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TOWARD UNDERSTANDING THE FANAROFF-RILEY DICHOTOMY IN RADIO SOURCE MORPHOLOGY AND POWER

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ABSTRACT

In Paper I we presented the results of a study of the interrelationships between host galaxy magnitude, optical line luminosity, and radio luminosity in a large sample of Fanaroff-Riley classes 1 and 2 (FR 1 and FR 2) radio galaxies. We report several important differences between the FR 1 and FR 2 radio galaxies. At the same host galaxy magnitude or radio luminosity, the FR 2's produce substantially more optical line emission (by roughly an order of magnitude or more) than do FR 1's. Similarly, FR 2 sources produce orders of magnitude more line luminosity than do radio-quiet galaxies of the same optical magnitude, while FR 1 sources and radio-quiet galaxies of the same optical magnitude produce similar line luminosities. Combining these results with previous results from the literature, we conclude that while the emission-line gas in the FR 2's is indeed photoionized by a nuclear UV continuum source from the AGN, the emission-line gas in the FR 1's may be energized predominantly by processes associated with the host galaxy itself.

The apparent lack of a strong UV continuum source from the central engine in FR 1 sources can be understood in two different ways. In the first scenario, FR 1's are much more efficient at covering jet bulk kinetic energy into radio luminosity than FR 2's, such that an FR 1 has a much lower bolometric AGN luminosity (hence nuclear UV continuum source) than does an FR 2 of the same radio luminosity. We discuss the pros and cons of this model and conclude that the efficiency differences needed between FR 2 and FR 1 radio galaxies are quite large and may lead to difficulties with the interpretation since it would suggest that FR 2 radio source deposit very large amounts of kinetic energy into the ISM Intracluster Medium. However, this interpretation remains viable.

Alternatively, it may be that the AGNs in FR 1 sources simply produce far less radiant UV energy than do those in FR 2 sources. That is, FR 1 sources may funnel a higher fraction of the total energy output from the AGNs into jet kinetic energy versus radiant energy than do FR 2 sources. If this interpretation is correct, then this suggests that there is a fundamental difference in the central engine and/or in the immediate "accretion region" around the engine in FR 1 and FR 2 radio galaxies. We note also the absence of FR 1 sources with nuclear broad line regions and suggest that the absence of the BLR is tied to the absence of the "isotropic" nuclear UV continuum source in FR 1 sources.

We put forth the possibility that the FR 1/FR 2 dichotomy (i.e., the observed differences in the properties of low- and high-power radio sources) is due to qualitative differences in the structural properties of the central engines in these two types of sources. Following early work by Rees et al. (1982), we suggest the possibility that FR 1 sources are produced when the central engine is fed at a lower accretion rate, leading to the creation of a source in which the ratio of radiant to jet bulk kinetic energy is low, while FR 2 sources are produced when the central engine is fed at a higher accretion rate, causing the central engine to deposit a higher fraction of its energy in radiant energy. We further suggest the possibility that associated differences in the spin properties of the central black hole between FR 1 (lower spin) and FR 2 (higher spin) sources may be responsible for the different collimation properties and Mach numbers of the jets produced by these two types of radio-loud galaxies. This scenario, although currently clearly speculative, is nicely consistent with our current picture of the triggering, feeding, environments, and evolution of powerful radio galaxies. This model allows for evolution of these properties with time—for example, the mass accretion rate and BH spin may decline with time causing an FR 2 radio source or quasar to evolve into a FR 1 radio source.

Subject headings: galaxies: structure — radiation mechanisms: nonthermal — radio continuum: galaxies — ultraviolet: galaxies

1. INTRODUCTION

In 1974, Fanaroff & Riley first noted the remarkable difference between the radio appearance of low and high power radio galaxies. In their classic paper, Fanaroff & Riley (1974) split radio sources into two classes; the FR 1 sources in which the radio source was brightest in the inner half of the source, and the FR 2 sources in which the radio source was brightest in the outer half of the source. They went on to show that high-power radio sources (total power at 178 MHz greater than 2.5×10^{26} W Hz^{-1})[2] had almost exclusively FR 2 radio morphologies, while low-power sources have almost exclusively FR 1 radio morphologies.

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[2] As in Paper I, we adopt a Friedman cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$.

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It has been 20 years since Fanaroff & Riley's surprising finding, and much progress has been made defining the radio and optical properties of these two classes of radio sources. We now know that the dichotomy between these two classes encompasses much beyond their radio appearances, including the nature of their host galaxies, their host galaxy environments, and their optical emission-line and far-infrared properties. We also now know that the split between FR 1 and FR 2 radio morphology is not a clean one: there is a transition region of ~ 2 orders of magnitude in radio power in which FR 1, FR 2 and transition-morphology sources exist (e.g., Baum & Heckman 1989a; Owen & Laing 1989; Morganti, Killeen, & Tadhunter 1993), and the radio power at which the split occurs has been shown to be a function of the optical magnitude of the host galaxy (Owen 1993; Owen & Ledlow 1994).

In Zirbel & Baum (1995, hereafter Paper I), we analyzed the correlations between total radio power, core radio power, emission-line luminosity, and host galaxy optical magnitude for a large sample of radio galaxies (taken from the literature). Our sample spans nearly 10 orders of magnitude in radio luminosity and, most important, contains a large number of FR 1 and FR 2 sources which overlap in radio luminosity. Thus, this sample can be used to disentangle the effects of radio luminosity from radio morphology and is well suited to an analysis of the origin of the FR 1/FR 2 dichotomy.

In this paper, we analyze and interpret those results with a view to determining the origin of the differences between FR 1 and FR 2 radio galaxies. Specifically, we suggest that some of the differences between FR 1 and FR 2 radio galaxies are most easily understood in the context of a model in which the central engines of FR 1 and FR 2 radio galaxies are fundamentally different. The alternate scenario, in which the different manifestations of activity seen in FR 1 and FR 2 radio galaxies are due to the combined effects of differing environments operating on fundamentally similar AGNs of differing absolute power is also still possible, and we explore this scenario as well. We refer the reader to Baum, Heckman, & van Breugel (1992) and Heckman et al. (1994) for a detailed description of the optical and far-IR differences between FR 1 and FR 2 radio galaxies and to Laing (1993), Leahy (1991), Muxlow & Garrington (1991), Bridle & Perley (1984), and Bridle (1984) for detailed discussions of the differences in the radio properties of FR 1 and FR 2 sources.

This paper is organized as follows. In § 2, we summarize and review the results presented in Paper I. In § 3, we discuss the implications of these results for the source of the ionization energy for the emission line gas in FR 1 and FR 2 radio galaxies. We show that at a given radio power, the central engine of FR 1's produce significantly fewer ionizing (UV) photons than do the central engines in FR 2's. In § 4, we discuss possible explanations for the difference in the strength of the nuclear UV continuum source in the FR 1 and FR 2 galaxies and finally, in § 5, we present a possible "grand overview" picture for the origin of the FR 1/FR 2 dichotomy.

2. RESULTS

In Paper I, we analyzed the correlations of total radio luminosity, rado core power, emission-line luminosity, and optical magnitude, separately for FR 1 and FR 2 radio galaxies. The principle results of this work are enumerated below. Here we discuss only the results for radio sources with $z < 0.5$, since (1) at higher redshifts, the radio morphology is frequently not known, (2) there are no known FR 1 sources in our sample at these higher redshifts, and (3) there are many known (or suspected) changes in the properties of active galaxies with redshift which are likely to dominate the characteristics of the high-redshift (FR 2) sources (e.g., McCarthy et a. 1987, 1991; Chambers, Miley, & van Breugel 1987). Our results for redshifts less than 0.5 are as follows:

1. FR 1 and FR 2 radio galaxies display strong but distinct correlations of total and core radio luminosity with emission-line luminosity, each having a unique functional dependence and zero point (see Fig. 1).
2. The line luminosity of FR 1 radio galaxies correlates with the optical magnitude of the host galaxy, while the line luminosity of FR 2 radio galaxies does not (see Fig. 2). Removing the correlation of line to optical luminosity leaves a residual 2 σ correlation of line and radio luminosity for the FR 1's alone; the significance of this residual correlation is increased to 3 σ for the combined sample of FR 1's and optically selected ellipticals.
3. In the median, FR 2 radio galaxies produce significantly more total line luminosity than do FR 1 radio galaxies of the same total (and core) radio power. That is, FR 2 sources are 5–30 times more luminous in emission lines than FR 1 sources of the same total radio luminosity and 10–40 times more luminous than FR 1 sources of the same core radio power.
4. There is a strong correlation, albeit with a very large scatter, between core and total radio luminosity for FR 1 and FR 2 radio galaxies. However, more important, (see Fig. 3), FR 1 and FR 2 radio galaxies show the same functional dependence of core to total radio luminosity.

Below, we discuss the implications of these results for our understanding of (1) the source of the ionization energy for the emission-line regions in FR 1 and FR 2 radio galaxies (§ 3) and (2) our understanding of the origin of the differences between these two classes of radio galaxies (§§ 4 and 5).

3. ENERGY SOURCE FOR THE EMISSION-LINE GAS

Below we consider the source of ionizing energy for the line luminosity from FR 1 and FR 2 radio galaxies.

3.1. *FR 1 Galaxies*

As presented in detail in Paper I and summarized in § 2 above, our statistical analyses have revealed or confirmed the following important points about the properties of the emission-line gas in FR 1 radio galaxies:

1. The emission-line luminosity of FR 1 radio galaxies correlates both with radio luminosity and with the optical magnitude of the host galaxy.
2. The emission-line luminosity of FR 1 radio galaxies, while at the upper end of the distribution for normal elliptical galaxies, overlaps with the emission-line luminosity of radio-quiet elliptical galaxies of the same optical magnitude.
3. Removing the correlation of optical magnitude with line luminosity leaves only a weak (2 σ), flattened residual correlation of line and radio luminosity in the FR 1's.

These results suggest that the emission-line gas in FR 1 radio sources is primarily energized by processes associated with the host galaxy itself (e.g., old stars; Binette et al. 1994) and not by the AGN. We can explore this possibility further by examining the emission-line ratios of FR 1 radio galaxies and comparing

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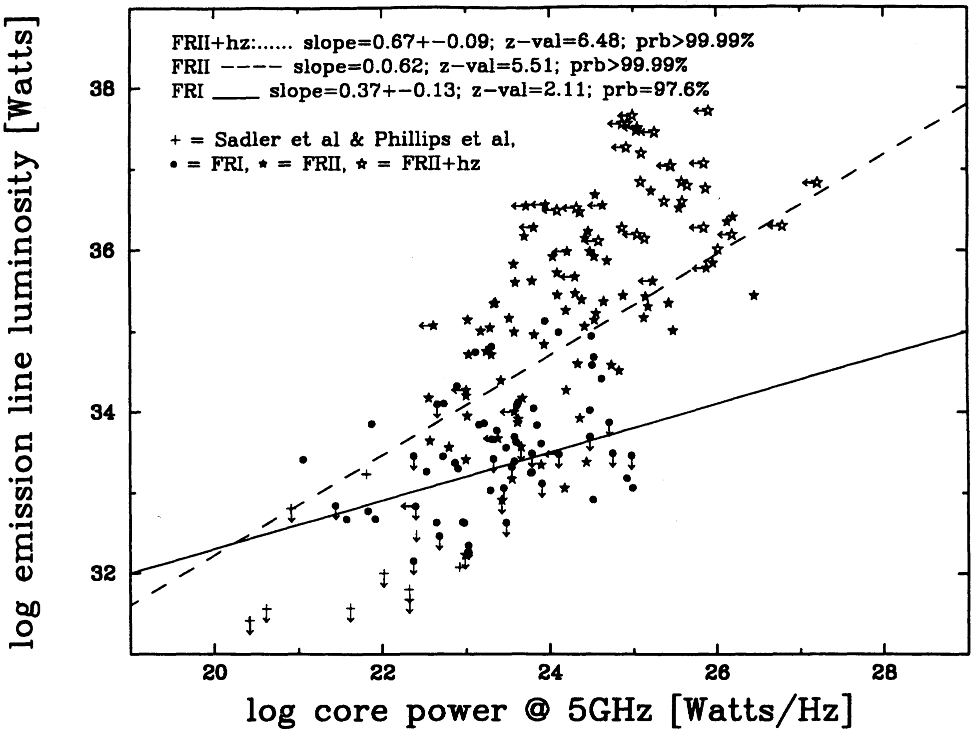

FIG. 1*a*

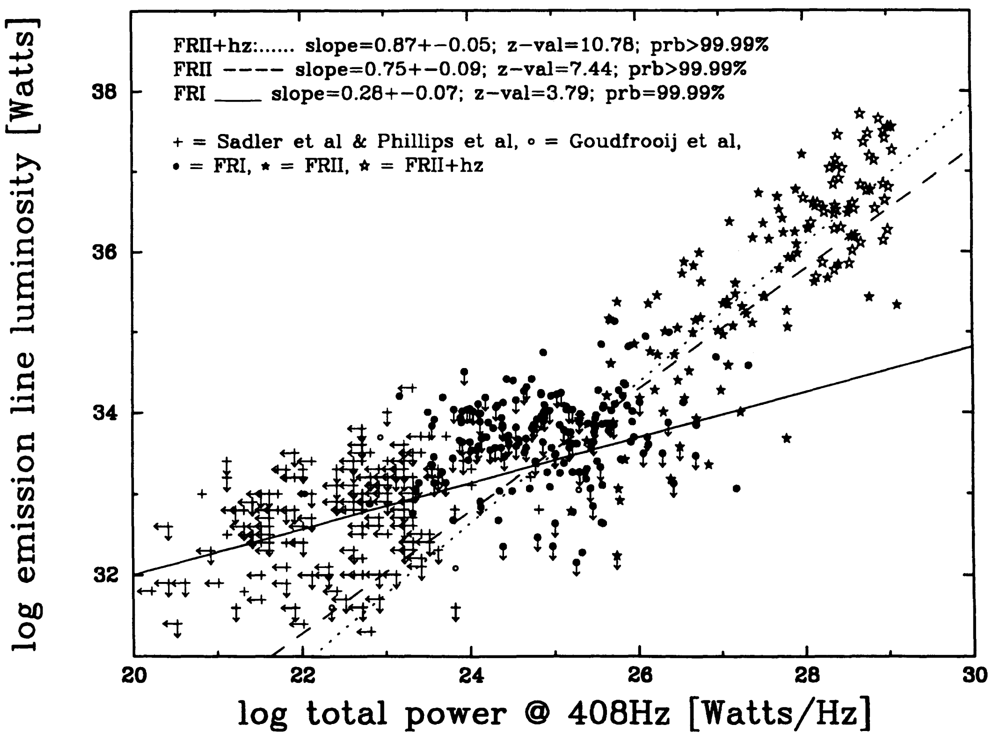

FIG. 1*b*

FIG. 1.—Log emission-line luminosity plotted against the log of the core radio power, in (*a*), and plotted against the log of the total radio power, in (*b*). Sources with FR 1 radio morphologies are indicated as filled circles, sources with FR 2 radio morphologies are indicated as stars (where filled stars indicate sources with redshifts less than 0.5). Lines showing the best-fit correlations for FR 1 radio sources and FR 2 radio sources are shown as solid and dashed curves, respectively. In (*b*), the optically selected galaxies from the control samples of Goodfrooij et al. (1995b) and Sadler et al. (1989) are shown as pluses and open circles. Arrows indicate limits. Reproduced from Paper I.

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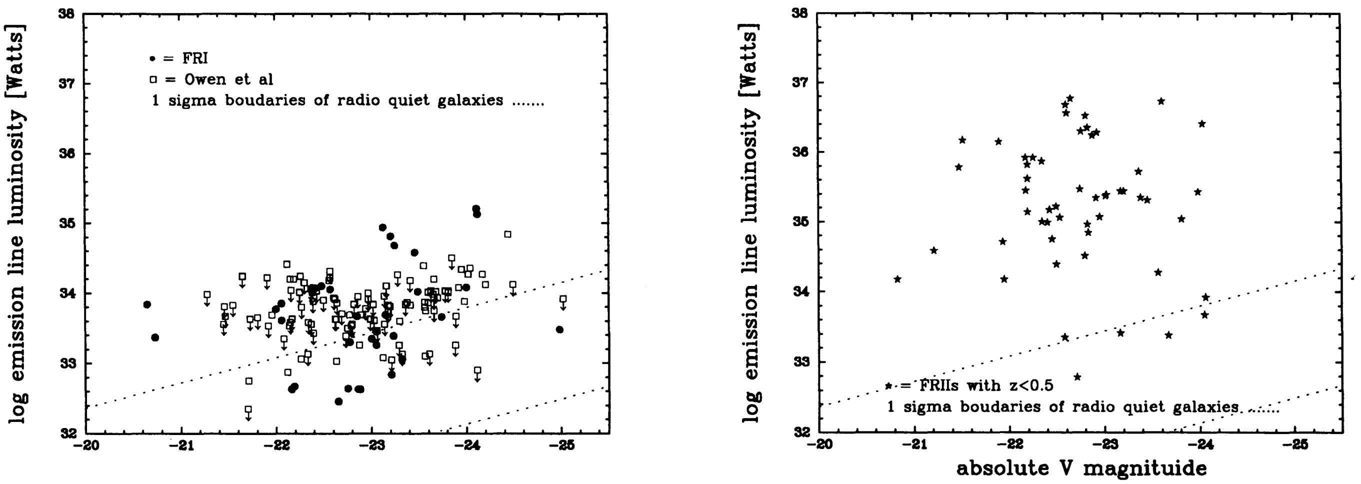

FIG. 2*a*

FIG. 2*b*

FIG. 2.—Log emission-line luminosity plotted against the absolute *V* magnitude of the galaxy where the 1 σ boundaries of the correlation of line to radio luminosity found for optically selected early-type galaxies is shown as dashed lines. (*a*) The relation for FR 1 sources, where FR 1 sources from the Owen et al. (1994) sample are indicated as open squares and the remainder of the FR 1 sources from our literature sample are indicated as filled circles. (*b*) The relation for FR 2 sources at redshifts less than 0.5 (indicated as filled stars). Reproduced from Paper I.

them to other classes of galaxies—specifically "inactive" normal galaxies and very active galaxies like the Seyfert 1 galaxies, quasars, and powerful radio galaxies. For easy reference, we list, in Table 1, the [O III] to Hβ ratios typically seen in starburst galaxies, cooling flow nebulosities, elliptical galaxies, FR 1 radio galaxies, FR 2 radio galaxies, quasars, and high-ionization Seyfert galaxies (note that there is also a "low-ionization" class of Seyfert galaxies, which may be those in which a circumnuclear starburst contributes significantly to the line fluxes but these warrant more study). From this it can be seen that the line ratios are bifurcated with Seyfert galaxies, FR 2 radio galaxies, and quasars showing similar [O III] to Hβ

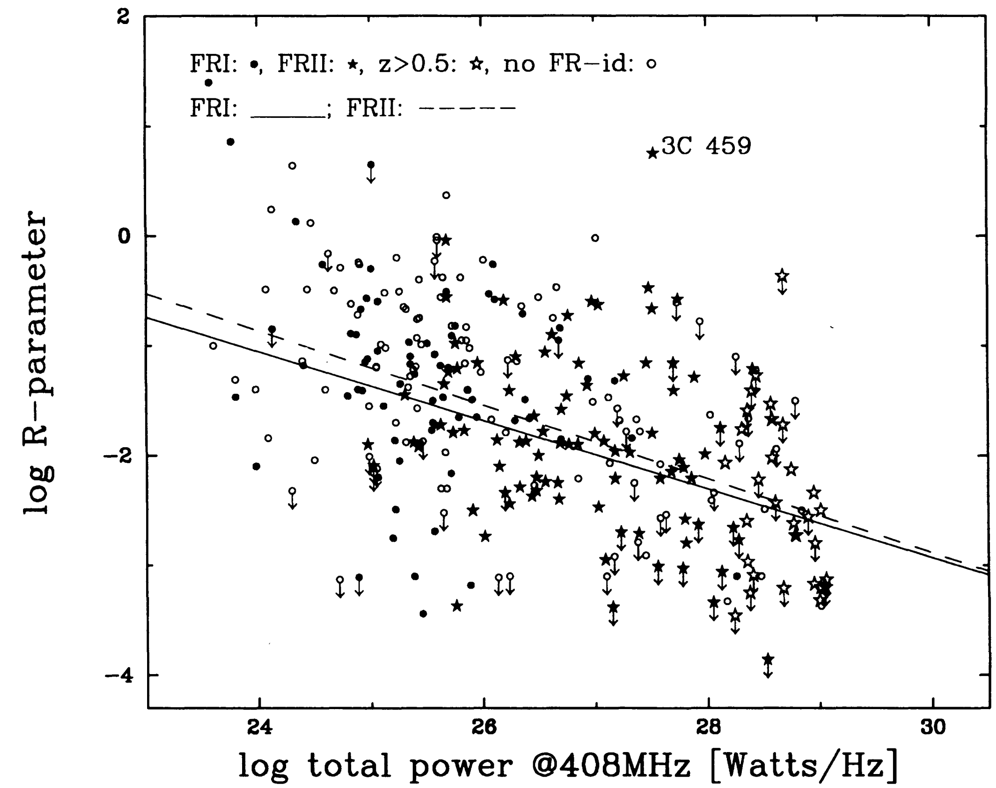

FIG. 3.—Log of the ratio of the core to total radio flux (the "*R*" parameter) vs. log of the total radio power, where filled circles indicate FR 1's, filled stars represent FR 2's at $z < 0.5$, and open stars represent FR 2's at $z > 0.5$. The best-fit relations for FR 1's alone and FR 2's alone are shown as solid and dashed lines, respectively. There is no significant difference between the relations. Reproduced from Paper I.

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TABLE 1

EMISSION-LINE PROPERTIES

Object Type	[O III]/Hβ
FR 1's	0.4–4
FR 2's	3–16
Quasars	5–20
Seyfert galaxies	3–12
LINERS	0.3–3
Cooling flows	<0.2–2.5
H_2 regions	2.2

TABLE 1 [O III] (λλ5007+4959)/Hβ RATIOS OBSERVED IN DIFFERENT CLASSES OF ACTIVE AND NORMAL GALAXIES. Values taken from Baum, Heckman, & van Breugel 1990; Cohen & Osterbrock 1981; Ferland & Netzer 1983; Grandi & Osterbrock 1978; Heckman 1980; Johnstone, Fabian, & Nulsen (1987); Koski 1978; Maoz et al. 1994; Penston & Fosbury 1978; Robinson & Binette 1987; van Breugel, Fillipenko & Heckman 1985; Yee & Oke 1978.

ratios, and FR 1 radio galaxies, typical normal elliptical galaxies, and starburst galaxies typically showing ratios which while similar to one another, are systematically lower than those seen in the higher ionization active galaxies. Cohen & Osterbrock (1981) showed that sources with low [O III]/Hβ ratios also typically did not exhibit detectable emission from the very high ionization lines such as Fe^{+6}.

Thus we see that FR 1 radio galaxies exhibit low-ionization emission lines (i.e., have LINER type spectra), which are similar to those of radio-quiet ellipticals and cooling flow galaxies, but quantitatively different from the high-ionization emission lines found in quasars, Seyfert galaxies, and high power radio galaxies which are generally believed to be photoionized by a hard UV ionizing continuum from the AGN itself. In the Seyfert 1 galaxies, some high-power radio galaxies, and quasars this ionization continuum is directly observed (e.g., Yee & Oke 1978; Cohen & Osterbrock 1981; Wilkinson, Hine, & Sargent 1979; Hine & Longair 1979; Robinson et al. 1987; Baum et al. 1992; Zirbel & Baum 1995).

Based on the overlap in the emission-line properties of FR 1 sources with those of optically selected early-type galaxies, and based on the lack of evidence for the presence of a hard nuclear ionizing continuum from the AGN in FR 1 sources, we suggest that the base level of ionization for the emission-line gas in FR 1 radio galaxies is provided by the host galaxy (and/or its surrounding intracluster medium [ICM]) and is not associated with the presence of a central engine in the active nucleus.

FR 1 radio galaxies and optically selected galaxies do exhibit a residual (3 σ) correlation of line luminosity with radio luminosity, once the correlation of line luminosity with optical magnitude has been removed. This may suggest the presence of a secondary component of ionization associated with an AGN in both FR 1 radio galaxies and normal (optically selected) elliptical galaxies. The extra ionization energy may come from a weak nuclear UV continuum source from the AGN (Maoz et al. 1994) or may be due to shocks associated with the dissipation of jet bulk kinetic energy as the nuclear radio jet dissipates energy and decelerates in the inner few hundred parsecs (e.g., Norman & Miley 1984).

However, it is also possible that the residual correlation of line and radio luminosity does not reflect a direct correlation of line luminosity with radio luminosity but is instead a secondary (or induced) correlation. For example, the very processes in the host galaxy which make it a strong emission-line emitter also lead to the production of a strong nuclear radio source. Sources in richer, denser environments (for example, those with more ample fuel sources for the central engine) are more likely to be radio loud. Yet another possible explanation for the residual radio and line correlation is that radio sources preferentially inhabit low mass-to-light ratio systems. Such an effect might be expected if radio activity is associated with ongoing star formation in the host galaxy (e.g., Smith & Heckman 1989). Nelson (1994) has recently suggested this possibility for Seyfert galaxies, which he observed appear to be preferentially in low M/L ratio systems (based on an application of the Faber-Jackson relation to Seyfert galaxies).

We note that the source of the energy for the ionization of the emission-line gas in LINERS generally, and normal lenticular and elliptical galaxies more specifically, is a subject of controversy. Many suggestions have been made for the energy source, including (to name but a few) the thermal energy in the hot gaseous corona and/or ICM surrounding these galaxies, shocks from cloud cloud collisions, photoionization by UV bright stars, a weak nuclear UV ionizing source from an AGN (e.g., Heckman 1980; Terlevich & Melnick 1985; Ferland & Netzer 1983; Fillipenko & Terlevich 1992; Shields 1992; Baum 1992). An investigation of the origin of the emission line energy in LINERS is outside the scope of the current paper.

3.2. *FR 2 Galaxies*

Contrary to what was found for the FR 1's the emission-line luminosity of FR 2 radio galaxies does not correlate with the optical magnitude of the host galaxy. The emission-line luminosities of FR 2 radio galaxies are orders of magnitude stronger than those in elliptical galaxies of comparable magnitude, as is clearly illustrated in Figure. 2. The emission-line luminosity of FR 2 radio galaxies has been shown to correlate strongly over 5 orders of magnitude with the radio luminosity in FR 2 radio galaxies (and quasars) (e.g., Baum & Heckman 1989b; Rawlings & Saunders 1991). As discussed above, the emission-line regions in FR 2 radio galaxies tend to be of high ionization (e.g., Yee & Oke 1978; Cohen & Osterbrock 1981; Wilkinson, Hine, & Sargent 1979; Hine & Longair 1979; Robinson et al. 1987; Baum et al. 1992; Zirbel & Baum 1995) similar to the narrow-line regions of Seyfert galaxies and quasars. Studies of the correlation of optical/UV continuum output from the nucleus in FR 2 radio galaxies with line luminosity have shown that the two are strongly correlated and that in almost all cases sufficient energy exists in the nuclear continuum to photoionize the emission-line gas that is observed (Yee & Oke 1978; Tadhunter et al. 1989; Baum & Heckman 1989a). Finally, detailed analysis of the line ratios in both the nuclear and extended emission-line gas in FR 2 radio galaxies have shown that a very consistent picture can be made in which the emission-line gas is predominantly photoionized by the UV continuum source from the nucleus in these galaxies though shocks along the radio jet or outflow regions may also contribute to the ionization of the gas, particularly in localized regions along the radio source (Robinson et al. 1987; Baum et al. 1992; Sutherland, Bicknell, & Dopita 1993; Koekemoer 1995).

Thus, our results are entirely consistent with the previously assembled picture in which the emission-line gas in FR 2 radio sources is ionized by the active nucleus itself.

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4. WHERE IS THE NUCLEAR UV CONTINUUM SOURCE IN FR 1 RADIO GALAXIES?

In § 2, we showed that FR 1 and FR 2 radio galaxies exhibit separate correlations of line to radio (core and total) luminosity, with different slopes and offsets, which, as discussed in more detail in § 3, is easily understood if the dominant ionizing source for the gas differs in the two classes of radio galaxies. One of the remarkable findings of these correlations is that FR 2 radio galaxies exhibit systematically *higher* (5–30 times higher) emission-line luminosities than do FR 1 radio galaxies of the same total radio power (and 10–40 times higher than FR 1's of the same core radio power). We quantify this finding as follows. At a total (core) radio power of 10^{26} W Hz^{-1} ($10^{24.5}$ W Hz^{-1})[3] FR 2 radio galaxies emit ~ 10 (20) times as much line luminosity as do FR 1 radio galaxies of the same total (core) radio power.

The low level of emission-line luminosity in FR 1 radio galaxies relative to FR 2 radio galaxies may be caused by a lack of ionizing radiation in the FR 1's (the case of photon bounded nebula) or by a lack of cold gas to be ionized in the FR 1's (the case of matter bounded nebula). However, the observed or estimated mass in emission-line gas in FR 1 and FR 2's is typically 10^4–10^6 solar masses (e.g., Baum & Heckman 1989a; Heckman et al. 1989; Phillips et al. 1986), and it appears that the majority of lenticular and elliptical galaxies have between 10^7 and 10^8 solar masses of cold atomic and/or molecular gas in their interstellar media (e.g., Knapp et al. 1989; Lees et al. 1991; Goudfrooij et al. 1994a; Knapp 1990). Thus, most elliptical galaxies appear to have sufficient reserves of cold material to be photoionized, if a strong UV continuum source was indeed present. Thus, we are led to the conclusion that the dearth of emission-line luminosity in FR 1 radio galaxies most likely reflects a dearth of photoionizing radiation. Since the *bulk* of the line luminosity in FR 1 radio galaxies probably originates from processes associated with the host galaxy (see above), this suggests that the nuclear UV ionizing source is much stronger in FR 2 radio galaxies than in FR 1 radio galaxies of the same radio power (i.e., *at least* 10 times as strong).

The result has (at least) two possible explanations. The first possibility is that FR 1 radio sources convert jet bulk kinetic energy into radio luminosity much more efficiently than FR 2 radio sources of the same jet bulk kinetic energy. In this scenario, the ratio of jet bulk kinetic energy to UV continuum luminosity from the AGN is the same in FR 1 and FR 2 radio galaxies, but since FR 1's convert jet bulk kinetic energy into radio luminosity more efficiently than do FR 2's, an FR 1 radio galaxy has a much lower bolometric AGN luminosity than does the AGN of an FR 2 of the same radio luminosity. The second possibility is that the central engines of FR 1 and FR 2 radio galaxies differ fundamentally in the ratio of UV continuum flux to jet bulk kinetic energy which they produce, i.e., that the UV continuum source is absent (or very weak) in FR 1 radio galaxies. We discuss each of these in turn in the sections below.

4.1. *Model 1: Differing Radio Conversion Efficiencies in FR 1 and FR 2 Galaxies*

The possibility that different types of radio sources convert jet bulk kinetic energy into radio luminosity with different efficiencies has been discussed in the past (e.g., Eilek & Shore 1989; De Young 1993a; Gopal-Krishna & Wiita 1991). Gopal-Krishna & Wiita in particular have suggested that a dense ISM surrounding the radio jet can enhance the conversion efficiency by as much as a factor of ~ 6 in powerful radio galaxies. Thus, it is not too far fetched to consider that FR 1 and FR 2 radio galaxies, whose jets are thought to interact with the surrounding ISM in fundamentally different ways (FR 1's through entrainment and deceleration, FR 2's principally through a cocoon around the jet and the termination shock at the end of the jet) and whose interstellar media may well be different (since the host galaxies are of different types [Smith & Heckman 1989; Prestage & Peacock 1988; Owen & Laing 1989]) would have different conversion efficiencies.

However, there are several pieces of evidence which argue against this simple and appealing explanation. These are

1. We have shown (see § 2 and Paper I) that the functional relationship between core and total radio luminosity is the same for FR 1 and FR 2 radio sources. This suggests common conversion mechanisms in the two types of radio sources.
2. The magnitude of the difference in conversion efficiencies between FR 1 and FR 2 radio sources which is required is large and would suggest that FR 2 sources pour orders of magnitude more (kinetic/thermal) energy into their surrounding media than do FR 1 sources. However, there is little or no independent evidence for this.

We discuss each of these issues, in turn, in more detail below.

4.1.1. *Implications of the Common Ratio of Core to Total Radio Power*

We have shown that at a fixed radio luminosity, FR 1 and FR 2 radio galaxies have the same ratio of core to total radio luminosity. This is a surprising result, which is difficult to understand in standard contexts, since it implies that FR 1 and FR 2 radio galaxies convert the same *fraction* of their jet bulk kinetic energy into radio luminosity in their cores. Almost all models for FR 1 radio galaxies suggest that their jets decelerate significantly within the inner ~ 100–1000 pc due to turbulent entrainment (e.g., Begelman 1982; Bicknell 1984, 1986a, b, 1994; Komissarov 1990a, b, 1993). However, almost all models for the jets in FR 2 radio galaxies suggest that their jets remain moderately relativistic until they reach the termination shock (hot spots) at the ends of the source (e.g., Williams 1991; Leahy 1991; Laing 1993), some tens to hundreds of kiloparsecs from the nucleus.

How, then, can we understand our surprising result? We know that the kiloparsec scale jets in FR 1 radio sources are systematically brighter than the kiloparsec scale jets in FR 2 radio sources. Evidence suggests that the jets in FR 1 sources begin to brighten at 10–100 pc, when they first decelerate due to interaction with their surrounding medium. If we take as a given that the jets in FR 1 sources interact with their surroundings much more than do the jets in FR 2 sources within the inner few kiloparsecs, slowing and brightening in the process, then the only way we can understand our result is if the following three conditions are met.

1. The "core" radio emission is dominated by a true compact component, which is similar in FR 1 and FR 2 sources. That is, the core emission we are measuring in FR 1's comes from a small region (~ 10 pc or smaller) and is not contaminated by emission from the decelerated jet.

[3] As discussed in Paper I, we must pick a fiducial point because of the different slopes which cause the exact ratio to be a function of radio luminosity.

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2. When a jet decelerates—either by turbulent entrainment within the inner ~ 100 pc of the jet length as in the FR 1 sources, or at the Mach disk at the termination shock as in the FR 2 sources—the principal effect of this shock is to slow the jet flow down to subluminal speeds, thereby removing the effects of Doppler boosting on the radio brightness (appearance) of the source. In FR 2 sources this occurs at the termination shocks, in FR 1 sources it occurs within the inner ~ 100 pc of the jet length. However, the net result is the same in either case: it allows us to see the true radio luminosity of the source.

3. Any additional particle acceleration (radio brightening) of the source which occurs in shocks must either (*a*) have little effect on the total radio luminosity of the source (i.e., the total radio luminosity is dominated by the initial conditions set in the central engine) or (*b*) the efficiency of conversion of jet bulk kinetic energy into radio luminosity must be similar in turbulent mixing layers along the jets and in the termination shocks.

To summarize, the result that the core to total radio power is the same in FR 1 and FR 2 sources is difficult to explain in any context. However, it does suggest a common conversion mechanism between FR 1 and FR 2 radio sources, which argues somewhat against the two types of sources having radically different conversion efficiencies.

4.1.2. *Magnitude of the Efficiency Differences Required*

The second, perhaps more important concern, is the magnitude of the efficiency difference which must exist between FR 1 and FR 2 radio galaxies in order to explain the observed offsets in the correlation of radio and line luminosity. If we make the assumption that the line luminosity can be used as an indicator of the bolometric luminosity of the central AGN, then we can use the observed differences in radio luminosity between FR 1 and FR 2 radio galaxies at a fixed line luminosity to determine the difference in the conversion efficiencies which this model requires. This is a reasonable assumption to make because (1) we strongly suspect that, at least in FR 2 sources, the UV continuum is responsible for photoionizing the emission-line gas whose line luminosity we observe and (2) there is evidence for abundant cold gas in host galaxies of FR 1's which should have been photoionized if a UV ionizing continuum was present (see § 3.2).

To explain the difference in the ratios of radio to line luminosity seen in FR 1's and FR 2's entirely on the basis of differing conversion efficiencies, we require that FR 1 radio galaxies be 5–60 times as effective at converting jet bulk kinetic energy into total radio luminosity as are FR 2 radio galaxies (where 5–60 are the factors needed to shift the best-fit point for the observed relation of line to radio luminosity for FR 1's onto the relation for the FR 2's, if we assume the shift is in radio luminosity alone). Similarly, using the same reasoning, we would conclude that the jets of FR 1 radio galaxies must be between 15–400 times as efficient at converting jet bulk kinetic energy into core radio power than are jets in FR 2's. Since a substantial fraction of the measured line luminosity for FR 1's is likely to be energized by processes association with their host galaxies (and not the AGN), these factors are in reality lower limits. We also note that in this model the conversion efficiency must be a function of AGN bolometric luminosity (or line luminosity) to explain the differences in the slopes in the line-radio planes exhibited by FR 1 and FR 2 sources.

FR 1 radio sources are commonly believed (although it has never been actually measured) to have conversion efficiencies of order 0.01–0.1 for their total radio luminosity (e.g., O'Dea 1985; Bicknell 1986a). To explain the line luminosity differences between FR 1 and FR 2 sources in terms of differing conversion efficiencies, this would then imply that FR 2 radio galaxies would have total conversion efficiencies of order 0.0002–0.002. Such low efficiencies, while certainly plausible, would imply that the jet bulk kinetic energy in FR 2 sources exceeds the radiant bolometric AGN luminosity (as measured, for example by the observed optical or mid to far IR continua; see Heckman et al. 1994); i.e., it would suggest that the AGNs in FR 2 radio galaxies deposit the *bulk* of their energy output in jet bulk kinetic energy not radiant energy.

If the conversion efficiencies really are substantially higher in FR 1 sources than in FR 2 sources, then this implies that FR 2 sources deposit kinetic energy into their surrounding media at substantially higher rates than do FR 1's. For example, given an efficiency of 0.002, Cygnus A and 3C295 would deposit $\sim 10^{48}$ ergs s^{-1} or 3×10^{62} ergs over a lifetime of 10^7 yr, which would clearly dominate the energetics of the local ICM and contributing significantly to the total energy content of the cluster gas (see also Carilli, Perley, & Harris 1994). For an efficiency of 0.0002, the radio source energy input would dominate everything as it would provide the entire hot gas energy content of the ICM over the course of just 10^7 yr.

In addition, the size of the extended radio structure is expected to be dependent on the amount of work done by the jet on the ambient medium in order to push it out of the way, integrated over the lifetime of the radio source. Thus the source size should depend on the density of the surrounding medium, the kinetic energy in the jets, and the source lifetime. If FR 2's transport more kinetic energy through their jets (at fixed radio luminosity) than do FR 1 sources, and FR 1 sources are not substantially longer lived than FR 2 sources, then FR 2 sources should produce larger radio sources (since we know that at low redshift the densities of the ambient media around FR 2 sources are if anything lower than those around FR 1 sources). However, FR 1 sources are not found to be systematically smaller than FR 2 sources of the same radio luminosity. FR 1 and FR 2 sources have a similar distribution of linear sizes, roughly independent of radio power (e.g., Muxlow & Garrington 1991).

Thus, to summarize, if FR 1 and FR 2 sources really do have dramatic differences in their efficiency of conversion of jet bulk kinetic energy into radio luminosity, then we would expect to be able to see evidence for the additional energy FR 2 sources are pouring into their surrounding media. Alternately, it may be that the jet bulk kinetic energy and the radio luminosity are essentially decoupled (see also above), with the radio luminosity being determined principally by the production rate of relativistic electrons in the nucleus with no further gains or losses of relativistic electrons in the large-scale radio structure.

4.2. *Model 2: Differing Ratios of Jet Bulk Kinetic to Radiant Energy?*

In the previous section, we discussed the possibility that FR 1's and FR 2's convert their jet bulk kinetic energy into radio luminosity with very different efficiencies. While this remains plausible, we showed that such a model has several consequences which are not observed. In this section we therefore discuss an alternate model, in which FR 1 and FR 2 sources have similar jet kinetic energy to radio conversion

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efficiencies, but the nuclei of FR 1 sources produce significantly less ($\sim 10\%$) ultraviolet ionizing radiation than do the nuclei of FR 2 sources.

In fact, evidence for radiant energy from the AGNs in FR 1 radio galaxies is in general scarce in the infrared (Heckman et al. 1994) and the optical (Costero & Osterbrock 1977; Yee & Oke 1978; Hine & Longair 1979; Wilkinson et al. 1979; Koski 1978). The data is much harder to interpret in the UV (e.g., Keel & Windhorst 1991), where the number of sources which have been looked at or detected is limited, or in the X-ray where confusion persists as to the contribution to the X-ray emission from a diffuse (intracluster or interstellar) component which may dominate the existing observations (Fabbiano et al. 1984; Feigelson & Berg 1983). However, all the data at least point toward the result that FR 1 radio galaxies produce significantly *less* radiant energy at IR-optical-UV wavelengths than do FR 2 radio galaxies of the same radio luminosity.

Interestingly, it is not only evidence for radiant energy from the nuclear component which is absent in FR 1 radio galaxies. There are also no (clear) examples of FR 1 radio galaxies which possess broad Balmer emission lines. While $\sim 20\%$ of FR 2 radio galaxies show broad permitted lines in the optical,[4] there are no known clear examples of FR 1 radio galaxies with broad-line regions. Unification schemes (e.g., Barthel 1989, 1994; Antonucci 1993) argue that broad-line regions are present in all FR 2 radio galaxies, but we are only able to see them when we look near the radio axis of the galaxy, due to the presence of an obscuring "torus" whose axis aligns with the radio source axis. This torus blocks our view of the central continuum source and the broad-line region when we view the source edge-on.

Thus it is interesting to ask the question, Are there broad-line regions in FR 1 radio galaxies? To our knowledge, there are over 100 FR 1 radio galaxies currently known and classified, and none of these appears to have a classical broad-line region. Thus, if there are broad-line regions in FR 1 sources, they are hiding much better in FR 1's than they do in FR 2's! We might be tempted to try and explain the apparent absence of broad-line regions in FR 1 sources by arguing that the obscuring torus in FR 1 galaxies covers a much larger fraction of the solid angle to the central source than in FR 2 sources. However, since the "blocked" energy must be reradiated, this model would predict that the bolometric luminosity of FR 1 radio sources be equal to or larger than that of FR 2 radio sources. However, as shown by Heckman et al. (1994) the mid- to far-IR luminosities of FR 1's are substantially less than those of the FR 2's.

Further, if there were hidden broad-line regions in FR 1, then when we view the FR 1 radio galaxy along its radio axis, we should see a broad-line region. However, even the BL Lac objects, which most current unification schemes argue are FR 1 radio galaxies seen pole on, do not show broad-line regions.[5]

Note that if the FR 1's are indeed the parent population of the BL Lac objects (see, e.g., Urry, Padovani, & Stickel 1991; Urry & Padovani 1995), then they must have a highly *beamed polarized* UV-optical component, such as might be expected to arise from the jet itself. We do not argue against the presence of such a highly beamed UV component—we suggest only that the more *isotropic* component, which is responsible in the FR 2's for powering the emission lines in the NLR and BLR, is deficient or absent in the FR 1's. As we suggest above, the lack of this "unbeamed" or semi-isotropic UV continuum in the FR 1's may be tied directly to the absence of the broad-line region in these sources (see, however, Guilbert, Fabian, & McCray 1983 for an alternate explanation).

To summarize, we suggest that it may not simply be that the broad-line region and the nuclear UV continuum source are *hiding* in FR 1 radio galaxies. They may be truly absent in FR 1 radio galaxies—or present at greatly reduced levels relative to FR 2 radio galaxies.

5. TOWARD A POSSIBLE PICTURE OF THE ORIGIN OF THE FR 1/FR 2 DICHOTOMY

In this section we discuss the idea that the FR 1/FR 2 dichotomy (i.e., the observed differences in the properties of low- and high-power radio sources) is due to qualitative differences in the structural properties of the central engines in these two types of sources.

5.1. *Do FR 1 and FR 2 Sources Have Different Accretion Rates?*

We suggest that the apparent lack of radiative energy from the AGNs in FR 1 radio galaxies compared to FR 2 radio galaxies may reflect a real difference in the fraction of energy from the central engine which is funneled into jet bulk kinetic energy versus radiant energy in these two types of sources. This difference may be due to fundamental structural differences in the central engines and/or surrounding accretion regions (disks?) in FR 1 and FR 2 radio galaxies. This suggestion is not new (e.g., Baum et al. 1992; Heckman et al. 1994), nor is it entirely without theoretical underpinnings.

Rees et al. (1982) pointed out that while some AGNs appear to emit the bulk of their energy as radiant energy, there may also be classes of AGNs which issue the bulk of their energy as jet bulk kinetic energy, and emit only much smaller fractions of their luminosity radiatively. For instance, a spinning black hole surrounded by an ion-supported torus and fed at a very low accretion rate may allow the extraction of the spin energy from the black hole in such a way that the bulk of the extracted energy is funneled into jet bulk kinetic energy, while only low levels of radiant energy are emitted (e.g., Rees 1984; Begelman 1985; Blandford 1986, 1990). However, at higher accretion rates, the fraction of radiant energy produced increases, until the accretion disk becomes radiation pressure supported, and the bulk of the energy extracted from the black hole is emitted radiantly, with only a negligible fraction of the energy going into jet thrust. Rees and collaborators have used such a continuum of models to explain the wide range of AGNs seen—ranging from those which produce little or no radio luminosity

[4] A value of 20% is obtained using the samples of 3CR radio galaxies matched in redshift and radio power by Heckman et al. (1994).

[5] Note that there is the possibility of a selection effect here. Blazars which turn out to have broad permitted lines are then classified as OVV quasars, while blazars which do not (yet?) show broad lines are classified as BL Lac objects (e.g., Antonucci et al. 1987). The extended radio properties of the BL Lac objects which do not show broad line are, however, consistent with them being end-on FR 1 radio galaxies (Perlman & Stocke 1993, 1994; Kollgaard et al. 1992; Ulvestad & Antonucci 1986; Antonucci & Ulvestad 1985; Wardle, Moore, & Angel 1984). We also note that the parsec-scale radio jets in BL Lac objects have different polarization properties than the jets in quasars (Gabuzda et al. 1994) suggesting that BL Lac objects and quasars are intrinsically different.

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but emit radiant energy at or near the Eddington luminosity (e.g., the radio quiet quasars and Seyfert galaxies) to the powerful radio quasars and radio galaxies which produce large scale radio jets and lobes.

We suggest here the possibility that such models may also be applicable to the FR 1/FR 2 dichotomy in radio galaxies. We suggest (within the context of the Rees et al. scenario) that FR 1's have low accretion rates and thus ion-supported tori which are faint sources of UV continuum. On the other hand, we argue that FR 2's have higher accretion rates (possibly with a radiation-supported torus—although if the black hole mass is large enough this may not be the case) and are sufficiently bright sources of UV continuum that they power their luminous emission-line regions.

Note that although we discuss our results in the context of the Rees et al. accretion disk/torus models, our results do not depend on the details of these models. Other models for producing differences in the ratio of UV radiation to jet kinetic energy are possible and would also be consistent with our results (e.g., the advectively cooled disks discussed by Abramowicz et al. 1995). For another approach to this question, see Falcke & Biermann (1994), Falcke, Malkan, & Biermann (1994), and Falcke, Gopal-Krishna, & Biermann (1994).

5.2. *Observational Underpinnings*

There is observational evidence to support the idea that the accretion rates and perhaps mechanisms are different in FR 1 and FR 2 sources. First, there is fairly compelling evidence which suggests that the central engines of FR 1 sources have appreciably lower accretion rates than FR 2 sources. As shown by Owen & Laing (1989) and as described in this paper and Paper I, at the same host galaxy optical magnitude, FR 2 sources typically emit 10 times the radio luminosity and 10 times the line luminosity as do FR 1's. Or said a different way, at apparent fixed AGN output, FR 1 sources inhabit host galaxies which are appreciably *more massive* than the host galaxies of FR 2 radio sources. In almost all models, the energy extracted from the central engine scales with the accretion rate and mass of the central black hole. Under the appealing assumption that the mass of the black hole will scale with the host galaxy mass (optical magnitude), we would expect FR 1 and FR 2 host galaxies of the same optical magnitude to harbor the same mass black holes at their centers. The observed reduced energy output of the FR 1 galaxies for a fixed host magnitude would then suggest that they have appreciably lower accretion rates. The alternate interpretation would be that the black holes in FR 1 radio galaxies are systematically smaller (per host galaxy magnitude) than those in FR 2's.

In addition, there is also (circumstantial) evidence to suggest that the fuel source itself is different in FR 1 and FR 2 sources. Baum et al. (1992) observed that the kiloparsec scale emission-line gas in FR 1 sources was turbulently support and exhibited little rotation. Based on the low observed angular momentum of the kiloparsec scale emission-line gas in FR 1's, the lack of strong evidence for recent large-scale mergers in the optical properties of the host galaxies, and the typically richer environments inhabited by FR 1 host galaxies, Baum et al. suggested the possibility that FR 1 sources are fed predominantly by steady, continual accretion of low angular momentum gas from normal stellar mass loss (see, e.g., Padovani & Matteucci 1993) and accretion from the hot ISM or ICM. Likewise, based on the high observed angular momentum of the kiloparsec scale emission-line gas they observed in FR 2 radio galaxies (which exceeds that of the stars), the alignment of the angular momentum vector of that gas with the radio source axis, and the high observed incidence of tidal tails and other clear evidence for a recent merger event in the optical properties of the host galaxies, Baum et al. suggested that FR 2 radio galaxies are likely to be fed by high angular momentum gas acquired in a merger event (see also Heckman et al. 1989).

5.3. *Producing Jets of Different Mach Numbers in FR 1 and FR 2 Galaxies*

Differences in the properties of the accretion disks and central engines in FR 1 and FR 2 radio galaxies might not only lead to differences in the fraction of radiant energy to jet bulk kinetic energy which they produce, but also to differences in the collimation, confinement, and physical properties (e.g., Mach Number) of their jets. For example, one type of central engine/accretion disk might produce jets which are predominantly pressure confined, the other magnetically confined. One might be high Mach number, the other not. The details of such a model and the link between collimation and the accretion "disk" properties clearly need to be worked out. Differences in jet collimation and internal properties must play an important factor in determining how the jet interacts with its surrounding environment, and therefore will exert a heavy influence (in conjunction with the properties of that environment; see, e.g., De Young 1993b; Bicknell 1994) in determining whether the jet is slowed within the inner kiloparsec (leading to the production of an FR 1 radio morphology) or proceeds through the inner parts of the galaxy ISM relatively unimpeded until it impacts on the working surface at the end of the source (leading to an FR 2 morphology).

Blandford (1994) has suggested that FR 2 galaxies are powered by very rapidly spinning black holes which produce jets with very powerful relativistic cores surrounded by nonrelativistic and collimating hydromagnetic sheaths. He suggests that when these two components interact in FR 2's, the sheaths are accelerated to the speed of the inner fast core. In the FR 1's which would have more slowly rotating black holes and thus slower or less powerful relativistic cores, the interaction between the fast core and the slow sheath decelerates the jet.

Thus, it is possible that in addition to differences in the *accretion* rates onto the central black hole, there may also be differences in the *rotation speed* of the central black hole in FR 1 and FR 2 sources which lead to the observed differences in the collimation properties of their jets. How might the accretion rate and rotation speed of the black hole be tied together? Rees (1984) noted that black holes might be spun up by accreting gas with high angular momentum. Baum et al. (1992) have suggested that the emission-line gas in FR 2's has high angular momentum, while that in FR 1's is low angular momentum and is supported mostly by turbulence. If this difference in angular momentum content of the gas is maintained down to small scales (which is clearly very uncertain), and the gas is effective in spinning up the black hole, then this could result in FR 2's having more rapidly spinning black holes than FR 1's. Alternatively, Wilson & Colbert (1995) have suggested that the dominant way that massive black holes spin up is through mergers with another massive black hole. Thus, the merger process may not only provide the gas to fuel the central engine, but the companion black hole which spins up the central black hole as well. The low-velocity dispersion groups in which FR 2's are found favors the possibility of ongoing mergers. The richer environments with higher velocity dispersions in which

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FR 1's are found could supress on-going mergers (e.g., Merritt 1983, 1984a, b; Lauer 1986).

5.4. *Intermediate Objects*

It is clear that not all objects will fall cleanly into the two categories we have suggested (e.g., high accretion rate and high spin BHs in FR 2's and low accretion rate and moderate spin BHs in FR 1's). There are 2 orders of magnitude in radio luminosity in which the transition from FR 1 to FR 2 galaxies occurs. In this range, there are objects which are intermediate in radio morphology between FR 1 and FR 2 (e.g., Baum & Heckman 1989b; Owen & Laing 1989; Morganti et al. 1993; Capetti et al. 1993). These may have intermediate values of accretion rate or BH spin and so produce radio structures which are intermediate between those of FR 1 and FR 2. Alternately, these may be objects where the environment is critical in influencing the radio properties.

There is also evidence for a subset of FR 2's which have weak and/or low-ionization optical emission lines (Hine & Longair 1979; Laing et al. 1994). In the context of this scenario, these could be objects with rapidly spinning BHs but with low accretion rate so that the UV continuum is weak in these objects.

5.5. *Implications for FR 2/Quasar Unification*

We note that our suggestions of high accretion rate and rapidly spinning black hole for the FR 2 radio galaxies should apply also to the radio-loud quasars if the FR 2 radio galaxies are the parent population of the radio-loud quasars (e.g., Scheuer 1987; Barthel 1989). Even if the FR 2's are not the parent population of the quasars, since quasars power similar luminosity-extended radio sources and similar luminosity-extended narrow-line nebulae and follow the same relationship between radio and line luminosity (e.g., Baum & Heckman 1989b; Rawlings & Saunders 1991; Hes, Barthel, & Fosbury 1993) as the FR 2 sources, we would expect the arguments above to apply equally to the radio-loud quasars.

5.6. *Evolutionary Effects: Dependence on Accretion Rate*

If, as we have suggested, FR 1 and FR 2 sources differ critically in the rate at which matter accretes onto the central black hole, then clearly it should be possible for a source to evolve from an FR 2 into an FR 1, simply by reducing the accretion rate into the nucleus. In fact, Yee & Ellingson (1993) have found that at intermediate-redshift ($z \sim 0.5$) radio loud quasars (FR 2 radio sources) are frequently found at the centers of rich clusters of galaxies. However, at low redshift, there are no quasars associated with the central dominant galaxies in clusters; instead, cluster dominant galaxies tend to be weak (sometimes amorphous) FR 1 radio sources (e.g., O'Dea & Baum 1986; Ball, Burns, & Loken 1993; Ledlow & Owen 1994). Yee & Ellingson have therefore suggested that the quasars evolve into FR 1 radio galaxies.

In the context of our model, we would understand this in the following way. At earlier epochs, mergers should have been common in cluster centers—such mergers would have provided large amounts of high angular momentum cold gas to fuel accretion at a rapid rate onto the black hole in the nucleus of the central dominant cluster galaxy and thus produce an FR 2 radio source (or quasar if seen end-on). As the universe evolved, however, clusters relaxed, the velocity dispersions increased, and mergers between the central dominant galaxy and a gas-rich cluster member became rare. The gas accreted in the merger event was used up, the accretion rate onto the central black hole slowed down, and the FR 2/quasar associated with the central dominant galaxy "dried up" and was replaced by an FR 1 source, fueled, now, at low redshift, via slow and steady accretion from the ICM.[6] Another driver of evolution might be a decrease in the BH spin with time. If the rotation speed of the BH is also important in determining the radio source morphology as we have suggested above, then a decrease in the spin with time, as the angular momentum of the BH is extracted to power the radio jet (Blandford & Znajek 1977; Wilson & Colbert 1995) could also cause an FR 2 to evolve into an FR 1.

5.7. *Environmental Effects*

Whether a radio galaxy jet decollimates within the inner kpc to produce a radio source with an FR 1 morphology or maintains its jet thrust along its full length to produce an FR 2 morphology must also be governed at least in part by environmental effects. Laing (1993) has suggested that this interaction may be mediated by (and see also Bicknell 1994; DeYoung 1993b): (1) the jet bulk kinetic energy (it is harder to slow a powerful jet than a less powerful one), (2) the jet collimation, Mach number, and other internal properties (which govern the mode of interaction between the jet and the environment), and (3) the density/pressure/magnetic profile of the surrounding environment (on the tens of parsec to kiloparsec scale).

Although it is clear that environmental factors must operate, our model posits that the accretion rate and central engine properties determine both the resultant jet bulk kinetic energy (1) and the collimation and physical properties of the jet (2) and thus dominate the appearance of a source as an FR 1 or FR 2 source. If the accretion rate and/or central engine properties can then be simply linked to the larger scale properties of the galaxies (e.g., Baum et al. 1992; Wilson & Colbert 1995), then this provides a simple way to understand the association of FR 1 sources with optically luminous galaxies in rich environments and the association of FR 2 sources with L_* galaxies in less dense environments.

6. SUMMARY

We have analyzed the results of a study of the interrelationships between host galaxy magnitude, optical line luminosity, and radio luminosity in a large sample of FR 1 and FR 2 radio galaxies (Paper I). We report several important differences between the FR 1 and FR 2 radio galaxies. At the same host galaxy magnitude or radio luminosity, the FR 2's produce substantially more optical line emission (by ~ 1 order of magnitude or more) than do FR 1's. Similarly, FR 2 sources produce orders of magnitude more line luminosity than do radio-quiet galaxies of the same optical magnitude, while FR 1 sources and radio-quiet galaxies of the same optical magnitude produce similar line luminosities. At the same host galaxy magnitude or radio luminosity, the FR 2's produce substantially more optical line emission (by ~ 1 order of magnitude or more) than do the FR 1's. If we combine these results with previous results from the literature, we conclude that while the emission-line gas in the FR 2's is indeed photoionized by a nuclear UV continuum source from the AGN, the emission-

[6] See also Fabian & Crawford (1990) for an alternate explanation.

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line gas in the FR 1's is energized predominantly by processes associated with the host galaxy itself.

The apparent lack of a strong UV continuum source from the central engine in FR 1 sources can be understood in two different ways. In the first scenario, FR 1's are much more efficient at converting jet bulk kinetic energy into radio luminosity than FR 2's, such that an FR 1 has a much lower bolometric AGN luminosity (hence nuclear UV continuum sources) than does an FR 2 of the same radio luminosity. We discuss the pros and cons of this model and conclude that the efficiency differences needed between FR 2 and FR 1 radio galaxies are quite large and may lead to difficulties with the interpretation, since it would suggest that FR 2 radio source deposit very large amounts of kinetic energy into the ISM/ICM.

Alternatively, it may be that the AGNs in FR 1 sources simply produce far less radiant UV energy than do those in FR 2 sources. That is, that FR 1 sources funnel a higher fraction of their total energy output into jet thrust versus radiant energy than do FR 2 sources. If this is correct, then this suggests that there is a fundamental difference in the central engines and/or immediate "accretion region" around the engine in FR 1 and FR 2 radio galaxies. We note also the absence of FR 1 sources with nuclear broad line regions and suggest that the absence of the BLR is tied to the absence of the "isotropic" nuclear UV continuum source in FR 1 sources.

We posit that the FR 1/FR 2 dichotomy (i.e., the observed differences in the properties of low- and high-power radio sources) may be due to qualitative differences in the structural properties of the central engines in these two types of sources. Following early work by Rees et al. (1982), we suggest that FR 1 sources are produced when the central engine is fed at a lower accretion rate, leading to the creation of a source in which the radiant to jet bulk kinetic energy is low, while FR 2 sources are produced when the central engine is fed at a higher accretion rate, causing the central engine to deposit a higher fraction of its energy in radiant energy. We further suggest the possibility that associated differences in the spin properties of the central black hole between FR 1 (low-spin) and FR 2 (high-spin) sources may be responsible for the different collimation properties and Mach numbers of the jets produced by these two types of radio-loud galaxies. This scenario, although speculative, is nicely consistent with our current picture of the triggering, feeding, environments, and evolution of powerful radio galaxies as discussed in more detail in the main body of the paper.

These properties may evolve with time; for example, the mass accretion rate and BH spin may decline with time, which causes a FR 2 radio source or quasar to evolve into a FR 1.

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