Large Scale Radio Structures

Alan H. Bridle

National Radio Astronomy Observatory, Edgemont Road
Charlottesville, Virginia 22903-2475, U.S.A.

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Alan H. Bridle
National Radio Astronomy Observatory
Charlottesville, Virginia 22903-2475, U.S.A.

> "Our choicest plans have fallen through, our airiest castles tumbled over,
> because of lines we neatly drew, and later neatly stumbled over."
> (Piet Hein, *Grooks, Vol.1*)

1. INTRODUCTION

The radio sources associated with AGNs were once classified either as "compact, flat spectrum" objects, or as "extended, steep spectrum" objects, *e.g.,* [1]. "Compact" sources were studied by VLBI and "extended" sources by connected-element interferometry (often by orthogonal sets of observers). The most significant remnant of this distinction may be that meeting organizers still arrange separate discussions of each class of source, so that radio properties get two reviews rather than only one! It now seems likely that all AGN radio sources with powers above $\sim 10^{22}h^{-2}$ W.Hz^{-1} at 1.4 GHz (for $H_0 = 100h$ km.s^{-1}.Mpc^{-1}) will turn out to have both compact flat spectrum "cores" and extended steeper-spectrum "jets", "plumes" or "lobes" when observed with enough sensitivity and dynamic range at the right resolution. The terms "compact" and "extended" are therefore being replaced by "core-dominated" and "lobe-dominated". Both classes of radio feature are believed to be leakage from a machine whose power plant is at the center of the AGN, whose transmission is the jets (the cores being their optically thick bases), and whose exhaust is the radio plumes and lobes. The physical question raised by the old classification has become: "what determines the *relative prominence* of the radio cores, jets and lobes associated with different AGNs?" Many believe that, at least in powerful sources, orientation to the line of sight is an important part of the answer. The current status of radio structure classification therefore resembles that of the spectroscopic typing of Seyfert nuclei (discussed at this meeting by Don Osterbrock, Joe Miller and Bob Goodrich). The "lines we neatly drew" fifteen or more years ago are being stumbled over today, and we are trying to decide how much of what we see is governed by the viewing angle, and how much by intrinsic properties.

With this in mind, I will review four main topics, interpreting the "large" scale in my title to mean "kiloparsec and larger" scale. First, what properties of the large scale radio sources are generic, *i.e.,* shared by most examples of their general type? Second, how are these properties described by recent models of radio source dynamics? Third, are there observations that may require significant re-thinking

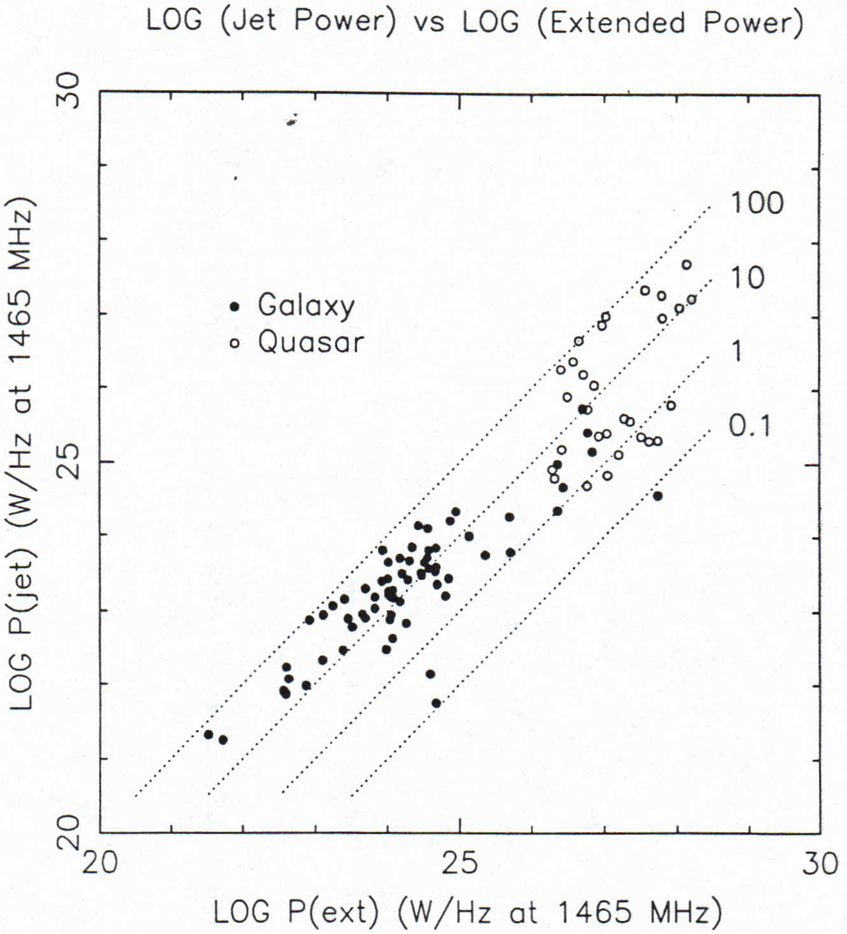


Figure 1. Logarithmic plot of jet power against total extended power at 1465 MHz for 98 sources, distinguishing galaxies and quasars. The dotted lines show where the jets contain 100, 10, 1 and 0.1% of the total extended power respectively. Points above the 100% line would be unphysical; points below the 0.1% line can be obtained only from data of exceptionally high dynamic range.

of these models? Finally, I will discuss some new observations that may steer us towards understanding the main structural asymmetry of powerful sources—that their lobes are usually two-sided while the jets that supposedly "feed" them usually appear to be one-sided.

2. GENERIC PROPERTIES OF LARGE-SCALE RADIO SOURCES

Most properties of radio-loud galaxies change with their extended (*i.e.*, jet plus lobes) radio power P_{ext} within about a decade of $10^{24.5}h^{-2}$ W.Hz^{-1} at 1.4 GHz.

Below this power, most of the large scale structures are edge-*darkened* [2] with ill-defined outer boundaries. The steepest radio spectra (a rough tracer of the most radiatively-aged particles) are in the *outer* extended regions. The sources have *prominent* jets that often contribute more than 10% of the extended power (see Figure 1). These jets are mostly *two*-sided and *rapidly*-widening. The straight jets are dominated by $\mathbf{B}_{\parallel}$ magnetic field components near the core but by $\mathbf{B}_{\perp}$ further out; the bent jets sometimes remain $\mathbf{B}_{\parallel}$-dominated on the outside of the bend [3]. The jets turn into broad plumes or trails, in which $\mathbf{B}$ tends to follow the intensity ridges (sometimes with superposed vortex-like structure). The jet-plume transition is not always well-defined, but is sometimes associated with a *sudden* widening and brightening of the radio structure. The parent galaxies of nearby low-power sources are typically "big, round, pink and friendly", *i.e.,* large, not very flattened, slightly redder-than-normal elliptical galaxies with extended outer envelopes, often in regions of high galaxy density [4,5]. Their nuclear emission lines are generally weak.

Above this power, most radio galaxies have large scale structures that are edge-*brightened* [2] with well-defined outer boundaries, though a few edge-darkened structures occur up to $P^{1.4}_{\rm ext} \approx 10^{26} h^{-2}$ W.Hz^{-1}. The steepest spectra are in the *inner* extended regions. The jets and cores are *less prominent* than in the weaker radio galaxies, rarely having >10% of the total extended radio power (if indeed they are detected at all). The detected jets are usually *one*-sided, *i.e.,* they have side-to-side brightness asymmetries >4:1 [3]. They widen *slowly,* and are $\mathbf{B}_{\|}$-dominated (except near bright knots, where $\mathbf{B}$ is sometimes perpendicular to the steepest brightness gradient [3,8]. They usually end *near* bright emission, or, in the most powerful sources, near compact *hot spots.* The magnetic fields in the lobes are usually circumferential around the outer lobe "caps", and parallel to the major axis in the inner lobe "bridges". The parent galaxies tend to be "disturbed, blue and lonely", *i.e.,* bluer-than-normal ellipticals that prefer regions of low galaxy density but for which deep broad-band optical images often show disturbed morphologies [4,5]. They often have strong emission lines.

Several notable phenomena occur *near* the transition regime of $P^{1.4}_{\rm ext} \approx 10^{24.5} h^{-2}$ W.Hz^{-1}. The local radio luminosity function changes its slope significantly near this power. In a poster at this meeting, Saul Caganoff and colleagues show that the nuclear (Hα+ [NII]) emission line strength is positively correlated with the extended radio power above, but not below, this regime.

The radio properties of quasars generally resemble those of galaxies with similar extended radio powers, except that their radio cores and jets are often more prominent, and the visible jet tends to end at or near the most compact "hot spot" in either lobe [6]. Figure 1 shows how jet prominence varies with extended power for 98 sources whose integrated jet powers and total extended powers are both known, distinguishing the sources by their optical identifications. The decrease in prominence of the radio galaxy jets above $P^{1.4} \approx 10^{24} h^{-2}$ W.Hz^{-1} is not likely to be a *radio* selection effect — the jet detection rates in well-observed complete samples [7,8] confirm the deficiency of powerful radio galaxies with prominent jets. It might however be an optical selection effect, if core and jet prominence are correlated, as the "radio galaxies" and "quasars" clearly differ in the prominence of their optical cores (nuclei).

The re-appearance of *prominent* jets in some quasars (but not, so far, in radio galaxies) with $P^{1.4}_{\rm ext} > 10^{26.3} h^{-2}$ W.Hz^{-1} (Figure 1) is, however, also related to their extended radio morphologies. Figure 2 shows this explicitly by distinguishing the sources according to the type of extended emission that remains *after subtracting the jet(s).* Many powerful radio quasars with extended edge-brightened double lobes — FR class II [2] — have relatively weak radio jets. But some quasar extended structures are complex — the lobes are neither clearly edge-brightened nor clearly bilaterally symmetric. In others, the known extended structure is entirely one-sided. Figure 2 distinguishes these "non-classical" morphologies and shows that *the jets are often more prominent in quasars with complex or one-sided extended structures.* These prominent jets are all "one-sided". Section 6 returns to this in detail.

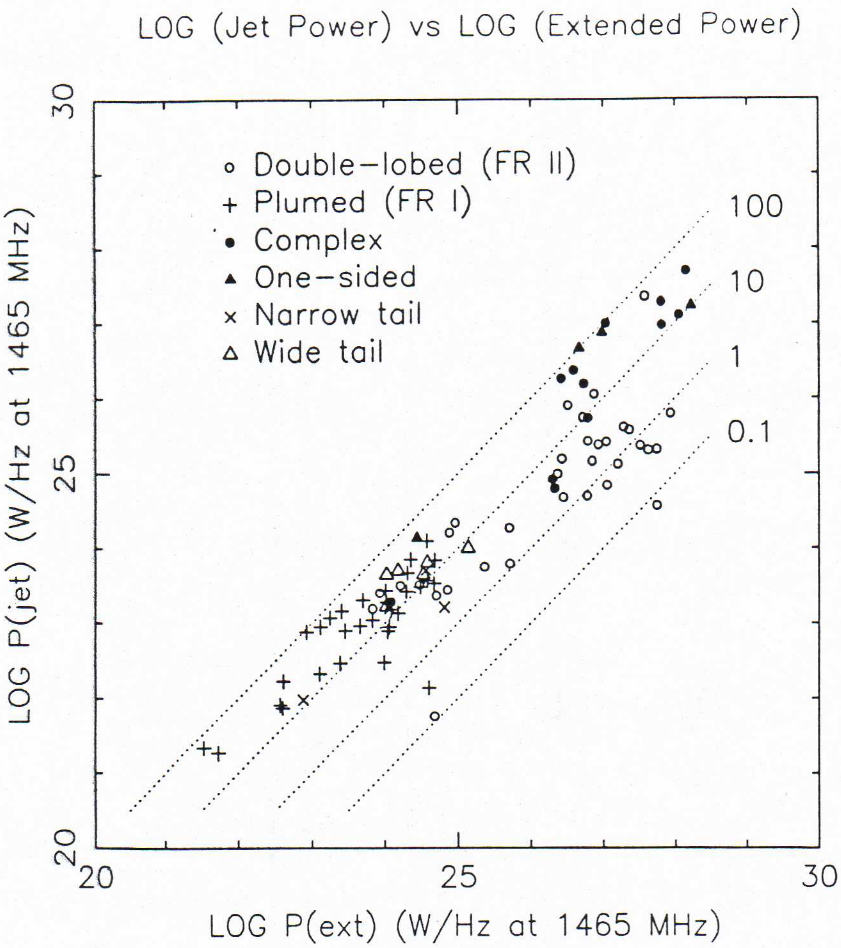


Figure 2. Logarithmic plot of jet power against total extended power at 1465 MHz for 95 sources, distinguishing different extended morphologies. The basic Fanaroff-Riley [2] classes I (plumed) and II (double-lobed) are distinguished (a) from the two classes of severely bent "tailed" sources and (b) from the sources whose extended structures, after subtracting the jet(s), are either "complex" (not clearly edge brightened or bilaterally symmetric) or entirely one-sided.

3. OUTFLOW DYNAMICS

Dynamical models of radio sources are expected to explain the generic structural features outlined above. In recent years, important insights have come from comparing the radio data a) with laboratory observations of supersonic and transonic jet propagation in ambient media, and b) with numerical modeling of supersonic and hypersonic jet propagation in media with finite pressure gradients. It appears that the two principal types of large scale radio structure may be related to two principal jet propagation regimes in the domain of jet Mach number ($\mathrm{M_J = v_J/c_J}$) and density contrast $\eta = \rho_\mathrm{J}/\rho_\mathrm{ext}$ [8]. The radio structures will then be governed by how jets evolve from different starting conditions in the ($\mathrm{M_J}$, η) domain as they propagate down pressure gradients in galactic haloes and the IGM.

An outline of jet dynamics at powers below $\mathrm{P^{1.4}_{ext}} \sim 10^{24.5}\mathrm{h}^{-2}$ W.Hz^{-1} has been given by Geoff Bicknell [9,10,11]. Many features of such low-power sources can be understood if their jets are *transonic* and have well-developed turbulent boundary layers. Such jets interact with ambient gas primarily by ingesting (entraining) it. They spread rapidly (in the laboratory, about as rapidly as the fastest-spreading radio jets). Rapid spreading decreases $\mathbf{B}_\perp$ more slowly than it does $\mathbf{B}_\parallel$. Jet propagation in this regime is an ongoing competition between pressure gradients and buoyancy (which try to accelerate the jet), and entrainment (which decelerates it and increases η). This competition can explain why individual jets spread at non-constant rates [7,8,11]. Adiabatic deceleration can help to keep the jets "lit up", by longitudinally compressing the particle population and $\mathbf{B}_\perp$ [8,9]. Even if such jets reach kiloparsec scales at low density contrast ($\eta \ll 1$), η increases towards unity as they propagate further. Eventually they become subsonic plumes and trails at the mercy of buoyancy effects and pressure gradients in the surrounding medium. The relativistic particles are swept to the outer parts of the sources, where the radio spectra are steepened by synchrotron and inverse Compton losses. The spectacular U–shaped "narrow angle tails" are low-power sources; they can be modeled as low-momentum jets of this type, bent by ram pressure as the parent galaxy moves through an ambient medium.

Models relevant to the dynamics at powers above $\mathrm{P}_{\mathrm{ext}}^{1.4} \sim 10^{24.5}$ h^{-2} $\mathrm{W.Hz}^{-1}$ have been given by Tony Williams and colleagues [12,13,14], and by Mike Norman and colleagues [15,16,17]. The large scale structures of high-power sources can be explained if their jets are initially hypersonic ($\mathrm{M_J} \geq 10$) and light ($\eta \leq 10^{-2}$), so that they interact with surrounding gas more through shocks than by entrainment. Such jets remain supersonic until they reach a shock-dominated interface that travels slowly into the ambient medium. The region near this interface is radio-loud because the shocks compress the field components that are parallel to them, and may both compress and reaccelerate the relativistic particle population. (Recent models of the interface *e.g.*, [13,17], refine the view of the "beam working surface" sketched by Blandford and Rees in [18]). If $\eta \ll 1$, the outward velocity of the interface is much less than the jet velocity, so the flow first decelerates, then deflects back around the jets. Light hypersonic jets therefore propagate through extensive shock-heated backflow cocoons, not through undisturbed IGM. (Parts of the jet may thus be significantly overpressured relative to the undisturbed IGM, especially near internal X-shocks associated with the saturation of reflection-mode instabilities on the jet-cocoon interface [15,16]. This may help to explain why the minimum pressures p_{min} inferred from synchrotron properties of jet knots sometimes exceed p_{IGM} estimated from low-resolution X-ray data, even though the jets seem not to expand freely.) In this picture, the relatively clear outer boundary of the radio lobes traces the contact discontinuity between the backflow and shocked IGM. The relativistic particles in the outflow from the jet are left behind as the interface moves outward, and may also be actively swept back towards the galaxy by backflow. The extended emission should thus have a steeper high-frequency spectrum towards the center of the source, as is indeed observed [19].

Williams *et al.* showed how some further common features of the powerful sources can be understood if large-scale flow indeed continues *beyond* the well-collimated radio jets. If a jet deviates from strict axi-symmetry (either due to wobbling of the "central engine" or to the growth of instabilities in the jet-cocoon boundary layer) it will enter the interface region across an *oblique* shock, rather than across a perpendicular "Mach disk". By integrating the pressure through numerical simulations of the "splatter" flows beyond such oblique initial shocks, Williams and Gull [13] produced model radio brightness distributions that strongly resemble the multiple off-axis hot spots and edge-brightened *lobes* that are often seen in powerful sources. The spectral indices and magnetic field structures of multiple hot spots reinforce this picture [6]. The L-, X- and C-shaped distortions of the inner lobes ("bridges") of many sources can also be accounted for by deflections of the backflows as they try to flow "uphill" in misaligned pressure gradients in the atmosphere of the parent galaxy [14].

Plausible dynamics have therefore been suggested for the two main types of large scale radio sources, though the origin of some features remains obscure. For example, it is not clear what shapes the "wide angle tails" [19] — large, bent sources near the transition power whose structures are less severely distorted than the "narrow tails", but whose parent galaxies are dominant cluster members that should not move rapidly or far through the ambient gas. Are these sources a sign that an important dynamical factor has still to be identified?

Despite the promise of these dynamical descriptions, two major issues must be addressed before we can be sure that they are on the right track. The first is to explain why the critical transition in the (M_J, η) domain usually occurs near $P^{1.4}_{\rm ext} = 10^{24.5} h^{-2}$ W.Hz^{-1} now (and then to predict how it varies with cosmic epoch). Paul Wiita's papers at this meeting suggest a direction in which the explanation may lie. The second is to reassess whether synchrotron radiation traces flow properties as directly as modelers usually assume when they relate jet dynamics to the "facts" of Section 2. Section 4 reviews why this reassessment is needed.

4. IS WHAT WE THINK WE SEE WHAT'S REALLY GOING ON?

Synchrotron radiation is far from an ideal flow visualization tool. To relate radio observables to the supposed flows we should compute how four Stokes parameters vary with frequency while relativistic and thermal particle densities, magnetic fields, particle energy spectra and pitch angle distributions are processed through shocks and turbulence. In practice, we can do neither the computations nor the physics. We know little about the composition or temperature of the jets. Are the "positive ions" mainly protons, or positrons? How and where are relativistic particles accelerated, and with what efficiency? Are hydrodynamic flow models adequate, or do the jets carry net currents and magnetic fields that influence their dynamics? How are the magnetic fields modified by velocity shear, or by reconnection? Different models make different guesses, with fragile, or no, constraints from the data. This is unlikely to improve soon.

The data are, however, sending us a few signals that we should not ignore. Are the kiloparsec-scale "radio jets" indeed synchrotron emission from a volume filled by outflowing material? When these jets were first transversely resolved, their apparent center-brightening (at resolutions of a few HPBW per jet FWHM) was used as evidence that the emission comes from a filled volume. This view was reinforced by the discovery that the wider jets were $\mathbf{B}_\perp$-dominated — in contrast to what was expected in boundary layers or in backflow cocoons, where the fields are likely to be stretched into $\mathbf{B}_\parallel$ configurations. But the spectacular VLA images of the M87 jet, which Phil Hardee describes here, say we should go back over this ground again. The filamentary, edge-brightened structure and the dark "central thread" force us to ask anew: "what parameters of the putative flow control the synchrotron emissivity?" If most of the radio flux resolves into filaments, the process that governs the filamentation controls how we diagnose the underlying flow — are we seeing shocks, or helical instabilities in the boundary layer, or individual strands in a magnetic "flux rope"? Does the process that produces the fine structure modify the vector parameters that affect the synchrotron emissivity (the pitch angle distribution of the particles and the field geometry), and not just the scalar densities and field strengths? Similar problems are raised by the larger-scale filaments and rings detected in the lobes of Cygnus A [21] and Hercules A [22]. Until we understand what creates such structures we must be skeptical of how well the envelope of the synchrotron emission diagnoses the overall shape of a *flow*. Might the M87 data be interpreted as a dark "jet" in a bright "cocoon"?

A related question is whether the apparent "overpressures" in some jets are evidence that $\mathbf{J}\times\mathbf{B}$ forces are needed to confine them. The pure hydrodynamic (HD) models suggest that light, hypersonic jets can cocoon themselves in overpressured backflow for significant fractions of their length. But should the synchrotron radiation from the long lines of sight through the backflow then be expected to overwhelm that from the jet at modest resolution, contradicting observation? The answer depends on how uniquely the synchrotron *emissivity* diagnoses the *total pressure* — are there ways that "radio-loud" jets can have "radio-soft" backflows at similar total pressures? We need to understand this before judging whether the wide-open (*i.e.*, rich but poorly constrained) parameter spaces of MHD must be added to those of HD when making models for the large-scale structures.

We should also ask if the centimeter-decimeter chauvinism of most data from today's imaging radio telescopes (VLA, MERLIN, WSRT) biases our view of large-scale radio structures. Might jet sidedness, cocoon sizes and shapes, or the relative prominence of jets and cocoons, vary with wavelength? Our radio view is occasionally checked from the short-wave side by optical images of jets, such as those shown at this meeting by Bill Keel. But the meter- and decameter-wavelength side is mostly *terra incognita*, despite its formal inclusion in the standard equipartition calculations! Section 5 reports a jet system in 3C288 whose sidedness varies with wavelength, as a cautionary tale.

Finally, if jets in powerful sources have high Mach numbers and pressures but low densities, their velocities are high. In modeling Cygnus A, Williams [12] estimates $M_J \sim 10$, $\eta = 10^{-4}$ to 10^{-3} and $v_J \rightarrow c$. How far do bulk relativistic motions extend beyond the parsec-scale phenomena reviewed at this meeting by Marshall Cohen? May relativistic boosting, light travel time, and aberration effects distort our view of larger-scale sources significantly? For example, is jet one-sidedness in the powerful sources (a) a relativistic (Doppler boost) effect, (b) an asymmetry in the synchrotron emissivities of two otherwise symmetric flows, or (c) an indicator of intrinsic one-sidedness in the energy outflow from the AGN? Are there intrinsically "radio-dark" flows in two-lobed sources with one-sided jets (or with no detected jets), or are jets that we *don't* see being "hidden" by beaming their radio emission away from us? There is no evidence for, and substantial evidence against, bulk relativistic motion in the two-sided jets of low-power sources, but the flow velocity in high-power jets is poorly constrained [7,8]. An important trend in high-power sources, as Peter Scheuer has emphasized [23,24], is that the one-sided parsec-scale jets always point towards the bases of the one-sided kiloparsec-scale jets when both are seen in the same source. The cause of the one-sidedness is therefore likely to be the same on both scales. If we are convinced that the Doppler boost produces the parsec-scale brightness asymmetry, we must ask if it produces the kiloparsec-scale one. Conversely, if we are convinced that the kiloparsec-scale asymmetry is intrinsic, we must question the relativistic-jet interpretation of the parsec-scale phenomena. (Unless, of course, the jet designer is perverse enough to make *intrinsically one-sided relativistic jets*, in which case we can only detect her perversion statistically [25]). The rest of this review discusses new data that bear on the interpretation of large-scale jet sidedness in powerful sources.

5. "TALES FROM THE DARK SIDE", OR — COUNTERJETS IN STRONG SOURCES

We need to know *how* one-sided the kiloparsec-scale jets in powerful sources are, as the probability of observing a given brightness asymmetry due to the Doppler boost in a randomly oriented sample decreases as the asymmetry increases. It is therefore crucial to detect counterjets in these sources.

Several examples of counterjet emission have now been documented in radio galaxies with $P_{\rm ext} > 10^{26}h^{-2}$ W.Hz^{-1} at 1.4 GHz. I will distinguish those in which the main jet appears not to continue all the way to the bright parts of the lobes from those that appear to be more continuous.

In 3C 219 ($P^{1.4}_{\rm ext} = 10^{26.44}h^{-2}$ W.Hz^{-1} [26]) and 3C 288 ($P^{1.4}_{\rm ext} = 10^{26.36}h^{-2}$ W.Hz^{-1} — Bridle, Byrd, Fomalont and Valtonen, in preparation) the brighter jets disappear well before they reach the edge-brightened parts of the lobes. In both sources, the counterjets ($P^{1.4}_{\rm cj} = 10^{23.22}$ and $10^{23.68}$ h^{-2} W.Hz^{-1} respectively) have bright tips that are closer to the core than the tips of the main jets. In 3C288, the spectral index of the main jet between 4.9 and 15 GHz is 0.72±0.04, while that of the counterjet is 1.30±0.17. These are all asymmetries that are *expected* in "born-again" relativistic jets that have restarted after a period of inactivity. In this picture, the tips of the counterjets are where an unfavorable Doppler factor that hides their inner sections can be removed, or decreased, at shocks. The brightest part of a Doppler-hidden counterjet opposite a "born-again" main jet should therefore be furthest from the core. As the counterjet must (in this picture) be on the far side of the source, it is seen at an earlier time, so its bright tip must appear to be closer to the core than the tip of the main jet. The counterjet is also red-shifted, whereas the main jet is blue-shifted. Any steepening of the radio spectrum with frequency in the rest frames of the jets must translate to the counterjet having a steeper spectrum than the jet in the observer's frame. The asymmetries of the jet/counterjet pairs in 3C219 and 3C288 are thus *all* of the kind expected for intermittent relativistic jets. The brightness maxima of the counterjets are, however, anticorrelated in position with those of the main jets; this could be taken as evidence for "flip-flop" behavior, as an alternative to the relativistic asymmetry.

In three other powerful radio galaxies, the main jet is detected most of the way into the lobe; the counterjet is either similarly extended, or it is hard to tell because both jets are confused with lobe emission. The sources are 3C 341 ($P^{1.4}_{\rm ext} = 10^{26.78}h^{-2}$ W.Hz^{-1}), 3C 438 ($P^{1.4}_{\rm ext} = 10^{26.84}h^{-2}$ W.Hz^{-1}) and Cygnus A ($P^{1.4}_{\rm ext} = 10^{27.74}h^{-2}$ W.Hz^{-1}). The counterjets in these sources ([7] and private communications from R. A. Laing and R. A. Perley) have $P^{1.4}_{\rm cj} \approx 10^{24}$ to $10^{25}h^{-2}$ W.Hz^{-1}. 3C438 is remarkable for the exceptional symmetry of its jet and counterjet, given its high power.

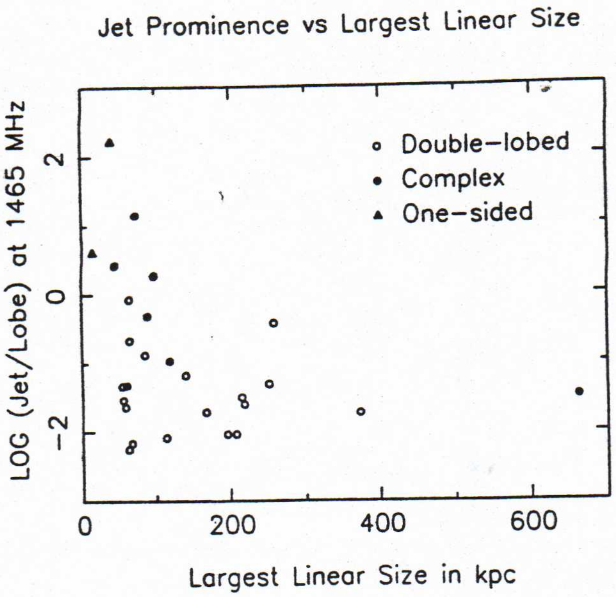
I am also, with many collaborators, systematically looking for counterjets in 3CR quasars with angular sizes >10 arcsec, using 8-hr integrations on the VLA at 4.9 GHz. We have yet to find a clear, continuous, counterjet extending all the way from a core to the lobe, but there are "bits and pieces" of possible counterjets in three or four of the dozen sources observed so far. The 1.4-GHz extended powers of these sources range from $10^{26.9}$ to $10^{28.2}h^{-2}$ W.Hz^{-1}, and the counterjet candidates again have $P^{1.4}_{\rm cj}$ from 10^{24} to $10^{25}h^{-2}$ W.Hz^{-1}. A counterjet of similar power has also been seen in the quasar 1928+73 ($P^{1.4}_{\rm ext} = 10^{26.32}h^{-2}$ W.Hz^{-1}), which has superluminal motions on parsec scales [27].

Several conclusions can be drawn from these first glimpses of counterjets in strong sources. First, there *is* detectable emission on the counterjet side of some powerful sources in images made with dynamic ranges of which the VLA, MERLIN and the WSRT are all capable with modern calibration techniques. Intensive searches for counterjets with these instruments may therefore find enough examples for the statistics of jet/counterjet symmetries to become useful constraints on the jet-asymmetry problem. Second, integrated jet to counterjet ratios (in the sources where counterjets have been detected) range from around two to several hundreds. Such ratios can be accounted for by Doppler boosting without requiring Lorentz factors as high as those inferred for the superluminal parsec-scale jets, or demanding improbable orientations. Third, the jet/counterjet ratio may depend on frequency, as in 3C288. Whether or not this effect is a hallmark of a relativistic jet, it may lead to observational selection problems, and some counterjet hunting should be done at low frequencies to allow for this possibility. (To get enough angular resolution, this may require the extended MERLIN array or a combination of the VLA and VLBA). Fourth, the detected *counterjets* in the more powerful sources generally have $P_{cj}^{1.4}$ from 10^{24} to $10^{25}h^{-2}$ W.Hz^{-1}, and are thus more powerful than the *symmetric* jets in the weak radio galaxies. Even if Doppler boosting and dimming produces the apparent side-to-side asymmetries of the jets in these powerful sources, *the underlying flows must emit more radio power than those in weaker sources* (as we see directly in 3C438).

6. BRIGHT JETS IN POWERFUL SOURCES

I will separate two interesting phenomena that fall under this heading, although they may later prove to be related. The first was discovered by Peter Barthel, Colin Lonsdale, George Miley and Richard Schilizzi [28,29,30] in a sample of 80 steep-spectrum radio sources identified with quasars at $z>1.5$. The source structures in this sample are more bent than those in sources of similar powers at lower redshifts, and the prominence of their jets (the jet-to-lobe intensity ratio) correlates positively with the jet curvature but not with not with the core-to-lobe ratio [30]. They interpret this as evidence for epoch dependence of the environment at high redshifts, *e.g.* that sources at $z>1.5$ must force their way into a denser ambient medium than that around the local sources. An alternative (suggested to me by Jim Condon) is that the radio sample may be biased, despite the steep-spectrum filter, if the quasars must have *both* an unusually luminous optical continuum and prominent emission lines for the sources to have been optically identified. This could introduce an *orientational bias* if the optical continuum or lines escape anisotropically (this need not require that the light is *relativistically beamed* — obscuration by an accretion disk or torus would do). It could also introduce a *bias towards immature sources* that are still establishing their double lobed structures, if optical cores are brighter while the sources are young. Whatever the physical reason for the Barthel *et al.* effect, I wish to minimize it in what follows, so I restrict the analysis below to sources with $z<1.5$.

The second effect is present in the sample of all 27 sources in the redshift range $0.15<z<1.5$ with $P_{ext}^{1.4} > 10^{26}h^{-2}$ W.Hz^{-1}, for which integrated jet and lobe flux densities are available. (These luminosity and redshift limits are chosen to give a sample in which largest linear size is not *strongly* correlated with redshift or with source power, but which contains enough sources to be interesting). Figure 3 plots the ratio between the integrated flux densities of the *kiloparsec scale* jet emission and the lobe emission against the largest linear size of the source. The symbols distinguish the structure type of the emission that remains after subtracting the jet and the core, as in Figure 2. The sources



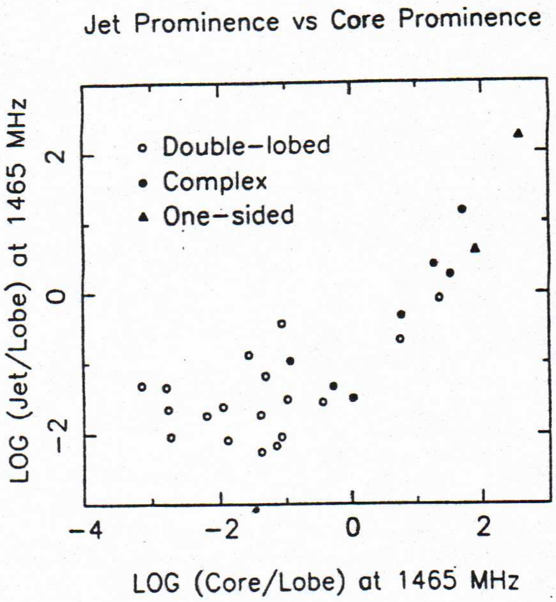


Figure 3 (left). Plot of the logarithm of the ratio of the jet flux density to the lobe flux density against largest linear size, for 27 sources with $P^{1.4}_{\rm ext} > 10^{26}h^{-2}$ W.Hz^{-1} and 0.15<z<1.5, distinguishing different extended morphologies.

Figure 4 (right). Logarithmic plot of the jet-to-lobe flux density ratio against the core-to-lobe flux density ratio, for the same 27 sources.

with $S_{\rm jet}/S_{\rm lobe} > 1$ all have "complex" or "one-sided" extended structures, and apparently small linear sizes. There are (at least) two ways to interpret this. If apparently small linear size and apparently complex morphology *occurring together* in powerful sources are taken to indicate orientation away from the plane of the sky, Figure 3 suggests that some *kiloparsec-scale* jets at z<1.5 are Doppler boosted, by analogy with the arguments for Doppler boosting of the *cores* in double radio sources **[31,32]**. A viable alternative is that some intrinsically small (young, smothered?) sources have intrinsically complex structures *and* intrinsically bright jets. Such sources might be regarded as "local" examples of the Barthel *et al.* high-redshift effect, if this is intrinsic.

Colin Lonsdale **[30]** has emphasized that jet prominence and core prominence are uncorrelated for the 25 jetted sources in his high-redshift sample. Figure 4 plots the jet-to-lobe ratio against the core-to-lobe ratio for the 27 sources in Figure 3, for comparison with his Figure 2(a). Such plots are prone to systematic error, as the data at high prominence are obtained by dividing the jet and the core flux densities by the same, weak, lobe flux density. Even so, it is clear that the most prominent jets in the lower-redshift sample are accompanied by prominent cores. This difference between the two samples should be checked when more data are available, as it may signify that the factors linking jet and core prominence also change with redshift. I urge observers to record integrated jet and lobe flux densities when publishing their data, so that larger samples can be compiled for such studies.

One should not conclude from Figures 3 and 4 that core prominence, jet prominence and linear size are *un*correlated for all classical double-lobed sources with $P^{1.4}_{\rm ext} > 10^{26}h^{-2}$ W.Hz^{-1} and 0.15<z<1.5. Many such sources have no detected jets and are thus not shown in these Figures, which must be only an *upper envelope* to the full distributions. We cannot judge whether jet prominence is correlated with largest linear size or core prominence at *low* levels of jet prominence until most of the jets have been detected in a complete sample of such sources. (Upper limits cannot be given reliably for undetected jets, as one does not know *a priori* which areas of sky the jets may occupy.)

To distinguish the Doppler boosting interpretation of Figures 3 and 4 from the alternative that there is a class of small sources whose cores and jets are intrinsically prominent, we need diagnostics for source and jet orientations that are independent of apparent linear size and morphology. Section 7 discusses a recently-discovered candidate for this diagnostic role.

7. FARADAY SCREENS, DEPOLARIZATION AND JET SIDEDNESS

Evidence is rapidly accumulating that many of the large-scale radio structures are surrounded by magnetoionic media whose Faraday depths are significant at centimeter wavelengths. In most cases, the media appear to be outside the radio sources, but associated with the parent optical object. I will not discuss the physical conditions in, or the origin of, the material here. I will instead concentrate on the evidence for, and the consequences of, its finite Faraday depth.

a) Evidence from rotation measure data

There is now evidence for extremely large Faraday rotation measures (RM > 1000 rad.m^{-2}) in front of several extragalactic sources. The best documented is Cygnus A **[33]**, where the RM ranges from -4000 rad.m^{-2} to $+3000$ rad.m^{-2}, with ∇RM reaching 400 rad.m^{-2}.kpc^{-1} (if the screen is at the distance of the radio source). As there is no internal depolarization of either the lobes or the jet, most of the Faraday rotating material must be *outside* the source (in a sheath or in the surrounding IGM). If the screen was mixed with the radio source, differential rotation between the front and the back sides would have depolarized the emerging radiation so that we could not have detected the very signal from which the rotation measure was inferred! RMs $>$1000 rad.m^{-2} have since been detected in several other extended sources: M87 (Frazer Owen, private communication), 3C295 and 3C218 **[34]**. It will be important to learn whether these exceptionally thick Faraday screens correlate with the presence of cluster X-ray sources, of cooling flows, or (for high-redshift quasars) of the broad systemic-velocity Lyα absorption discussed at this meeting by Ray Weymann.

Possibly more significant here however is the evidence that Faraday screens with more modest rotation measures (10's to 100's of rad.m^{-2}) may be widespread. Screens with RMs in this range have been imaged in several radio galaxies **[35]**. In several cases their symmetries and ∇RM amplitudes show that they are associated with the source's parent galaxy, rather than with foreground gas in our galaxy. The RM data also show directly that the Faraday depths across these screens do not vary smoothly, but have substructure on 1 to 10-kiloparsec scales in which ∇RM can be $\sim$ 10 to 20 rad.m^{-2}.kpc^{-1}. In most cases, there is again little evidence for *internal* depolarization of the radio emission, so the screens are generally *outside* the radio emitting volumes, in sheaths or in larger-scale ambient gas. The RM substructure will however cause differential Faraday rotation across the synthesized beams of imaging radio telescopes at decimeter wavelengths, producing low-frequency depolarization whether or not the lobes and jets contain thermal material. It is therefore not surprising that evidence for Faraday screens around radio galaxies is also accumulating from low-frequency depolarization data.

b) Evidence from depolarization data

Systematic depolarization gradients have been detected in several samples of radio galaxies observed at 0.6 and 1.4 GHz with the WSRT [36,37]. The degree of linear polarization $p^{0.6}$ is systematically less than $p^{1.4}$ in the *inner* parts of radio galaxies, *i.e.,* the ratio $p^{0.6}/p^{1.4}$ increases with distance from the galactic nuclei over scales that are typically from $50h^{-1}$ to $100h^{-1}$ kpc.

These results, and the direct RM imaging discussed above, together suggest that there are *structured* Faraday screens on $\sim$ 100 kpc scales around *many* radio galaxies. If the screens are not thin sheaths, but surround the sources on scales greater than or comparable to those of the radio lobes, depolarization data can distinguish the *front* side of the source from the *back* side. The front is seen along a shorter path through the screen, so it depolarizes less than the back at a given frequency.

c) Depolarization asymmetries

It has been known for several years that depolarization asymmetries are common in large-scale double radio sources [38]. It has only recently become clear, however, that in powerful sources these asymmetries are strongly correlated with the brightness asymmetries of the radio jets. Robert Laing and co-workers [39,40] have determined the depolarization asymmetries between 1.4 and 4.9 GHz of two samples of powerful extended sources with one-sided radio jets. They find that in about 33 of 35 cases, the jetted side of the source is less depolarized than the unjetted side at 1.4 GHz. Of the other two cases, one can be ascribed to the unjetted side having depolarized at a higher frequency, the other to observational uncertainties.

If the depolarizing screens are symmetrically distributed around the sources, *the one-sided jets are systematically on the side facing us* in the cases studied by Laing *et al.*. This is good news for the Doppler-boost model of the jet brightness asymmetry, but I expect that the effect will also be explained *post hoc* in terms of an intrinsic linkage between jet brightness and the screen parameters. While we wait for this to happen, the uncertainty about the geometry and scale of the screen can be addressed directly by imaging ∇RM across sources that show the depolarization asymmetries. Do the RM distributions show the edge effects expected of thin sheaths around the lobes or jets, or do they suggest larger-scale media? The depolarization of low-power sources with *symmetric* jets will also be relevant. If these sources also depolarize asymmetrically, it will be harder to believe that depolarization and jet brightness are intrinsically anti-correlated in sources with asymmetric jets.

8. SUMMATION

It seems likely that hydrodynamic models for the outflows in AGN radio sources will be able to explain many generic properties of the large-scale structures (Sections 2 and 3). The Mach numbers and density contrasts of the flows, plus the ambient pressure gradients, appear to be the key variables.

There is evidence that one-sided kiloparsec-scale jets are more prominent in the powerful sources at $z<1.5$ that have apparently small sizes *and* complex morphologies (Section 6). The one-sided jets in double sources may also be systematically on the side of the source that faces us (Section 7). These results, the gradually increasing number of counterjet detections in powerful sources, and the detailed asymmetries of some jet/counterjet pairs (Section 5), are all consistent with some kiloparsec-scale outflows in powerful sources being *mildly relativistic, e.g.* $v_J \sim 0.8c$. This hypothesis connects a wide range of properties of the large scale structures with the parsec-scale phenomena described at this meeting by Marshall Cohen, and explains the strong correlation between kiloparsec-scale and parsec-scale brightness asymmetries (Section 4). It thus offers a *coherent* explanation of a range of phenomena in powerful sources that otherwise must be attributed to a "conspiracy" of seemingly unrelated effects — some involving small, complex sources; some involving intrinsically one-sided (and intermittent) jets; and others involving jet-related asymmetries in Faraday screens.

The major difficulties of the hypothesis are (a) that the symptoms may be seen more often than they should be in a randomly oriented sample, and (b) that "de-projecting" some sources by the required angles implies that they have larger physical sizes than some feel comfortable with. These difficulties could evaporate if there is an orientational bias in present "complete samples" of *optically identified* radio sources (or if relativistic jet velocity fields are as complex as those in present hydrodynamic models). The discovery that some Seyfert nuclei may look different from different directions emphasizes the issue of whether there is orientational bias in the radio source identifications. Could samples of "radio quasars" be biased more towards the line of sight than samples of the (more often jetless) powerful radio galaxies [7]?

Although we do not yet have decisive evidence in favor of either the relativistic-jet or intrinsic-asymmetry pictures, dynamical models for the large-scale structures should consider the possibility that mildly relativistic bulk motions extend all the way to the lobes in the powerful sources. Modelers should also attempt to describe the detailed linkages between their flow variables and the synchrotron emissivity (Section 4). We also need diagnostics for whether "disappearing" jets like those in 3C219 and 3C288 (Section 5) are indeed being "born again", or whether something else reduces the synchrotron emissivity for most, but not all, of their lengths. *Direct* evidence of variability in AGNs on time scales from hours to decades is discussed in detail at this meeting. Could features of the large-scale structures of sources such as 3C219 and 3C288 tell us about variability on time scales of tens of thousands of years, if properly interpreted? Numerical models of *intermittent* jets may help us to do this.

Ultimately, our models must explain why so many large-scale features of radio sources change qualitatively near a local 1.4-GHz extended luminosity of $P_{ext} = 10^{24.5}h^{-2}$ W.Hz^{-1} (Section 2). There are so many correlations between large-scale radio morphology and radio power that we must ask for *quantitative* interpretations of them in terms of the interactions between the outflows from AGNs and their environment. Our goal should be to find predictive relationships between source power, jet variables such as initial Mach number, density and collimation, and environmental variables such as density and pressure gradients (possibly functioning both as an "exhaust system" and as a "fuel tank" for the central engine). The new computer-intensive tools of radio imaging and of numerical jet modeling have suggested plausible directions to go in, but most of the road is still ahead.

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DISCUSSION

Marshall Cohen: You are convincing us that the powerful kiloparsec-scale jets are two-sided and relativistic. What then of 3C273, which remains one-sided no matter how hard we look?

Alan Bridle: I can think of two possibilities. The first would be that we have still not looked hard enough, despite the Herculean (Perleyan?) efforts made so far — it's been hard to find convincing *lobe* emission on *either* side of this source. If this is right, the "other side" may appear in an extremely high dynamic range image (possibly at a low frequency!). We might then conclude that the kiloparsec scale jet in this source has a higher-than-average Lorentz factor. The second possibility is that this is a "born-again" relativistic jet at such a small angle to the line of sight that the emission from the far side has not reached us yet. In that case the "news from the other side" will appear if we wait long enough. The counterjet tip could be too far out and too resolved to be detected by VLB, but still be too close to the core to be detected by the VLA.

Wil van Breugel: Do the brighter, or one-sided, jets always point to the lobe with the larger total flux density?

Alan Bridle: I have not looked at that recently. But there is no correlation between jet sidedness and the maximum distance from the core to the edge of the lobe, in the sample of jets that I used here. As several groups have found that the lobe with the larger total flux density is usually closer to the core, I would be a bit surprised if there is a strong effect of this kind. But I agree that it should be looked at again, as there are over 200 jetted sources known now.

Oved Dahari: Are curved jets found to be more luminous on average?

Alan Bridle: In the weak U-shaped "head-tail" sources, the jet with the greater curvature is often the brighter one. In the powerful sources, the only correlation that anyone has published is the one between jet prominence and jet curvature at $z>1.5$ [30]. I have not yet looked at that correlation in my own sample.

Oved Dahari: In the picture where relativistic jets slow down, do counter-jets appear further from the core?

Alan Bridle: In a source with "born-again" relativistic jets, the counterjets should slow down, or even splash back, at their tips. The observer sees an asymmetry because the counterjet tip is on the far side, so that it is seen at an earlier stage of development and thus *closer* to the core than the main jet tip. The slowdown also helps us to see the far tip, by reducing an unfavorable Doppler factor. If jets in a steady flow slow down, their *lengths* are defined by the history of how the interface has moved relative to the cocoon wall, but the counterjets may then become *more visible* in the outer parts of the source. If jets slow down between parsec and kiloparsec scales, we might find sources with counterjets in VLA images but not in VLBI images of equal dynamic range.