Models Developed to Describe FRIIb and FRIIa Radio Sources

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Abstract

Several models developed to describe the properties of FRIIa and FRIIb radio sources are compared and contrasted here. The fundamental picture of a classical double (edge-brightened, FRII) radio source powered by highly collimated outflows from a central compact object is common to most models. However, models do differ substantially, and some of the key differences are discussed here. Models must be tested and constrained by comparisons with radio data. The extensive, detailed, radio data that can be used to constrain the physical properties of FRII sources will be described.

The radio bridge properties of FRII sources indicates they should be divided into two categories: FRIIa and FRIIb sources. Low-power FRIIa sources are typically found at low-redshift and have distorted radio bridge structure. High-power FRIIb sources are typically found at high-redshift and have fairly regular, "cigar-like" bridge shapes. It is anticipated that two model formalisms may be needed to describe FRIIb and FRIIa sources. Unlike FRIIa sources, FRIIb sources are found to inhabit gaseous environments similar to those found in low-redshift clusters of galaxies, though the sources have redshifts between zero and two. Thus, FRIIb sources most likely lie in clusters of galaxies. The importance of X-ray measurements to determine the density and temperature of the gas in the vicinity of FRIIb sources is stressed.

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1 Introduction

This is an exciting time for radio astronomy and the study of radio sources! Our understanding of powerful, extended (FRII) radio sources has been significantly developed through a combination of observational and theoretical breakthroughs. Some of these will be presented and discussed here.

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The paper begins with a presentation of the general properties of models currently being used to describe FRII radio sources. All models require assumptions, and one of the basic differences between models is the assumptions that are adopted before the model is applied; these differences will be discussed in §2. Key observational aspects of the sources that must be addressed by any model will be presented in §3. Given that a model is able to accurately reproduce the observed characteristics of one or more sources, the application of the model to large (possibly inhomogeneous) samples of sources will be discussed. The statistical properties of very large samples MAY provide some constraints, but ONLY after it has been shown that the model can accurately reproduce the properties of one (and hopefully of many) individual sources in detail.

It will be shown in §3 that the observed properties of FRII sources indicate they should be divided into two distinct categories: FRIIa, and FRIIb sources. The division should be based on radio bridge structure, but can also be based on radio power, since the two are tightly coupled (Leahy & Williams 1984; Leahy, Muxlow, & Stephens 1989). Based on the different observational properties of each category, it is likely that a model that accurately describes FRIIa sources will not accurately describe FRIIb sources, and vise versa. Thus, great care should be taken in applying a model, especially if the application is to a large sample of sources that contains both FRIIa and FRIIb sources. In addition, care should be taken in applying a model to radio galaxies and radio loud quasars. This is especially true when the comparison is statistical, as discussed in §3. The role of projection effects, and methods to determine the projection angle of a source are presented in §4.

Source sizes and lifetimes are discussed in §5. Again, one can take the approach of studying individual sources in great detail, or considering statistical properties of a very large sample. Of course, since there are likely to be two distinct types of FRII sources, and since radio galaxies and radio loud quasars have different statistical properties, the large sample would have to be appropriately subdivided before any meaningful statistical properties could be extracted. Much can be learned by studying individual sources in great detail. If a particular model for source sizes and lifetimes can not explain the properties of a given source or a homogeneous class of sources, it seems premature to apply the model to a very large sample of inhomogeneous sources.

Conclusions follow in §6.

2 General Properties of Models for FRII Radio Sources

2.1 What Most People Seem To Agree On

There are several aspects of models developed to describe FRII sources that are common to most models, and that most researchers agree are likely to be correct. First: almost everyone agrees that the original models of Scheuer (1974) and Blandford & Rees (1974) are correct. The radio hotspots, lobes, and bridges of classical double (FRII) radio sources are powered by two oppositely-directed, highly collimated outflows from a compact object (probably a black hole) that lies close to the center of the host galaxy or quasar (for an alternative view, see, for example, Kundt 2000). The beam power, L_j, or energy per unit time, impacts the ambient medium, and terminates in a very strong shock near or at the radio hotspot; the radio hotspot is the direct result of this interaction. The source size (distance between the two hotspots, or distance between the core and each hotspot) increases with time as long as the beam power is maintained by the compact object. The source also expands laterally (perpendicular to the core-hotspot axis). Thus, over time, the length, width, and radio surface brightness at different points within the radio emitting region all evolve.

Second: most researchers agree that Scheuer's dentist drill model (Scheuer 1982) provides an accurate description of the sources. Scheuer's idea is that the axis between the core and the hotspot does not maintain a fixed position. That is, the position of the hotspot wanders a bit, so the overall rate of growth of the source size is slower than the instantaneous hotspot velocity. This wandering is similar to the wandering of a dentist drill on a tooth. The wandering may be caused by precession of the black hole, or by some other physical process(es). Whatever the cause of the wandering, there is strong evidence that the overall rate of growth of the source is significantly less than the instantaneous velocity of the hotspot (Scheuer 1982).

Third: most researchers in the field agree that a strong shock exists in the immediate vicinity of the radio hotspot. Thus, we all agree that the position of the hotspot moves forward with a speed that is much greater than the sound speed of the ambient medium.

Fourth: we all agree on the set of equations that are valid at the "point of contact" (i.e. the hotspot):

$$\frac{L_j}{v_j \; A_h} \propto n_a \; v_h^2 \propto p_h \tag{1}$$

(e.g. Scheuer 1974; Blandford & Rees 1974; Norman et al. 1982; Bridle & Perley 1984; Begelman, Blandford, & Rees 1984; De Young 1986; Leahy 1991). Note that, in most sources, NONE of these quantities can be empirically determined. So, typically, we do not know the values of the beam power L_j, the cross sectional area of the point of contact A_h, the jet velocity v_j, the ambient gas density n_a, or the pressure just behind the area of contact p_h.

Fifth: Along the direction of the core-hotspot axis, there are two separate shock systems in the dentist drill model, and each moves forward with a different velocity. This occurs because of the wandering of the point of contact. Thus, the instantaneous rate of growth of the source along the jet axis, v_h, is typically much larger than the average rate of growth of the source in this direction, called the lobe propagation velocity v_L (Scheuer 1982; Cox, Gull, & Scheuer 1991; Daly 1990, 1995). The lobe propagation velocity, v_L, is the spatial and temporal average of v_h over the forward region (sometimes called the "lobe" or the "head") of the source.

Sixth: The following equations are valid over the forward region of the lobe (along the direction of the jet axis) **when the lobe is moving supersonically**:

$$n_a \, v_L^2 \propto p_L \ , \tag{2}$$

and

$$L_j \propto n_a \, a_L^2 \, v_L^3 \ \propto p_L \, a_L^2 \, v_L \ , \tag{3}$$

where p_L is the lobe pressure, or average pressure of the full forward region that is moving into the ambient medium in the direction of the jet axis; the other symbols are defined above (e.g. De Young 1971; Daly 1990, 1994, 1995; Falle 1991; Rawlings & Saunders 1991; Loken et al. 1992).

2.2 Where the Models Diverge

The primary differences between models has to do with the assumptions adopted, and the approach taken. Key differences between models arise over the following points. First: Does the model account for $v_L \neq v_h$? Given our current understanding of these sources, this seems to be required by any model. Second: Does the model assume that BOTH v_L and v_h are supersonic FOR ALL FRIIs? Once it is acknowledged that $v_L < v_h$, the possibility that some sources have v_h supersonic, and v_L sub- or transonic immediately arises. Third: Does the model use the "direct" equations, equations (2) and (3) to describe v_L, or does the model follow a prescription to take some kind of spatial and temporal average of equations (1) (which only apply to the point of contact), to estimate v_L? If some kind of averaging is carried out, a whole list of assumptions related to how the averaging will be done must also be adopted, and these assumptions must be reviewed.

Fourth: How does the model treat the lateral expansion of the bridge? (This is the bridge expansion in the direction perpendicular to the jet axis.) Some models treat this as a shock system (e.g. Daly 1990). Others treat this expansion self-similarly (e.g. Falle 1991). And, in many models the point is simply not addressed, and it is not clear what approach and assumptions are taken.

Fifth: Does the model include a detailed history of the relativistic electron population, such as the models of Eilek & Shore (1989), Alexander and Leahy (1987), Alexander (1987), Leahy, Muxlow, & Stephens (1989), Wellman, Daly, & Wan (1997a,b), and Blundell, Rawlings, & Willott (1999)? If so, is the approach realistic? What initial conditions are chosen, and are the initial conditions empirically or theoretically determined?

Sixth: Does the model assume minimum energy conditions to determine the magnetic field strength, B? Is this assumption a good one? How does this assumption propagate through the theoretical calculations and predictions of quantities to be compared with observations? Wellman, Daly, & Wan (1997a,b) do not assume minimum energy conditions, and, in fact, find that the sources are significantly offset (by a factor of about 4 or 5 in field strength) from minimum energy conditions.

2.3 Discussion of a Few Specific Models

Here, a few specific models developed over the past decade will be reviewed. The models are meant to be representative of the types of models being considered, but, because of space limitations, only a few models can be discussed.

The models seems to focus on different areas. Three main areas of focus may be identified. These are: (1) Models that focus on properties of the relativistic electron population. (2) Models that focus on radio source evolution through the P - D diagram, where P is the total radio power, and D is the separation between the two radio hotspots. And, (3) models that focus on the evolution of the size, shape, and radio properties of the radio lobe and bridge of individual sources.

Examples of models that focus on the properties of the relativistic electron population are those of Eilek & Shore (1989), and Alexander (1987). Eilek & Shore (1989) modelled the evolution of an FRII source with time including the dynamical and energetic evolution of the source. A detailed analysis of the evolution of the relativistic electrons is included. They find that a source with a steady rate of energy input will be brightest (in the radio) at an age comparable with the electron radiative lifetime, and will fade thereafter. Alexander (1987) modelled the relativistic electron population in 3C234 in detail, including acceleration, and adiabatic and radiative losses. The model was compared in detail to multi-frequency observations (obtained at five frequencies). **This kind of modelling and comparison with observation can lead to a deep understanding of the physical processes that determine the radio properties of FRII sources.** The source is in a cluster of galaxies. If the ambient gas density can be estimated with X-ray data, any offset of the magnetic field from minimum energy conditions can be determined (as has been done by Carilli et al. 1991 for Cygnus A). **This type of detailed comparison between the model and the radio observations is quite valuable.**

Other models focus on the evolution of sources through the P-D plane. Comparisons of this type are statistical in nature; the evolution of a population of sources through this diagram is investigated, and compared with the P-D diagram for a large sample of sources. To be accurate, the large sample of sources should be subdivided into FRIIa and FRIIb sources (discussed in §3), and into radio galaxies and radio loud quasars. For example, Kaiser, Dennett-Thorpe, & Alexander (1997) studied the evolution of sources through the P - D plane. A detailed model of the evolution of sources was included, and source beam powers ranging from 10^{45} erg/s to 10^{47} erg/s were used. The data points fill the region between their upper and lower theoretical curve. Given the scatter of points on the P-D diagram, and the many parameters that enter into the model, it seems likely that just about any model would fit the data. Blundell & Rawlings (1999) study the evolution of sources in the P-D diagram in a detailed model with many parameters. They consider jet powers in the same range as those considered by Kaiser, Dennett-Thorpe, & Alexander (1997). Blundell, Rawlings, & Willott (1999) present results similar to those obtained by Kaiser, Dennett-Thorpe, & Alexander (1997). A detailed evolution of the relativistic electron population is included.

Other models focus on the temporal evolution of the size, shape, and radio properties of the radio lobe and bridge of individual sources. For example, Daly (1990) applied strong shock physics to determine the properties of the radio lobe and bridge. The shape of the radio bridge, and other properties were predicted; in later work, it was found that these predictions were accurate (see §3.2). The same bridge shape was also predicted by Begelman & Cioffi (1989) using an independent argument. **If the radio lobe of a source moves forward supersonically, this model provides an accurate description of the shape and dynamical evolution of the radio source.**

Falle (1991) obtained similarity solutions that describe the dynamical evolution of a supersonic source. His equation describing the growth of the source along the jet axis is identical to that obtained by Daly (1990) using completely different arguments. However, the similarity solution obtained by Falle (1991) for the lateral growth of the source differs from that of Daly (1990) and Begelman & Cioffi (1989), and is inconsistent with observations (see §3.2). Falle (1991) notes in his paper that a similarity solution may not provide an accurate description of the lateral expansion of the source.

Cox, Gull, & Scheuer (1991) studied the evolution of a radio source using the "dentist drill" model of a source. It is shown that the lobe propagation velocity is lower than the hotspot velocity (as anticipated by Scheuer 1982). The numerical code uses equations (1) that apply to the hotspot, allows the hotspot to "wander," and solves numerically for v_L; the results obtained for v_L in this manner are in agreement with those predicted using the strong shock physics model of Daly (1990), and the similarity solution of Falle (1991), (which are identical) applied to the entire forward shock front.

Kaiser & Alexander (1997) study self-similar solutions for the radio bridge and cocoon (of shocked ambient gas). As mentioned above, the self-similar solution for the growth of the source along the jet axis is likely to be correct, since it was obtained using independent approaches by Daly (1990) and Falle (1991), and has been shown by Wellman, Daly, & Wan (1997a,b) to accurately predict the properties of FRIIb radio sources. However, the self-similar solution probably does not provide an accurate description of the lateral expansion of the bridge, since the independent approaches of Begelman & Cioffi (1989) and Daly (1990) yield identical results, which differ from those of Falle (1991), and which have been shown to accurately predict the properties of the sources (Wellman, Daly, & Wan 1997a,b).

3 Observational Constraints

Any model developed to describe FRII radio sources MUST address certain observational constraints. At the present time, extensive, detailed, radio data on many individual FRII sources is available, as is statistical information for very large samples of sources. My philosophy is that a model should FIRST be able to accurately reproduce the detailed properties of several individual sources; only after this step should the model be applied and compared with the statistical properties of a large sample. Otherwise, a model can reproduce the statistical properties of a very large sample for all of the wrong reasons, and may not be able to reproduce the observed characteristics of individual sources, such as the shape, size, and radio properties across a given source. In addition, great caution must be used when comparing statistical properties to insure that a homogeneous sample is compiled, and **does not include**

sources that are governed by different physical processes. Statistical results will change depending on whether the FULL population includes ALL FRIIs, and whether galaxies and quasars are analyzed separately.

Given the great importance of the comparison between a model and the properties of individual sources, I will focus on some of the detailed radio observations that are invaluable in constraining models. For example, much can be learned from detailed studies of the structure of radio bridges of FRII sources, such as the studies of Leahy & Williams (1984), Alexander and Leahy (1987), Leahy, Muxlow, & Stephens (1989), and Liu, Pooley, & Riley (1992).

Leahy & Williams (1984) obtained VLA images of a complete sample of 39 3C FRII sources. Sources with $z < 0.5$ were studied in detail, and have relatively low power for FRII sources (powers in the range from about $10^{24.4}$ to $10^{27.4}$ W/Hz/sr for $H_o = 100$ km/s/Mpc). ALL of the sources were found to have radio bridges, and many of the bridges are distorted. Given the diversity of the radio bridge structure, **Leahy & Williams (1984) defined 5 categories of FRII sources based on the type of bridge distortion**. They also defined the axial ratio, and found that high power sources are longer and thinner than low power sources.

Alexander & Leahy (1987) observed 21 3CR classical doubles (FRII sources) at 4 frequencies at the VLA. The 178 MHz radio powers of the sources range from 10^{25} to 10^{28} W/Hz/sr for $H_o = 50$ km/s/Mpc. They used the variation in the radio spectrum to estimate the mean rate of growth of each source; this is the lobe propagation velocity, v_L. Alexander & Leahy (1987) found that $v_L \propto P^{0.33\pm0.13}$, where P is the radio power. Similar results were obtained by Daly (1995) using the sample of Leahy, Muxlow, & Stephens (1989). **This relationship implies that more powerful sources grow faster**.

It is interesting and significant that Alexander & Leahy (1987) find no correlation between the overall rate of growth of a source v_L, and the source size (defined as the physical separation between the radio hotspots). This was, perhaps, the first indication that the total time an AGN is on (producing beams that power the growth of a source) is smaller for sources with larger velocities. If more powerful sources grow faster, but are not larger (on average) than less powerful sources, the more powerful sources must have shorter lifetimes.

Alexander & Leahy (1987) note the growth rate obtained using synchrotron aging is a combination of the true rate of growth of the source v_L and the backflow velocity v_{bf}: $|v_{obs}| = |v_L| + |v_{bf}|$. The authors note that their results, combined with the results of Leahy & Williams (1984) suggest that backflow is less important for higher power sources.

Leahy, Muxlow, & Stephens (1989) report on observations obtained with Merlin of 12 3C radio galaxies and 7 3C quasars; all of the sources have 178 MHz radio powers greater than 10^{27} W/Hz/sr for $H_o = 100$ km/s/Mpc and $q_o = 0$. They detected complete bridges in 15 sources, and partial bridges in the other sources. They confirmed the trend found by Leahy & Williams (1984), that the bridges of more powerful sources are more elongated (that is, they have a larger axial ratio) than the bridges of less powerful FRII sources.

Leahy, Muxlow, & Stephens (1989) also find that the radio galaxies and radio loud quasars in their sample have different bridge structure, and the difference is probably not due to projection effects alone. Note that this implies that it is important to distinguish between radio galaxies and radio loud quasars in studies.

Leahy, Muxlow, & Stephens (1989) also find that radio galaxies with $P_{178} > 10^{27}$ W/Hz/sr (for $H_o = 100$ km/s/Mpc) all have a "cigar-like" bridge shape. **The radio bridges of these sources have a very regular "cigar-like" shape, with few bridge distortions, and they all correspond to a single type, given the bridge types defined by Leahy & Williams (1984)**. Thus, all of the sources are likely to be governed by the same physical processes, and, perhaps can all be explained by a single model for radio source development. For example, the authors note that backflow is probably not important in these sources.

Leahy, Muxlow, & Stephens (1989) also find, for high power sources, most of the radio power comes from the hotspots/lobe region, and not from the radio bridge (see figure 22 in their paper). Thus, in terms of the evolution of the radio power of the source with time, losses in the bridge will not significantly affect the total radio power of these sources, since most of the power is generated in the forward region of the source. In addition, the authors find that there is a correlation between bridge power and total power, so the radio power of a source is not likely to undergo large variations over the source lifetime.

3.1 What Does All This Mean?

As demonstrated above, a significant and ample body of data about the properties of the radio bridges of individual FRII sources exists. This information should be used to constrain models of FRII sources.

For example, modellers should try to constrain the models with existing detailed information on radio bridges, **such as the radio surface brightness and bridge width as a function of position along the bridge**. This has been done by some authors, such as Eilek & Shore (1989), Alexander (1987), and Wellman, Daly, & Wan (1997a,b), but has not been addressed by others.

The observational results suggest that the physics of lower power FRIIs (which typically show highly distorted radio bridges), and higher power FRIIs (which, especially radio galaxies, typically show smooth, regular, cigar-like radio bridges) may be different. In particular, the equations used by modellers to describe the sources may only apply to some fraction of the sources. If some physical processes are different for high- and low-power FRIIs (as indicated empirically) then different models should be developed to describe the different types of FRII sources, since one set of equations may not describe all types of sources. For example, as already suggested by Leahy & Williams (1984) and Leahy, Muxlow, & Stephens (1989), the lower power sources may have significantly more backflow than the higher power sources.

An intriguing possibility is that in the higher power sources (those with 178 MHz radio power $P_{178} > 3h^{-2} \times 10^{26}$ W/Hz/sr for $H_o = 100\ h$ km/s/kpc) have a lobe propagation velocity and a hotspot velocity that are **both supersonic**, while for the lower power FRIIs the hotspot velocity is supersonic while the lobe propagation velocity is subsonic (or transonic). Thus, the physics of the sources may be different. Note that this type of explanation may go hand in hand with that proposed by Leahy & Williams (1984) and Leahy, Muxlow, & Stephens (1989), and would serve to explain why the backflow properties of high- and low-power FRIIs may be different.

Because of the fundamental difference in the radio bridge structure for FRIIs with high and low radio power, we should really talk about 2 categories of FRII sources: FRIIa sources are those with distorted radio bridges, and FRIIb sources are those with regular, well-behaved, cigar-like bridges. Since bridge distortion is strongly correlated with radio power, this can also be defined in terms of radio power. **Roughly, FRIIa sources have 178 MHz radio powers less than about $3h^{-2} \times 10^{26}$ W/Hz/sr for $H_o = 100\ h$ km/s/Mpc, and FRIIb sources have 178 MHz radio powers greater than about $3h^{-2} \times 10^{26}$ W/Hz/sr.**

To be accurate, all analyses of FRII sources, especially statistical comparisons between a model and the data, should always split the radio data into these two power ranges before comparing theoretical predictions with observations. This simply follows from the fact that it is very unlikely that a single model formalism will be able to explain both types of sources. A split into radio galaxies and radio loud quasars would further clarify how well model predictions compare with observations.

3.2 The Power of the Strong Shock Physics Model

The strong shock physics model of FRIIb radio sources is powerful because **it allows the fundamental physical variables that describe the radio**

source and its environment to be determined using radio observations. The model is similar to many other models proposed to describe FRII radio sources. For example, as mentioned earlier, the results of the strong shock physics model for the growth of the source along the jet axis are identical to those of Falle (1991), and the results of the strong shock physics model for the growth of the source in the lateral direction are identical to those of Begelman & Cioffi (1989). The model is presented by Daly (1990) and is developed and applied by Daly (1994,1995), Wellman, Daly, & Wan (1997a,b), Wan & Daly (1998a,b), Guerra & Daly (1998), Wan, Daly, & Guerra (2000), and Guerra, Daly, & Wan (2000).

Some characteristics of the model will be described here.

3.2.1 The Shape of the Radio Bridge

The strong shock physics model and the model of Begelman & Cioffi (1989) independently predicted that the width a_L of the radio bridge (perpendicular to the core-hotspot line) would vary with distance x from the radio hotspot as $a_L \propto \sqrt{x}$ up to some distance x_b from the hotspot. At this distance x_b from the hotspot a break is predicted, and the bridge width should remain roughly constant for larger x (see the detailed discussion by Wellman, Daly, & Wan 1997a,b).

The strong shock physics model was only applied to FRIIb sources, for the reasons described in the previous section. The model is designed to describe FRII sources with regular bridge shape, such as the FRIIb sources, in which both v_L and v_h are supersonic. To test the prediction, a sample of FRIIb sources with sufficient bridge data was compiled. All FRIIb sources with radio bridge information were taken from the samples of Leahy, Muxlow, & Stephens (1989) and Liu, Pooley, & Riley (1992). This yielded a sample of 14 radio galaxies and 8 radio loud quasars. Only sources with sizes greater than 20 kpc were included (so the sources would all have a significant radio bridge to study). Amazingly, the radio bridge width was found to vary as $a_L \propto x^{0.49\pm0.01}$ (Wellman, Daly, & Wan 1997a), where approximately 30 radio bridges were used (for many sources we were able to use both radio bridges, and in some sources, we could only use the radio bridge on one side of the source) and approximately 6 points along the bridge were used for each source. In many of the sources the break location was determined. For these, sources, the location of the break can be used to determine the Mach number with which the lobe is propagating into the ambient gas.

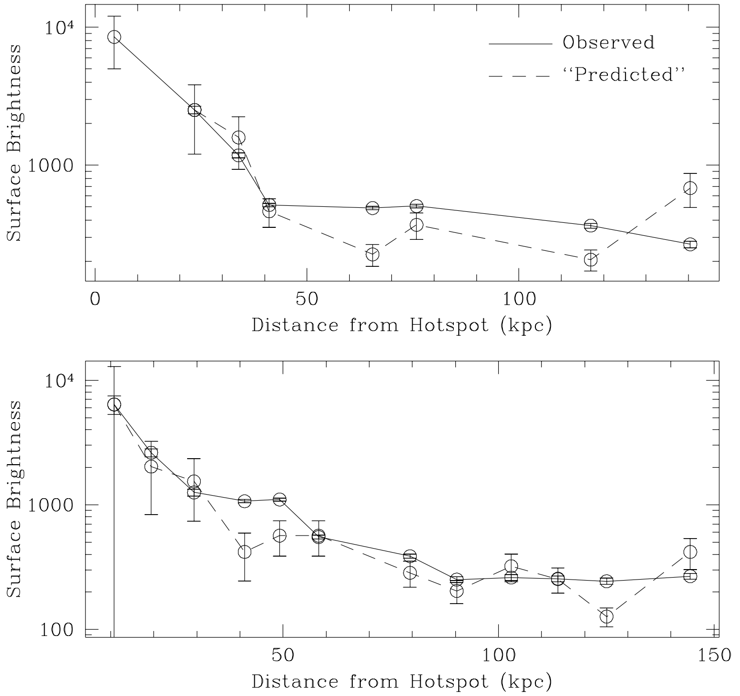

Fig. 1. Comparison between the predicted and observed surface brightness across each of the two bridges of a radio galaxy (see figure 6 from Wellman, Daly, & Wan 1997a)

3.2.2 The Radio Surface Brightness Profile

The radio surface brightness from the radio hotspot to the radio core, or host galaxy center, was studied. It was found the the radio surface brightness could be very accurately predicted by assuming the lobe width and radio power of a given source are roughly constant over time, and that adiabatic losses dominate at low radio frequency. That is, the radio power at any position x can be accurately predicted by assuming the radio power was identical to that currently seen at the radio lobe (forward region of the radio bridge) and decreased due to adiabatic expansion in the lateral direction by an amount given by the width at that point and the width currently seen at the lobe. **There is no indication that the radio power of a given radio source decreases with time**.

This suggests a very simple model for these very powerful FRIIb sources: the radio power and size of the radio emitting region near the forward edge of the radio bridge are roughly constant over the source lifetime, and the decrease in radio surface brightness across the source is due to adiabatic expansion. The fact that the radio surface brightness across the source can be so accurately predicted suggests that backflow of relativistic plasma within the bridge, and particle re-acceleration within the bridge, are not significant.

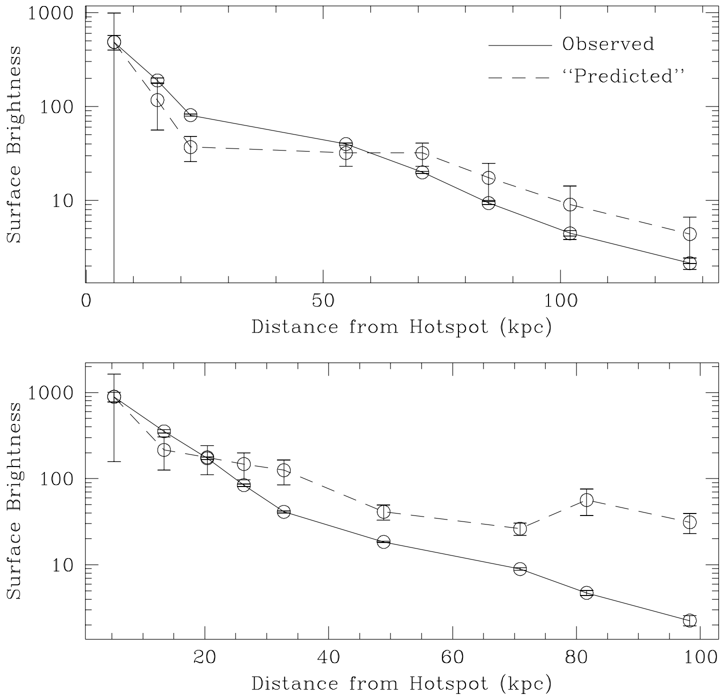

Fig. 2. Comparison between the predicted and observed surface brightness across each of the two radio bridges of a radio galaxy (see figure 9 from Wellman, Daly, & Wan 1997a)

3.2.3 The Mach Number of Lobe Advance

The Shape of a radio bridge of an FRIIb source can be used to estimate the Mach Number, M, of lobe advance. The ratio of lobe pressure to ambient gas pressure is determined by the Mach number: $P_L/P_a \simeq 2\ M^2$. As mentioned above, many sources in our sample exhibit a break in radio bridge shape. The location and width of this break may be used to estimate the Mach number with which the radio lobe propagates into the ambient gas. Values of M were obtained for about 16 radio bridges (Wellman, Daly, & Wan 1997a), and the values of M range from about 2.5 to 10. **For M ranging from 2.5 to 10, the pressure ratio P_L/P_a ranges from about 10 to 200.**

3.2.4 The Pressure in the Radio Lobe

The pressure of the relativistic fluid within the radio lobe is estimated assuming a magnetic field strength $B = bB_{min}$, where B_{min} is the minimum energy magnetic field. Note that minimum energy conditions are not assumed. The total pressure in the lobe is then

$$P_L = (4/3\ b^{-1.5} + b^2)(B_{min}^2/24\pi). \tag{4}$$

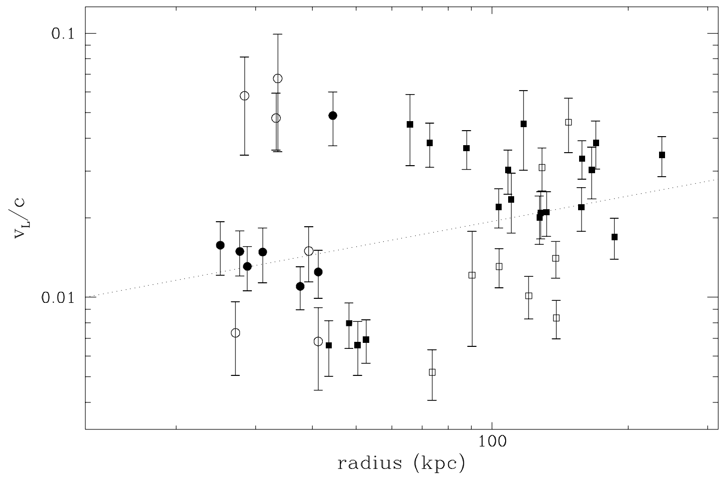

Fig. 3. The lobe propagation velocity as a function of core-hotspot separation, from Wellman, Daly, & Wan (1997b). Filled symbols represent galaxies, open symbols represent quasars, square symbols represent sources from the sample of Leahy, Muxlow, & Stephens (1989), and circular symbols represent sources from the sample of Liu, Pooley, & Riley (1992).

This may also be written $P_L = \kappa\ B^2_{min}$ when b is a constant (i.e. constant offset from minimum energy conditions).

The offset from minimum energy conditions will be discussed with the ambient gas density. It turns out that there is an offset from minimum energy conditions, and that there must be small dispersion in the offset. The dispersion in the offset must be less than about 15 %, and the offset, determined using Cygnus A, and is found to be $b \sim 0.2$ to 0.25 (Carilli et al. 1991; Wellman, Daly, & Wan 1997a,b).

3.2.5 The Ambient Gas Pressure

The ambient gas pressure can be estimated using the lobe pressure and the Mach number of lobe advance. This follows because

$$P_a = n_a\ k\ T_a \simeq P_L/(2M^2) = \frac{\kappa B^2_{min}}{2\ M^2}\ . \tag{5}$$

The pressure of the ambient gas was estimated for all of our sources, and **it is found that the pressure and composite pressure profile are similar to those in low-redshift clusters of galaxies** (Wan, Daly, & Guerra 2000).

3.2.6 The Velocity of Lobe Propagation

The velocity of lobe propagation was estimated using a synchrotron and inverse Compton aging model (Wellman, Daly, & Wan 1997a,b). **The lobe propagation velocities for the Liu, Pooley, & Riley (1992) sources are significantly less than the hotspot velocities obtained by Liu, Pooley, & Riley 1992.** This echos comments made earlier in this paper: there are many reasons to expect the lobe propagation velocity to be less than the hotspot velocity, and this is exactly what was found.

The velocities of lobe propagation obtained range from about 2×10^3 km/s to about 2×10^4 km/s. They are similar for radio galaxies and radio loud quasars, and there is no strong dependence on source size.

3.2.7 The Density of the Ambient Gas

Once the velocity of lobe propagation is obtained, the density of the ambient gas can be estimated using the equation

$$n_a \propto \frac{P_L}{v_L^2} \propto \frac{\kappa B_{min}^2}{v_L^2}. \tag{6}$$

This method was applied by Wellman, Daly, & Wan (1998b). **It is found that the ambient gas density is similar to that in low-redshift clusters of galaxies** both in terms of the absolute value of the density, and the composite density profile. Some mild evolution with redshift was found. The normalization for the ambient gas density was obtained using Cygnus A, for which the ambient gas density is estimated using X-ray data. **If the ambient gas density can be estimated around other sources using X-ray data, the density and lobe pressure may be used as a check on the velocity of lobe propagation.** This will indicate whether the use of radio data to estimate the lobe propagation velocity is reliable, and can be used to estimate ambient gas densities out to very high redshift. Note, the sources in this sample are evenly distributed between a redshift of zero and two.

Interestingly, the ambient gas density estimated using radio data has a very strong dependence on the offset from minimum energy conditions: $n_a \propto b^{-4.5}$ when $b < 1$, which is suggested by the current data. Given this very strong dependence, the dispersion of the ambient gas density, estimated as described above, can be used to limit the dispersion of b. If we assume that all of the sources are in identical environments, and all of the "excess" dispersion of the ambient gas density is due the dispersion in b, then the dispersion in b must be less than about 15 % (Wellman, Daly, & Wan 1997a,b). In fact, the environments are not identical, and there will be other causes of dispersion, so the source to source scatter in b must be even smaller than 15 %. The actual value of b is estimated from Cygnus A (Carilli et al. 1991).

3.2.8 The Temperature of the Ambient Gas

The temperature of the ambient gas can be estimated using radio data since

$$T_a \propto \frac{v_L^2}{M^2} \; . \tag{7}$$

The temperature was estimated in this way for 16 radio bridges. That obtained for Cygnus A matches the X-ray temperature in the vicinity of the radio source. Most of the temperature estimates fall in the range from 1 to 10 keV, with a few above 10 keV. The composite temperature profile is fairly flat, similar to profiles seen in low-redshift clusters of galaxies. **If the temperature of the ambient gas in the vicinity of these sources can be estimated using X-ray data, it will be possible to turn this around and constrain the synchrotron and inverse Compton velocities using the radio data**. This could be very important as a check of whether this method can be applied to still higher redshift.

3.2.9 FRIIb Radio Sources Lie in Clusters of Galaxies

The FRIIb radio sources studied lie in environments with ambient gas pressures, ambient gas densities, and ambient gas temperatures that are similar to low-redshift clusters of galaxies. Thus, these high-power FRII sources (FRIIb sources) most likely lie in clusters of galaxies, though they have redshifts all the way to a redshift of 2! The symmetry of the sources, and the composite density profile obtained for the sources argue that they lie within the central core of the cluster, and may be a giant elliptical galaxy located very close to core of the X-ray gas.

3.2.10 The Beam Power Can be Estimated

The beam power that goes into each side of the radio bridge of an AGN can be estimated using the radio data:

$$L_j \propto P_L \; a_L^2 \; v_L \propto \kappa \; B_{min}^2 \; a_L^2 \; v_L \; . \tag{8}$$

Beam powers have been estimated for all of the sources in our sample. The beam power ranges from about 10^{44} to 10^{46} erg/s, for b = 0.25, and is rather sensitive to the value of b assumed.

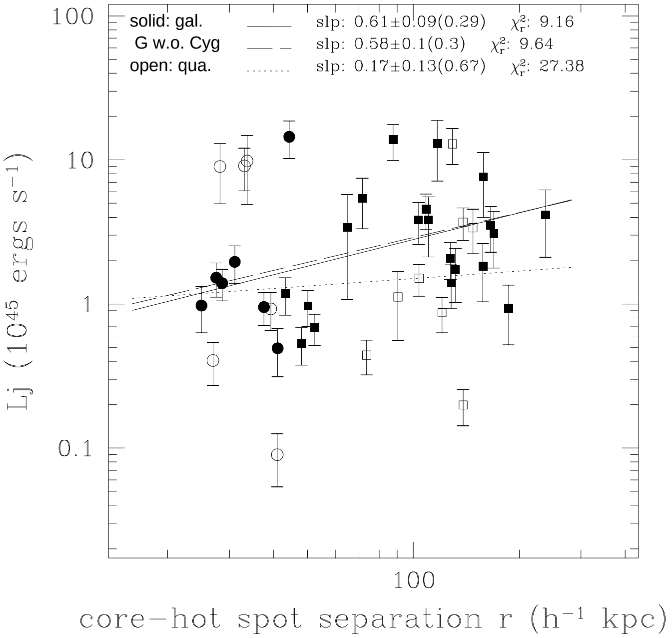

Fig. 4. Beam Power as a function of core-hotspot separation, from Wan, Daly, & Guerra (2000). The symbols are identical to those in figure 3.

For the radio galaxies in this sample, the beam power increases weakly with source size, though there is significant scatter in this, and for the quasars in this sample, the beam power does not change significantly with source size (Wan, Daly, & Guerra 1999).

The total lifetime, t_*, of a given radio galaxy can also be estimated. This follows because at a given redshift, the average source size for FRIIb radio galaxies has a rather small dispersion. Thus, it can assumed that a given source will have an average size similar to that of the full population of FRIIb radio galaxies at that redshift. In this case, its lifetime, t_*, can be estimated from its lobe propagation velocity and expected average size: $t_* = D_{av}/v_L$, where D_{av} is the average size of the full population at that redshift. Note that a factor of 2 enters the numerator because of the two sides of the source, and then enters the denominator because the total source size is twice its average size, and thus does not appear in the final equation.

Ages estimated in this way range from about 3×10^6 years to 10^8 years. There is no strong dependence of age on source size, no difference between the ages obtained for quasars and galaxies, and a strong dependence of age on redshift: the low-redshift sources are more long-lived than the high-redshift sources.

The total energy that a central compact source will put out over its lifetime can be estimated by combining the beam power with the source lifetime: $E_* = 2\ L_j\ t_*$, since there are two sides to the source. **The total energy estimated in this way has a remarkably small dispersion, and most of the sources have E_* that corresponds to a rest mass (using $M = E/c^2$) in the range from 4×10^5 to $2 \times 10^6\ M_\odot$ solar masses.** The total energy is independent of source size, and very mildly increasing with redshift. **High-redshift sources have significantly larger beam powers and shorter lifetimes than low-redshift sources, yet the product of the two is basically the same for all sources, quasars and galaxies, at all redshifts at about $10^6\ M_\odot$.**

3.2.11 Summary

With single frequency radio data, the strong shock physics model applied to FRIIb sources allows estimates of the Mach number of lobe advance, the pressure ratio between the radio lobe and the ambient gas, the lobe pressure, and the ambient gas pressure. With a multi-frequency radio maps (and hence an estimate of v_L) the ambient gas density, ambient gas temperature, beam power, total source lifetime, and total energy output (in the form of a collimated outflow) over the source lifetime can be estimated. Note that the strong shock physics model should not be applied to FRIIa sources, which show significant bridge distortion, because v_L may not be supersonic for these sources.

It will be very important to check the velocity estimated using radio data with X-ray data. X-ray estimates of the ambient gas density and/or temperature can be used to determine the velocity of lobe propagation. If the radio velocities are accurate, then this method can be extended to higher redshift.

4 The Role of Projection Effects

Radio galaxies may differ in appearance from radio loud quasars due to projection effects, or due to intrinsic differences. Projection effects must alter the appearance of some sources. A detailed analysis of the way that projection effects alter radio bridge properties of radio sources was carried out by Wan & Daly (1998a); radio power selection effects were discussed in great detail in a separate paper (Wan & Daly 1998b).

It turns out that the radio bridge width, a, is fairly insensitive to projection angle, but the radio surface brightness, both along the radio bridge axis, and perpendicular to the radio bridge axis are significantly changed if the radio source is closer than about 45^o from the line of sight to the observer.

Detailed radio observations of the radio surface brightness along either direction can be used to estimate the projection angle of the source (with some model assumptions).

Wan & Daly (1998) used this method to estimate the projection angle of Cygnus A, and find that it must be greater than 40^o (at 3 σ) to 55^o (at 2 σ, in agreement with the independent results of Sorathia et al. (1996).

For the sample discussed here, the radio surface brightness across the radio bridges of the sources in our sample (or WDW97a,b) have large projection angles, greater than 30^o (at 3 σ) to 40^o (at 2 σ), so the sources are likely to lie fairly close to the plane of the sky.

Wan & Daly (1998) also found differences between low-redshift radio loud quasars and radio galaxies that could not be explained by projection effects. This was related to the radio surface brightnesses of the sources. This result is consistent with that of Leahy, Muxlow, & Stephens (1989), that the quasars and galaxies exhibit differences in axial ratio that can not be explained by projection effects alone.

5 Source Sizes and Lifetimes

In this section, the following question is addressed: Are radio sources at high-redshift small (compared with low-redshift sources) because they have short lifetimes, or because the radio power of a given source is monotonically decreasing with time, and the source falls below the flux limit when it is still small?

At the present time, it would appear that high-redshift sources are smaller than low-redshift sources because they have shorter lifetimes.

It has been shown by a number of people (e.g. Alexander and Leahy 1987; Daly 1994, 1995) that more powerful sources have larger velocities, and more powerful sources are at high redshift. So, higher redshift sources are not smaller because they grow more slowly. In any case, since $v_L \propto (L_j/n_a\ a_L^2)^{1/3}$, an increase in the ambient gas density would not have a very large effect on the rate of growth of the source. If more powerful sources at high redshift have higher velocities, and yet are smaller (on average) than lower redshift sources, surely they must have shorter lifetimes, as suggested by Neeser et al (1995). This is another reason it will be important to check the source velocities using X-ray data, to insure that the velocities estimated using radio techniques (synchrotron and inverse Compton aging models) are accurate.

There is no observation that indicates that the **radio power of a given FRIIb radio source** decreases with time. All of the high redshift sources are FRIIb, and most of the radio power comes from the hotspot/lobe region of these sources.

There are several observations that indicate that the radio power of a given FRIIb radio source is roughly time independent. For example, (1) Neeser et al. (1995) find that there is no correlation between radio size and radio power. In addition, (2) the radio surface brightness across an FRIIb source is very accurately modelled by assuming a constant radio power from the radio lobe and hotspot, and a roughly constant lobe size over the source lifetime (see §3.2.2). Finally, (3) a roughly constant power over a source lifetime followed by an exponential drop in radio power would explain the relative sizes of radio galaxies and radio loud quasars in the context of the orientation unified model (Gopal-Krishna, Kulkarni, & Wiita 1996). An exponential drop is certainly rapid enough that the exponential timescale could be identified with the source lifetime.

In short, there is no evidence that the radio power of a given FRIIb source decreases with time, and there are several observations that indicate it is roughly constant over the source lifetime. As suggested by Neeser et al (1995), Gopal-Krishna, Kulkarni, & Wiita (1996), and Daly (1994, 1995), most likely the radio power is roughly constant over the source lifetime, and then drops precipitously as the beam power drops. In this regard, it is interesting to note that Wellman, Daly, & Wan (1997a) find that FRIIb sources have Mach numbers of about 2.5 to 10, indicating lobe over-pressures of about 10 to 200, so the lobe will rapidly expand and drop in radio power as soon as L_j drops (as suggested by Neeser et al. 1995).

6 Conclusions

Models developed to describe the properties of FRII sources have come a long way! A significant quantity of radio data is available, including detailed radio observations of radio bridges, and will be very useful in constraining the models. Any model should be able to predict/explain the observed shape and radio surface brightness of the radio bridges of known sources, such as those of Leahy, Muxlow, & Stephens (1989), Alexander & Leahy (1987), and others.

All comparisons with observations should be done for FRIIa and FRIIb sources separately, since the differences in their bridge structure indicate that different physical processes may be important in these sources. All comparisons with observations should be done separately for radio galaxies and radio loud quasars, whether their different appearance and characteristics are due to projection effects or to intrinsic differences.

In the "dentist drill" model of Scheuer (1982) there must be sources for which v_h is supersonic, but v_L is subsonic (or transonic). Presumably, these would be classified as FRII sources since the hotspot would be moving supersonically, and they would be edge-brightened. But, we should ask, would these be categorized as FRIIa sources? Could this cause the distinction between the radio bridge properties of FRIIa and FRIIb sources?

Deviations from minimum energy conditions should be taken into account. Current results indicate that in the radio lobes and bridges of FRIIb sources, there is a constant offset from minimum energy conditions. Typical magnetic field strengths are about 0.2 to 0.25 of the minimum energy value, with a small source to source dispersion in this offset for FRIIb sources.

X-ray data that can be used to estimate the density and/or temperature of the ambient gas in the vicinity of FRIIb sources will be very useful! Wellman, Daly, & Wan (1997a,b) predict densities and temperatures for the gas in the vicinity of many FRIIb sources (with redshifts between zero and two). If the predicted densities and temperatures are confirmed it would mean: (1) the velocities estimated from the radio data are reliable; (2) the offset from minimum energy conditions can be confirmed; and (3) ambient gas densities and temperature can be determined in the vicinity of many additional high-redshift sources based on their radio properties.

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