk Lorentz factors γ_j, we can account for a variety of observed phenomena:

(i) superluminal separations of discrete knots in some VLBI core-jet structures,

(ii) the almost-universal one-sidedness of the VLBI core jets,

(iii) very high brightness temperatures implied by rapid centimetre-wavelength variability,

(iv) low Compton X-ray fluxes from bright, compact radio sources, and

(v) large apparent curvatures of jets, or misalignments between parsec- and kiloparsec-scale jets in strongly core-dominated sources.

Not all compact sources show all of these effects simultaneously, but many show several of them simultaneously. It is attractive to infer that some parsec-scale jets contain bulk relativistic flows with Lorentz factors $\gamma_j \approx 5$. If all sources contained such flows on parsec scales, the fraction oriented within $\sim\gamma_j^{-1}$ rad of our line of sight (as needed to produce the above effects) would be $\sim(2\gamma_j^2)^{-1}$, i.e., a few percent. This is consistent with present lower limits to the occurrence rates of these effects in those complete samples of AGNs that we might expect to be randomly oriented with respect to us. However, the nature of the parent (randomly oriented) population is still debated, so it is important to see whether more sensitive VLBI monitoring of the radio cores of AGNs raises the occurrence rates of the phenomena in this relativistic smorgasbord.

There is much controversy about jet velocities on kiloparsec scales. All estimates of average flow velocities $\bar{v}_j$ on kiloparsec scales in extragalactic jets are distressingly sensitive to the initial assumptions (1, 3, 11). Methods frequently used assume jet properties to be stationary in time and include estimating $\bar{v}_j$ from observables via (a) lobe energetics, (b) thrust balance, (c) mass-flux constraints, (d) wiggle wavelengths and (linear) instability theory, (e) galaxy kinematics and dynamical models of jet bending, (f) spreading rates and assumptions about freedom or confinement, (g) spectral curvature arguments, and (h) Doppler-boost interpretations of one-sidedness. Equipartition between relativistic particles and fields is assumed to obtain relevant energy densities, pressures, or field strengths, (usually with but a guesstimate of electron-proton energy ratios and related particle acceleration efficiencies). Depolarization data and assumptions about field geometry and Faraday-depth distributions are sometimes used to estimate thermal densities. The chain of assumptions usually prescribes the result more firmly than do the data.

All we can be sure of is that if there is outflow on kiloparsec scales, its velocity is somewhere between the escape velocity from the appropriate height above the parent object and the velocity of light. The sensitivity of Doppler boosting to $v_j \sin i$ also argues against $v_j \geq 0.2c$ in the C-shaped jets in narrow head–tail sources (33). These C-shaped jets appear to be confined by the ram pressure of the IGM, and v_j changes direction along some of them by almost 90°. If $v_j \approx c$, their side-to-side asymmetries and brightnesses should change systematically as they bend, in conflict with observation.

The questions in the basic velocity debate can be summarized as follows. Collimation and brightness data suggest that jet Mach numbers increase with increasing source power. Do jet velocities also increase with power? Core-jet properties in core-dominated sources suggest that some parsec-scale jets have bulk relativistic components. How far from the nucleus does bulk relativistic flow persist? One-sidedness in extragalactic sources extends further from the core as $P_{\rm core}$ increases. Does this increasing range of brightness asymmetry indicate a similarly increasing range and dominance of bulk relativistic effects with increasing $P_{\rm core}$? Are there extended sources whose radio appearance is completely dominated by bulk relativistic effects such as beaming and boosting?

Our answers are constrained by two correlations between the parsec- and kiloparsec-scale properties of the sources. First, we do not see coreless kiloparsec-scale radio jets, so some fraction of the core emission is no more narrowly beamed than is the emission from the kiloparsec-scale jets. Second, the one-sided parsec-scale jets always point on the same side of the core as one-sided kiloparsec-scale jets when both are seen in the same source, so the prime cause of jet one-sidedness must be the same on both parsec and kiloparsec scales.

Three interpretations of the correlation between parsec-scale and kiloparsec-scale sidedness have been proposed.

(i) Both scales are the approaching sides of intrinsically symmetric (i.e., two-sided), bulk-relativistic energy flows.

(ii) Both scales have symmetric, two-sided energy flows but one side dissipates a larger fraction of its energy as synchrotron radiation.

(iii) The energy flow is intrinsically greater on one side of the source than on the other at any given time.

Both non-Doppler interpretations of jet sidedness should be taken seriously, as there is evidence for non-Doppler brightness asymmetries in the jets of low-power sources. First, studies of jets in weak radio galaxies with dust lanes (34) can be used (assuming that we are dealing with outflows) to show which jet is approaching and which is receding. In over half of the cases studied, the jet with the one-sided base is either the receding flow or is too close to the line of sight for the brightness asymmetry to be produced by Doppler boosting. Second, the asymmetries that do occur in the jets in C-shaped sources (33) are not correlated from side to side as they would be if they were produced by Doppler boosting. Third, there are sources (35, 36) in which asymmetric jets are associated with narrow line-emission regions of similar extent. In these sources, the line emission shares the jet asymmetry. The low peculiar velocities of the lines preclude Doppler boosting as the source of the asymmetry, so presumably both optical and radio asymmetries are non-Doppler in these sources.

These three lines of evidence show that there are non-Doppler brightness asymmetries in some AGN jets, so it would be reckless to ascribe all one-sidedness in powerful sources to the Doppler effect. However, the light, hypersonic jet-propagation regime accounts for the lobe morphologies of the high-power sources and, when coupled with energetic and thrust arguments, suggests at least mildly relativistic jets in some powerful doubles (37). The present status of the debate is that all three of the pure interpretations of large-scale jet one-sidedness described above have some difficulties.

The main problem for the all-Doppler picture is the large fraction of extended, lobe-dominated QSRs in which one-sided jets are being detected. Any orientational bias in a source sample selected by the strength and large extent of the lobe emission should favor alignment near the plane of the sky. The jets in such a sample should be hard to detect and have relatively low sidedness ratios $\mathcal{S}$, if their sidedness is due entirely to the Doppler boost. High dynamic-range images of these jets will put this picture to a stringent test.

The differential-dissipation picture requires an asymmetry that begins on parsec scales to propagate to 100-kpc scales in some sources, and to be present in *all* high-power sources but *no* low-power ones. There is presently no convincing model for the physics of a dissipative asymmetry with these properties.

The intrinsic-asymmetry picture requires a flip-flop mechanism to explain all symmetric features of the powerful sources. The switching time scale for a continuous one-sided jet must be longer than the dynamical time scale of the jet but shorter than the depletion time for the particles that radiate in the brightest symmetric features of the lobes. Sources with one-sided jets and bright, symmetric hot spots, e.g., Cyg A, create difficulties for this model if (i) the jets are slow and (ii) the particle-depletion times in the lobes are set by synchrotron loss times in equipartition fields, rather than, for example, by a longer turbulent decay time scale in the lobes.

To summarize, the evidence for bulk relativistic flows in jets decreases with distance from the AGN and with decreasing source power. The jets in weak sources appear to be subrelativistic and may also be subsonic in their outer regions. Some of their asymmetries are intrinsic. The connection between sidedness and jet velocity on parsec and kiloparsec scales is still far from clear, however, and none of the simple interpretations of the observed correlations appears very convincing. Perhaps any given jet may have components with a range of Lorentz factors and also some intrinsic asymmetry (38). AGNs may not make outflows as simply as we build our models!

8. Problems for observers

Some key questions may be settled by observations that are within the capabilities of present or planned instruments.

(i) How faint are the counterjets in strong sources, and how do their shapes and spreading rates compare with those of the brighter jets? Mild brightness asymmetries, compatible with weak Doppler boosting or small differences in the ratio of radiative losses to bulk energy transport, are much easier to explain in large samples than asymmetries $\geq 100:1$. High dynamic-range radio maps of jet sources whose cores are not too dominant are much needed.

(ii) How many superluminals are there in complete samples of sources with one-, two-, and no-sided kiloparsec-scale jets? How does large-scale jet sidedness correlate with core superluminal motion and parsec-scale jet sidedness? This requires very long baseline array studies of complete samples of sources not selected for core brightness alone.

(iii) What are the relative statistics of core, jet, and lobe powers? Are jets indeed brighter relative to their lobes when the cores are also brighter? Does this relationship vary with structure type, optical identification, or projected linear size?

(iv) What are the structures of the extended components in strongly core-dominated sources? This impacts the discussion of the nature of the parent population of the core-dominated sources in "unified" models.

(v) Do the shapes, spectra, and degrees of polarization of hot spots in jetted and unjetted lobes differ systematically? Is there further evidence in the lobes for or against Doppler boosting, asymmetric dissipation, or flip-flop models of jet sidedness?

(vi) Where are the relativistic particle regeneration sites in jets? What are their shapes and sizes? Spectral imaging and polarimetry of jets at optical (and shorter) wavelengths are vital.

(vii) Are there "uncontaminated" regions of jets whose intrinsic Faraday-depth variations can be determined without confusion by foreground Faraday screens? Such jets could be used to constrain 3-D jet magnetic-field models, to estimate jet densities more reliably, and to test for entrainment and adiabatic slowdown.

(viii) What are the densities and temperatures in the X-ray haloes 1–50 kpc from the nuclei of AGNs with recollimating jets? Can such jets be thermally confined between their knots?

We also need heroic efforts by both observers and theorists to find new diagnostics for jet velocities. Uncertainties about jet velocities seriously obstruct physical analysis of jet properties. Stronger (more direct) evidence for outflow along the large-scale radio jets would also be welcome.

1. A. H. BRIDLE and R. A. PERLEY. Annu. Rev. Astron. Astrophys. **22**, 319 (1984).
2. A. H. BRIDLE and J. A. EILEK. (*editors*). Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985.
3. M. C. BEGELMAN, R. D. BLANDFORD, and M. J. REES. Rev. Mod. Phys. **56**, 255 (1984).
4. R. A. LAING, J. M. RILEY, and M. S. LONGAIR. Mon. Not. R. Astron. Soc. **204**, 151 (1983).
5. W. VAN BREUGEL. Can. J. Phys. **64**, this issue (1986).
6. J. J. BRODERICK. Proceedings of the National Radio Astronomy Observatory Workshop No. 7. *Edited by* K. Kellermann and B. Sheets. NRAO, Green Bank, WV. 1984. p. 221.
7. A. H. BRIDLE. Astron. J. **89**, 979 (1984).
8. R. A. LAING. Mon. Not. R. Astron. Soc. **193**, 439 (1980).
9. R. A. LAING. Astrophys. J. **248**, 87 (1981).
10. R. D. BLANDFORD. Astron. J. **88**, 245 (1983).
11. R. A. PERLEY, A. H. BRIDLE, and A. G. WILLIS. Astrophys. J. Suppl. Ser. **54**, 292 (1984).
12. H. ALFVÉN and C.-G. FÄLTHAMMAR. Cosmical electrodynamics. Oxford University Press, London, United Kingdom. 1963. p. 113.
13. K. L. CHAN and R. N. HENRIKSEN. Astrophys. J. **241**, 534 (1980).
14. R. D. BLANDFORD and M. JAROSZYŃSKI. Astrophys. J. **246**, 1 (1981).
15. A. C. S. READHEAD, D. H. HOUGH, M. S. EWING, R. C. WALKER, and J. ROMNEY. Astrophys. J. **265**, 107 (1983).
16. S. R. SPANGLER. Astron. J. **84**, 1470 (1979).
17. J. O. BURNS. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 25.
18. D. FABRICANT, D. M. LECAR, and P. GORENSTEIN. Astrophys. J. **241**, 552 (1980).
19. J. A. BIRETTA, F. N. OWEN, and P. E. HARDEE. Astrophys. J. **274**, L27 (1983).
20. R. I. POTASH and J. F. C. WARDLE. Astrophys. J. **239**, 42 (1980).
21. J. F. C. WARDLE and R. I. POTASH. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 30.
22. H. COHN. Astrophys. J. **269**, 500 (1983).
23. A. H. BRIDLE. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 1.
24. M. D. SMITH and C. A. NORMAN. Mon. Not. R. Astron. Soc. **194**, 785 (1981).
25. M. D. SMITH. Mon. Not. R. Astron. Soc. **207**, 41P (1984).
26. R. N. HENRIKSEN, A. H. BRIDLE, and K. L. CHAN. Astrophys. J. **257**, 63 (1982).
27. G. V. BICKNELL. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 229.
28. M. L. NORMAN, K.-H. A. WINKLER, and L. L. SMARR. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 150.
29. D. G. PAYNE and H. COHN. Astrophys. J. **281**, 655 (1985).

30. J. C. LAU. J. Fluid Mech. **105**, 193 (1981).
31. A. G. WILLIAMS and S. F. GULL. Nature (London), **313**, 34 (1985).
32. J. P. LEAHY and A. G. WILLIAMS. Mon. Not. R. Astron. Soc. **210**, 929 (1984).
33. C. P. O'DEA. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 64.
34. R. A. LAING. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 119.
35. W. J. M. VAN BREUGEL, G. K. MILEY, T. HECKMAN, H. BUTCHER, and A. H. BRIDLE. Astrophys. J. **290**, 496 (1984).
36. L. RUDNICK. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 114.
37. J. W. DREHER. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 109.
38. A. H. BRIDLE. Proceedings of the National Radio Astronomy Observatory Workshop No. 9. NRAO, Green Bank, WV. 1985. p. 134.