LARGE-SCALE STRUCTURE: JETS ON KILOPARSEC SCALES

R.A. LAING
Royal Greenwich Observatory
Madingley Road, Cambridge CB3 0EZ, U.K.

1. Overview

This paper examines some of the consequences of the hypothesis that jets in *all* radio galaxies and quasars are relativistic on small scales, in the sense that the flow velocity >0.5c. This idea is suggested by a number of lines of evidence. Firstly, Unified Models (Urry & Padovani, 1995) imply that the relativistic motion required in core-dominated objects must also occur in a larger parent population consisting of most, if not all, extended sources. Secondly, superluminal motion is detected in the nuclei of extended sources and in the kpc-scale jet of M 87 (Hough, 1994; Biretta, Zhou & Owen, 1995). Thirdly, jets are one-sided in the same sense on pc and kpc scales; at all luminosities, the radio emission tends to become more symmetrical on larger scales, as expected if an initially relativistic flow decelerates (Bridle & Perley, 1984; Bridle *et al.*, 1994a; Parma *et al.*, 1994). Finally, depolarization asymmetry occurs in both low (Parma, de Ruiter & Fanti, 1996) and high (Laing, 1988; Garrington *et al.*, 1988) luminosity sources: the implication is that the brighter jet is on the near side of the source. It is likely that the key difference between radio sources in the two morphological classes defined by Fanaroff & Riley (1974) are that relativistic flow persists to the extremities of FRII sources, but that FRI jets decelerate smoothly on intermediate scales (Laing, 1993; Bicknell, 1995). On kiloparsec scales, we can identify structures which we propose should be called *fast jets*. These are well-collimated and generally one-sided (in the sense that the jet/counterjet ratio >4:1). They also have longitudinal apparent magnetic field ($\mathbf{B}_{||}$). They occur both in FRII sources, and at the bases of FRI jets (Bridle & Perley, 1984). We suggest that they are relativistic flows, and that this fact is crucial to an understanding of their evolution. A framework for the understanding of the variety of ex-

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tended structures in extragalactic radio sources in this context is illustrated in Figure 1, which is an improved version of the diagram presented by Laing (1993). A fast jet appears to be able to: decelerate and recollimate to form a *slow jet* with $\beta \ll 1$ (therefore two-sided unless external effects dominate); disrupt, as in wide-angle tail sources, or hit the external medium and form a ***hot-spot***. Slow jets are probably formed only when a decelerating fast jet can be recollimated by the external pressure gradient (Phinney, 1983; Bowman, Leahy & Komissarov, 1995). This may not be possible for more powerful sources in flatter pressure gradients and it is likely that wide-angle tail sources are formed when a fast jet decelerates rapidly but cannot recollimate. Deceleration by entrainment is efficient when the jet is transonic, and Bicknell (1994) showed that this corresponds to $\beta \approx 0.3 - 0.7$ for a relativistic jet. If the jet does not slow down sufficiently (*e.g.* by mass loading; Komissarov 1994), then the flow will remain supersonic until it impacts on the external medium, and an FRII source will result. The radio morphology is therefore determined by a combination of initial jet speed and thrust and the effects of the environment, via the rate of stellar mass loss and the pressure gradient. On the largest scales, a *bridge*(backflow) or *tail* (outflow) will be formed. If the jet remains supersonic as far as the end of the lobe (as in an FRII source), then it is inevitable that a backflow (bridge) will be generated. As emphasised by Parma, de Ruiter & Fanti (1996), the majority of FRI sources also show bridges: the residual momentum of the jets, their density contrast with the external medium and the external pressure gradient are all likely to be important in determining their large-scale morphologies.

2. FRII Sources: Orientation and Intrinsic Asymmetries

The jet intensity, depolarization, spectral index, arm length and emission-line sidednesses of FRII sources are all correlated in various ways. In order to make sense of these relations, we adopt a deductive approach with the following assumptions:

1. Jets in FRII sources are intrinsically symmetrical and relativistic.
2. Quasars are only seen if their axes are within 45° – 60° of the line of sight, and a subset of FRII radio galaxies are side-on quasars,
3. Faraday effects are due to magnetic field and/or density irregularities in the medium surrounding the radio sources.
4. There is an intrinsic mechanism which associates higher external gas densities, smaller lobes and steeper radio spectra (most obviously the combination of synchrotron and adiabatic losses).
5. Jets, jet-side hot-spots and some associated material have flatter radio spectra than does the lobe emission.

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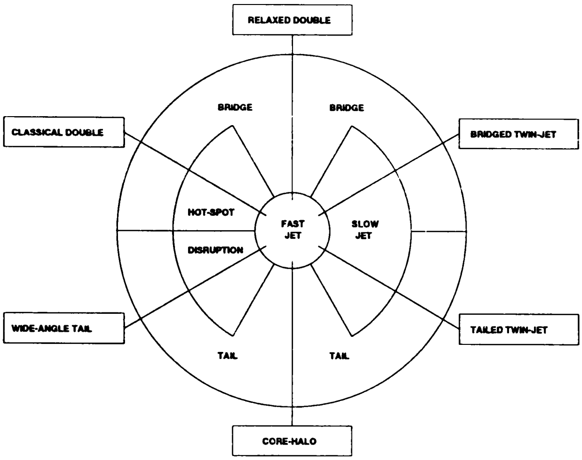

Figure 1. A schematic representation of the main morphological classes of radio source. Each radial line refers to a particular type of source; increasing radius represents the evolution of the jet flow.

6. The average advance speed of the radio source is small ($\leq 0.1c$), so light-travel effects are small.

From these assumptions, we make the following deductions, which are illustrated in Figure 2:

Sources with strong, one-sided jets are selected to be within about 50° of the line of sight: most quasars satisfy this condition. The differential Faraday depth to the two lobes of such a source is dominated by orientation, so:

the far (counter-jet) side shows stronger depolarization.

The ratio of lobe lengths on opposite sides of the source is determined primarily by intrinsic effects, rather than by light travel, although the latter effect may just be detected in sources close to the line of sight (Scheuer, 1995). Therefore:

depolarization (and jet sidedness) are only weakly correlated with arm length in jetted sources.

By contrast, sources without strong jets are close to the plane of the sky, so the differential Faraday depths to the lobes are determined primarily by variations in external density and

depolarization is stronger on the short side in jetless sources.

In jetless sources, emission on the two sides is (on average) equally boosted. Spectral differences therefore reflect intrinsic effects, so:

The lobe with the steeper spectral index is shorter and more depolarized.

Finally, in jetted sources, the high-brightness emission (jet, jet-side hot-spot, ...) is Doppler-boosted, with a flat spectrum, whilst the spectrum of

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the lobe emission is determined by intrinsic effects.
Depolarization is greater in the steeper-spectrum lobe if either effect dominates.

The data in Figure 2 are taken from the references given in Laing (1993), and refer to powerful FRII quasars and radio galaxies. Similar results appear also to hold for CSS sources (Garrington & Akujor, 1996). Bridle *et al.* (1994b) also showed that, whilst the spectral index of high-brightness structure in quasars is correlated with jet sidedness, that of the low-brightness (lobe) emission is correlated with arm length, indicating a mixture of orientation and intrinsic effects in individual sources.

3. FRI Sources as Decelerating Jets: Observations of 3C 31

Parma, de Ruiter & Fanti (1996) describe the evidence that statistical results on asymmetries in FRI jet bases require the flow to be relativistic on small scales. Laing (1993) proposed a simple model in which jets consist of a fast, perpendicular-field *spine* surrounded by a slower longitudinal-field *shear layer*. This model predicts the brightness and polarization structure of the jets as functions of angle and velocity distribution. If jet sidedness is determined entirely by Doppler effects and the jet is axisymmetric, then the three-dimensional velocity field can be deduced from a map of $S(x,y)/S(-x,-y)$ where $S(x,y)$ is the flux density at a point (x,y) on the map. This section describes preliminary results from a detailed study of the low-luminosity radio galaxy 3C31 by Feretti, Giovannini, Parma, Bridle, Perley and the present author. At 8.4 GHz, using a combination of VLA B, C and D-configuration observations (FWHM 0.7 arcsec), the counter-jet is detected all the way into the nucleus, and we can make a detailed sidedness map by dividing the image by a copy of itself rotated through 180° about the nucleus. A profile along the ridge-line of the jet shows that the jet/counter-jet ratio decreases from 15 – 25:1 in the inner region (0 – 5 arcsec from the nucleus) to 1:1 at 30 arcsec, after which the main jet bends significantly. Fine structure in the main and counter-jets causes the sidedness ratio to vary erratically in the innermost region. The ratio is highest along the ridge line, as expected if a slow boundary layer is present, but does not fall to 1 at the jet edges, at least at current sensitivity levels. The inferred velocity for the central spine of the jet falls from $\beta \approx 0.8$ at 2 arcsec from the nucleus to $\beta \approx 0.1$ at 30 arcsec, assuming an angle to the line of sight of 50°. Larger angles are ruled out by the maximum jet/counter-jet ratio, whilst smaller ones are inconsistent with the degree of polarization observed at large distances from the nucleus, assuming the models of Laing (1993). Details of the polarization results (in particular the fact that the flip from $\mathbf{B}_{\parallel}$ to $\mathbf{B}_{\perp}$ occurs closer to the nucleus

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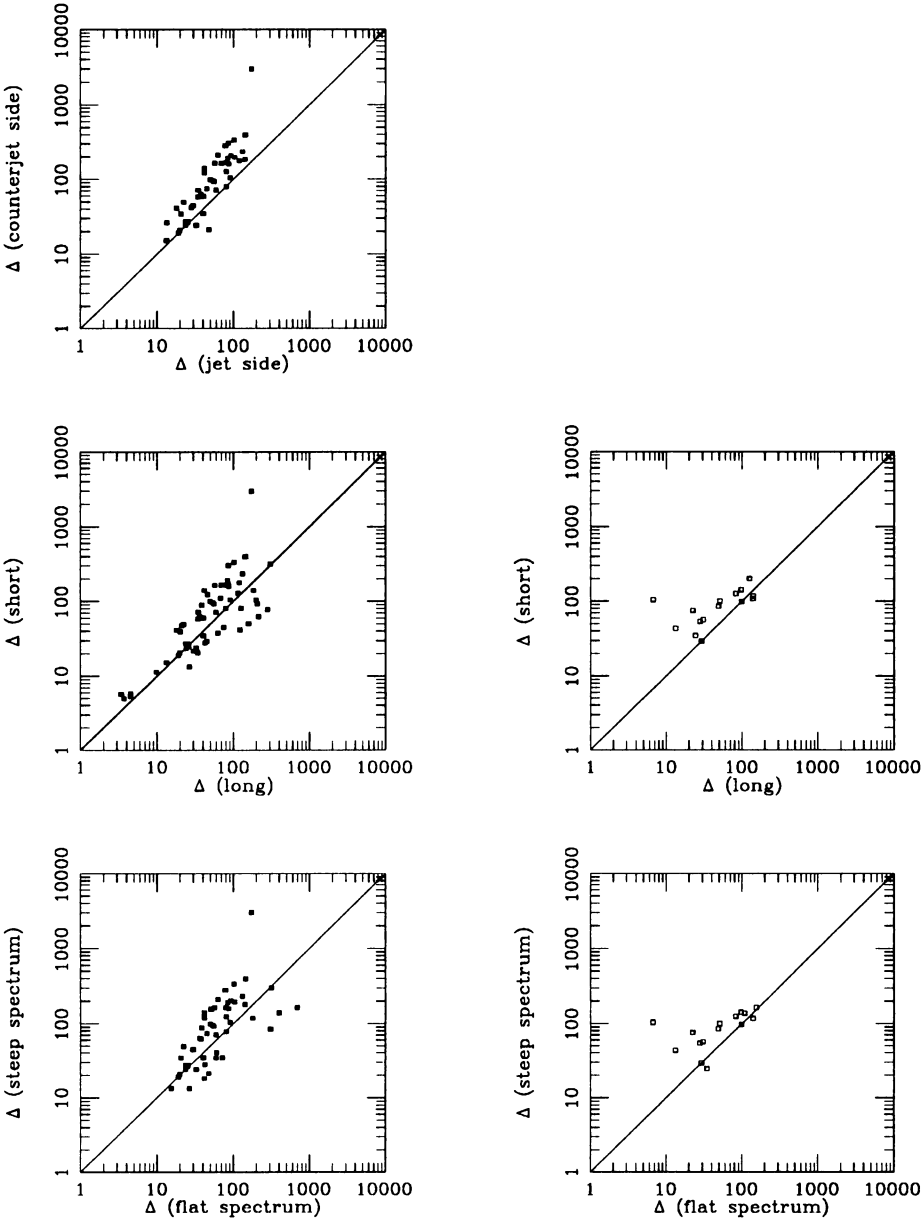

Figure 2. **Plots of Faraday depth, Δ (in μGcm^{-3}pc) on opposite sides of FRII radio sources. The left-hand panels represent sources with detected jets; the right-hand panels those without jets. Top: jet side against counter-jet side. Middle: longer lobe against shorter lobe. Bottom: steeper against flatter-spectrum lobe.**

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in the counter-jet) suggest that the field in the shear layer is not longitudinal, as in the original model, but rather has roughly equal components in the longitudinal and azimuthal directions, with no radial component. This might be produced by averaging over a number of randomly-orientated $\mathbf{B}_{\parallel}$ filaments in the shear layer as, for example, in M87 (Owen, Hardee & Cornwell, 1989). Sufficiently detailed observations might resolve individual filaments, leading to oblique apparent magnetic fields. The initial conclusions of this study are that a decelerating jet model with a $\mathbf{B}_{\perp}$ spine and a shear layer is in good qualitative agreement with the observations, but that further refinement of the shear-layer field structure is needed. Similar conclusions are reached from a study of 3C 66B (Hardcastle *et al.*, 1995). We plan more detailed modelling of the velocity field in 3C 31, together with a comprehensive study of its Faraday rotation properties: it is already known to show a substantial depolarization asymmetry (Burch, 1979; Strom *et al.*, 1983).

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