JETS ON LARGE SCALES

Alan H. Bridle
National Radio Astronomy Observatory

Invited review article to appear in "Testing the AGN Paradigm",
Proceedings of the 2nd October Astrophysics Conference in Maryland,
AIP Conference Series in Physics and Astrophysics, February 1992

JETS ON LARGE SCALES

Alan H. Bridle
National Radio Astronomy Observatory

ABSTRACT

Jets tell us that the AGN problem has a symmetry axis, at least for the radio-loud systems. The jets come in two primary "flavors", whose properties resemble those of the two primary modes of propagation of confined, light supersonic flows. In strong sources, many of the jet-lobe relationships and asymmetries are consistent with bulk relativistic velocities ($\geq c/2$) in the outflows on many-kpc scales. Viable alternatives exist, however, and some brightness asymmetries of weak sources and geometrical asymmetries of strong sources are unlikely to be the results of bulk relativistic motions. There is little evidence that the outflows are strongly magnetized, and there is some evidence that they are not.

INTRODUCTION

My subject appears to be as far (in physical scale) from the "central point" of this meeting as the organizers could allow in an invited paper! But despite their disparity in scale with most of the topics discussed here, the many-kiloparsec jets in strong radio sources are relevant to this meeting's theme in at least three ways.

First, "jets" have now been detected in over 300 extragalactic radio sources, including examples of all known types of source that reach > 10 kpc scales. Their ubiquity implies that radio-loud AGNs have a symmetry axis along which outflows can be collimated, i.e. that the axis so often assumed at this meeting actually exists in some cases. The abundance of jets in radio sources has elevated "beam" models of radio-loud AGNs to the status of dogma, even though we are unsure which parameters of the supposed "beams" dominate our ability to visualize them as radiative "jets".

Second, although photons at microvolt energies do not dominate the power radiated by AGNs, the radio plumes and lobes associated with jets can extend over immense volumes. The total energy reservoirs required to support the synchrotron luminosities of these regions can be a significant part of an AGN's energy budget. It is therefore important to classify AGNs by the power, size and shape of their radio sources (if any) when sorting them into "families".

Third, the radio sources can be imaged in great detail. Resolvable features such as the shapes, sizes, prominence and orientation of their jets, plumes and lobes, can give us clues about how AGN axes are oriented, both for individual galaxies and, statistically, for entire AGN families.

Much current research on large-scale jets does, however, have little contact with this meeting's topic. Many detailed models of jets (e.g. the review by Burns et al. 1991) treat only their propagation, not their origin, and the beams appear in them magically as "initial conditions". Such models do not discuss how, or of what, the beams are made, except that they assume supersonic, sub-relativistic, fluid flow. They are relevant here because they show how the range of plumed and lobed shapes in radio sources can be mimicked by

(a) varying a few dimensionless parameters of the beams (internal Mach number, density contrast, plasma β),

(b) sending beams across discontinuities in the ambient medium, or

(c) shaking beams in direction or pulsing their power output.

These models show how the spreading rates, directions and field configurations of confined beams can be modified by propagating them through simple models of kpc-scale gaseous environments. Jet data support such kpc-scale "reconditioning" of beams, because no well-resolved jet goes straight or at constant opening angle from an AGN to the outer reaches of a large radio source. If the jet shapes resemble the underlying flow patterns, this is evidence that the beams are not free, but are continually adjusting toward pressure balance with their surroundings. The good news is that such beam-reconditioning provides a probe of the ISM and IGM around AGNs. The bad news is that it limits the "resolving power" of kpc-scale data for some important questions about the primary outflows, e.g. "what are their initial opening angles?"

I will focus on the large-scale jet/plume/lobe properties that may nevertheless carry residual intelligence about the primary outflows. But first, recall that large-scale jets come in two dominant "flavors".

THE TWO DOMINANT JET FLAVORS

In "weak" radio sources (total extended powers $P_{ext} < 10^{24}$ W/Hz at 1.4 GHz, H = 100 km/s/Mpc) most of the detected jets are:

- "two-sided" (<4:1 brightness ratio between jet and counterjet),
- "rapidly spreading" (synchrotron FWHM opening angles >8°),
- dominated by $B_\perp$ (presumably azimuthal) field components over most of the jet, $B_{||}$ (axial) fields being common only in the first few kpc or on the outer edges (especially at bends),
- similarly bright in sources of all sizes (average power per unit length near $10^{21.5\pm1}$ W/Hz/kpc at 1.4 GHz, see Figure 1),
- prominent, often with >10% of the total extended power (see Figure 2).

In contrast, in "strong" sources ($P_{ext} > 10^{25}$ W/Hz at 1.4 GHz) most of the detected jets are:

- "one-sided" (>4:1 brightness ratio wherever measured),
- "slowly spreading" (FWHM opening angles <4°, except near the AGN),
- often dominated by strings of bright "knots" amidst fainter emission,
- dominated by $B_{||}$ (except possibly at bright knots, where B may align better with the local emission ridges than with the overall jet axis),
- brighter per unit length in apparently smaller sources (see Figure 1).
- rarely prominent in radio galaxies, but often prominent in quasars,

especially at small apparent sizes (see Figures 2 and 3).

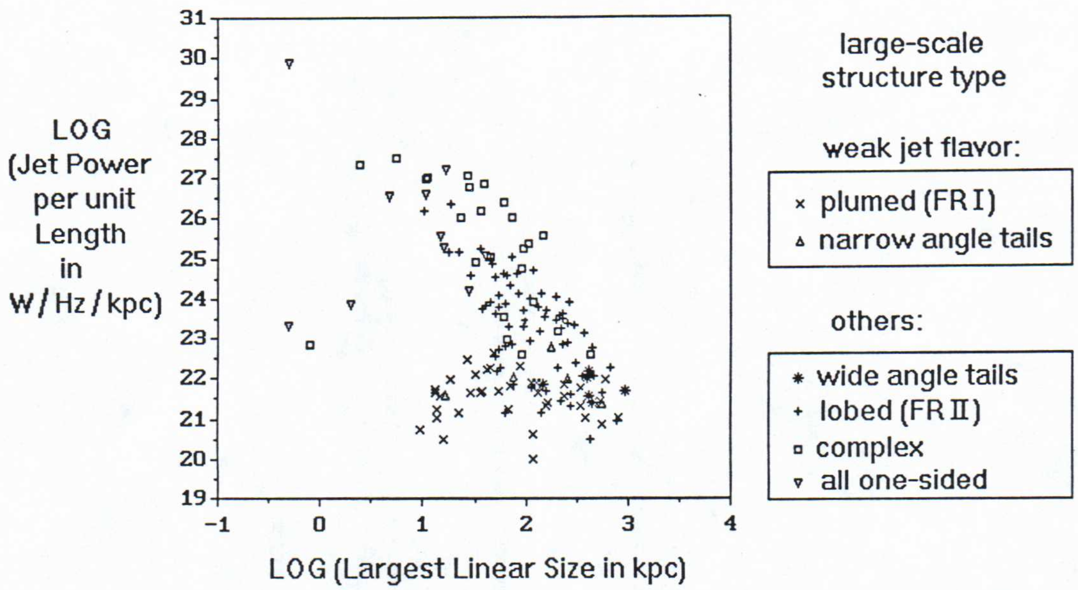

Figure 1: Jet power per unit length against largest linear size plotted logarithmically for all sources for which such data are available, distinguishing large-scale structure types. Jets of the weak flavor are denoted by crosses and broad-based triangles. Classical double-lobed sources are denoted by plus symbols, sources with complex structures by squares and fully one-sided sources by broad-topped triangles.

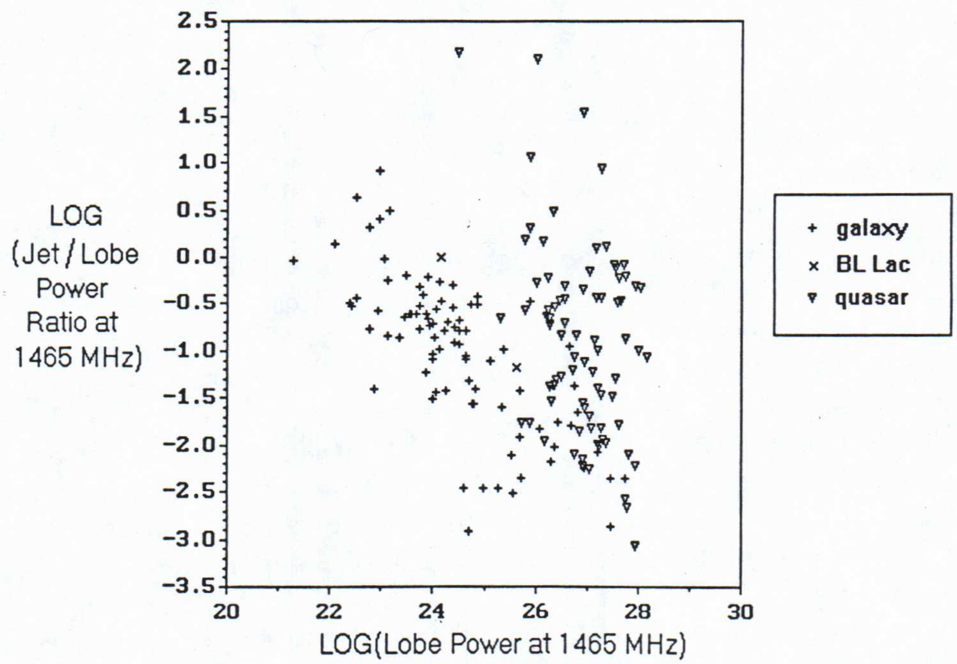

Figure 2: Jet-to-lobe prominence (the ratio of power in the brighter jet to that in the "lobes", defined here as all of the extended emission other than the jets) plotted logarithmically against "lobe power". Note the decrease in jet prominence with increasing lobe power for radio galaxies, the large dispersion in prominence for the quasars, and the high prominence of BL Lac jets.

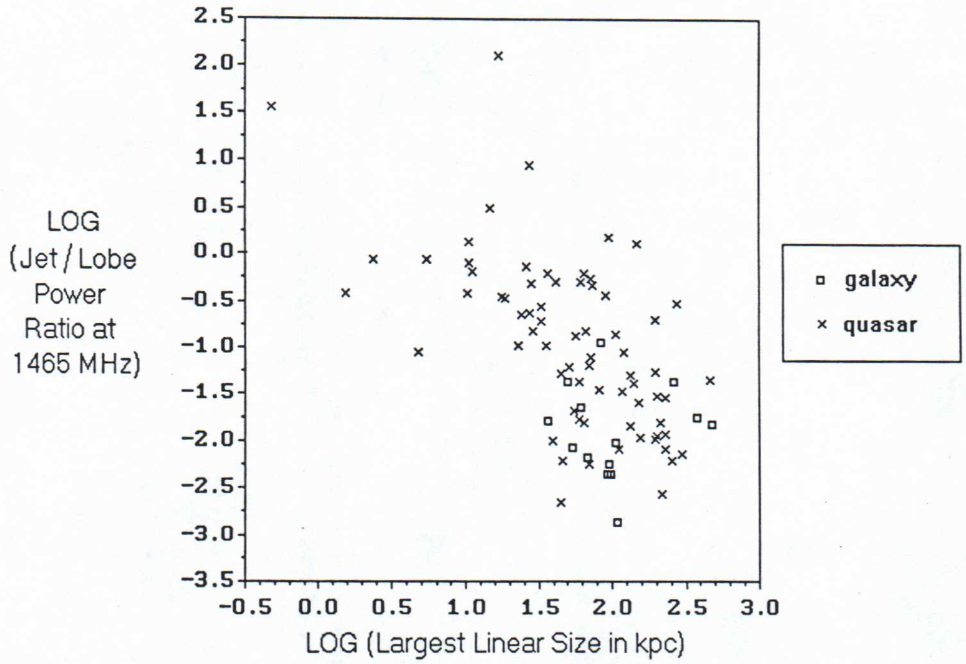

Figure 3: Jet-to-lobe prominence plotted logarithmically against the largest linear size for the strongest sources, those with $P_{ext} > 10^{26}$ W/Hz at 1.4 GHz. Note the decrease in jet prominence with apparent linear size for the quasars, plotted here as crosses.

Both jet flavors are common in the intermediate range of extended powers, $10^{24} < P_{ext} < 10^{25}$ W/Hz at 1.4 GHz. "Twin" jets of the weak flavor often have a bright one-sided segment at the base of whichever jet is marginally brighter on larger scales. A transition from $B_{||}$-dominated to $B_{\perp}$-dominated fields often occurs near the end of the one-sided basal region of a weak jet. These regions therefore resemble miniature, unterminated, jets of the strong flavor.

The two flavors are produced in different environments (e.g. Owen and Laing 1989) and in association with different kinematics in the extended narrow-line regions (Baum et al. 1991). The weak jet flavor is usually produced by luminous elliptical galaxies with flat light profiles, often in clusters or groups. The strong jet flavor is produced by radio-loud quasars and by more isolated elliptical galaxies with normal light profiles, luminosities near L*, and evidence of rotation in their emission-line systems.

Because Figure 1 shows only detected jets, it is probably an upper envelope to a plot of these data with unlimited sensitivity. Despite this, it illustrates a clear difference between the two jet flavors: the normalized powers of the weak-flavor jets are independent of their length, but there is a deficit of bright strong-flavor jets with $> 10^{26}$ W/Hz/kpc in large sources ($D > 100$ kpc). Such jets would be trivial to observe if they existed. The data for the strong-flavor jets lie in a band that parallels the top of Baldwin's (1982) total P-D diagram, and most are within about a decade in power of $10^{31} D^{-3.3}$ W/Hz/kpc. They overlap the data of the weak flavor at $D > 100$ kpc.

JET EXHAUSTS - PLUMES AND LOBES

Weak-flavor jets usually broaden into plume-like, edge-darkened, outer structures. The strong flavor forms edge-brightened lobes bounded by sharp brightness gradients across the major axis. At high powers, these lobes usually contain bright, compact hot spots, of which the brightest and most compact is usually on the side fed by the brighter (or only detected) jet (Laing 1989).

In strong radio galaxies, the lobes are relatively symmetric in intensity and in placement around the AGN (to within a factor of two). They often wrap back around the jet paths, forming conspicuous "bridges". Radio galaxy lobes are also narrower at high powers. The widest-lobed radio galaxies, whose powers are near the transition range between the weak and strong jet flavors, have light profiles and luminosities resembling those of the "weak" flavor (Owen & Laing 1989).

In radio-loud quasars, the lobes can be much less symmetric (in intensity and in surface brightness) than in strong radio galaxies. Quasar lobes are more likely than galaxy lobes to have extensions at odd angles, usually in the outer half of the lobe (e.g, Leahy et al. 1989) and to be asymmetric in length, though whether there is also a significant deficit of highly symmetric quasars is controversial (Hutchings et al 1988; Padrielli et al. 1988; Neff et al. 1989). Some radio-loud quasars make sources that are entirely one-sided even at high sensitivity (e.g. Saikia et al. 1989). These may be an extremum of the symmetry distribution.

KEY QUESTIONS ABOUT THE BEAMS FROM AGNs

A. What are we looking at?

We usually assume that the observed "jets" and the presumed "beams" are intimately connected. For kpc-scale jets, the connection owes more to faith than to direct observation. But this may be improving, as there are now signs of kpc-scale proper motions from VLA data. Biretta and Owen (1990) report pattern speeds between 0.6c and 1.0c in the first 1.2kpc of the M87 jet (greater than those measured by VLBI closer to the nucleus). Walker et al. (1988) report a pattern speed of 3.7 ± 1.2c at 2 kpc in 3C120 (H=100). In both sources, the angular motions are much less than the FWHM of the VLA's synthesized beam, so the observations depend on exceptional dynamic range and careful elimination of sampling differences. They also need confirmation: Biretta and Owen stress that their results are preliminary, and Muxlow and Wilkinson (1991) could not detect the motion in 3C120 using MERLIN. But if these proper motions survive further scrutiny, they could be a direct sign that kpc-scale jets visualize properties that are well coupled to the beams, rather than (for example) static cocoons around them. (Such high pattern speeds would also strengthen the case for high flow velocities in the one-sided bases of jets in two relatively weak sources.)

High-resolution imaging is also telling us that we should revisit the field-particle microphysics of the jet-beam connection before we can say what we are looking at. Synchrotron radiation "visualizes" places where high densities of relativistic electrons and high magnetic fields coexist. Our view of a "beam" by its synchrotron emission also depends on the particle pitch angle distributions relative to the fields, and on the orientation of the fields to our line of sight. For lack of specific alternatives, we usually presume that particle motions are isotropic and that fields are random on small scales. When inferring physical parameters, we often assume large filling factors and that the fields and particles have relaxed to equipartition. But no well-resolved jet, plume or lobe looks fully-filled. Bright filaments abound, and "dark filaments" are seen, e.g., near the axis of M87's jet beyond knot "A" (Owen et al. 1989, Macchetto 1991). There are also total-intensity "dark spots" in the lobes of 3C353 (Bridle & Williamson 1990) and Cygnus A (J.W.Dreher, private communication). The nature of such dark spots is unclear, but they do not seem to be merely interstices among bright filaments. Bright filaments in jets and lobes also tend to be highly linearly polarized, and the magnetic fields follow them. Do the particles move isotropically in such structures? Are the filaments rope-like or sheet-like? Are they uniform, or are they themselves braided from finer strands? Are they near equipartition? Could they be bright when viewed from some directions and dark when viewed from others? How are the particles distributed between high- and low-field regions?

Our usual assumptions of isotropy and uniformity may serve us poorly in the face of such complexity, and jet models that challenge them may be overdue. In what follows, I will however review what can be inferred if we assume that the overall shapes of radio jets, plumes and lobes trace those of the beams and their exhausts. For an alternative viewpoint, see, e.g., Corbelli and Veltri (1989).

B. What are beams made of?

We would like to know the distributions of particle masses and energies in the beams, but the synchrotron radiation of jets tells us little about heavy particles or non-relativistic components (despite occasional claims to the contrary). The shapes of large-scale jets, coupled with the dynamical models of how jets create plumes and lobes, do however constrain the ratio of densities between the beams and the ambient media. The strong beam flavor must be lighter (i.e. less dense) than the ambient media on 10-100 kpc scales in radio galaxies and quasars whose lobes are much wider than their jets. This follows from elementary physics, as pointed out by Scheuer (1974). If the head of a supersonic beam with velocity v_J, bulk Lorentz factor ≈ 1 and density ρ_J advances into an IGM of density ρ_M at an instantaneous velocity v_H, then pressure balance at the beam head is dominated by the ram pressures of the beam and the IGM. It follows that $v_H/v_J = \sqrt{\eta}/(1+\sqrt{\eta})$ where $\eta = \rho_J/\rho_M$. To make a lobe, the material that reaches the beam head must be slowed down and deflected, so $v_H << v_J$, i.e. $\eta << 1$ -- light supersonic beams can make wide lobes but heavy ones cannot. The lobe expands laterally at a velocity governed (at least near the head) by $\sqrt{(p_H/\rho_M)}$, and ram pressure balance shows that for large Mach numbers the ratio of lobe width to jet width scales as $M_J^{(1/\Gamma)}\eta^{(-1/4)}$. For Cygnus A, Williams (1991) found $M_J=8$, η=few x 10^{-4} (which may be unusually low as Cygnus A is in an unusually rich gas environment for a source with its morphology).

Leahy (1990) notes that beams that are in pressure balance with the ambient medium and that are light on kpc scales are probably lighter still closer to the AGN. Spreading beams cool, but the ambient media are either isothermal or are hotter at larger radii. Pressure-matched beams propagating in such media should therefore have η increasing outward, even without entrainment.

It is less clear that the beams in the weak flavor must also be lighter than their surroundings. The best constraints come from jets that bend as AGNs move through cluster atmospheres. Recent 3-D models (Balsara 1990) have shown that both light and heavy beams can be shocked and bent by the ram pressure of a transonic crosswind without being totally disrupted. Both types can therefore approximate the U-shapes of the radio "narrow trail" sources. Energetic arguments favor the light jets, though the results are somewhat model-dependent (O'Dea 1985; O'Dea & Owen 1987).

The idea that "all beams start out light" appeared to conflict with early detections of internal Faraday depolarization in jets (e.g., Saunders et al. 1982). We now know that we are viewing many radio-loud galaxies and quasars through inhomogeneous magnetoionic screens that extend many tens of kpc from the AGN. At low angular resolution, the fluctuations in these screens can masquerade as evidence for Faraday depolarization within the jets. The screens must be resolved before depolarization data can be used as evidence for thermal matter in jets. Most of the "evidence" has withered under this test.

What are the "ions"? In sources as strong as Cygnus A, there is a problem of "excess momentum" if they are protons or heavier (Williams 1991). This leans toward models that have electron-positron beams. But electron-proton beams suffer less Compton drag than electron-positron beams as they leave the central engine (e.g., Phinney 1987). If the kpc-scale data for a particular source were to convince us that its beams are highly relativistic, we might therefore constrain the nature of its ions by asking how to launch it with a high enough Lorentz factor in the presence of the radiation field near an accretion disk.

C. Is there a Mach number sequence?

A key to the relationship between the two main jet flavors may be the beam's internal Mach number $M_J = v_J/c_J$ on scales of a few hundred parsecs to a few kiloparsecs. Many features of the two jet flavors resemble those of the two dominant modes of supersonic beam propagation, which differ by whether or not the beam is supersonic with respect to the sum of the internal and external sound speeds (Payne & Cohn 1985).

In light, mildly supersonic beams, interaction with the ambient medium is mediated mainly by turbulent entrainment of material. Ingestion of ambient gas slows them, increases their density contrast with the external medium, and eventually turns them into subsonic plumes. The observed properties of weak-flavor jets can be modeled plausibly with Mach numbers 1-3 and density contrasts increasing toward unity at 10-kpc distances from initial values around 10^{-2} to 10^{-1}

closer to the AGN (e.g. Bicknell et al. 1990). The slowdown produced by entrainment also helps to keep these jets bright as they widen, because it compresses the fields and particles longitudinally. In these models, the true internal depolarization may be greatest in the outer plumes of weak-flavor jets.

In hypersonic beams, the dominant interaction with the ambient medium is via oblique shock cells. Mach numbers can stay high (5-20) and the beams can stay light until they "hit the wall" (which may be oblique) of their own detritus. This is a good recipe for making narrow knotty jets that form hot spots and edge-brightened lobes with well-marked edges, as observed in the strong sources.

The progression from the weak jet flavor to the strong may therefore be at least partly a progression of initial Mach numbers in light jets with $\eta = 10^{-2}$ to 10^{-3} at about 1 kpc from the AGN, the weak flavor becoming heavy and subsonic by entrainment. A positive correlation between initial Mach number and power output from the central engine would not be surprising. But as the high and low-power sources live in different types of galaxy and environment, it is unclear how much of the Mach number progression might be determined by the engine alone and how much by its environment. (Note however that the observation that radio-galaxy lobes are relatively narrower at high powers does not fit a picture of a pure Mach number-power sequence in beams with similar density contrasts.)

D. Are the beams balanced?

The predominant one-sidedness of the strong jet flavor can be explained by Doppler boosting if these jets are so light and so hypersonic that they have relativistic bulk velocities. The trends in large-scale jet prominence shown in Figures 1, 2 and 3 are could then be explained if (a) most "weak" jets are sub-relativistic on large scales, and (b) the mean jet axes in radio-loud quasars are systematically closer to our line of sight than those in radio-loud galaxies with similar lobe powers. Doppler hiding of strong-flavor jets that are near the plane of the sky could produce the low prominence of the jets in large, powerful radio galaxies (Figure 2). Doppler boosting of approaching jets near the line of sight could produce both the large range in prominence of the quasar jets (Figure 2) and the decrease in jet prominence at large apparent linear size in the strongest sources (Figure 3). There is some direct evidence for counterjets in strong sources (e.g. Bridle 1990), however, and the detected features are brighter than the main jets in weak sources. The full range of "strong" jet luminosities cannot therefore be obtained from those of the weak jets by relativistic beaming alone.

The trends in jet prominence, taken by themselves, are also consistent with two non-relativistic pictures. In an "evolutionary" picture, jets are intrinsically brighter in young, small sources (Hutchings et al. 1988). In an "environmental" picture, jets are brighter when "smothered" by dense environments. (At high redshifts, we may therefore see both effects together.) Neither picture accounts simply for the one-sidedness of the strong-flavor jets, however. Both must be supplemented by postulating either that the outflow from the central engine "flip-flops" on time scales of 10^5 or so years, or that intrinsically balanced beams can make asymmetric jets by interacting with asymmetries of the AGN's environment.

Two lines of evidence suggest that, in some sources, beam momenta are better balanced than jet brightness. In 3C120, velocity splitting in the OIII emission line shows an interaction between the ISM and an invisible counterjet (Axon et al. 1989). There are also clues to beam symmetry in the "hot spots" of strong sources, which should dissipate rapidly if not continually supplied with momentum. The observation that the most compact hot spot in a strong source is usually in the lobe with the brighter jet is consistent either with the "flip-flop" or with mildly relativistic flow through the hot spots and some co-beaming with their jets (Laing 1989). But there are sources (e.g. 3C175) with compact hot spots in lobes with no visible jet. These are hard to explain in the "flip-flop" case, but can be explained with balanced beams and redirection of relativistic flows.

Saslaw and Whittle (1988) have suggested a way to test specifically for momentum imbalance in the beams. They found that, under some conditions, AGNs that emit unbalanced beams might be "jet-propelled" to an observable distance from the center of the surrounding gravitational potential. It might therefore be possible to detect systematic positional offsets between the unresolved radio "cores" and the central light distributions of nearby radio galaxies if the "flip-flop" model is correct. For this test, the reference frames of the radio and optical images must be aligned either by independent astrometry or by registering common features of the images outside the nuclear region. The general similarity of some large-scale jets at radio and optical wavelengths (e.g. M87, Macchetto 1991) may help to align images for this test.

The alternative in which environmental gradients produce asymmetries in strong radio sources is encouraged by correlations between asymmetries of the lobes and of extended narrow-line regions (McCarthy et al. 1991; Heckman et al. 1991). In radio galaxies, the side with brighter emission lines usually has the shorter lobe, suggesting that density gradients affect lobe development. Note that if such length asymmetries were produced by light travel time differences for beam heads moving at mildly relativistic velocities, the greatest asymmetries would be seen in the smallest sources, which appears not to be the case (Fokker 1986). There is also evidence that interactions influence the prominence of strong-flavor counterjets: there is usually no sign of radio counterjets opposite long, straight, uninterrupted segments of strong-flavor jets, but there are signs of counterjets opposite some that are "bent or broken" (Bridle 1990). Counterjet prominence (relative to the lobes) is also positively correlated with jet prominence in strong sources where both jets are detected, whereas it would be anti-correlated if Doppler favoritism alone controlled their apparent brightness.

The depolarization of the lobes of strong sources is also asymmetric: the lobe on the side with the brighter jet is almost always less depolarized at long wavelengths (Laing 1988; Garrington et al. 1988; Garrington & Conway 1991). If the depolarizing media are symmetric around the sources, this asymmetry implies that the brighter jet is on the nearer side of the source, as it must be if jet prominence is governed by relativistic effects. Rotation measure mapping of wide-lobed sources that have strong depolarization asymmetries may show whether the symmetry assumption is correct. In sources where the distribution of narrow emission lines suggests association with the jets, van Breugel (1989) finds that the lines associated with the brighter jet are always blue-shifted relative to the parent galaxy, again consistent with the brighter jet being on the nearer side. It is unclear whether the depolarization asymmetries are related to the line-emitting regions, but any correlation between the jets and arm length ratios is weaker than the correlation between the jets and depolarization. It therefore seems more likely that the asymmetries of the optical emission line regions are uncorrelated with those of the gas in the depolarizing screen.

What of asymmetries in the weak sources? There is evidence for brightness asymmetries that cannot be relativistic in origin. The jets are roughly perpendicular to dust lanes when both are seen on the same scale in the same galaxy. So, if kpc-scale jets and dust lanes are also roughly orthogonal in three dimensions, jets that appear perpendicular to edge-on dust lanes are likely to be near the plane of the sky. Nevertheless, some (e.g. M84), display brightness asymmetries and one-sided basal regions. The one-sided bases are also usually on the side of the jet that is brighter overall and better collimated. The observed brightness asymmetries in weak U-shaped sources are inconsistent with large-scale velocities $>0.2c$ (O'Dea 1985). It is therefore important to look for superluminal motions in weak jets with strongly one-sided bases, to test whether the "fading" of the bases with distance could be due to the removal of initially relativistic velocities. Such velocities are assumed in the weak flavor by models that seek to "unify" BL Lacs and weak (plumed) radio galaxies by re-orientation.

E. Are the beams strongly magnetized?

Magnetic collimation has been invoked to explain apparent "overpressures" in jets relative to estimates of pressures in the surrounding media from X-ray data. The evidence that minimum pressures in jets systematically exceed plausible environmental pressures is patchy, however. Local overpressuring (at features that do not fill the jet volume) is inescapable in shocked supersonic flows. As compression boosts synchrotron emissivity, lists of jets that are prominent relative to emission from the much longer lines of sight through their lobes may unduly favor beam segments that are still adjusting towards pressure balance. As it is important to be sure that claimed overpressures refer to the extended inter-knot emission in a jet, high resolution data are needed. Jet pressure estimates also depend on the standard, but possibly shaky, assumptions about particle content, filling factors and the unobserved bandwidth of the emission. As light, straight hypersonic beams travel through their own shocked cocoons rather than in unperturbed IGM, the significance of overpressures relative to the unperturbed medium is particularly unclear for the strong lobed sources (Begelman & Cioffi 1989).

The best case for overpressuring (by factors of 3 to 50), is M87 (Owen et al. 1989) because this jet has been well resolved from the radio to the optical, and because it is not obviously self-cocooned. It may be significant that the best evidence comes where we have the best data, and the complex structure of the M87 jet itself encourages strong-field models. But it is not clear that this jet, which most resembles the one-sided base of a weak-flavor jet, offers a good paradigm for strong sources. Active fields may indeed conflict with observation of lobes in strong sources, as the available models of magnetically-collimated jets predict lobe-less, or "naked", jet structures (Clarke et al. 1986; Lind et al. 1989). The best naked-jet candidates are in quasars, such as 3C273 and 0800+608, but these are also prime candidates for being jets that appear prominent relative to their lobes because of relativistic boosting.

We therefore lack clear evidence for strong magnetic fields in most cases, but wide-lobed strong sources provide some evidence against them. Plausible models can however be made for the wide-lobed sources using only passive fields (Clarke et al. 1989; Matthews & Scheuer 1990).

CONCLUSION

The systematic properties of large-scale jets are consistent with a sequence of initially light, weakly magnetized electron-proton beams in which internal Mach number and flow velocity increase with power output from the central engine. A major transition in beam propagation modes occurs near powers of 10^{24} to 10^{25} W/Hz at 1.4 GHz. The assumption of bulk relativistic motions in intrinsically balanced beams for the strong jet flavor unifies many of their attributes, including their sidedness and prominence characteristics and the depolarization asymmetry of their lobes. There is no clear evidence for unbalanced beams, but optical emission line and hot spot data suggest that the beams in some sources are more symmetric than the observed jets. There is however no evidence for relativistic outflow in the weak jet flavor, and some evidence against it. There are brightness asymmetries in jets of the weak flavor, and geometrical asymmetries in sources of both flavors, that are probably non-relativistic in origin. These may reflect asymmetries in AGN environments that could influence the appearance of both weak and strong sources.

The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

References

Axon,D.J., Unger,S.W., Pedlar,A., Meurs,E.J.A., Whittle,D.M. & Ward,M.J. (1989), Nature 341, 631.

Baldwin,J.E. (1982), IAU Symp. 97, eds. D.S.Heeschen & C.M.Wade, p.21.

Balsara,D.S. (1990), Ph.D. thesis, U. of Illinois, Chapter Five.

Baum,S.A., Heckman,T.M. and van Breugel,W.J.M. (1991), poster presentation at this meeting.

Begelman,M.C. & Cioffi,D.F. (1989), Ap.J.Letts. 345, L21.

Bicknell,G., de Ruiter,H.,Fanti,R., Morganti,R. & Parma,P. (1990), Ap.J. 354, 98.

Biretta,J.A. & Owen,F.N. (1990), in "Parsec-Scale Jets", ed. J.A.Zensus & T.J.Pearson, Cambridge University Press, p.125.
Bridle,A.H. (1990), in "Parsec-Scale Jets", ed. J.A.Zensus & T.J.Pearson, Cambridge University Press, p.186.
Bridle,A.H. & Williamson,C.E. (1990), Bull.A.A.S. 21, 1093.
Burns,J.O., Norman,M.L. & Clarke,D.A. (1991), Science 253, 522.
Corbelli,E. & Veltri,P. (1989), Ap.J. 340, 679.
Clarke,D.A., Norman,M.L. & Burns,J.O. (1986), Ap.J.Letts. 311, L63.
Clarke,D.A., Norman,M.L. & Burns,J.O. (1989), Ap.J. 342, 700.
Fokker,A.D. (1986), Astron.Astrophys. 156, 315.
Garrington,S.T. & Conway,R.D. (1991), M.N. 250, 198.
Garrington,S.T., Leahy,J.P., Conway,R. & Laing,R.A. (1988), Nature 331, 147.
Heckman,T.M., Lehnert,M.D., van Breugel,W.J.M. & Miley,G.K. (1991), Ap.J. 370, 78.
Hutchings,J.B., Price,R. & Gower,A.C. (1988), Ap.J. 329, 122.
Laing,R.A. (1988), Nature 331, 149.
Laing,R.A. (1989), in "Hot Spots in Extragalactic Radio Sources", ed. K.Meisenheimer & H.-J. Roser, Springer-Verlag, p.27.
Leahy,J.P. (1990), in "Parsec-Scale Jets", ed. J.A.Zensus & T.J.Pearson, Cambridge University Press, p.174.
Leahy,J.P., Muxlow,T.W.B. & Stephens,J.W. (1989), M.N. 239, 401.
Lind,K.R., Payne,D.G., Meier,D.L. & Blandford,R.D. (1989), Ap.J. 344, 89.
Macchetto,F.D. (1991), "HST Observations of the Jet in M87", poster presentation at this meeting.
Matthews,A.P. & Scheuer,P.A.G. (1990), M.N. 242, 616 and 623.
McCarthy,P.J., van Breugel,W. & Kapahi,V.K. (1991), Ap.J. 371, 478.
Muxlow,T.W.B. & Wilkinson,P.N., M.N. 251, 554 (1991).
Neff,S.G., Hutchings,J.B. & Gower,A.C. (1989), Astron.J. 97, 1291.
O'Dea,C.P. (1985), Ap.J. 295, 80.
O'Dea,C.P. & Owen,F.N. (1987), Ap.J. 316, 95.
Owen,F.N. & Laing,R.A. (1989), M.N. 238, 357.
Owen,F.N., Hardee,P.E. & Cornwell,T.J. (1989), Ap.J. 340, 698.
Padrielli,L., Rogora,A. & de Ruiter,H.R. (1988), Astron.Astrophys. 196, 49.
Payne,D.G. & Cohn,H. (1985), Ap.J. 291, 655.
Phinney,S. (1987), in "Superluminal Radio Sources", ed. J.A.Zensus & T.J.Pearson, Cambridge University Press, p.301.
Saikia,D.J, Junor,W., Muxlow,T.W.B. & Tzioumis,A.K. (1989), Nature 339, 286.
Saslaw,W.C. & Whittle,D.M. (1988), Ap.J. 325, 142.
Saunders,R., Baldwin,J.E., Pooley,G. & Warner,P.J. (1982), M.N. 197, 287.
Scheuer,P.A.G. (1974), M.N. 166, 513.
van Breugel, W.J.M. (1989), in "Hot Spots in Extragalactic Radio Sources", ed. K.Meisenheimer & H.-J. Roser, Springer-Verlag, p.121.
Walker,R.C, Walker,M.A. & Benson,J.M., Ap.J. 335, 668 (1988).
Williams,A.G. (1991), in "Beams and Jets in Astrophysics", ed. P.A.Hughes, Cambridge University Press, Chapter Seven.