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Hotspots, Jets and Environments

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Abstract. I discuss the nature of 'hotspots' and 'jet knots' in the kpc-scale structures of powerful radio galaxies and their relationship to jet-environment interactions. I describe evidence for interaction between the jets of FRI sources and their local environments, and discuss its relationship to particle acceleration, but the main focus of the paper is the hotspots of FRIIs and on new observational evidence on the nature of the particle acceleration associated with them.

1. Introduction

In the conventional picture of powerful extragalactic radio sources, the Fanaroff-Riley classification of an object (Fanaroff & Riley 1974) is determined by the physics of the interaction between the kiloparsec-scale jets and the external medium. This is thought to take place in two very different ways. In the low-power FRI sources there is a good deal of evidence (see, e.g., Laing & Bridle 2002; Laing, these proceedings) that the jets normally decelerate from relativistic to sub-relativistic speeds gradually over scales of 1–10 kpc. Deceleration requires entrainment of external material in order that momentum should be conserved (e.g., Bicknell 1984; Komissarov 1994) and the jets on these scales are often apparently in direct contact with the external medium, so that direct jet-medium interactions are a possible mechanism for the deceleration. By contrast the jets in the more powerful FRII sources remain relativistic, often out to scales of hundreds of kpc or more, until they decelerate abruptly (i.e., on scales that are much less than the length scale of the jet) at a shock or shocks which involve the direct interaction of the jet not with the external medium but with the relativistic plasma that fills the lobes in which the jets are typically embedded, giving rise to the observed hotspots. (For the purposes of this paper I will ignore the vast range of intermediate cases and peculiar objects that should really be accommodated in a scheme of this kind.)

One important *similarity* between the deceleration regions of the two types of source is that both are associated with particle acceleration. In the FRII sources the detection of optical synchrotron emission from hotspots provided early evidence in favor of a beam model with local particle acceleration at the hotspots (e.g., Meisenheimer et al. 1989; Meisenheimer et al. 1997; but cf. Gopal-Krishna et al. 2001). The current probable detection of X-ray synchrotron emission from hotspots (e.g., Kraft et al. 2005, and see below) makes it very hard to evade the conclusion that *in situ* particle acceleration at the hotspots is necessary. In the FRIs the situation is similar: optical jet detections meant that only models involving special geometries could evade the necessity for *in situ* particle acceleration (e.g., Biretta & Meisenheimer 1993; Hardcastle et al. 1996) and these models are essentially completely ruled out by the X-ray data (e.g., Hardcastle et al. 2001). X-ray jet detections are common (Worrall et al. 2001) in powerful FRI sources, so that it seems likely that particle acceleration is always associated with jet deceleration in FRI jets. Since we have no direct evidence for particle acceleration anywhere else in the large-scale structure of either class of radio source, these regions may be the place where the electron energy spectrum observed throughout the rest of the source is determined, and so it is important to understand the physical processes that are going on in the jets of FRIs and the hotspots of FRIIs, using, if possible, insights gained from each class of source to understand the other.

In this paper my focus will be on several outstanding problems in our understanding of the compact features of FRII sources and what we can learn from them about jet-environment interaction, but I begin by briefly and subjectively reviewing what we can learn about jet-environment interaction and particle acceleration from the FRIs, the closest of which can be studied in much more detail than is possible for any FRII.

2. FRI Sources

As discussed above, the 1–10 kpc-scale jets of FRI sources have to interact with the environment in order to decelerate, although the present observational modelling of this process (see Laing, these proceedings) does not allow us to extract the microphysics of the jet-environment interaction. FRI jets should therefore be good places to look for evidence for jet-environment interactions.

Detailed radio and optical images of FRI jets often show a 'knotty' structure with many compact features — the best-known example is the well-studied radio and optical jet of M87 (e.g., Owen et al. 1989). The nature of the knots is not obvious. At least some appear to affect the whole jet (e.g., knot A in M87) which raises the possibility that they are hydrodynamical features such as internal shocks. If this were the case, there would be some analogy between these features and the hotspots of FRII sources. However, bright compact features do not seem to be present in the radio emission of all FRI jets, and X-ray observations of jets (backed up in some cases by optical data) often show smooth diffuse X-ray emission, which implies distributed particle acceleration, since the X-ray loss spatial scale (defined as the speed of light multiplied by the synchrotron loss timescale for an electron radiating in the X-ray assuming a magnetic field strength of the order of the equipartition value) is so short that X-ray synchrotron emission always tells us the location of *current* particle acceleration.

The closest FRI radio galaxy, Centaurus A, provides an important testbed for models of jet deceleration and particle acceleration in FRI jets. Its distance (3.4 Mpc) means that the resolution of *Chandra* is $\sim$ 10 pc, comparable to the loss spatial scale. This cannot be achieved in any more distant FRI source. Cen A's detailed X-ray and radio structure (e.g., Kraft et al. 2002; Hardcastle et al. 2003, 2006; see Hardcastle et al. , these proceedings, for images) shows complex, knotty structure in both the radio and X-ray images, with structure on scales that would be unresolved in any other FRI jet. Crucially, there is a good deal of small-scale dissimilarity between the X-ray and radio structures: there are bright radio knots that are poor X-ray sources while many of the compact X-ray sources have only faint or absent radio counterparts. In Hardcastle et al. (2003) we used the dynamical information available from multiple VLA images to argue that the X-ray bright knots are stationary while the radio-bright, X-ray-faint knots are moving down the jet at $\sim 0.5c$. This led us to argue that the compact X-ray bright features are localized shocks in the fluid flow, probably as a result of interaction with features from the external medium in the manner proposed by Blandford & Königl (1979). This is the first direct association between the small-scale dynamics of an FRI jet and the acceleration of high-energy particles.

It is important to realise, though, that the emission in compact knots in the inner jet of Cen A represents only a fraction of the total X-ray emission in the jet (moreover, a fraction that clearly decreases with distance from the active nucleus). A second, diffuse component of X-ray emission is also present, and both from the luminosity function of knots (Kataoka et al. 2006) and from the spectral differences between knots and diffuse emission (Hardcastle et al. , these proceedings & in prep.) it seems likely that this has its origin in a different particle acceleration process. In some cases (e.g., Hardcastle et al. 2006) we may be able to associate diffuse particle acceleration with hydrodynamical features affecting the whole jet, but in others we are not. It seems likely that this diffuse acceleration process is related to the bulk deceleration of the jet flow (although we do not have evidence for bulk deceleration in Cen A) and it may well be the dominant process in other, more distant jets. Both in Cen A and in other jets with better-studied optical properties, the overall radio-through-X-ray spectra are inconsistent (Hardcastle et al. 2001; Perlman & Wilson 2005; Hardcastle et al. 2006) with simple continuous-injection models (Heavens & Meisenheimer 1987) and the nature of the 'diffuse' particle acceleration changes as a function of distance along the jet, with a decreasing X-ray/radio ratio and a steepening X-ray spectral index up till the point where the X-rays disappear. We do not as yet have any clear idea what the microphysics of this 'diffuse' acceleration process are, but it is essential to understand it to make further progress in this area, and I will argue in the following section that we can no longer ignore it in FRII hotspots as well.

3. FRII Sources

3.1. When Is a Knot Not a Knot?

I begin this section by making a trivial point about nomenclature that is nevertheless important for what follows in the rest of the paper, particularly §3.2.. This concerns when, and why, we refer to a compact feature as a hotspot rather than a 'jet knot'. It is worth noting first of all that the definition of 'hotspot' itself, as applied to radio maps, is not widely agreed on: for example, two widely cited papers on the detailed structure of FRII sources, Bridle et al. (1994) and Leahy et al. (1997), propose incompatible definitions. However, all definitions generally expect the hotspots to be found at the end of the source, since our theoretical expectation (e.g., Blandford & Rees 1974) is that these will be the ones associated with the jet termination. In particular, features that are part of a well-collimated jet are generally classed as 'jet knots'. This division can be ambiguous — some features near the end of jets but with clearly continu-

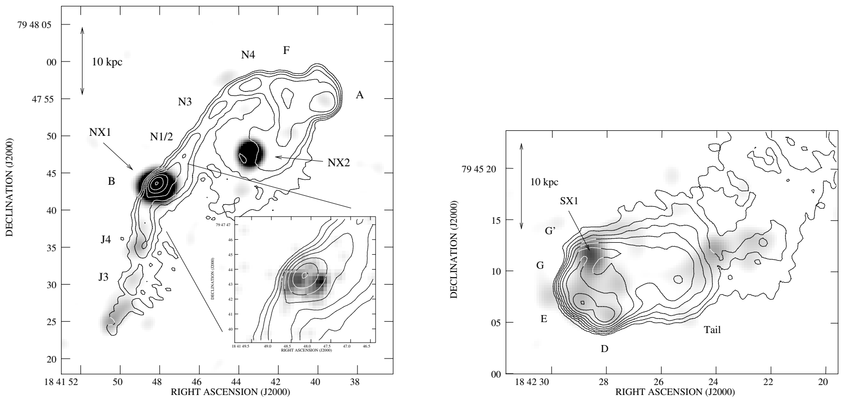

Figure 1. The hotspots of 3C 390.3 in radio and X-ray (adapted from Hardcastle et al. 2007b). The greyscales show X-ray emission and the contours are from a 5-GHz VLA map. In the radio, note the continued collimated outflow after knot B (usually called the primary hotspot). In the X-ray, note the non-detection of the northern hotspot A and the diffuse emission seen from the southern hotspot.

ing well-collimated outflow are nevertheless usually referred to as hotspots (e.g., hotspot B of 3C 390.3: Leahy & Perley 1995, and Fig. 1). The existence of multiple bright compact features associated with the jet termination (see §3.4., below) is evidence that a definition of hotspots as directly equivalent to 'the location of jet termination' is inadequate: in many places the jet does not seem to terminate at a single location or in a single step. We know that some features that would generally be classed as jet knots (e.g., knot F6 in 3C 403, Kraft et al. 2005) produce optical and X-ray emission and are thus probably sites of particle acceleration, blurring the distinction between jet knots and hotspots further. This ambiguity can be and has been used in a self-serving way (the present writer is as guilty of this as anyone else) to 'define away' problems with the picture that is being presented. A better definition would include some of the actual physics of the jet at the location of the compact feature, but this is hard since in many cases jets are faint or invisible — the 'jet knot' may be the only indication that a jet is present at all. In what follows I will use the traditional terminology, but the reader should be aware that the term 'jet knot' is thus used to encompass a number of features with diverse characteristics and probably significantly different physical origins.

3.2. Jet Knots as Environmental Interactions

Is there a class of jet knots in FRIIs that are related to direct environmental interactions with the jet, as we have argued in the case of Centaurus A? One place to look for such jet knots would be in sources where there is an independent suggestion of a jet/external medium interaction in the shape of 'jet-induced star formation'. Well-studied candidates for this process include 3C 285 (van Breugel & Dey 1993) and 3C 34 (Best et al. 1997). However, there is little evidence in any of these sources that the interaction, if present, affects the jet itself. In 3C 285,

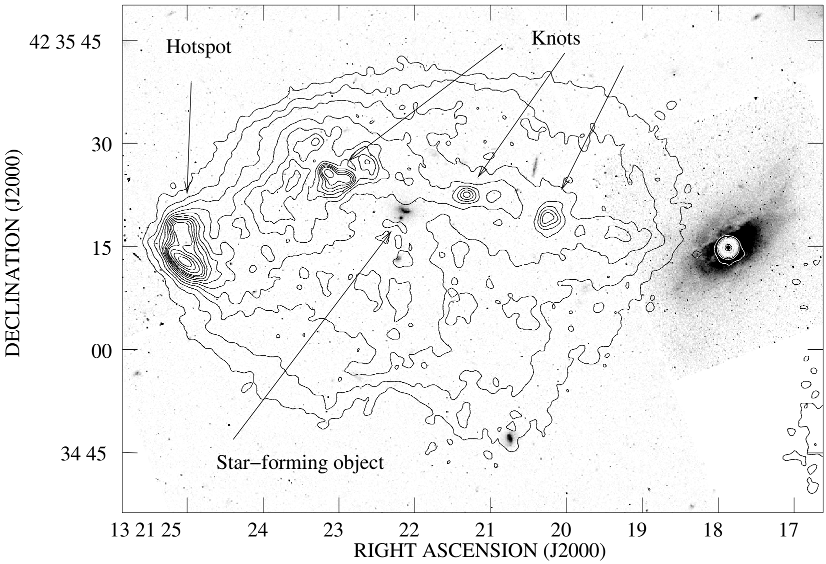

Figure 2. Hotspots, jet knots and environmental interactions in the E lobe of 3C 285 (from data presented by Hardcastle et al. 2007a). Greyscale shows *HST* image, contours are from an L-band VLA image.

for example, the images of van Breugel & Dey show the jet to contain several knots, but none is spatially coincident with the position of the star-forming object that is believed to be interacting with the jet (Fig. 2). Thus not only are the knots in the jet not apparently related to environmental interactions, but the proposed environmental interactions do not apparently produce knots.

One FRII source where a jet-environment interaction apparently does affect the jet is 3C 321 (Evans et al. , ApJ submitted). Here an otherwise normal FRII source has a jet that is disrupted downstream of a close passage between the jet and a companion galaxy, forming an FRI-like jet structure on one side. The clear compact hotspots on the same side suggest that this is a temporary interaction that has been going on for only $\sim 10^6$ years. Immediately adjacent to the companion galaxy is a compact jet knot. However, this knot is relatively faint and is not a source of any detectable optical or X-ray emission, unlike some other jet knots in FRIIs: nor is the downstream 'FRI-like' jet an X-ray or optical source. The analogy between this source and the jet-medium interactions seen in FRIs is thus not particularly strong.

The lack of any strong relationship between jet knots and environmental interactions lends support to a picture in which jet knots in FRIIs have multiple possible origins. The regularly or quasi-regularly spaced knots seen in many jets (see, e.g., Bridle et al. 1994) seem most likely to be related to internal shocks in the jet or to fluid dynamical instabilities.

3.3. Hotspots and the Jet-External Medium Interaction

Can the features conventionally classed as hotspots give us information about jet-environment interactions? Since, as discussed above, the 'environment' of the jet at the jet termination point is the lobe or cocoon, it is clear that hotspots can in principle tell us about interactions with the lobe plasma: I discuss this in §3.4.. Here, however, we can ask whether hotspots tell us anything about the *external* environment.

We expect that the jet should terminate close to a boundary of the lobe or plume that the jet inhabits: the boundary is, of course, the location of the contact discontinuity between the external medium and the relativistic plasma that has previously passed through the jet. A consequence of this is that we do not expect to see hotspots that are physically in the centre of the lobe. A true hotspot (as opposed to a jet knot) seen at a distance from any lobe boundary is assumed to be there as a result of projection of an interaction between the jet and the front or back boundary of the lobe. A nice example of the jet/lobe boundary interaction is given by the jet termination in wide-angle tail radio galaxies (Hardcastle 1999; Hardcastle & Sakelliou 2004): in these sources, which we argue are similar to FRII radio galaxies with peculiarly-shaped lobes, compact hotspots are sometimes present and sometimes absent, and it is plausible that they are present only when the geometry of the plume and the current direction of the jet are such that the jet intersects the edge of the plume. Here the interaction between the external environment and the 'cocoon' plasma determines where the contact discontinuity is, and the intersection of the jet and the contact discontinuity, if present, determines where the hotspot is — giving an indirect but important relationship between the hotspot and the external environment. Other examples are provided by the 'bottle-neck' hotspot structures seen in some FRII radio galaxies, particularly at low radio luminosities (see, e.g., Leahy et al. 1997), which suggest an interaction between the lobe and a low-density region of the external medium. In general, though, while the *location* of hotspots can tell us something about the location and nature of the external medium, the detailed properties of hotspots do not.

3.4. Hotspots and the Jet-Environment Interaction in the Lobes

What then do the detailed properties of hotspots tell us? I shall argue in this section that their complex structure and particle acceleration behavior are telling us about the nature of the interaction between the jet and its environment, the cocoon.

The two traditional tools for study of hotspots have been monochromatic high-resolution (polarimetric) imaging, usually in the GHz-frequency radio, and broad-band spectral energy distributions usually based on data of comparatively low resolution.

The first of these shows us that hotspots are not structurally simple: the terminations of jets rarely resemble the idealized axisymmetric structures seen in early (and, regrettably, some current) analytical and numerical modelling. This first became clear in the early days of high-resolution radio imaging when multiple hotspots started to be routinely detected in a given lobe (e.g., Laing 1982). Observationally we try to distinguish between the most compact, 'primary' hotspot in a lobe and the more diffuse 'secondary' hotspot or hotspots, though sometimes this distinction is ambiguous. Leahy et al. (1997) introduced the useful concept of a 'hotspot complex' which covers a group of hotspots and the high-brightness emission that surrounds them. Models for this complexity fall into two basic classes: those that seek to preserve a single true termination for the jet, such as the still popular dentist's drill model of Scheuer (1982) or the disconnected-jet variant of Cox et al. (1991), or those that propose that both the primary and secondary hotspot have a connection to the energy supply, so that the jet termination takes place in stages at the various hotspots, such as the splatter-spot model of Williams & Gull (1985) or the jet-deflection model of Lonsdale & Barthel (1986).

On the other hand, the radio through optical spectral energy distributions of hotspots (primary and secondary) have often been found to be in agreement with relatively simple models of first-order Fermi particle acceleration at strong shocks (e.g., Meisenheimer et al. 1989), although even just based on SEDs some discrepancies were apparent (see Meisenheimer et al. 1997, in particular the prescient closing paragraph) while the optically resolved synchrotron emission seen in some nearby hotspots also points to a distributed acceleration mechanism (e.g., Prieto et al. 2002). Inclusion of X-ray information in principle would give important information about the location and nature of particle acceleration to the highest observable energies, as in the FRI jets. However, the use of hotspot X-rays has been limited until recently because of uncertainty about the extent to which inverse-Compton emission is responsible for the observed X-rays. In Hardcastle et al. (2004) we argued that inverse-Compton emission dominates only in the highest-luminosity hotspots, and that synchrotron emission is the only emission process that can produce detectable X-rays in the hotspots with the lowest radio luminosities (i.e., in the least powerful sources). Low-power FRII sources are therefore the best places to search for synchrotron X-rays that trace the locations of high-energy particle acceleration.

Our work in this area has been presented by Kraft et al. (2005), Hardcastle & Croston (2005), Kraft et al. (2007) and most recently Hardcastle et al. (2007b). The key results can be summarized as follows:

- X-ray emission associated with compact hotspots is common: the SEDs are usually consistent with a synchrotron origin for the X-rays and inconsistent with inverse-Compton models. There are often, though not always, significant offsets on ~ 1 kpc scales between the peak of the emission in the X-ray and the peak in the X-ray, which is not expected in a simple synchrotron/shock acceleration model (e.g., Figs 1 and 3: see also Erlund et al. , these proceedings).

- X-ray emission is also often seen from diffuse regions around or behind the hotspots, with size scales > 10 kpc (e.g., Fig. 1). If this X-ray emission is also synchrotron — and no other model is at all plausible — then distributed particle acceleration must be taking place on these scales. This is very plausibly related to the distributed acceleration mechanism required in the FRI jets.

- Some secondary hotspots are X-ray sources and so inferred to be sites of high-energy particle acceleration (e.g., Fig. 3). This implies that at least some secondary hotspots have ongoing access to a supply of energy, and are

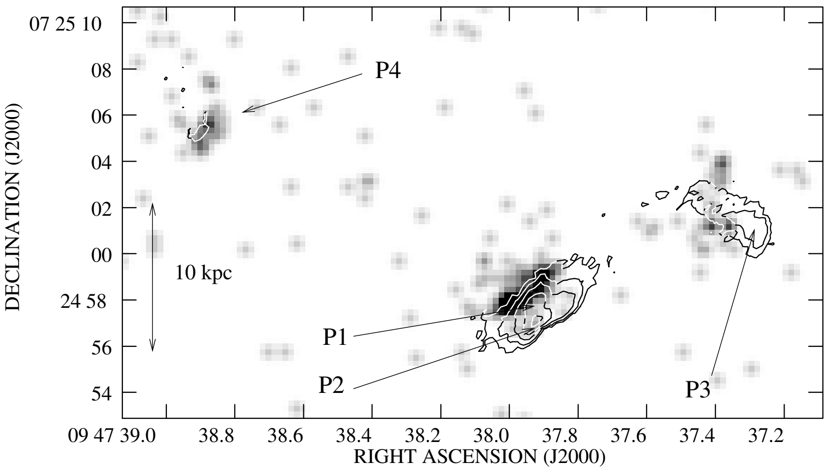

Figure 3. Radio and X-ray emission from the double W hotspot of 3C 227. Contours are from an 8.3-GHz radio map with 0.37×0.22 arcsec resolution. Grayscale shows the *Chandra* X-ray data. Note the detection of X-rays associated with the 'jet knot' P4, the primary hotspot P1/2 and the secondary P3, as well as the clear kpc-scale offsets between the radio and X-ray peaks in the primary and secondary. Image from Hardcastle et al. (2007b).

thus *not* produced by the simple dentist's drill mechanism. Other hotspots are not detected in the X-ray and are therefore significantly less efficient at accelerating particles to the energies required for X-ray emission. We find that all X-ray-emitting hotspots are compact, but not all compact hotspots are X-ray sources.

We interpret these complex hotspot behaviors in the context of models in which the hotspots are transient features created by the interaction of the lobe fluid with the jet. This process has been seen in many detailed simulations of light jets in which the assumption of axisymmetry has been removed (e.g., Norman 1996). The jet/lobe interaction causes the jet to move about in the head of the source on scales much less than the source lifetime. In this picture individual hotspots are telling us more about 'weather' in the lobe than about source physics: in particular, we cannot hope to understand the mechanisms of multiple hotspot formation by looking at any individual source, since the simulation shows that all the traditional processes may be capable of operating at different times. Simulations that trace shocks and particle acceleration also give important clues to the interpretation of the X-ray emission. Tregillis et al. (2001) carried out three-dimensional MHD simulations that modeled the transport of relativistic electrons and of particle acceleration at shocks. They found that the interaction of the jet and the backflowing plasma at the head of the jet produced what they called a 'shock-web complex', "a region of shocks of varying strengths and sizes spread throughout the source". Even when there was a simple terminal shock, not all the jet material necessarily passed through it, and the terminal shock was not always the strongest shock in the system.

While it is not clear that their simulations are perfectly matched to real radio sources, they are capable of producing simulated synchrotron images that show apparent clear discrete multiple hotspots (Tregillis et al. 2002) and in these cases the particle acceleration is not necessarily well matched to the locations of the hotspots: hotspot locations in their model can have more to do with magnetic field amplification than with particle acceleration. The notion of a 'shock-web complex' at the head of the jet could help to explain the diffuse X-ray emission now seen in the radio-bright but non-compact source head regions of a number of objects, as discussed above, while the idea that the particle acceleration region may not always be co-spatial with the observed radio hotspot might help to explain observed offsets.

It seems very likely therefore that hotspots are indeed telling us about jet-environment interactions, but that the environment with which they are interacting is the cocoon, whose properties we cannot probe directly. Progress in this area may come from further numerical modelling or possibly from a better understanding of the nature of the cocoon plasma and the distribution of particles and magnetic field within it.

4. Summary

The key results from the work described in this paper can be summarized as follows:

- In FRI jets, there is some direct evidence that some jet knots are due to environmental interaction, and we have an idea of the mechanism by which the interaction produces the knots. However, localized interactions are most likely not responsible for most of the high-energy particle acceleration in these jets.
- In most FRII jets there is little evidence that knots know about the environments, but there are counterexamples. 'Jet knots' in FRII jets are a heterogeneous class and the terminology should be used cautiously.
- The detailed properties of hotspots in FRIIs are predominantly a result of interaction between the jet and the cocoon plasma, and there is much still to be understood about how this works. However, simple models of the locations and mechanisms of particle acceleration in these objects are now ruled out by a variety of observations.

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References

Best, P.N., Longair, M.S., & Röttgering, H.J.A. 1997, MNRAS, 286, 785
Bicknell, G.V. 1984, ApJ, 286, 68
Biretta, J.A., & Meisenheimer, K. 1993, in Röser H.-J., Meisenheimer K., eds, Jets in Extragalactic Radio Sources, Springer-Verlag, Heidelberg, p. 159

Blandford, R.D., & Königl, A. 1979, Astrophs. Lett., 20, 15
Blandford, R.D., & Rees, M.J. 1974, MNRAS, 169, 395
Bridle, A.H., Hough, D.H., Lonsdale, C.J., Burns, J.O., & Laing, R.A. 1994, AJ, 108, 766
Cox, C.I., Gull, S.F., & Scheuer, P.A.G. 1991, MNRAS, 252, 588
Fanaroff, B.L., & Riley, J.M. 1974, MNRAS, 167, 31P
Gopal-Krishna, Subramanian, P., Wiita, P.J., Becker, P.A., & 2001, A&A, 377, 827
Hardcastle, M.J. 1999, A&A, 349, 381
Hardcastle, M.J., & Sakelliou, I. 2004, MNRAS, 349, 560
Hardcastle, M.J., & Croston, J.H. 2005, MNRAS, 363, 649
Hardcastle, M.J., Alexander, P., Pooley, G.G., & Riley, J.M. 1996, MNRAS, 278, 273
Hardcastle, M.J., Birkinshaw, M., & Worrall, D.M. 2001, MNRAS, 326, 1499
Hardcastle, M.J., Worrall, D.M., Kraft, R.P., Forman, W.R., Jones, C., & Murray, S.S. 2003, ApJ, 593, 169
Hardcastle, M.J., Harris, D.E., Worrall, D.M., & Birkinshaw, M. 2004, ApJ, 612, 729
Hardcastle, M.J., Kraft, R.P., & Worrall, D.M. 2006, MNRAS, 368, L15
Hardcastle, M.J., Kraft, R.P., Worrall, D.M., Croston, J.H., Evans, D.A., Birkinshaw, M., & Murray, S.S. 2007a, ApJ, 662, 166
Hardcastle, M.J., Croston, J.H., & Kraft, R.P. 2007b, ApJ in press
Heavens, A.F., & Meisenheimer, K. 1987, MNRAS, 225, 335
Kataoka, J., Stawarz, Ł., Aharonian, F., Takahara, F., Ostrowski, M., & Edwards, P.G. 2006, ApJ, 641, 158
Komissarov, S.S. 1994, MNRAS, 269, 394
Kraft, R.P., Forman, W.R., Jones, C., Murray, S.S., Hardcastle, M.J., & Worrall, D.M. 2002, ApJ, 569, 54
Kraft, R.P., Hardcastle, M.J., Worrall, D.M., & Murray, S.S. 2005, ApJ, 622, 149
Kraft, R.P., Birkinshaw, M., Hardcastle, M.J., Evans, D.A., Croston, J.H., Worrall, D.M., & Murray, S.S. 2007, ApJ, 659, 1008
Laing, R.A. 1982, in Heeschen, D.S., Wade C.M., eds, Extragalactic Radio Sources, IAU Symposium 97, Reidel, Dordrecht, p. 161
Laing, R.A., & Bridle, A.H. 2002, MNRAS, 336, 328
Leahy, J.P., Black, A.R.S., Dennett-Thorpe, J., Hardcastle, M.J., Komissarov, S., Perley, R.A., Riley, J.M., & Scheuer, P.A.G. 1997, MNRAS, 291, 20
Leahy, J.P., & Perley, R.A. 1995, MNRAS, 277, 1097
Lonsdale, C.J., & Barthel, P.D. 1986, AJ, 92, 12
Meisenheimer, K., Röser, H.-J., Hiltner, P.R., Yates, M.G., Longair, M.S., Chini, R., & Perley, R.A. 1989, A&A, 219, 63
Meisenheimer, K., Yates, M.G., & Röser, H.-J. 1997, A&A, 325, 57
Norman, M.L. 1996, in Hardee P.E., Bridle A.H., Zensus J.A., eds, Energy Transport in Radio Galaxies and Quasars, ASP Conference Series vol. 100, San Francisco, p. 319
Owen, F.N., Hardee, P.E., & Cornwell, T.J. 1989, ApJ, 340, 698
Perlman, E.S., & Wilson, A.S. 2005, ApJ, 627, 140
Prieto, M.A., Brunetti, G., & Mack, K.H. 2002, Sci, 298, 193
Scheuer, P.A.G. 1982, in Heeschen, D.S., Wade C.M., eds, Extragalactic Radio Sources, IAU Symposium 97, Reidel, Dordrecht, p. 163
Tregillis, I.L., Jones, T.W., & Ryu, D. 2001, ApJ, 557, 475
Tregillis, I.L., Jones, T.W., Ryu, D., & Park, C. 2002, NewAR 46 387
van Breugel W.J.M., & Dey, A. 1993, ApJ, 414, 563
Williams, A.G., & Gull, S.F. 1985, Nat, 313, 34
Worrall, D.M., Birkinshaw, M., & Hardcastle, M.J. 2001, MNRAS, 326, L7