Energy Transport in Radio Galaxies and Quasars
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P. E. Hardee, A. H. Bridle, and J. A. Zensus (eds.)
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Observations of Energy Transport

Alan H. Bridle
National Radio Astronomy Observatory,
520 Edgemont Road, Charlottesville, VA 22903-2475, U.S.A.

Abstract. There is now good evidence for long-expected ingredients of the jet-launcher in nearby galaxies, and for possible miniatures of it in our galaxy. There is also now a strong case for energy transport at bulk relativistic velocities to kiloparsec scales in FR I sources, and to the hot spots in FR II sources. It therefore seems that the dynamical pictures of (outward) energy transport in FR I and FR II sources can be unified, by studying (both theoretically and observationally) how jets decelerate in elliptical galaxies. Our view of jets in lobe-dominated FR II sources may be conditioned by Doppler "hiding", which favors the emission from their slower-moving outer layers. Some old problems in jet confinement have faded as we learned more about hypersonic jet propagation, but some old solutions may be jeopardized by recent X-ray data. Radio source environs are now understood to be dynamic, and able to bend jets without large peculiar motions of the "engine". Some important transition scales, both across and along jets, are being identified: imaging and polarimetry of radio galaxies and quasars on these scales should help to refine models of jet acceleration, deceleration and disruption.

1. A Long-Range Perspective

This workshop's scope was designed to resemble that of one held eleven years ago in Green Bank (Bridle & Eilek 1984). It is interesting to compare the scientific foci of the two meetings, to clarify what has been learned (or un-learned!) about energy transport in powerful radio sources in the eleven years between them.

The database is immensely richer, thanks to major new instruments across the whole spectrum (VLBA, IRAS, HST, ROSAT, ASCA, GRO). We also have better data from old instruments, due to faster detectors, better imaging methods, and more capable computers. Imaging, photometry, polarimetry and spectroscopy that were available in 1984 for only a few, bright, sources now exist for more representative, and deeper, samples (e. g., Ledlow & Owen, these Proceedings, Page 359; Owen et al., these Proceedings, Page 353). The brightest, and best-resolved objects have been studied at more wavelengths and better resolutions (e. g., Cygnus A—Carilli et al., these Proceedings, Page 287; M 87—Biretta, these Proceedings, Page 187). VLBI imaging of parsec-scale jets has been extended to small but representative samples of the nuclei in lobe-dominated FR II sources and plumed FR I sources (see Pearson, these Proceedings, Page 97). What have these advances told us about energy transport in radio galaxies and quasars?

2. Jet Launching

The jet-launching paradigm (black hole plus accretion disk plus twisted magnetic fields—B++?) is basically the same as in 1984, though the launching models are more refined (see Wiita, these Proceedings, Page 395). Direct evidence for the presumed small-scale mass concentrations and disk-like geometries has burgeoned in all wavebands (Scheuer, these Proceedings, Page 1). The ability to measure mass concentrations on sub-parsec scales via the kinematics of molecular masers (Miyoshi et al. 1995) has added an exciting new tool to the kit. So far, our first glimpses of the environs of the central engine seem to reinforce old ideas about what this engine contains.

3. The Nearest Engines?

The one galactic "relativistic jet" known in 1984 was SS 433, with outflow at $0.26c$. Cygnus X-3 has since hinted of expansion at about $c/3$ (Spencer et al. 1986; Schalinski et al. 1995), though its kinematics and distance are ambiguous. As noted by Scheuer (these Proceedings, Page 2), stronger candidates for the "mini-quasar" appellation have surfaced in the X-ray transients GRS 1915+105 (Mirabel & Rodríguez 1994) and GRO J1655-40 (Tingay et al. 1995; Hjellming & Rupen 1995), both with relativistic pattern speeds approaching those of quasars. The galactic γ-ray sources 1E 1740.7−2942 (Mirabel et al. 1992) and GRS 1758-258 (Rodríguez, Mirabel, & Martí 1992) also show signs of jet-like radio structure, though nothing is known of their proper motions. The validity of calling all such sources "mini-quasars" is unclear, but studying their (rapid) evolution may well illuminate the AGN-jet problem.

4. Transport Velocities

There was little doubt at Green Bank that bulk relativistic motions occur in the jets of quasars and of some radio galaxies on *parsec* scales. There was much debate over whether such motions survive to *kiloparsec* scales in radio-loud sources of any luminosity, or occur on any scale in most FR I sources.

In 1984, the case for large-scale relativistic flows came from the prevalent one-sidedness of jets in quasars and (where detected) in FR II radio galaxies. This same one-sidedness was also argued as a symptom of intrinsic asymmetries, however, and "flip-flop" models were debated. The fact that one-sided jets are more prominent in quasars than in FR II radio galaxies was adduced (e. g., Bridle & Perley 1984) as evidence that the two might be similar objects seen from different angles. But this idea had to be married to that of an obscuring torus (Barthel 1989) to launch a "unified scheme" for the radio and optical properties of FR II sources. Many lines of evidence now make this scheme attractive, at least in its broad outlines:

1. the depolarization asymmetries of FR II radio sources with prominent one-sided radio jets correlate well with the jet sidedness (Laing 1988; Garrington et al. 1988, 1991),

2. in FR II quasars, correlations between the sidedness (intensity asymmetry) and prominence (fractional flux density relative to the lobes) of parsec-scale and kiloparsec-scale jets improved as more objects were imaged in detail on both scales (Bridle et al. 1994a; Hough 1994; Wardle & Aaron, these Proceedings, Page 123),
3. some narrow-line AGN have broader emission lines in scattered light, consistent with orientation-dependent obscuration (e. g., Antonucci 1984; Antonucci & Miller 1985; Antonucci, Hurt, & Kinney 1994).

Orientation-based unification has also been extended (e. g., Urry & Padovani 1995) to blazars and FR I sources, for which we have learned that:

1. they, too, have depolarization asymmetries, correlated with the sidedness of the *bases* of their large-scale jets (Parma, de Ruiter, & Fanti 1996),
2. their *parsec*-scale jets generally resemble those of FR II sources, and correlate well in sidedness with their kiloparsec-scale jet *bases* (Giovannini et al. 1995; Venturi et al. 1994, 1995; Tingay et al., these Proceedings, Page 215),
3. the emission on their outer edges is initially much more symmetric in intensity across the nucleus than that on their axes, where the flow is expected to be faster (Laing 1993, 1994 and these Proceedings, Page 241).

So it is not surprising that the debate about the *range of scales* over which jets have relativistic bulk motions, which energized the Green Bank meeting, was absent here[1]. Discussion of transport velocities has now shifted towards unifying the pictures of FR I and FR II sources by asking how relativistic jets decelerate in galactic environments (e. g., Bicknell, these Proceedings, Page 253).

4.1. "Speed bumps"

One former stumbling-block to accepting *large-scale* energy transport at bulk-relativistic speeds got short shrift here. Theoretical *beams* emerge at right angles to small theoretical disks. The rough perpendicularity between kiloparsec-scale *jets* and kiloparsec-scale dust "lanes" in a few radio galaxies (Kotanyi & Ekers 1979; Laing 1984) may have been given undue[2] weight because of this. If such dust was used as a guide to jet orientation, the jets often seemed too near to the sky plane for their (initial) sidedness—and in some sources the brighter jet was apparently receding. The radio depolarization asymmetry has now supplanted the dust as a guide to jet orientations, both because the data are easier to come

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[1] Proponents of intrinsic asymmetries in FR II sources were probably not entirely wrong, however—FR II radio galaxies without strong radio jets, which are expected to lie near the plane of the sky and so to show few relativistic asymmetries, have asymmetries in depolarization and in spectral index that correlate with the lengths of their lobes and with optical emission line asymmetries (Liu & Pooley 1991a,b; Pedelty et al. 1989). The relativistic effects may therefore be superposed on intrinsic (environmentally-produced?) asymmetries that correlate with lobe length (e. g., Bridle et al. 1994b).

[2] given the small size of the sample, and the complexity of elliptical-galaxy dynamics.

by and because they correlate so well with jet sidedness. HST images of the inner dust in radio galaxies (Jaffe et al. 1994; Lynds et al. 1994; S. A. Baum, private communication) also show that its distribution is not as simple as is needed for it to be a jet-orientation gauge. Benign neglect of the dust (while exploring relativistic-jet models for all source powers) may be justified. But the dust should eventually fit into the picture—perhaps in the context of the dynamics of fueling the engine, rather than of orienting its exhaust?

A second "speed bump" could be the high incidence of counterjet candidates in 3CR quasars, especially as these features are more prominent (relative to their lobes) than the jets in some FR II radio galaxies (Bridle et al. 1994). This result may be a problem if it persists in larger samples. If not, it may say that not every FR II radio galaxy "hides" an FR II quasar, as also suggested on spectroscopic grounds by Laing et al. (1994).

5. Velocity Fields

It has long been clear that steady, single-velocity jets should not have discernible features, in conflict with the VLBI data that first suggested parsec-scale relativistic outflow! But in 1984, aside from 3C 345, there were few detailed studies of velocity fields in jets on any scale: little was, or could be, said at Green Bank about jet velocity fields. In contrast, this meeting saw good evidence for, and explored consequences of, velocity fields in jets over a wide range of scales.

5.1. Acceleration and collimation near the nucleus

Velocity differences among features in the same source, and with time in the same feature, are common in parsec-scale jets, (e. g., Pearson, these Proceedings, Page 97 and references therein). 3C 345 remains the prime example of a rich parsec-scale velocity field (Lobanov & Zensus, these Proceedings, Page 109): both the organization of the trajectories and the pattern speeds increase away from the nucleus. Increasing jet collimation away from the nucleus is also a key part of Conway & Murphy's (1993) explanation for the "90°-misaligned" population (Pearson, these Proceedings, Page 97; Appl, Sol, & Vicente, these Proceedings, Page 181).

For M 87 (Biretta, these Proceedings, Page 187), a difficult VLA experiment implying large-scale pattern speeds ranging from stationary to superluminal has been bolstered by HST data (with completely different systematic errors) also suggesting superluminal motion. This jet also shows increasing pattern speeds between parsec and few-hundred-parsec scales, and improving (angular) collimation with increasing distance from the nucleus.

The velocity fields within parsec-scale jets and the velocity dispersion among different source types are both key factors in testing unified schemes via the statistics of apparent Lorentz factors. Both can now be explored more fully (e. g., Pearson, these Proceedings, 97; Vermeulen, these Proceedings, Page 117; Daly, Guerra, & Güijosa, these Proceedings, Page 73) by sensitive imaging of samples that include weaker radio nuclei, and thus should be freer from orientation bias than earlier VLBI work.

5.2. Deceleration on kiloparsec scales in FR I sources

Both *longitudinal deceleration* (Komissarov 1988) and *transverse velocity shear* in a boundary layer (Laing 1992, 1994) are essential ingredients of Laing's explanation for the sidedness and polarization evolution at the bases of FR I jets. The effects of relativistic Doppler boosting/hiding on intensity (Komissarov 1988, 1990) apparently combine with those of aberration on polarimetry in the right way to relate the apparent magnetic field directions and jet sidedness much as observed (Laing, these Proceedings, Page 241).

The Green Bank meeting debated how to weigh symmetry constraints on the speeds of FR I jets on *multi*-kiloparsec scales (O'Dea 1985) against the similarities in sidedness and magnetic field configuration (e. g., Bridle 1982) between their *bases* and entire FR II jets. Many ingredients of the decelerating-jet model were available in 1984: the "spine" field configuration (Laing 1981), the surface shear layer (Baan 1980), the deceleration and recollimation mechanism for low-Mach-number jets (Phinney 1983), and evidence for superluminal motion at the base of an FR I jet (3C 120—Walker et al. 1982; Walker 1984). But the path to the model had still to be cleared by imaging of complete samples of FR I jets on both parsec and kiloparsec scales, and by using the depolarization asymmetry as a primary orientation guide. The model now unites so many distinct correlations for FR I jets that its essentials must surely be correct, even if key details are not yet in place: e. g., the boundary-layer field structures and depths, the magnitude and origin of the mass influx.[3] If the strong-deceleration region of many FR I sources is indeed accessible to our work-horse instruments, we may be able to constrain jet velocity fields and mass influxes in the regime where the FR I vs. FR II character of large-scale sources is settled. These constraints should help to establish dynamical models for the FR I/II division in the radio-optical luminosity plane (Owen & Ledlow 1994), as proposed here by Bicknell (these Proceedings, Page 253). It will also be important to see if the field ordering required by the observed polarization near the boundaries of FR I jets is compatible with the large-scale "gulping" (De Young, these Proceedings, Page 261) needed to decelerate them rapidly by entrainment. Where is the entrainment region (if any) relative to the observed jet?

5.3. Boundary layers and Doppler "hiding" in FR II sources?

For lobe-dominated FR II sources, a jet velocity *field* may imply that Doppler "hiding" does more than just make jets in radio galaxies appear less prominent than those in quasars. The key point is this: when imaging relativistically-moving flows at large enough angles to our line of sight, we will preferentially see the emission from their *slower-moving* parts. This biases us *towards* visualizing emission from an outer shear layer in such jets, and *against* visualizing emission from faster-moving inner "spines".

Emphasis on emission from a shear layer can explain the preponderance of parallel (i. e., axial) B-fields in FR II jets (Bridle 1984), the polarization "rails"

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[3] Is the mass added mainly by turbulent entrainment across the jet boundaries (Bicknell 1984, 1986, 1995, and these Proceedings, Page 253; De Young, these Proceedings, Page 261) or by winds from stars within the jets (Komissarov 1994)?

and flat-topped intensity profiles in 3C 353's well-resolved jet (Swain, Bridle, & Baum, these Proceedings, Page 299), and the edge-brightening of the outer jet in Cygnus A (Carilli et al., these Proceedings, Page 287). Could we distinguish Doppler "hiding" from true emissivity enhancements in the boundary layers or cross-sectional evolution due to surface instabilities (Hardee, these Proceedings, Page 273)? High-resolution studies of FR II sources might do this statistically by looking for systematic differences in the transverse profiles of intensity and polarization in the jets *and counterjets* of narrow-line radio galaxies, broad-line radio galaxies, and quasars, and by looking at the evolution of these profiles along individual jets.

Bias against emission from the spines may mean that a significant fraction of the energy transport is in Doppler-hidden "beams" *within* the FR II jets. Could this be why the hot spots in extended 3CR quasars "know" whether they are on the jetted or counterjetted side—those fed by the brighter jet are more compact, and more prone to recession into their lobes, than those fed by counterjets (Laing 1989; Bridle et al. 1994a)? If the *jet* asymmetry is due to bulk relativistic motion, the *hot spot* asymmetry asks that flow with an appreciable Doppler factor persists as far as, even through, the hot spots[4]. This is easier to reconcile with the modest estimates of Lorentz factors in the observed FR II quasar jets (Bridle et al. 1994a; Wardle & Aaron, these Proceedings, Page 123) if these are biased low by Doppler-hiding of their spines. If the most compact hot spots mark where jet *spines* finally decelerate and decollimate, their asymmetries may contain the "last gasp" of relativistic beaming in FR II sources.

6. Jet Confinement

In 1984, most jets appeared (from their collimation and brightness evolution[5]) to be confined, but we could not agree how. Few of the X-ray environs of well-imaged radio sources had been detected. The exceptions (e. g., M 87, Cygnus A) were exceptionally gas-rich systems with high inferred values of $\dot{M}$. Given these few, generous, X-ray detections and high upper limits, there was good reason to hope that FR I jets with modest minimum pressures are confined thermally by galactic atmospheres. But some FR II jets were clearly over-pressured relative to X-ray limits on surrounding free-free emission, and geometry alone made it difficult to explain this away by relativistic beaming. Magnetically-assisted collimation of current-carrying jets was seen as an escape from this dilemma.

Since then, we have seen how light, hypersonic FR II jets can be significantly over-pressured relative to the ambient medium by protectively cocooning themselves (Loken et al. 1992; Cioffi & Blondin 1992). Magnetic collimation of such jets not only seems inessential, but undesirable—MHD models show that it inhibits lobe and filament formation, in conflict with the data (Clarke, these Pro-

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[4] Komissarov & Falle (these Proceedings, Page 327) showed an axi-symmetric numerical model that contained such effects and suggested that they may be larger than were predicted by Wilson & Scheuer (1983); it will be important to see if their result persists in 3D.

[5] The evidence for static confinement may be worth re-examining in the context of sheared flows—are the collimation measures robust and the brightness-radius "adiabats" appropriate?

ceedings, Page 311), especially as filamentation is so widespread (Perley, Dreher, & Cowan 1984; Fomalont et al. 1989; Hines, Owen, & Eilek 1989; O'Donoghue, Eilek, & Owen 1990; Bridle et al. 1994a; Swain, Bridle & Baum, these Proceedings, Page 299). In contrast, the limits for the extended X-ray emission around some ostensibly confined FR I jets have tightened (Birkinshaw & Worrall, these Proceedings, Page 335). These large sources show uncomfortably little evidence for the putative confining medium—just as it assumes new importance to the dynamics of decelerating-jet models. Are jets in FR I and FR II sources trading places as the vexing problem? For reassurance that this may not be so, see the contributions by Burns, (these Proceedings, Page 341) and Owen et al. (these Proceedings, Page 353).

One constant through the confinement debate has been the M 87 jet: highly one-sided, significantly over-pressured (Owen, Hardee, & Cornwell 1989), and not obviously self-cocooned. Its sharp features had been seen as an obstacle to interpreting it as a Doppler-enhanced jet, but Bicknell & Begelman (these Proceedings, Page 199) show that the statistics of relativistic aberration make this solution less contrived, and the proper motions strongly support it (Biretta, these Proceedings, Page 187).

7. Jet Bending and the Environment

In 1984, the jet-confining media were expected to approximate hydrostatic equilibrium conditions. C-shaped distortions of jets in head-tail sources were explained by motion of the parent galaxy through a calm intracluster atmosphere. Jets with S-shaped distortions were explained by "precession", or at least wobbling, of the central engine. The wide-angle-tail (WAT) sources did not fit such owner-driver pictures of jet distortion, however, as they imputed large peculiar velocities to massive galaxies that should be nearly at rest in the cluster potential. As detailed by Burns (these Proceedings, Page 341), the X-ray emission around many radio sources is clumpy, suggesting dynamic environments prone to high-velocity "weather" driven by cluster mergers. If most WAT distortions result from collective motions in surrounding gas rather than from peculiar motions of their parent galaxies, the WATs are no longer a problem, but an opportunity—their distortions may identify recent examples of cluster coalescence.

8. Evolution of Radio Sources

We heard several new results on the growth and evolution of radio sources. Compact Symmetric Objects (CSOs: Readhead et al., these Proceedings, Page 79; Taylor, Readhead, & Pearson, these Proceedings, Page 91) appear to be candidates for the long-sought precursors of FR II sources. They show signs of intrinsic asymmetries on parsec scales (and also exemplify the exquisite difficulty of finding the true radio nuclei of small sources in the presence of free-free absorption). Studying proper motions on both sides of the nucleus in double-jetted CSOs may also allow more reliable estimates of speeds and orientations in small-scale jets (Pearson, these Proceedings, Page 97). At another extreme, Scheuer (these Proceedings, Page 333) showed that the lobes of FR II sources with prominent jets may exhibit the jet-related length asymmetry expected for mildly relativistic advance—but, if so, at speeds less than those naïvely inferred from synchrotron aging. Whether or not one trusts aging calculations—see Rudnick & Katz-Stone (these Proceedings, Page 233) and Eilek (these Proceedings, Page 281) for reasons why one might not—the small size of the asymmetry in Scheuer's data puts a lower bound on source lifetimes.

9. Tranverse Scales

Several results shown here re-raise the most basic observational questions about jets: *what are we looking at*, and *what are the scales of the underlying outflows?*

9.1. Exoscales—sheaths around FR I and FR II jets

Distinct emission excesses around, and approximately coaxial with, bright radio jets were mentioned at Green Bank (Bridle 1984; O'Dea & Owen 1984). New evidence for this phenomenon[6] was shown here for several sources.

Rudnick & Katz-Stone (these Proceedings, Page 233) used "spectral tomography" to show that the jets in the FR I radio galaxy 1231+674 have two spectrally-distinct components with different transverse scales. Varying proportions of "inner jet" and "sheath" account for spectral gradients that would otherwise be attributed to aging. As well as providing new evidence for FR I jet sheaths, their result emphasizes the importance of exploring *multi-frequency* visualizations of both intensity and spectral index before choosing how to model the spectral properties of radio sources.

A miscellany of aligned ridges, filaments, rings and some diffuse emission was noted within a few radii of two FR II jets—Cygnus A (Katz-Stone & Rudnick 1994; Rudnick & Katz-Stone, these Proceedings, Page 233) and 3C 353 (Swain, Bridle, & Baum, these Proceedings, Page 299). The *reality* of these features is clear, but searches for intensity, spectral, or polarization relationships between such putative "sheath" features and the jets (see Swain, Bridle, and Baum) are needed to test whether they are truly jet-related. Such relationships might also distinguish whether sheaths visualize an *outer* scale of the FR II jet outflow, or a distinct *inner* scale of the lobe/cocoon/backflow. The latter possibility might alleviate the "counterjet candidate" problem in the 3CR quasars, if some of the detections are backflowing sheaths, not outflowing counterjets.

9.2. Endoscales—more signs of the spines?

Besides the evidence mentioned in Section 5, other data hint at well-collimated substructure within features usually termed "jets":

1. WFPC2 observations of the jet in 3C 273 at V band (Bahcall et al. 1995) show that the optical emission is much narrower than the 18cm radio jet. This implies that the primary energy flow is in a narrow "channel" within a more diffuse, but strongly one-sided and elongated, radio feature.

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[6] After much debate, a group of the observers at this meeting agreed to call such features "sheaths"—unwittingly reinventing the term used at Green Bank by O'Dea & Owen!

2. The outer jet in M 87 has a "dark filament" along its axis at both radio and optical wavelengths. This feature, which connects to an emission "loop" on the otherwise-sharp core-ward side of Knot A (Biretta, these Proceedings, Page 187, Figure 4), is < 0.2 of the width of the rest of the jet (Owen, Hardee, & Cornwell 1989, Figure 3).
3. Both jets in the FR II radio galaxy 3C 219 contain similar ultra-compact knots at their tips, aligned across the radio nucleus to better than 0.2° (Perley, Bridle, & Clarke 1994). The compactness and near-perfect alignment of these knots argue that they mark the ends of a well-collimated flow within the broader "jets"—in this case a "restarting" jet/counterjet pair.

10. Longitudinal Scales—Jets in Transition

This meeting showed that three important transition scales along jets are accessible to observation:

1. A (few-parsec) scale of collimation and acceleration (see Section 5.1.)
2. A (few-kiloparsec, galactic-core) scale of deceleration and recollimation in FR I's (see Section 5.2.)
3. A (many-kiloparsec) scale of jet disruption and bending in FR II's, which (see Norman, these Proceedings, Page 319) may correspond to that of a self-actuated dentist's drill, entering the "box of shocklets" it has created in the lobes. This scale of bending and fraying of FR II jets into filaments (Clarke, these Proceedings, Page 311; Hardee, these Proceedings, Page 273) may be quantifiable in Cygnus A (Carilli et al., these Proceedings, Page 287) and in some quasars (e.g. 3C 175, Bridle et al. 1994a). 3C 353 (Swain, Bridle, & Baum, these Proceedings, Page 299) may be a case where one jet is presently within its disruption scale and forms a hot spot, while the other is beyond it and flails over the end of its lobe. Might a high-velocity spine stabilize part of a fraying relativistic jet as the boundary begins to disrupt? And, if many hot spots are transient, formed stochastically off-axis by fraying the *jet* boundaries, are the most compact hot spots better tracers of the *beam* paths? (In Cygnus A, the most compact lobe features are closer to the *initial* jet direction *and* to the longest axis of the lobe than are the brighter "classical" hot spots.)

11. Conclusion: Crossing the FR I/FR II Division

We seem to be approaching another "unified scheme"—for the dynamics of energy transport in FR I and FR II sources. In this scheme, FR I jets decelerate rapidly in the cores of elliptical galaxies, dissipating some bulk energy into internal heat and rapid spreading. FR II jets avoid this fate, leaving the galactic cores at higher Mach numbers, remaining better collimated, and perhaps preserving a "hidden" high-velocity spine until the hot spots. This picture accounts for many basic intensity and polarimetric properties of both types of jet, and may also be the key to understanding relationships between jets and hot spots in FR II sources. The root question of what determines the shape of the radio luminosity function and the relative numbers of FR I and FR II sources remains open. FR II galaxies have more luminous emission-line systems than FR I's (e.g., Baum, Zirbel, & O'Dea 1995), but the optical distinctions between radio-quiet and radio loud FR I galaxies are evaporating in the face of larger samples (Ledlow & Owen, these Proceedings, Page 359).

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