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THE MEGAPARSEC ENVIRONMENTS OF RADIO GALAXIES

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ABSTRACT

This paper presents an analysis of the Mpc environments of powerful radio galaxies (with $z < 0.5$ and radio powers $P_{408\,\mathrm{MHz}} > 10^{26}$ W Hz^{-1}, using $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$). We find that most radio galaxies reside in rather poor clusters (or loosely "groups") that have three to 10 members (whose magnitudes are brighter than -19 and that lie within 0.5 Mpc of the radio galaxy). Although there is a possibility that up to 5% of all radio galaxies are field galaxies (and up to 13% are pairs), our result is consistent with all radio galaxies being in groups. The distributions in group richness and Bautz-Morgan (BM) class of radio-selected groups are different from those of optically selected groups. Radio-selected groups are preferentially of BM type I, while optically selected groups are preferentially of BM type III. The richness distributions are comparable for rich groups (with $N_{0.5}^{-19} > 12$); however, poor radio-selected groups are ~ 1.5 times less abundant.

A second result is that the environments of FR I and FR II radio galaxies are different. FR I galaxies are found on average in richer groups than FR II galaxies. At low redshifts, FR II galaxies avoid rich groups; however, they do exist in rich groups at high redshifts. Most groups surrounding FR I galaxies (FR I groups) are of Bautz-Morgan class I, while most groups surrounding FR II galaxies (FR II groups) are of Bautz-Morgan class III. FR I groups have relatively fewer blue members than FR II groups. FR I galaxies are relatively closer to the nominal group centers than FR II galaxies. About twice as many FR II galaxies as FR I galaxies show either signatures of galaxy interactions and/or have a neighbor within 50 kpc. Together with the results presented in the first paper in this series, we argue that FR I sources are associated with centrally dominant cD-like galaxies that have been exposed to galactic cannibalism while FR II sources are more often associated with galaxies that are involved with galaxy interactions.

Finally, we show that the high- and low-redshift FR I and FR II groups belong to separate subsets of groups and that each subset is different from optically selected groups. We propose that FR I groups are dynamically more evolved and FR II groups less evolved than normal groups. Since no correlations exist between the properties of group members and the radio activity of the FR I and FR II sources, radio-selected groups can still be used to study the general evolution of galaxies in groups. Since radio-selected groups are richer at high redshifts, they provide a good method of finding distant groups.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: structure — radio continuum: galaxies

1. INTRODUCTION

Radio galaxies have been used extensively in cosmological studies, mostly because they can be seen at large distances owing to their high radio luminosities. Their stellar populations have been studied in detail with the aim of setting limits on the epoch of galaxy formation (see, e.g., Lilly & Longair 1984; Eisenhardt & Lebovsky 1987; Dunlop et al. 1989; Lilly 1989; Rigler et al. 1992; Dunlop 1996). Also, they have been used to find groups at high redshifts to study the evolution of galaxies in groups (see, e.g., Allington-Smith et al. 1993, hereafter AEZO). However, radio galaxies are, by definition, a special subset of galaxies. Therefore, it is most important to examine in what fashion they differ from "normal" galaxies and in what fashion radio-selected groups differ from "normal" groups.

The approach we have taken is to analyze the properties of the host galaxies of powerful radio sources and their cluster environments over a large range of redshifts (up to 0.5). In Paper I and Paper II (Zirbel 1996, 1997a), we analyzed their host galaxy properties (the magnitudes, colors, and surface brightness profiles), and here we determine their Mpc environments. In a final paper (Zirbel 1997b, hereafter Paper IV), we distinguish between the causes and the effect of the radio phenomenon. Overall, one of the goals of these papers is to describe the subset of galaxies from which radio galaxies are drawn and to determine what kind of galaxies in what kind of environments may turn into powerful radio sources. The special goal of this paper is to analyze how radio-selected groups differ from normal (i.e., optically selected) groups and to determine those environmental properties that are unique to radio galaxies.

In Paper I we found that the host galaxy properties of powerful radio sources are very diverse. Their magnitudes range from -24 to -20, although they are comparable to those of first-ranked radio-quiet elliptical galaxies in groups. Their colors can be as red as those of brightest cluster members but also ~ 1 mag bluer. Their optical structure may vary from cD to N galaxy behavior (cD galaxies are large elliptical galaxies with extended halos; N galaxies are dominated by the radiation from the active galactic nucleus [AGN] and have almost pointsource like images). Although the host galaxies of powerful radio galaxies are

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generally "emission-like" galaxies, less than one-quarter are normal elliptical galaxies that are well fitted by a $r^{1/4}$ law (de Vaucouleurs 1948). The only property that radio galaxies, as a class, have in common is that their galaxy sizes are relatively larger than those of normal elliptical galaxies of the same absolute magnitude.

Radio galaxies are often divided into two classes, the Fanaroff-Riley[3] type I (FR I) and type II (FR II) radio sources. In Paper I we found that the host galaxies of FR I and FR II sources are different. FR I sources prefer to be associated with cD-like galaxies or double nuclei galaxies and avoid N galaxies, while FR II sources prefer to be associated with N galaxies and avoid cD or double nuclei galaxies. Owen & Laing (1989) and Owen & White (1991) found that FR I's and FR II's separate out clearly in the radio power-magnitude domain. In Paper II we found that the FR I's are relatively larger than the FR II's and that only the FR I's exhibit a correlation between the size of the host galaxy and the radio power. Other differences between FR I's and FR II's are reported in their emission-line properties (Morganti, Ulrich, & Tadhunter 1992; Zirbel & Baum 1995; Baum, Zirbel, & O'Dea 1995), their infrared properties (Heckman et al. 1994), UV properties (Zirbel & Baum 1995) and their kinematics (Smith et al. 1992; Baum, Heckman, & van Breugel 1992). Therefore, whenever relevant, we differentiate between FR I and FR II radio galaxies.

The environments of radio galaxies have been studied in some detail starting with the work by Longair & Seldner (1978) and Seldner & Peebles (1978), followed by Prestage & Peacock (1988), Yates, Miller, & Peacock (1986, 1989) and Hill & Lilly (1991). It has become evident that radio galaxies in general do inhabit density enhanced regions, although it appears that the cluster environments of FR I and FR II radio galaxies are different. Hill & Lilly showed that there is a change in cluster environment with epoch in the sense that powerful radio sources are found in richer clusters at higher redshifts of $z \sim 0.5$. However, so far, studies of radio galaxy environments have centered on determinations of the cluster richness (i.e., the number of galaxies surrounding the radio galaxy). Here, we aim to determine additional environmental properties, such as the rank, the location, and brightness of the radio galaxy relative to other group members. Also, we examine in what fashion radio-selected groups differ from optically selected groups.

The origin and the cause of the radio activity of radio galaxies is rather poorly understood; even less well understood is the physics of the central engine. While it is beyond the scope of this paper to address those issues, it is nevertheless possible to learn more about the radio phenomenon by using an indirect approach. Thus, the final goal of this paper is to examine what the study of the environments of radio galaxies tells us the radio phenomenon itself.

The outline of this paper is as follows. In § 3.1 we analyze whether radio galaxies are always found in a group, and if so, determine how they differ from other group members. In particular, we determine their ranks, their locations, and their magnitudes and compare them to the properties of other group members. We also determine the Bautz-Morgan (Bautz & Morgan 1970) classes[4] and the distributions in group richness of radio-selected groups and compare then to those of optically selected groups. In § 3.2 we differentiate between the environmental properties of FR I and FR II radio galaxies. In § 3.3 we analyze how various environmental properties evolve with time. Finally, in § 4 we discuss the results. In particular, we focus on the following questions: What kind of galaxies in what kind of environments form what kind of radio galaxy? How do radio-selected groups differ from optically selected groups, and can they be used in cosmological studies? What do we learn from this work about the radio phenomenon itself?

2. SAMPLE SELECTION AND DATA REDUCTION

We use the same sample of radio galaxies that was analyzed by AEZO and in Paper I. Here we briefly review the selection criteria and some basics about the data reduction. For more details, the reader is referred to AEZO.

In order to study the evolution of the environments of radio galaxies over a substantial fraction of the Hubble time, it is important to adopt a selection criterion, which is as independent of redshift as possible. Possible properties of radio galaxies that we could use include the radio luminosity, spectral index, and radio morphology. Since it is not clear, a priori, which of these properties would be the least affected by the evolution of the radio galaxies themselves, the radio galaxies were selected within a narrow range in radio power (with powers measured at 408 MHz ranging from 10^{26} to 10^{28} W Hz^{-1}). The rationale of using this radio power range is to select "typical" radio galaxies that have radio luminosities within 1 order of magnitude of the break in the radio luminosity function. This radio power range is even narrower than that of Paper I, where the low radio power cutoff is at 10^{26} rather than at 10^{25} W Hz^{-1}.

The radio galaxies are chosen within two redshift intervals in the range $z = 0.03$–0.22 (the low-redshift sample) and in the range $z = 0.3$–0.5 (the high-redshift sample). Low Galactic latitude sources ($|b| < 16$) are excluded owing to the large amounts of foreground contamination. The low-redshift sources were selected from the 3C, 4C, 5C, and the Parkes catalogs, while some of the high-redshift sources were additionally taken from the Bologna and the 1 Jansky catalogs.

We obtained broadband Johnson B and V images for the low-redshift and V and R images for the high-redshift radio galaxies and for the field surrounding the radio galaxy by 0.5 Mpc. To correct for background galaxy counts, we obtained control fields that are about 20′–60′ away from the radio galaxy (this corresponds to roughly 4 Mpc). As explained by AEZO, this secures that the control fields are a fair distance away from the radio galaxy field but are still within the same supercluster. The integration times for each radio galaxy field and its comparison field were chosen such that galaxies with absolute V magnitudes of -19.0 could be included in our analysis. The apparent V magnitudes of the low-redshift galaxies and the R magnitudes of the high-redshift galaxies are transformed to rest frame V magni-

[3] Fanaroff & Riley (1974) classified the radio morphologies of radio sources according to a scheme that is based on the position of the radio hot spots relative to the total extent of the radio source. In Fanaroff-Riley type II (FR II), sources, the highest radio surface brightnesses are seen at the outer edges of the radio lobes, while in Fanaroff-Riley type I (FR I) sources, the highest radio surface brightnesses are observed close to the center of the radio galaxy.

[4] In BM type I clusters, the magnitude difference between the first- and second-ranked galaxies is largest (≥ 1.5 mag), and in BM type III clusters it is smallest.

tudes by using the "empirical K-corrections" developed by AEZO. The advantage of using the empirical method is that it does not involve any evolutionary model of the galaxies nor any cosmology. Basically, the rest-frame magnitudes and the colors are calculated by comparing their apparent magnitudes and colors to those of brightest cluster members of the same redshift. The galaxy colors are expressed in terms of the color difference, $\Delta(B-V)_0$, to the locus of E/S0 colors. For galaxies in the same fields as the radio galaxy, the rest-frame colors and magnitudes are calculated by assuming that they have the same redshift as the radio galaxy. Galaxaies that have anomalous colors [with $\Delta(B-V)_0 > 0.2$ or $\Delta(B-V)_0 < -0.6$] are then considered as foreground or background objects. The final sample of radio sources including galaxy names, redshifts, radio powers, absolute V magnitudes, colors, environmental properties, and radio morphology classifications are presented in the Appendix in Tables A1 and A2.

3. ANALYSIS

3.1. *Properties of Radio-selected Groups*

3.1.1. *Richness Distribution*

To determine the group richnesses, we count all galaxies that surround the radio galaxy within a radius of 0.5 Mpc and that are brighter than -19 and fainter than -25 mag. Since the brightness of the radio galaxy varies considerably (Paper I), ranging from -24.2 to -21.0 mag, we count all galaxies within a fixed region of the luminosity function. Since some of the fields are not observed deep enough, a "luminosity correction" is applied to account for the number counts of faint galaxies. This is done by assuming a Schechter luminosity function (Schechter 1976) of parameters $M^* = -21.9$ and $\alpha = -1.25$. The radius of 0.5 Mpc is appropriate for most groups, since they are not very rich (see below). However, for the richest groups, the counts may be underestimated because these tend to be larger. Nevertheless, a constant counting-radius clearly has its advantage. To correct for background contamination, we subtract the number counts of the control fields. Since the number counts of the background fields vary, we correct each radio galaxy field with its own background field rather than assuming a mean distribution of the background. Also, we exclude spurious objects (for example, stars and obvious background or foreground galaxies) that have anomalous color that are either -0.6 bluer or 0.2 mag redder than that of an elliptical galaxy of the same absolute magnitude. We refer to the final quantity as the "richness" of the group and denote it by $N_{0.5}^{-19}$. The procedure of calculating $N_{0.5}^{-19}$ and the errors is described and tested by AEZO. Since Hill & Lilly (1991, hereafter H&L) also studied radio galaxy environments, we include their measurements in this analysis. The necessary transformation of their richness to our scale is also described by AEZO.

Figure 1 displays the histogram of the distributions of group richnesses. The radio groups span richnesses ranging from negative values (due to background over subtraction) up to $N_{0.5}^{-19} = 70$ for the richest group. These richness measurements can be converted to the scale of Abell (1958) via $N_{\rm Abell} = 2.7\,(N_{0.5}^{-19})^{0.9}$. This correlation is derived from the density profiles of groups and clusters from West, Dekel, & Oemler (1987) and West, Oemler, & Dekel (1989) and is slightly different from AEZO's original correlation, however, only for poor groups. The threshold for richness 0

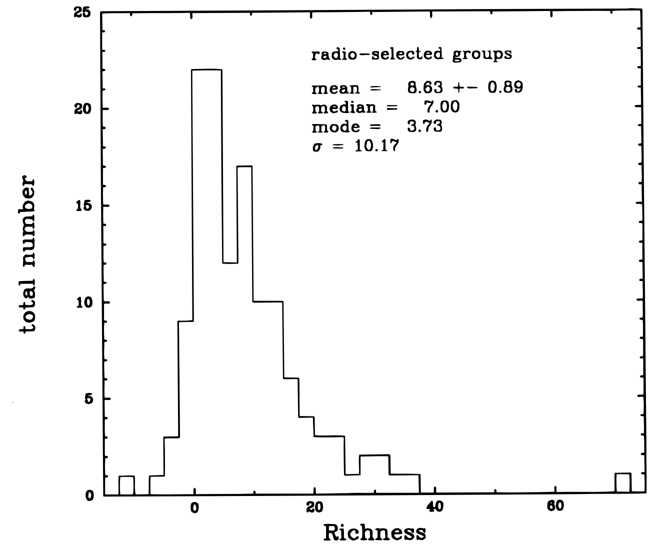

FIG. 1.—Histogram of the group richnesses of radio-selected groups

systems is now at $(N_{0.5}^{-19}) = 15$. Of 123 radio-selected groups, 97 are poorer than Abell class 0, 18 are of Abell class 0, seven are of Abell class 1, and one (the group surrounding 4C 29.44) is of Abell class 2. The mean richness of all radio-selected groups is $\langle N_{0.5}^{-19} \rangle = 8.6 \pm 0.9$, the median is 7.0, and the mode is 3.7. Thus, most radio galaxies are found in poor groups that have three to 10 members.

Traditionally, radio galaxies are thought to be always in groups; however, in Figure 1, it appears that 31 (27%) of the radio galaxies are either in pairs or in the field. Since there is a significant uncertainty associated with each group richness measurement, it is uncertain if field radio galaxies truly exist. Therefore, we perform the following test. We take a possible distribution of (synthesized) group richnesses, convolve that with an error function, and then analyze if this reproduces the richness distribution of Figure 1. We assume that the richness error distribution takes the form of a normal distribution whose 1 σ value is 5.7 (which corresponds to the mean richness error for the entire data set). Since the original distribution in group richness is unknown, we test two scenarios. In scenario A, we require that the radio galaxy is in a group with at least two other members, and in scenario B, we try to include as many single radio galaxies as possible. With these constraints, we produce the error-convolved distributions that produce the most optimal fits to the observed richness distribution. The resulting fits to scenarios A and B are displayed in Figure 2. To search for differences between the error-convolved distributions and the observed richness distribution, we also produce the cumulative richness distributions which are displayed in the upper boxes both parts of Figure 2. Comparing the richness distributions of scenarios A and B, one sees that both scenarios provide reasonable fits to the data. Thus, while some radio galaxies may be in the field or in pairs, our results are also consistent with all radio galaxies being in groups. Since as many single galaxies as possible were included in scenario B, this provides an upper limit. Up to 5% of all radio galaxies could be in the field and up to 13% in pairs.

It is of major interest to determine how the group richnesses of radio-selected groups compare to those of optically selected groups. This was already done by AEZO who

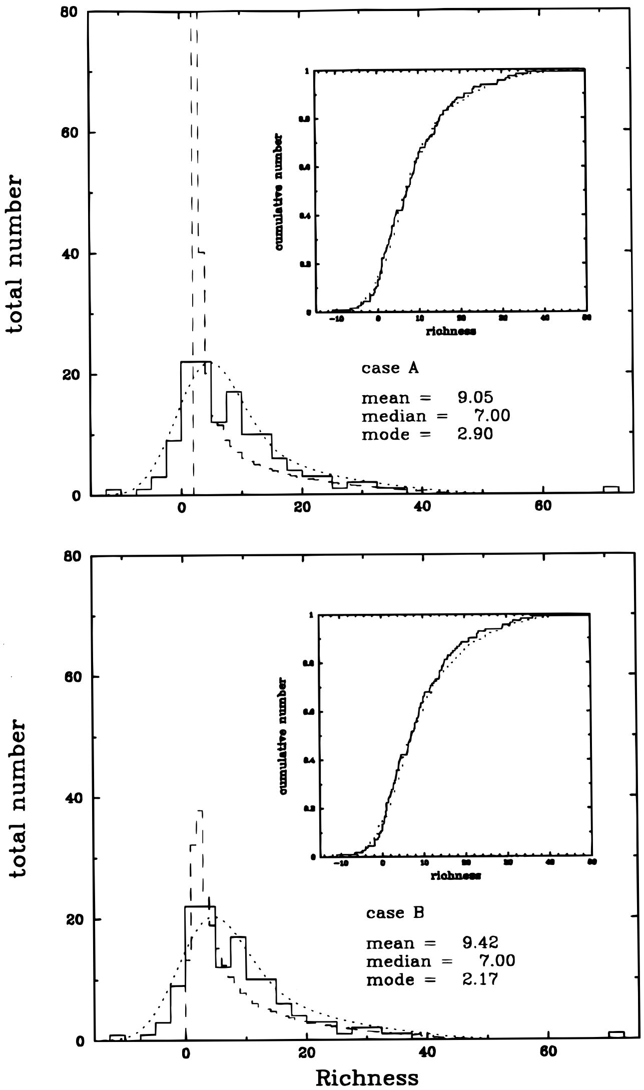

FIG. 2.—Comparing the distributions in group richness of scenario A (all radio galaxies are in groups) and scenario B (5% of all radio galaxies are in the field and 13% in pairs). The solid lines are the observed richness distribution of radio-selected groups, the dashed lines are the synthesized richness distributions, and the dotted lines are the error-convolved richness distributions. The boxes in the upper right-hand corner of both figures are the cumulative distributions of the observed and the error-convolved richness distributions. Note that scenario A and B both fit the observed richness distributions.

found that the distributions of radio-selected and optically selected groups (taken from the CfA survey; Geller & Huchra 1983) are comparable for groups that are richer than $N_{0.5}^{-19} = 12$, but that poor radio-selected groups are relatively underabundant. However, while our radio groups suffer from background contamination, the CfA groups do not, since Geller & Huchra have velocities and were able to establish group membership. Thus, we have to test if the difference between the radio-selected and optically selected groups could be due to the measurement uncertainties of our group richnesses. Since we cannot deconvolve the richness distribution of the radio groups, we convolve the richness distribution of the CfA groups with the same measurement error as that of the radio groups. The differences between the "error-convolved" CfA and the "observed" radio group richness distributions are shown in Figure 3. This is a plot of the logarithmic number of groups,

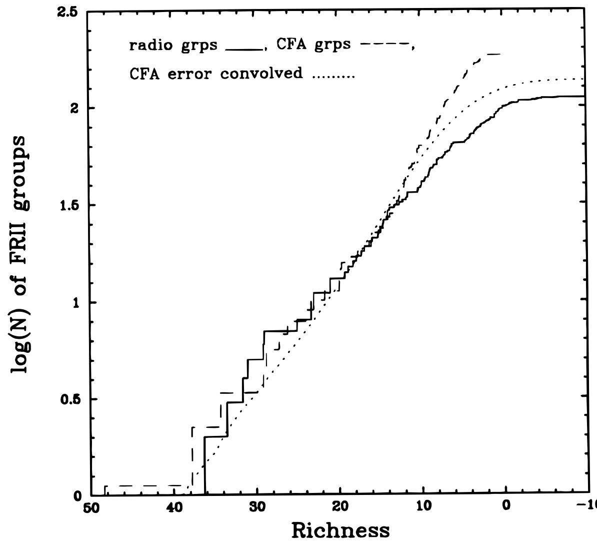

FIG. 3.—Cumulative richness distributions of radio-selected groups (*solid line*), of the CfA groups (*dashed line*) and of the "error-convolved" (see text) CfA groups. In each case we count the number of groups, $N(N_{0.5}^{-19})$, that are richer than $N_{0.5}^{-19}$. Note that there are discrepancies at the low group richness end in the sense that poor radio-selected groups are relatively underabundant.

log $N(N_{0.5}^{-19})$, whose richnesses are larger than $N_{0.5}^{-19}$. It is apparent that, while the error-convolved distribution of the CfA groups more closely resembles that of the radio-selected groups than the "raw" CfA distribution, there are still differences between CfA and radio-selected groups. For rich groups, the distributions are comparable; however, poor ($N_{0.5}^{-19} < 15$) radio-selected groups are approximately 1.5 times underabundant.

3.1.2. *Space Densities*

Radio galaxies are rare objects, and not every group contains a radio galaxy. It is of general interest to determine how many of all groups in the universe contain a "powerful" radio galaxy. However, determining the space density of radio-selected groups is not trivial. First of all, there is an evolution in the number counts of radio galaxies as shown by Longair (1966) and Peacock (1985). Second, at increasing redshifts, more and more radio sources are missed because their radio fluxes fall below the detection limits. Therefore, we determine the space densities of low-redshift groups (with $z < 0.1$) in which the radio galaxy is more powerful than 10^{26} W Hz^{-1}. A convenient list of radio galaxies that satisfy these constraints is provided by Burbidge & Crowne (1979). Altogether, we count 42 sources. However, because there is a discrepancy at the low-richness end between optically and radio-selected groups, we compare only the space densities of groups that have more than 12 members. Thus, assuming a richness distribution as displayed in Figure 1, $\sim$29% of the radio galaxies are expected to be in groups richer than $N_{0.5}^{-19} \sim 12$. This corresponds to 7.0×10^{-9} (rich) radio-selected groups per Mpc^3. Comparable estimates are obtained when using the known radio luminosity function (RLF) (e.g., from Peacock 1985). For the CfA groups, the probability of finding groups richer than $N_{0.5}^{-19} \sim 12$ is 7.8×10^{-6} per Mpc^3. Thus, the probability of finding a radio source that is more powerful than 10^{26} W Hz^{-1} in a (low-redshift) group is approximately one in a thousand. Clearly, this is strongly dependent on the radio luminosity cutoff. For example, finding sources that are more powerful than 10^{25} W Hz^{-1} in (rich) groups is relatively more common. Using the radio luminosity function (RLF), one finds that there are approximately one in a hundred. Radio sources with low radio powers (for example, a typical radio source from Sadler et al. 1989) of 10^{22} W Hz^{-1} are yet more common, and per group one would expect to find one to three of them. Nevertheless, the probability of finding one of the radio sources that are used in this analysis (i.e., with $P_{408} > 10^{26}$ W Hz^{-1}) in a group is approximately one in a thousand.

3.1.3. *The Rank of Radio Galaxies in Their Groups*

Traditionally, it has been assumed that the radio galaxy is the brightest galaxy in its group; however, no formal tests have been performed. If truly only the brightest member can turn into a radio galaxy, it means that the rank of a galaxy, and thus its environment, is critical in the formation of the radio source.

Since confirmed group membership of all galaxies does not exist, this test can be performed only in a statistical fashion. We therefore construct the background-corrected luminosity function of all galaxies in the group (excluding the radio galaxy) that lie within 0.5 Mpc of the radio sources and whose $B-V$ colors are redder than -0.6 and bluer than 0.25 than an elliptical galaxy of the same absolute magnitude. Since we are predominantly interested in the total number of galaxies that are brighter than the radio galaxy, we construct the "integral" luminosity function, $\Phi(M)$, which describes the number counts of all galaxies in the groups that are brighter than M. To determine the number of galaxies brighter than the radio galaxy, we normalize the luminosity function to the absolute magnitude of the radio galaxy. Since the magnitudes of the radio galaxies vary significantly (Paper I), we evaluate the luminosity function separately for each group, normalize each luminosity function to determine $\Phi(M-M_{rg})$, and then add all separate luminosity functions. Figure 4 shows the resulting luminosity function of the high- and low-redshift groups.

Among the 73 low-redshift groups, 3 ± 2 galaxies are brighter than the radio galaxy. To examine to which groups these galaxies belong, we inspect luminosity functions of each of the low-redshift groups. Apparently, two of the galaxies that are brighter than the radio galaxy belong to 3C 424 and that one belongs to PKS 1214+038. (Note, that although the probability that the bright galaxies do belong to either of these groups is rather high, they could also belong to any other group or be field galaxies.)

In the 3C 424 group, one of the "brighter" galaxies is much brighter than the radio galaxy (in excess of 1 mag), and thus it may be a foreground object. The other "brighter" galaxy is only marginally brighter than the radio galaxy, and it is only 30 kpc away from it. Therefore, this galaxy either may be interacting with 3C 424 or may be a foreground galaxy. Inspecting Smith (1988) CCD image of 3C 424, which has a higher resolution than our image, no obvious signs for galaxy interactions are visible. Thus, the "neighbor" is probably not associated with 3C 424. Clearly, redshifts are needed to establish group membership of this galaxy.

In the PKS 1214+038 group, the other bright galaxy is located at a projected distance of 0.48 Mpc from it. This galaxy is, in fact, another radio source, namely PKS 1215+039. In Figure 5 we show the PKS 1214+038/PKS 1215+039 field and see that both radio galaxies seem to belong to two separate groups that appear to be merging. Thus, each radio galaxy is the brightest galaxy in its group.

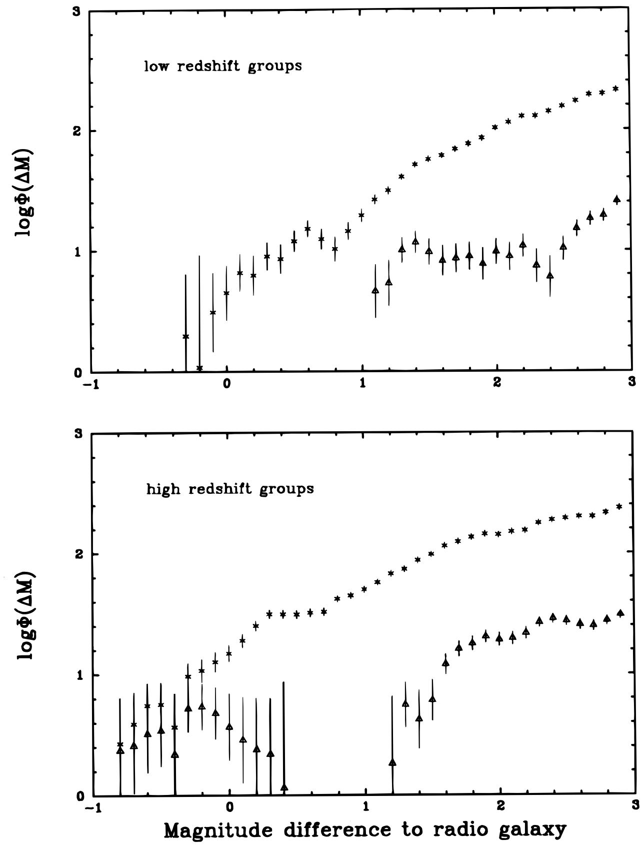

FIG. 4.—Luminosity functions of the high- and the low-redshift radio-selected groups as a function of the magnitude difference between that of the radio galaxy and its group members. The stars represent the luminosity function of all group members, while the triangles represent the luminosity function only of blue group members whose colors are -0.2 mag bluer than the locus of E/S0 galaxies.

Among the 34 high-redshift groups are 12 (± 3) galaxies that are brighter than the radio galaxy. This number is much higher than in the low-redshift sample. Another difference between the high- and the low-redshift groups is that the low-redshift groups contain more blue galaxies. This is discussed in extensive detail by AEZO and is generally referred to as the Butcher-Oemler effect (Butcher & Oemler 1984). It is now established that, at least in rich clusters, many of the blue galaxies either are disk galaxies or are starburst or poststarburst galaxies (see, e.g., Dressler & Gunn 1982; Couch & Sharples 1987; Dressler et al. 1994). If the blue galaxies in the radio-selected groups are indeed starburst galaxies, it means that they would be fainter otherwise. Therefore, we need to test whether any of the "brighter" galaxies in the high-redshift groups belong to this category of "blue" galaxies. Following AEZO, and thus Butcher & Oemler (1984), we define a galaxy to be "blue" if its color is 0.2 mag bluer than that of an elliptical galaxy of the same absolute magnitude. We then produce another luminosity function, however, only for these "blue" galaxies. This is displayed by the triangles in Figure 4 (*bottom*). It is evident that many of the galaxies that are more luminous than the radio galaxies actually have blue colors. In fact, of the 12 (± 3) brighter galaxies, 7 (± 2) have blue colors. However, there are still 5 (± 2) "red" galaxies

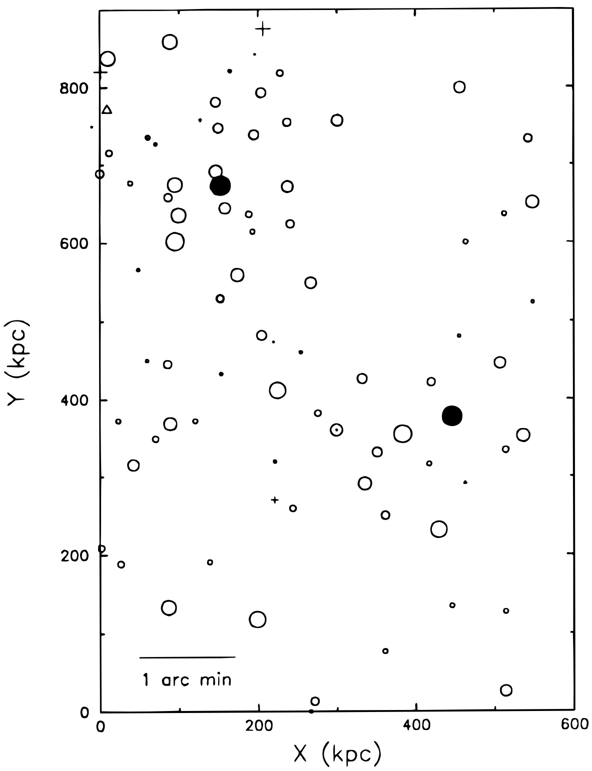

FIG. 5.—Positions of galaxies in the PKS 1214/PKS 1215 groups. The filled circles correspond to the radio galaxies (PKS 1215 is the upper radio galaxy). The circles are scaled according to the luminosity of the galaxies (ranging from $V = 19$ to -23.0). Note that the radio galaxies seem to belong to separate groups.

that will not fade, and these are definitely brighter than the radio galaxy.

To determine to which groups the "red" and "bright" galaxies belong, we once again produce the luminosity functions for individual groups. However, since background contamination is relatively important at high redshifts, even for brighter magnitudes, an inevitable uncertainty is associated with determining to which group each of the "brighter" galaxies belong. From the luminosity functions of individual groups it appears that three of these five "red" galaxies belong to 4C 29.44, one to 4C 27.51, and another one to 5C 6.142. Two of seven "blue" galaxies belong to 4C 25.51, two to 3C 457, one to 3C 20, and one to 4C 34.42. Clearly, redshifts are needed to confirm this. However, on average, seven of 34 high-redshift groups have galaxies that are brighter than the radio galaxy. Of these, in four groups, the brighter galaxies are blue, and they may fade as the galaxies evolve, thus perhaps becoming even fainter than the radio galaxy.

Despite that, in groups in which the radio galaxy is not the first-ranked galaxy, the radio galaxy is only marginally brighter than the first-ranked galaxy ($\Delta M = 0.10 \pm 0.04$ for groups with mostly "red" members and $\Delta M = 0.27 \pm 0.06$ for groups with "red" and "blue" members). In none of the groups is the brighter galaxy dominant; i.e., five groups are of BM type III and two are of BM type II (the BM types will be discussed later in § 3.2.2). Thus, although some radio galaxies may not be the brightest in their groups, the overall rank of the radio galaxy is still relatively high.

Contrary results are reported by Ledlow (1994), who finds that the radio galaxy is not always the first-ranked galaxy. In fact, he quotes that there are sometimes two, or in a few cases three, radio galaxies per cluster. However, the second- and third-ranked radio galaxies in Ledlow's sample are about 100 to 1000 times less radio luminous than the radio galaxies in our sample. Thus, the probability that the radio galaxy is the brightest galaxy in its vicinity may be dependent on its radio luminosity (this will be analyzed in more detail in Paper IV). The results so far suggest that the rank may be relatively more important in powerful than in less powerful sources.

In summary, at low redshifts, the radio galaxy is a confirmed brightest group member in 99% ($\pm 1\%$), of all cases and at high redshifts in 79% ($\pm 8\%$) of all cases [the latter case the number rises to 91% ($\pm 5\%$) if the bright blue bursting galaxies are excluded]. While the radio galaxy is almost always the brightest galaxy in its vicinity at low redshifts, this may have been different at higher redshifts. This is the first hint that the radio phenomenon among the high- and the low-redshift samples may have a different nature.

3.1.4. *Is the Rank or the Magnitude More Important in the Formation of a Radio Galaxy?*

To determine whether it is the rank or the magnitude of the radio galaxy that determines whether or not a galaxy may turn into a radio source, it is necessary to compare the magnitude distributions of the radio galaxies to those of second- (or third-) ranked galaxies. Because of background contamination, we determine the magnitudes of the second- and third-ranked galaxies, statistically, from the background-corrected luminosity functions of each individual group. The resulting magnitude distributions are displayed in Figure 6. From the overlap in the magnitude distributions between that of the radio galaxies and that of the second-ranked galaxies, we calculate that 31% of all second-ranked galaxies have magnitudes that are as bright as those of the radio galaxy. For the third-ranking galaxy, this number has dropped to 21%.

Distinguishing between the high- and the low-redshift groups, the corresponding number for the low-redshift groups is 28% for second-ranked and 19% for third-ranked galaxies. For the high-redshift groups, these values are 41% for second-ranked and 26% for third-ranked galaxies. Again, there is a difference between the high- and low-redshift groups. At high redshifts, relatively more radio galaxies have magnitudes that correspond to that of the second-ranked galaxy.

To determine whether the magnitude or the rank of the radio galaxy is more important, we need to correlate this result with that derived in the previous section. If the probability of turning any galaxy into a radio source is determined entirely by the absolute magnitude of the host galaxy, we would expect that the radio galaxy should be the first-ranked galaxy only in 69% of all low-redshift groups and in 59% of all high-redshift groups. However, we already showed that the radio galaxy is the first-ranked galaxy in 99% of all low-redshift groups and in 79% of all high-redshift groups. Thus, the rank of the radio galaxy within its group is indeed important in the formation of the radio source.

Nevertheless, it is possible that a combination of the rank and the absolute magnitude are important, particularly at high redshifts, where only 79% of all the radio galaxies are first-ranked galaxies. To test if the magnitude of the host

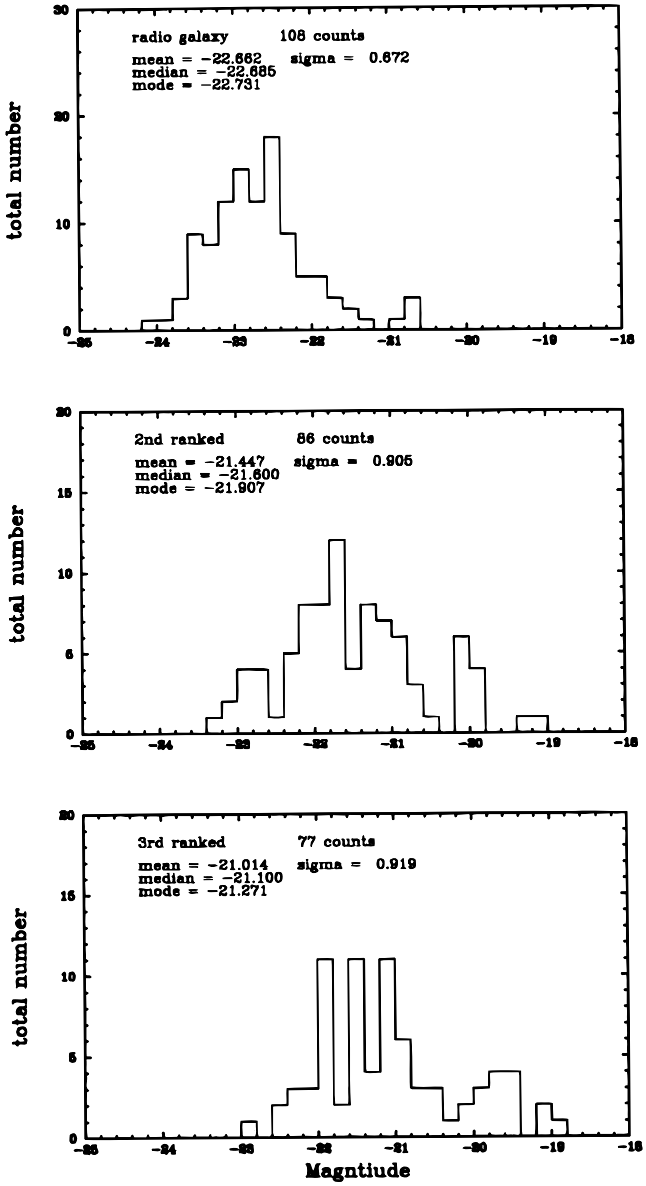

FIG. 6.—Histograms of the magnitude distributions of (*top*) the radio galaxies, (*middle*) the second-ranked galaxies, and (*bottom*) the third-ranked galaxies.

galaxy is nonetheless of importance, we compare the mean magnitude of all radio galaxies of groups in which the radio galaxy *is not* the first-ranked galaxy to the magnitudes of radio galaxies of groups where the radio galaxy *is* the brightest one. We find that the mean magnitude of radio galaxies which are the first-ranked galaxies is $\langle M \rangle_{\rm 1st\ rank} = -22.58 \pm 0.10$, while the magnitudes of radio galaxies that are the second-ranked galaxies is $\langle M \rangle_{\rm 2nd\ rank} = -22.65 \pm 0.19$. Since the magnitudes are comparable, regardless of the rank of the radio galaxy, it implies that the magnitude *is* important. Thus, together with the results of § 3.1.4, we conclude that both the magnitude and the rank of the radio galaxy play an important role in the formation of a radio source.

3.1.5. *Bautz-Morgan Classes*

The Bautz-Morgan (1970) classification system (hereafter called BM classes) is based on the apparent contrast in magnitudes between the first-ranked cluster member and fainter members. In BM type I clusters, the magnitude difference is largest, and in BM type III clusters, it is the smallest. This is shown quantitatively in Table 1. We define an additional BM class (BM0) in which the difference between the first and second ranked member is very large (1.85–2.30 mag). For the radio groups, the BM classifications are determined from the background-subtracted luminosity function by computing the magnitude difference between the radio galaxy and the second-ranked galaxy. In those groups in which the radio galaxy is not the brightest group member, the BM class is determined from the magnitude difference between the brightest galaxy and the radio galaxy. Individual Bautz-Morgan classifications of the radio groups are listed in Tables A1 and A2 in the Appendix. Even though the BM classes are also listed for very poor groups, they are only included in the analysis if the group has four or more members (five or more for BM type 0 groups).

It is important to compare the BM classes of the radio-selected groups to those of normal (i.e., optically selected) groups. For our sample of normal groups, we chose a combination of the CfA groups (Geller & Huchra 1983), the Hoessel, Gunn, & Thuan (1980) clusters, and Sandage's clusters (Sandage 1972a, 1972b, 1973a, 1973b; Sandage, Kristian, & Westphal 1976; Kristian, Sandage, & Westphal 1978) and refer to them as the CfA groups, the HGT, clusters, and the SKW clusters. The rationale of combining the poor CfA groups and the rich clusters (the HGT and the SKW clusters are mostly of Abell richness class 1 or 2) is to construct a non–radio-selected comparison sample that spans a wide range in group richness. Since there is no strong correlation between group richness and BM class for radio-selected groups (Fig. 7), or for rich clusters (see, e.g., Bautz & Morgan 1970; Sandage & Hardy 1973), it is justified to compare the BM distributions of different subsets of groups and clusters without worrying about their richnesses.

Table 2 lists the distributions of the BM classes of the radio-selected groups and the optically selected groups and clusters, and Figure 8 displays this graphically. Apparently, the BM classes of radio-selected groups are very different from those of the CfA groups and the SKW and HGT clusters. In all subsets of the optically selected groups and clusters, BM type I groups are the least and BM type III groups the most abundant. In contrast to optically selected groups, a relatively large fraction of radio selected groups seem to be of BM types 0, I, and I–II. To quantify the

TABLE 1

CORRELATION BETWEEN BAUTZ-MORGAN CLASS AND THE MAGNITUDE DIFFERENCE BETWEEN THE FIRST- AND THE SECOND-RANKED GALAXY IN A GROUP

Class	$\langle M_{\rm 1st} - M \rangle_{\rm 2nd}$[a]	$\langle M_{\rm 1st} - M_{\rm 2nd} \rangle$[a,b]	$\langle M_{\rm rg} - M^* \rangle$[c]
BM 0	2.3–1.85	n/a	>2.1
BM I	1.8–1.45	1.35–2.2	1.8–2.1
BM I–II	1.4–1.2	n/a	1.35–1.8
BM II	1.15–0.85	1.3–0.7	0.85–1.35
BM II–III ...	0.8–0.55	n/a	0.4–0.85
BM III	0.5–0.0	|0.65–0.0|[d]	|0.5–0.4|[d]

[a] Values extracted from Fig. 1 of Sandage & Hardy 1973.
[b] No intermediate classes.
[c] Values obtained from the radio groups.
[d] Negative values of $\langle M_{\rm rg} - M^* \rangle$ are obtained in cases where the radio galaxy does not correspond to the first-ranked galaxy in its group.

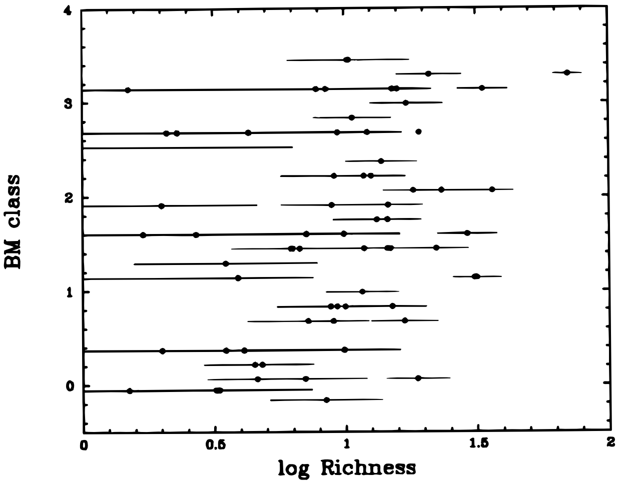

FIG. 7.—Correlation between the logarithm of the group richness and the Bautz-Morgan class.

difference between the radio-selected and the optically selected groups (the combination of the SKW and HGT clusters and the CfA groups whose first-ranked galaxy is an elliptical), we evaluate the ratio $N_{\rm radio\ groups}/N_{\rm optical\ groups}$ for each BM class. This is listed in Table 2, where we see that this ratio drops from 5.0 for BM type I groups to 0.4 for BM type III groups. The general trend is clear: radio groups prefer BM type I groups, while normal groups prefer BM type III groups.

We also analyze the BM classes of cD-selected clusters of Ball, Burns, & Loken (1993, hereafter BBL). These clusters are interesting, also for another reason, namely in that the cD galaxies are associated with weak radio sources (~ 100 times less radio luminous than our sources). Since cD galaxies are, by definition, much brighter than other group members (and thus reside mostly in BM type I and sometimes BM type II groups), it is not surprising that, compared to normal groups and clusters, there are relatively fewer BM type III BBL clusters. However, comparing the BM classes of BBL's clusters to those of our radio-selected groups that harbor a cD galaxy (the dashed line in Fig. 8*a*), we find that there are relatively fewer BM type I BBL clusters. From this we conclude that powerful radio cD galaxies seem to prefer BM type I clusters more strongly than Ball et al.'s weaker radio cD galaxies. Furthermore, according to Ball et al., their (relatively weaker) radio cD's prefer BM type I clusters more strongly than radio-quiet cD's. Thus, the cluster environment appears to play a role in the formation of a radio source.

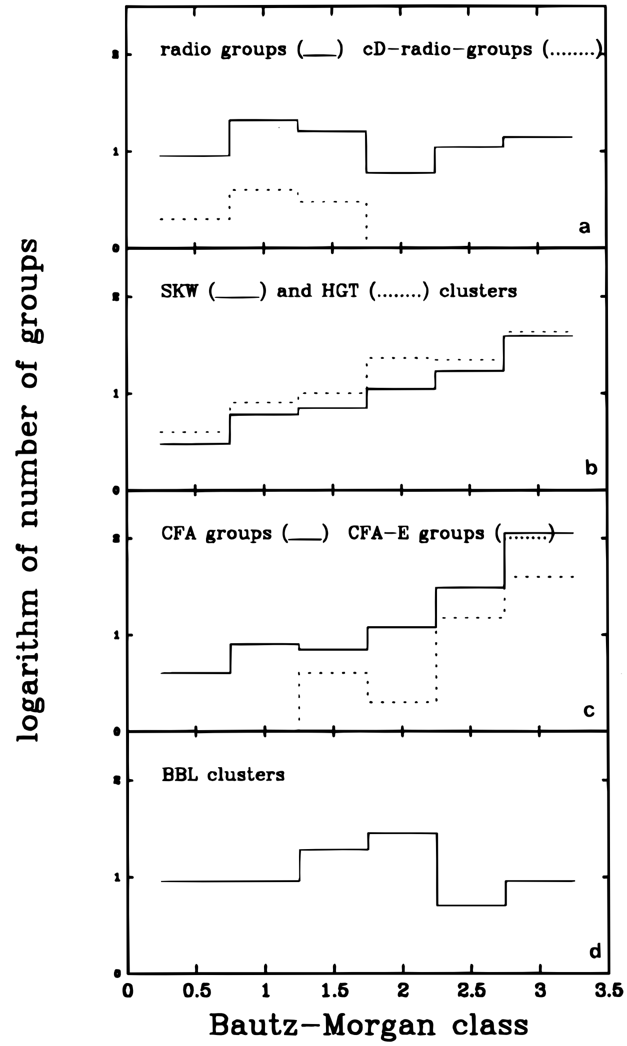

FIG. 8.—Histogram (in logarithmic units) of the number of groups within each BM class. Note that the trends for the radio-selected groups (*a*) are different from those of the optically selected CfA groups (*c*), the optically selected SKW or HGT clusters (*b*), and the cD-selected BBL clusters (*d*).

3.1.6. *Does the Radio Galaxy Magnitude Depend on the BM Type?*

The mean magnitudes of radio galaxies that belong to BM type I, I–II, II, II–III, and III groups are listed in Table 3. Similarly, we determine the mean magnitudes of the first-ranked galaxies of the CfA groups. For the SKW and HGT clusters, we obtain the mean magnitudes of the first-ranked galaxies from Sandage & Hardy (1973) and Hoessel et al.

TABLE 2

BM CLASSES OF RADIO-SELECTED AND OPTICALLY SELECTED GROUPS AND CLUSTERS

Group	Total	0	I	I–II	II	II–III	III
All radio groups	77	9	21	16	6	11	14
BBL clusters	69	?	18–?	19	28	5	9
SKW clusters	83	3	6	7	11	17	39
HGT clusters	110	4	8	10	23	22	43
CfA groups	175	4	8	7	12	31	113
CfA E groups[a]	62	0	1	4	2	15	40
All non–radio groups[a,b]	253	6	14	21	36	54	122
Ratio of radio/nonradio[c]	1	5.0	5.0	2.5	0.6	0.7	0.4

[a] This sample includes only groups whose first-ranked galaxy is an elliptical galaxy.
[b] SKW, HGT, and CfA groups whose first-ranked galaxy is an elliptical galaxy.
[c] The ratios are normalized such that the total number of radio to optically selected groups is 1.

TABLE 3

MEAN MAGNITUDES (AND r.m.s. ERRORS) FOR EACH BAUTZ-MORGAN CLASS

BM Class	SKW	HGT[b]	CfA Groups[c]	Radio Groups[d]
I → III[a]	-23.30 ± 0.03	-23.30 ± 0.03	-22.03 ± 0.04[a]	-22.62 ± 0.08 (74)
I	-23.66 ± 0.09	-23.60 ± 0.08	-21.83 ± 0.24	-22.73 ± 0.17 (25)
I–II	-23.43 ± 0.09	-23.41 ± 0.10	-21.86 ± 0.34	-22.71 ± 0.16 (15)
II	-23.32 ± 0.09	-23.48 ± 0.06	-22.04 ± 0.32	-22.57 ± 0.08 (13)
II–III	-23.35 ± 0.06	-23.31 ± 0.07	-22.01 ± 0.15	-22.48 ± 0.12 (9)
III	-23.08 ± 0.06	-23.19 ± 0.06	-22.05 ± 0.07	-22.60 ± 0.15 (12)

[a] Mean magnitude for all high- and low-redshift groups for which a BM class could be determined.
[b] Transformed from the $M_{\rm VI}$ system (and $H_0 = 60$, $q_0 = 0.5$) to ours.
[c] Transformed from Zwicky's $B(O)$ magnitude system to ours.
[d] The numbers in parentheses correspond to the numbers of groups within each BM class.

(1980). The corresponding correlations of the mean magnitude with the BM types are shown in Figure 9. As already noted by Sandage & Hardy and Hoessel et al., the first-ranked galaxy is progressively brighter in lower BM type clusters. This trend is not seen among the radio-selected groups. This is no surprise since we have shown in Paper I that the radio galaxies have a larger dispersion in their magnitudes than brightest cluster members. However, the CfA groups do not show any correlation between the magnitude of the first-ranked galaxy and the BM type, either. Therefore, we suspect that such a correlation may only be seen in relatively rich clusters.

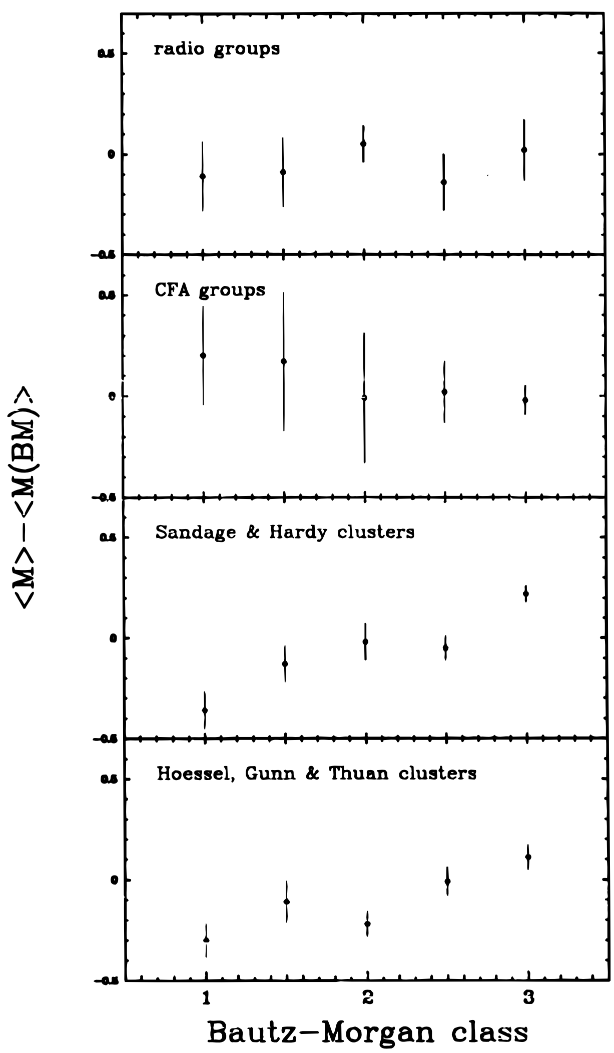

FIG. 9.—Correlating the difference in magnitudes between the mean magnitude of the first-ranked galaxy and the magnitude of the first-ranked galaxy of a certain Bautz-Morgan class to the Bautz-Morgan class itself. Note that rich clusters (the Sandage & Hardy and the Hoessel, Gunn, & Thuan clusters) show the expected correlation between the BM class and the magnitude difference, but that poorer groups (both radio-selected and optically selected) do not.

3.2. *Differences between FR I and FR II Groups*

So far, we have analyzed the environmental properties of the radio galaxies in general, without taking into account any differences in the radio galaxy properties. However, as shown below, there are substantial differences among the environments of FR I and FR II radio galaxies.

3.2.1. *Group Richness*

Figure 10 shows the cumulative richness distributions of both types of groups (the dashed and the dotted lines). FR I groups are on average 1.6 ± 0.3 times richer than FR II groups (the mean richness are $\langle N_{0.5}^{-19} \rangle_{\rm FR\,I} = 14.3 \pm 2.0$ and $\langle N_{0.5}^{-19} \rangle_{\rm FR\,II} = 8.7 \pm 1.2$). From the shapes of the richness distributions, it appears that the difference is mainly due to the relatively larger fraction of poor FR II groups. While there are equally many FR I's and FR II's in groups with 15

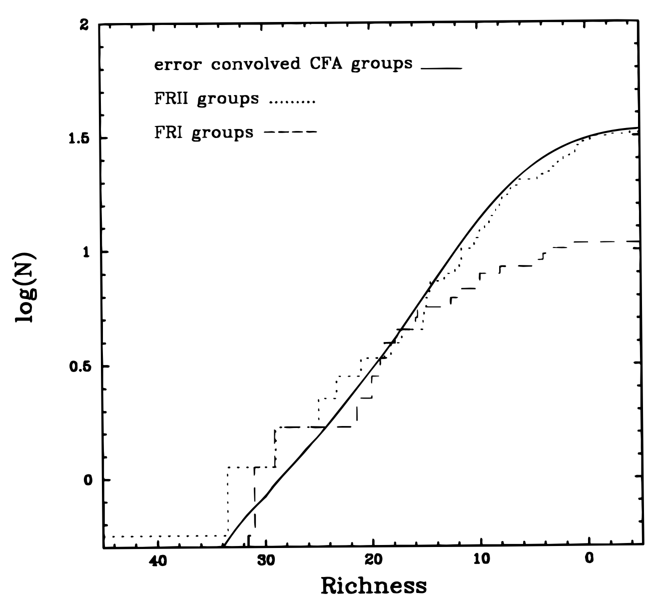

FIG. 10.—Cumulative richness distributions of FR I groups (*dashed line*), FR II groups (*dotted line*), and of the "error-convolved" (see text) CfA groups (*solid line*). In each case, we count the number of groups, $N(N_{0.5}^{-19})$, that are richer than $N_{0.5}^{-19}$. Note that the richness distributions of the FR II groups resemble that of the CfA groups, while poor ($N_{0.5}^{-19} < 15$) FR I groups are relatively underabundant by a factor of ~ 3.

TABLE 4

Richness Classes of FR I and FR II Groups

Group	Total	Very Poor ($N < 3.5$)	Poor ($3.5 \rightarrow 10$)	Interm ($10 \rightarrow 20$)	Rich ($N > 20$)	Mean	Scatter
FR I[a] ……	19	1	6	8	4	14.7 ± 2.3	9.3
FR II……	65	24	19	16	6	8.9 ± 1.2	11.2

[a] Contains 3C 433 and 3C 196.1, which have an amorphous radio structure and PKS 1928−340 and PKS 2130−538, which are the most likely FR I sources.

members or more, there are above 3 times as many FR II's than FR I's in poorer groups.

To analyze this result in more detail, we divide the FR I and the FR II groups into "very poor" ($N_{0.5}^{-19} < 3.5$), "poor" ($3.5 < N_{0.5}^{-19} < 10$), "intermediate" ($10 < N_{0.5}^{-19} < 20$), and "rich" ($N_{0.5}^{-19} > 20$) groups, and in Table 4 we list the number of groups within each richness class. The difference between FR I and FR II groups is most striking for the poorest groups. While about one-third of all FR II's reside in groups with richnesses below 3.5, FR I's seem to avoid those groups. If we perform the same test as in § 3.1.1 to determine if any of the FR I galaxies could be isolated galaxies or in pairs, we find that this possibility is rejected at the 99.99% confidence level. Also, only a maximum of 8% of the FR I's are in groups of three. On the other hand, up to 14% of the FR II galaxies may be in pairs and up to 6% in the field, although the richness distributions are also consistent with all FR II's residing in groups of three or more members. Thus, FR I galaxies are definitely found in groups, while some of the FR II galaxies "may" be field galaxies.

It is also important to analyze how the richness distributions of FR I and FR II groups compare to those of the optically selected (CfA) groups. However, since there are measurement errors associated with the group richnesses of the FR I and the FR II groups and none with the CfA groups, we compare them to the "error-convolved" richness distribution of the CfA groups. This error-convolved distribution is shown in Figure 10 along with those of the FR I and FR II groups. It is immediately clear that the richness distribution of the FR I groups is very different from that of the CfA groups. Compared to optically selected groups, there are equally many FR I groups with 15 members or more; however, poorer FR I groups are underabundant by a factor of about 3. On the other hand, FR II groups appear to be comparable to optically selected groups. However, the latter result may be deceiving as will be explained in § 3.3.1.

In summary, the richness distributions of FR I and FR II groups are very different. Also FR I groups are different from optically selected groups.

3.2.2. *Bautz-Morgan Classes*

To analyze the Bautz-Morgan classes of FR I and FR II groups, we count the number of FR I and FR II groups that are of Bautz-Morgan classes I, II, and III. We do not use intermediate BM classes as our sample of FR I and FR II groups is too small. The distributions of the BM classes are listed in Table 5 and illustrated graphically in Figures 11*a* and 11*b*. It is immediately clear that FR I galaxies prefer BM type I groups, while FR II galaxies prefer BM type III groups. Quantitatively, we express this difference in terms of the "BM ratio," defined by BMI:II:III. For FR I groups, this ratio is 53:33:13, and for FR II groups, it is 21:38:41 (the uncertainty within each BM class is ± 7 for FR I and ± 3 for FR II groups). Compared to FR II groups, about twice as many FR I groups are of BM type I and about half as many are of BM type III.

It is of general interest to analyze how the BM distributions of the FR I and the FR II groups compare to those of optically selected groups. As with the sample of optically selected groups we, again, take the combination of the HGT, SKW, and CfA groups. Comparing FR II groups to optically selected groups (Fig. 11*d*), it appears that both show the same trend in their BM distributions. On the other hand, the BM trend for the FR I groups is reversed. For a more quantitative approach, we compare the BM ratios. These are 53:33:13, 21:38:41 and 11:29:59 (with errors of ± 7, ± 3, and ± 0.5) for the FR I, FR II, and optically selected groups, respectively. Although the overall trends of the BM distributions of the FR II groups and optically selected groups are comparable, there are relatively fewer ($\sim \frac{2}{3}$) FR II groups that are of BM type III. On the other hand, the BM distributions of FR I groups are very different from both, the FR I and the optically selected groups. Compared to optically selected groups, there are about 4 times as many FR I groups that are of BM type I and about one-quarter as many that are of BM type III.

We also compare the BM distributions of FR I and FR II groups to those of the Ball et al. (1993) clusters. The Ball et al. clusters are interesting for two reasons. First, their radio galaxies are about 100 times less radio luminous than ours. We suspect that most of their radio sources are either FR I or compact sources and rarely FR II sources. Second, the first-ranked galaxies in their clusters are cD galaxies. Since many ($\sim \frac{2}{3}$) of the FR I's and none of the FR II's, are associated with "cD-like" galaxies (Paper I), it makes more sense to compare the FR I groups to the Ball et al. clusters. The distribution of the BM types of the Ball et al. clusters is displayed in Figure 11*c*. Compared to those clusters, relatively more FR I groups are of BM type I. Interestingly, Ball

TABLE 5

BM Classes of FR I and FR II Groups

Group	Total	I	II	III
Optically selected groups[a] ……	253	28	74	147
cD-selected groups[b] …………	79	27	40	12
FR I[c] …………………………	15	8	5	2
FR II …………………………	39	8	15	16
FR I/optical groups[d] ………	1	4.82	1.15	0.24
FR II/optical groups[d] ………	1	1.86	1.32	0.71

[a] SKW and HGT clusters and CfA groups whose first-ranked galaxy is an elliptical.

[b] The Ball et al. clusters.

[c] Contains 3C 433 and 3C 196.1, which have an amorphous radio structure and PJS 1928−340 and PKS 2130−538, which are most likely FR I sources.

[d] The ratios are normalized such that the total number of radio to optically selected groups is 1.

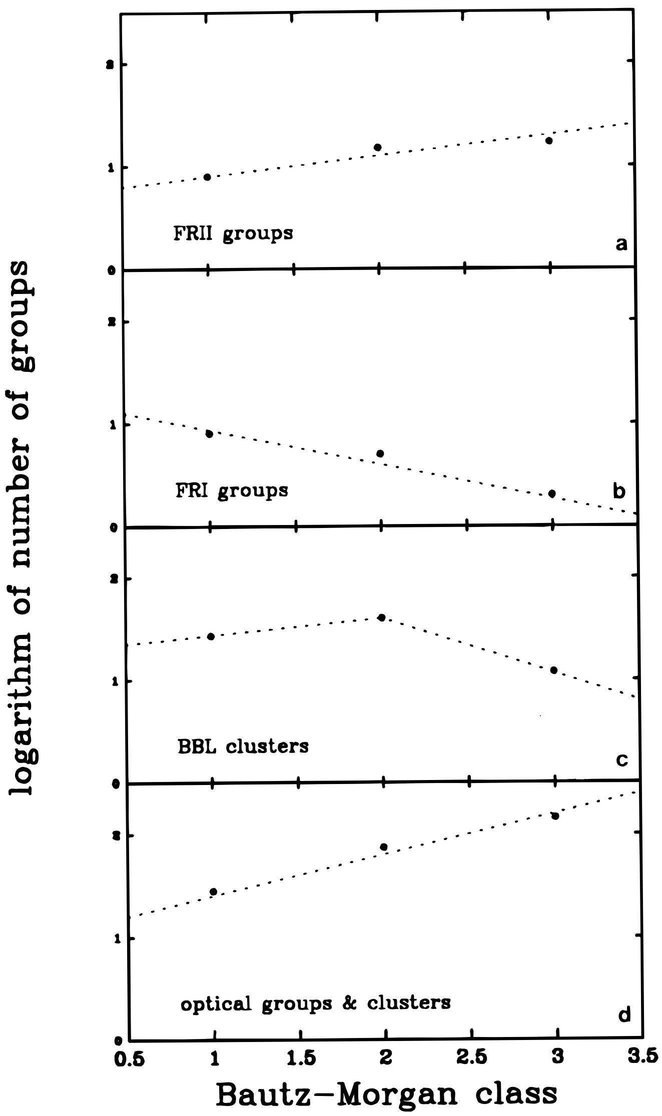

FIG. 11.—Comparison of the distributions of the Bautz-Morgan classes of (*a*) FR I, (*b*) FR II, (*c*) BBL, and (*d*) optically selected groups and clusters. We display the logarithmic number of galaxies of each subset of groups that are of BM class I, II, and III. The dashed line is for guidance only and shows the general trends among the data.

et al. noted that they detected a relatively larger fraction of radio sources in BM type I clusters than in BM type II or III clusters. This suggests that powerful FR I cD sources are found more often in BM type I clusters than weaker FR I cD galaxies, which again are found more often in BM type I clusters than radio-quiet cD galaxies.

In summary, the distributions in the BM classes of the FR I and FR II groups are different. Compared to optically selected groups, the BM distribution of FR I groups is reversed, while that of FR II groups is more comparable, although BM III FR II groups are relatively under abundant. For FR I's, not for FR II's, there appears to be a trend in the sense that more powerful sources prefer groups of BM type I rather than II or III.

3.2.3. *Magnitude Distributions of Group Members*

To search for differences in the magnitudes of group members of FR I and FR II groups, we produce the luminosity functions separately for both types of groups. Because the radio galaxy may be special and because we are predominantly interested in the magnitude distributions of the group members, we exclude it from the determination of the luminosity function. The resulting luminosity functions of the FR I and FR II groups are presented in Figure 12. Thus, we are unable to detect any differences among the magnitudes of group members of FR I and FR II.

The luminosity function of all radio-selected groups, including the radio galaxies, is analyzed by AEZO. They claim that it can be fitted by a Schechter function of parameters $M^* = -21.9 \pm 0.2$ and $\alpha = -1.2 \pm 0.1$ (i.e., parameters that are acceptable for optically selected groups). Thus, members of FR I and FR II groups are comparable to those of optically selected groups.

Nevertheless, the lack of a difference between FR I and FR II groups at the bright end of the luminosity function is somewhat surprising, particularly because the Bautz-Morgan distributions of FR I and FR II groups are different. However, because the error bars are substantial at the bright end of the luminosity function, any differences may be swamped. Clearly this analysis needs to be performed with a larger sample of groups. At the faint end, there might be a slight difference, in the sense that FR I groups have fewer faint ($-19 < M_V < -18$) group members. This difference, if statistically significant, is very intriguing and will be analyzed in a future paper.

3.2.4. *Colors of Group Members*

We express the colors of group members in terms of the fraction of blue galaxies. Following Butcher & Oemler (1984), we define the f_B as the fraction of galaxies whose

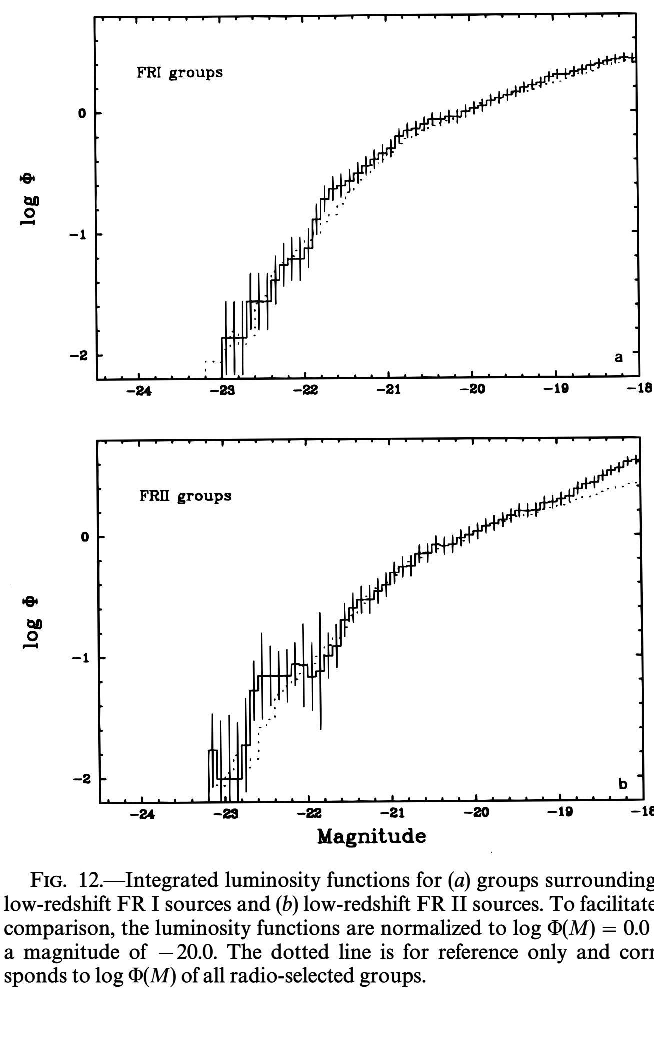

FIG. 12.—Integrated luminosity functions for (*a*) groups surrounding a low-redshift FR I sources and (*b*) low-redshift FR II sources. To facilitate a comparison, the luminosity functions are normalized to log $\Phi(M) = 0.0$ at a magnitude of -20.0. The dotted line is for reference only and corresponds to log $\Phi(M)$ of all radio-selected groups.

rest-frame $(B-V)$ colors are 0.2 mag bluer than the locus of E/S0 colors. The radio galaxy is excluded from this part of the analysis, because it is special and because its color may be affected by nonthermal process. For the FR I and FR II groups, we calculate mean f_B's of 0.14 ± 0.03, 0.29 ± 0.05. Thus, galaxies in FR II groups tend to have a larger fraction of blue members than FR I groups.

However, these numbers may be misleading, because, as demonstrated by AEZO, the fraction of blue galaxies in groups depends on both the richness of the group and the epoch of observation. At low redshifts, rich groups tend to have relatively fewer blue galaxies than poor groups; however, at high redshifts ($z \sim 0.4$), some rich groups may also have a relatively large fraction of blue galaxies. Therefore, we select only those low-redshift FR I and FR II groups that have richnesses in the range $N_{0.5}^{-19} = 4$–20. For those subsets of FR I and FR II groups, the mean f_B's are 0.15 ± 0.04 and 0.30 ± 0.06, respectively. Evidently FR I groups have relatively more red and fewer blue group members than FR II groups.

3.2.5. *The Location of the Radio Galaxy within Its Group*

Determining whether the radio galaxy is at the bottom of the potential well of the group is particularly interesting for radio galaxies because something must provide the fuel for the engine that produces the radio luminosities. For rich clusters, the cluster centers have been estimated by either determining the means (or the medians) in the positions (in R.A. and decl.) or the peak in the density distributions (see, e.g., Dressler 1980; Beers & Tonry 1986; Beers & Geller 1983; Merrit 1984; Whitmore 1990); however, for poor clusters and groups, there is clearly a problem. Therefore, our aim is not to find the exact position of the bottom of the potential well (although that would be desirable) but, rather, to search for differences in the mean offset of the FR I and FR II galaxies from their "nominal" group centers. As we expect that the background contamination is equally severe for FR I and FR II groups, any difference in the mean offset is presumably real.

We employ a rather crude method. First, we calculate the mean in the position of all group members that lie within 0.35 Mpc of the radio galaxy. Following that, we use the same radius of 0.35 Mpc about this mean position to find the second guess of the nominal group center, and we repeat this procedure 2 more times. Clearly, this method has a bias because it initially assumes that the radio galaxy is, in fact, at the center of the group. However, should the radio galaxy not be exactly at the group center, one would expect to find a better guess of the nominal center after three iterations.

For nine FR I groups, the mean offset of the radio galaxy from the nominal group center is 11 ± 1 kpc, and for 16 FR II groups, this offset is 33 ± 7 kpc (the quoted errors are the offsets in the mean distances). Thus, the FR I galaxies appear to be relatively closer to the nominal group centers than the FR II galaxies.

3.2.6. *Close Neighbors and Galaxy Encounters*

Galaxy interactions have been widely proposed to be important in the radio galaxy phenomenon (see, e.g., Heckman et al. 1986), particularly in the initial triggering of the radio activity. To analyze the importance of galaxy interactions among FR I and FR II radio galaxies, we determine the distances of the nearest neighbors of the radio galaxies. Since galaxy interactions can still have an effect on the galaxy even a few $\times 10^8$ yr after the initial encounter, the proximity of the nearest neighbor may not be sufficient information to determine if there could have been an encounter. Therefore, we additionally use the structural information of the radio galaxy shapes that was derived in Paper I. We then define a galaxy to be "interacting" (or possibly interacting) if it has a neighbor at a projected distance of 50 kpc or less or if its surface brightness profiles are relatively more disturbed than would be expected for normal elliptical galaxies (see Paper I).

For the FR I radio galaxies we find that three of 13 (23%) are (or could be) interacting, and for FR II's, we find that 13 of 27 (48%) are (or could be) interacting. Although our method of defining a galaxy interaction may not be rigorous enough for some readers, it is important to stress that the same method was applied to FR I's and FR II's. Thus, we claim that approximately twice as many FR II's as FR I's may have been involved in galaxy encounters. Perhaps galaxy encounters with group members are relatively more frequent (and also more severe as claimed by Heckman et al.) for FR II galaxies than for FR I galaxies.

3.3. *The Evolution of Radio-selected Groups*

The CfA groups have redshifts ranging from 0.003 to 0.03. Clearly these redshifts are much lower than those of our low-redshift radio groups ($0.03 < z < 0.22$), let alone those of the high-redshift sample ($0.3 < z < 0.5$). Unfortunately, there is no good comparison sample of "normal" groups at higher redshifts, mostly because these are extremely difficult to find, even at low redshift. Therefore, we analyze the evolution of the radio-selected groups and extrapolate to the optically selected lower redshift groups whenever that is possible.

In general, as groups of galaxies evolve, the mean richness is expected to increase owing to infall of single galaxies toward the groups and owing to merging of individual groups. In addition, there may be a shift toward higher BM classes if the infalling galaxies have magnitudes that are intermediate between those of the first- and second-ranked galaxies. If, however, the group is relaxed and galaxy velocities are low, the first-ranked galaxy may grow due to galactic cannibalism, thus causing a shift toward lower BM classes. Below, we discuss if the radio groups show any of these trends and if they can be used to trace the evolution of groups in general.

3.3.1. *Is There a Connection between the Low-Redshift FR I and FR II Groups?*

Figure 13 displays the cumulative richness distributions of the low-redshift FR I and FR II groups. It is clear that the overall shapes of the distributions are very different. On average, the low-redshift FR I groups are much richer than the low-redshift FR II groups. The mean richnesses are $\langle N_{0.5}^{-19} \rangle_{\rm FR\,I} = 15.3 \pm 2.4$ and $\langle N_{0.5}^{-19} \rangle_{\rm FR\,II} = 5.8 \pm 1.1$, respectively. To quantify these differences, we subdivide the FR I and FR II groups into "very poor" ($N_{0.5}^{-19} < 3.5$), "poor" ($3.5 < N_{0.5}^{-19} < 10$), "intermediate" ($10 < N_{0.5}^{-19} < 20$), and "rich" ($N_{0.5}^{-19} > 20$) groups. Table 6 lists the number of groups within each richness class. There are about 5 times as many very poor FR II groups than FR I groups, and there are many more rich FR I groups than rich FR II groups. In fact, at low redshifts, there are no rich FR II groups at all.

The BM distributions of the low-redshift FR I groups and the low-redshift FR II groups are also different. This is displayed in Table 7. For the low-redshift FR I groups, the

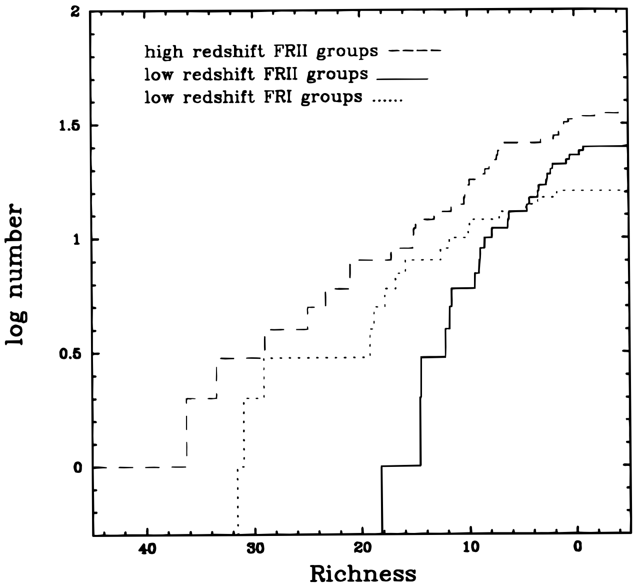

FIG. 13.—Cumulative richness distributions of low-redshift FR I groups (*dashed line*), low-redshift FR II groups (*solid line*), and high-redshift FR II groups (*dotted line*). In each case we count the number of groups, $N(N_{0.5}^{-19})$, that are richer than $N_{0.5}^{-19}$. Note that all richness distributions are different.

BM ratio is 53:33:13, and for the low-redshift FR II groups, it is 14:43:43. While the errors in these ratios are ± 5 for the FR I and ± 3 for the FR II groups, the overall trends are nevertheless clear: low-redshift FR I groups are preferentially of BM type I, while low-redshift FR II groups are preferentially of BM type III.

Evidently, the distributions in group richness and in BM class are both different for the low-redshift FR I and FR II groups. Thus, the environments of FR I and FR II radio sources at are different. FR I radio galaxies inhabit rich BM type I groups, while FR II radio galaxies inhabit poorer BM type III clusters.

3.3.2. *Is There a Connection between the Low- and the High-Redshift FR II Groups?*

The richness distributions of the high- and the low-redshift FR II groups (Fig. 13) are different. Apparently, the low-redshift FR II galaxies avoid rich groups totally, while they do exist in rich groups at higher redshifts. The mean richnesses of our high- and low-redshift FR II groups are 11.4 ± 2.1 and 5.8 ± 1.1, respectively, which makes the high-redshift FR II groups 2.0 ± 0.3 times as rich as the low-redshift FR II groups. This result is in agrement with that of Hill & Lilly (1991) whose ratio is 2.3. The main trend is clear: High-redshift FR II groups are about twice as rich as their lower redshift counterparts. Since the FR II groups cannot halve their richness as they evolve, the high- and low-redshift FR II groups must be different subsets of groups.

The implication of the result that the high-redshift FR II groups cannot evolve into low-redshift FR II groups is that FR II radio phenomenon must be relatively short lived. This is discussed in § 4.3.

As an aside, we note that our sample of radio galaxies is affected by the "artificial" radio power redshift relationship

TABLE 6

RICHNESS CLASSES OF HIGH- AND LOW-REDSHIFT FR I AND FR II GROUPS

Subset[a]	Total (Number)	Very Poor ($N < 3.5$) (percent)	Poor ($3.5 \rightarrow 10$) (percent)	Interm ($10 \rightarrow 20$) (percent)	Rich $N > 20$ (percent)	Mean	Scatter
FR I low-redshift[a,b]	17	6	23	47	23	15.3 ± 2.1	9.3
FR I high-redshift[a]	2	0	100	0	0	6.0 ± 2.0	2.8
FR II low-redshift[a]	29	41	35	24	0	5.8 ± 1.0	5.6
FR II high-redshift[a]	36	22	37	24	17	11.4 ± 2.1[d]	12.6
FR II low-power[c]	20	40	27	33	0	7.6 ± 1.6	7.4
FR II high-power[c]	45	26	31	24	9	9.7 ± 2.0	13.3

[a] High-redshift and low-redshift sources separated at $z = 0.25$.
[b] Contains 3C 433 and 3C 196.1, which have an amorphous radio structure and PKS 1928−340 and PKS 2130−538, which are most likely FR I sources.
[c] Powerful and less powerful sources separated at the break in the radio luminosity function ($P_{408\ \mathrm{MHz}} = 10^{26.6}$ W Hz^{-1}.
[d] Excluding the richest group (4C 29.44), the mean richness is 9.8 ± 1.5.

TABLE 7

BM CATEGORIES FOR FR I, FR II, AND OPTICALLY SELECTED GROUPS AND CLUSTERS

Group/Cluster	Total	BM I	BM II	BM III
Optically selected groups (with CfA-E)[a]	253	28	74	147
Optically selected groups (without CfA)[a]	190	25	59	106
cD-selected clusters	79	27	40	12
Radio groups—low-redshift	52	19	22	11
Radio groups—high-redshift	27	7	8	12
FR I groups—low-redshift[b]	15	8	5	2
FR II groups—low-redshift	21	3	9	9
FR II groups—high-redshift	18	5	6	7

[a] A combination of SKW, HGT, and CfA groups whose first-ranked galaxy is an elliptical.
[b] Contains 3C 433 and 3C 196.1, which have an amorphous radio structure and PKS 1928−340 and PKS 2130−538, which are most likely FR I sources.

(it is basically due to the fact that radio source catalogs are flux limited, and thus we are successively missing faint sources as we go to higher and higher redshifts). Consequently, it is necessary to test if the lower *redshift* FR II's avoid rich groups or if the lower *power* FR II's avoid rich groups. Thus, we subdivide the FR II's into powerful and less powerful, high- and low-redshift sources. We take the dividing line in the radio power to be at the position of the break in the radio luminosity function (at $P_{408\ \mathrm{MHz}} = 10^{26.6}$ W Hz^{-1}). The mean richnesses for groups that harbor powerful and less powerful FR II radio galaxies are 9.7 ± 2.0 and 7.6 ± 1.6, respectively. Since the difference between the high- and the low-redshift FR II groups is more pronounced than that between the high- and the low-power FR II groups, we consider the division according to redshift to be more significant. Therefore, we conclude that it is the low-redshift (as opposed to lower power) FR II's that avoid rich groups. The fact that the lower redshift FR II's are also on average less powerful than the high-redshift FR II's is, in this case, secondary.

In § 3.2.1 we found that the richness distribution of the FR II groups closely resembles that of the optically selected CfA groups. However, since the richness distributions of the high- and the low-redshift FR II groups are very different, it seems almost accidental that the overall richness distribution of the FR II groups should resemble that of the CfA groups.

3.3.3. *Is There a Connection between the Low-Redshift FR I and the High-Redshift FR I Groups?*

Unfortunately, our sample of high-redshift FR I groups is too small (altogether two groups) to analyze this issue. However, here, we would like to restate a result from Paper I, namely that all of the known most powerful FR I sources are at low redshifts. Although our data suffer from the "artificial" radio power–redshift correlation (a selection effect, because we can measure radio emission of distant sources only if their fluxes are above the detection limit of the radio telescopes), it is clear that there are fewer (or no) powerful FR I sources at higher redshifts. Although weaker FR I sources may well exist at earlier epochs, there is a lack of the most powerful ones (with $P_{408\ \mathrm{MHz}} > 10^{26.5}$ W Hz^{-1}). This suggests that there is strong evolution. However, this evolution is not in the group properties but, rather, reflects a property of the FR I radio phenomenon.

3.3.4. *Is There a Connection between the Low-Redshift FR I and the High-Redshift FR II Groups?*

It has often been proposed that there may be an evolution among the FR I and FR II galaxies themselves. Theoretical models have been constructed (see, e.g., Williams & Gull 1984; Bridle & Perley 1984; Bicknell 1984, 1986; Rawlings & Saunders 1991; Gopal-Krishna & Wiita 1991; De Young 1993) where the radio morphology (the FR type) depends on the interplay between the jet thrust energy and the density of the ISM though which the jets penetrate. If the jet thrust energies are relatively low and/or the density of the ambient medium is relatively high, the jets will become entrained, diffuse, and lose their energy to the surroundings, thus producing a FR I morphology. On the other hand, if the jet thrust energies are relatively high and/or the density of the ambient medium is relatively low, the jets will advance until they are stopped by the impact on the intergalactic medium, thus giving rise to the edge-brightened FR II radio morphology. Thus, as the radio activity of the AGN declines, one may potentially turn a FR II source into a FR I source.

With our data set, we can test the validity of this scenario. If the high-redshift FR II galaxies could evolve into low-redshift FR I galaxies, their group properties ought to be consistent with this possibility. One would expect to see a slight increase in group richness and a slight shift toward lower BM classes. In Table 6 and Figure 13, we see that the group richnesses are comparable ($\langle N_{0.5}^{-19} \rangle_{\mathrm{FR\ I}} = 15.3 \pm 2.1$ and $\langle N_{0.5}^{-19} \rangle_{\mathrm{FR\ II}} = 11.4 \pm 2.1$); however, the Bautz-Morgan distributions are very different. Most high-redshift rich groups are of BM type III, while most low-redshift rich groups are of BM type I. The BM ratios of the high-redshift FR II and the low-redshift FR I groups are 53:33:13 and 26:30:44, respectively. Since it makes no sense that the group richness should remain constant while the BM types evolve toward lower BM classes, the high-redshift FR II groups do not evolve into the low-redshift FR I groups. This also implies that FR II galaxies cannot evolve into FR I galaxies.

3.3.5. *Is There a Connection between the Optically Selected and Radio-selected Groups?*

We have shown that each subset of radio-selected groups (the high- and low-redshift FR I and FR II groups) has its unique distributions in group richness and BM class. Also all of the subclasses radio-selected groups are different from normal groups. The low-redshift FR I groups are richer than normal groups and preferentially of BM type I, the low-redshift FR II groups are poorer than normal groups, and the high-redshift FR II groups are slightly richer than normal groups and of lower BM class. Thus, none of the subsets of radio-selected groups can be used to study the general evolution in group richness and BM class; however, they may be used for other purposes, as will be explained in § 4.2.

4. DISCUSSION

4.1. *From What Subset of Groups are Radio-selected Groups Drawn?*

One of our main conclusions is that radio-selected groups are a special subset of groups in general. Moreover, radio-selected groups in themselves are a rather heterogeneous set of groups. In particular, FR I and FR II groups at high and at low redshifts are different from each other. Below, we describe the subsets of groups from which each of these groups are drawn.

FR I groups are on average richer than optically selected groups, and they are preferentially of BM type I as opposed to BM type III. In Paper I we found that the first-ranked galaxy of about $\frac{2}{3}$ of all FR I groups is a cD-like galaxy or a double nuclei galaxy. Thus, for the FR I's, a consistent picture emerges, in which (as described below) the FR I galaxy corresponds to the centrally dominant galaxy in relaxed groups in which galactic cannibalism is occurring.

Generally, it is believed that the initially dominant first-ranked galaxies may cannibalize intergalactic material or smaller galaxies (see, e.g., Sandage & Hardy 1973; Ostriker & Tremaine 1975; Hausman & Ostriker 1978), thus enlarging the gap between the first-ranked galaxies and other group members. In addition to increasing the magnitudes of the first-ranked galaxies, one would expect their size to grow, thus giving rise to a cD morphology. Evidence for this scenario is provided by Hoessel (1980) and Schombert (1987, 1988) who showed that cD galaxies have shallower surface brightness profiles than equally bright elliptical galaxies and also extended envelopes. In Paper I we have shown that radio-loud cD galaxies have on average shallower surface brightness profiles than radio-quiet cD galaxies. In this paper we have additionally shown that groups that harbor FR I galaxies tend to be more often of BM type I than groups that harbor radio-quiet cD galaxies. Thus, if the first-ranked galaxy indeed grows owing to galactic cannibalism, there is an indication that this happens to a larger degree in FR I groups than in other types of groups, even if they already harbor a cD galaxy.

We have also shown that FR I groups possess relatively fewer blue group members than FR II groups or normal groups. This suggests that star formation in galaxies in FR I groups has ceased some time ago. Either those galaxies are genuinely old or their gas has been stripped efficiently. In either case, together with the above information, it implies that the majority of FR I groups are dynamically relatively evolved. Thus, groups that harbor powerful FR I galaxies are likely to belong to the most evolved systems in the universe.

FR II groups are rather different from FR I groups. In addition, in Paper I we have shown that the host galaxies of FR I and FR II sources are different. Unlike the FR I sources, FR II sources avoid cD-like or double nuclei host galaxies. Instead, many of them are associated either with N galaxies or disturbed elliptical-like galaxies. Also, compared to FR I galaxies, about twice as many of the FR II galaxies may be or may have been involved in a galaxy encounter. The diversity seen among the colors and color gradients of FR II galaxies also supports this picture (although the colors of FR II galaxies may also be, in part, affected by the nuclear activity as will be shown in Paper IV). Furthermore, FR II groups have relatively more blue members than FR I or optically selected groups. Put together, this suggests that galaxy encounters are common in FR II groups. Thus, FR II groups are dynamically less evolved than FR I groups and probably belong to the most unevolved systems in the universe.

At high redshifts, FR II galaxies are more often found in richer groups. Since the group richness can increase only as the groups evolve, FR II groups at high and low redshifts belong to different subsets of groups. If it is true that FR II galaxies always prefer dynamically unevolved systems, one may speculate that the richer groups at high redshifts are relatively unevolved. Furthermore, since there are no FR II's in rich systems at low redshift, the low-redshift rich groups might be too evolved to harbor FR II galaxies. Thus, rich groups at high redshifts might be dynamically less evolved than equally rich groups at low redshifts. Indeed, the rich FR II groups at high redshifts have a higher fraction of blue members than other equally rich groups at lower redshifts. Thus, perhaps, FR II's at any redshift tend to inhabit only dynamically relatively unevolved systems and, in particular, systems where galaxy encounters are common.

So, how representative are radio-selected groups of normal groups? The main conclusion from this work is that radio-selected groups are a special subset of normal groups. However, radio-selected groups themselves are a rather heterogeneous set of groups because FR I and FR II groups at high and low redshifts have different sets of properties. In summary, we propose that FR I groups are drawn from the subset of normal groups that are dynamically evolved and that FR II groups are drawn from the subset of normal groups that are relatively unevolved.

4.2. *Can We Use Radio Groups to Study the General Evolution of Galaxies in Groups?*

Although radio-selected groups are different from normal groups, we might still be able to use them to study the general evolution of galaxies in groups. However, this is clearly only possible if the radio activity of the radio sources does not affect the properties of group members. To test this, we correlate the magnitudes and colors of group members and the richness and Bautz-Morgan class of radio-selected groups to the radio activity of the radio sources.

Perhaps the best method of quantifying the magnitude distributions of galaxies in groups is by fitting those distributions with a Schechter function (Schechter 1976) and determining the parameters M^* and α. However, since individual radio-selected groups are rather poor, M^* and also α are rather noisy, and thus this method is not applicable. Instead, we express the magnitude distributions of group members in terms of the mean magnitude of the second- and third-ranked galaxies (this is still more accurate than using the magnitude of only the second- or third-ranked galaxy). Figure 14 shows the correlation of this magnitude with the radio power. For both the FR I and FR II groups, there is no correlation. Thus, the magnitudes of members of radio-selected groups are not affected by the activity of the radio source.

As before, we express the colors of group members in terms of the fraction of blue galaxies. Figure 15 shows the correlation of the fraction of blue galaxies with the radio activity of the radio sources. Again, there is no correlation for neither of the two FR types. Thus, the colors of group members are not affected by the activity of the radio source.

Figure 16 shows the correlation between the Bautz-Morgan classes of radio-selected groups and the radio

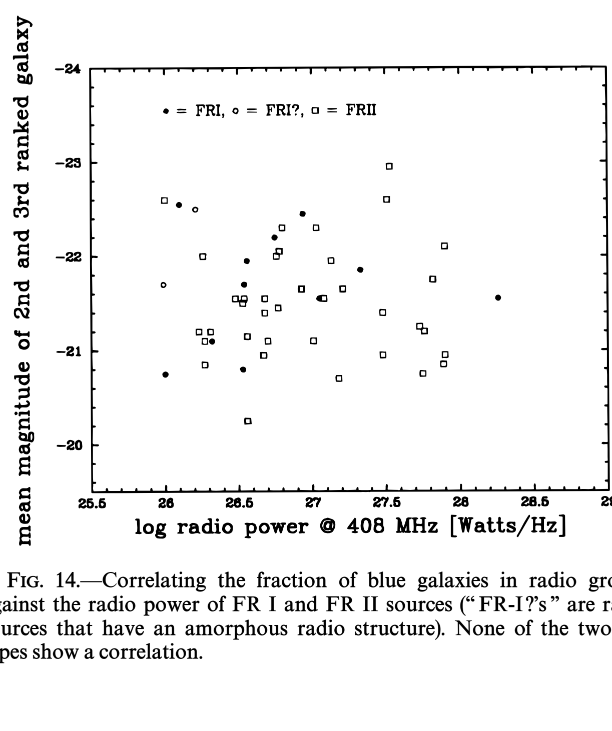

FIG. 14.—Correlating the fraction of blue galaxies in radio groups against the radio power of FR I and FR II sources ("FR-I?'s" are radio sources that have an amorphous radio structure). None of the two FR types show a correlation.

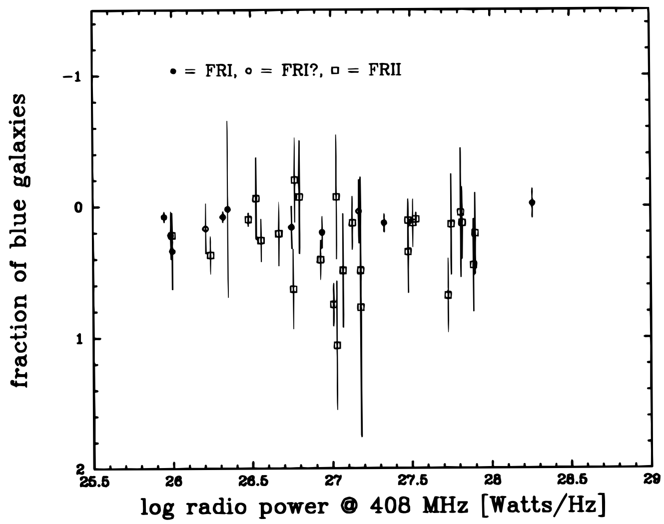

FIG. 15.—Correlating the average magnitude of the second- and third-ranked galaxy of radio groups against the radio power of FR I and FR II sources ("FR I?'s" are radio sources that have an amorphous radio structure). None of the FR type show any correlation.

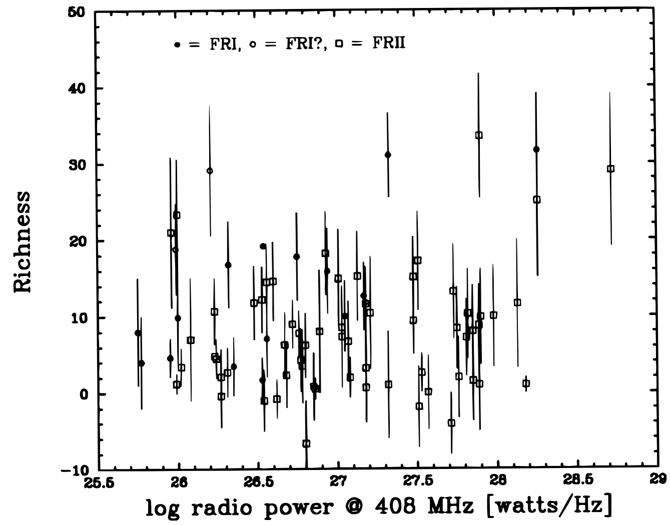

FIG. 17.—Correlating the group richness of radio groups against the radio power of FR I and FR II sources ("FR I?'s" are radio sources that have an amorphous radio structure). FR II groups show no correlation; however, for the FR I groups, there is a weak correlation (at the 2.5 σ level) in the sense that there are no powerful FR I sources in poor groups.

activity. Again, there are no clear correlations for FR I or FR II groups. Therefore, the BM classes of the radio groups are also unaffected by the radio activity.

Figure 17 shows the correlation of group richness with radio power. For the FR II galaxies, we find no correlation, but the FR I's show a weak correlation (at the 2.5 σ level). However, the latter correlation disappears if Ledlow's (1994) and Ball et al.'s (1993) samples are included. Although their radio galaxies inhabit richer environments, they are on average less powerful than ours. Thus, the radio activity does not affect (as expected) the richness of the group.

So, can we use radio-selected groups to study the evolution of galaxies in groups? Since the radio phenomenon itself does not seem to have an effect on the properties of other group members (or on global group properties), there is no reason that radio-selected groups should not be used for this purpose. However, we do have to remember that they are a special subset of groups in general. While this does not make them unsuitable for this purpose (provided we understand the selection criterion), it provides us with additional information that can be used positively. For example, we can use the finding that FR I groups are dynamically more evolved and FR II groups less evolved than normal groups to select groups in certain evolutionary stages.

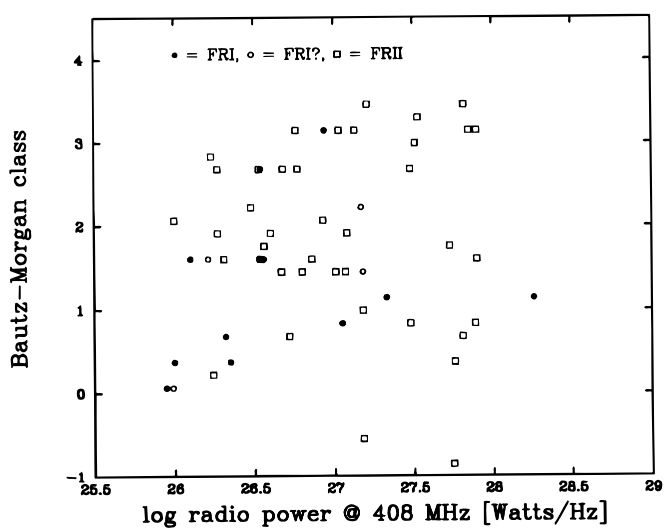

FIG. 16.—Correlating the BM class of radio groups against the radio power of FR I and FR II sources ("FR I?'s" are radio sources that have an amorphous radio structure). None of the two FR types show a correlation.

4.3. *What Do We Learn about the Radio Phenomenon from This Work?*

FR I and FR II radio sources differ in many ways. In Paper I, Paper II, we have shown that their host galaxies have different properties, and here we have shown that their large-scale environments are also different. Note that further differences are found among their far-IR properties (see, e.g., Heckman et al. 1994), their optical emission lines (see, e.g., Zirbel & Baum 1995), their UV properties (Zirbel & Baum 1997a, 1997b), the kinematics within their host galaxies (see, e.g., Smith et al. 1992; Baum et al. 1992), and perhaps even their nuclear engines (Baum, et al. 1995). Below, we list only those environmental and the host galaxy properties of FR I and FR II sources that were discussed in Paper I, Paper II, and this paper. The description of a more complete picture is left to Paper IV.

4.3.1. *FR I's*

1. Powerful FR I radio galaxies (with $P_{408\,\mathrm{MHz}} > 10^{26}$ W Hz^{-1}) are predominantly found at low redshifts (with $z < 0.3$).

2. About $\frac{2}{3}$ of the FR I sources are associated with cD, D, or double nuclei galaxies.

3. FR I galaxies are on average optically larger than radio-quiet ellipticals of the same magnitude. Even FR I cD galaxies are larger than radio-quiet cDs.

4. FR I galaxies show a correlation of the "excess" size (by how much bigger they are relative to radio-quiet ellip-

tical galaxies) with radio power. More powerful FR I's are progressively larger.

5. Powerful FR I galaxies are the first-ranked galaxies in their groups, although this may be different for weaker FR I galaxies.

6. There is some evidence that the FR I galaxy is relatively close to the bottom of the potential well of the group.

7. FR I galaxies are on average found in richer groups than radio-quiet first-ranked galaxies.

8. FR I galaxies prefer BM type I groups, while radio-quiet first-ranked galaxies prefer BM type III groups.

9. The group members of FR I groups tend to have relatively red colors.

Putting it all together, a consistent picture emerges for the FR I radio galaxies. Most often, they correspond to the centrally dominant cD galaxy in rich BM type I groups. In these types of environments, galactic cannibalism is thought to be common. In addition, since the optical sizes of FR I galaxies are larger than those of radio-quiet ellipticals, and, in particular, since FR I cD galaxies are larger than those of radio-quiet cD galaxies, FR I galaxies may have been exposed to a relatively larger degree of galactic cannibalism than normal cD galaxies. This is furthermore supported by the finding that relatively more FR I's reside in BM type I groups than normal cD galaxies. Since it is generally believed that groups surrounding cD galaxies are relatively evolved, we suggest that groups surrounding FR I cD galaxies are even more evolved. The colors of groups members of FR I groups also support this picture, since they are mostly red, and thus relatively old. Since powerful FR I sources are found predominantly at low redshifts, we speculate that FR I sources form mostly in dynamically relatively evolved groups that already harbor cD galaxies.

It has been suggested in the literature (see, e.g., Heckman et al. 1989; Burns 1990; Baum et al. 1992) that powerful FR I sources can be associated with cooling flow galaxies. In fact, there also appears to be a similarity in environments of cooling flow galaxies and the FR I galaxies in this analysis. Cooling flows are often associated with centrally dominant galaxies in relaxed rich clusters (see, e.g., Cowie & Binney 1977; Fabian & Nelson 1977) in which the gas can cool in less than a Hubble time and flow quasi-hydrostatically onto the elliptical of cD galaxy that sits at the bottom of the potential well of the cluster. However, some cooling flows have also been observed in poorer environments and even in isolated elliptical galaxies (Canizares, Steward, & Fabian 1983; Sarazin 1986), but these are generally giant elliptical galaxies that are comparable to brightest cluster members. Some of the classical examples of cooling flow radio galaxies are NGC 1275, 3C 218, 3C 317, and PKS 2322−123, of which the latter three are also within our sample. Thus, the results presented in this paper are consistent with FR I galaxies being cooling flow galaxies. If this scenario is correct, it provides a means of supplying the fuel that can power the engine of the FR I's

For less powerful FR I sources (with powers below the break in the radio luminosity function) the picture may be rather different. For example, lower power FR I sources do not always correspond to the first ranked galaxy (see, e.g., Ledlow 1994), and they may not always be in the center of the group. Also, deep CCD images of some of the less powerful FR I galaxies (see, e.g., Heckman et al. 1986; Baum et al. 1988) reveal evidence for violent galaxy interactions. Since cooling flows would be disrupted during violent galaxy encounters, this picture is probably not applicable to lower power FR I galaxies. Thus, it is possible that powerful and less powerful FR I sources are drawn from different subsets of galaxies and, furthermore, that they may even be different types of radio galaxies.

4.3.2. *FR II's*

1. The host galaxies of FR II sources are either N galaxies or elliptical galaxies or disturbed elliptical galaxies (whose surface brightness profiles are relatively noisier than those of radio-quiet elliptical galaxies). None of the host galaxies are cD-like or double nuclei galaxies.

2. Although the sizes of the host galaxies of FR II's are not as large as those of FR I's, they are still larger than normal elliptical galaxies.

3. The rank of the FR II galaxy within its group is important, although at higher redshifts, second-ranked galaxies may also become FR II sources.

4. FR II sources avoid rich groups at low redshifts, but they do exist in rich groups at higher redshifts.

5. On average, many group members of FR II groups have blue colors.

Compared to FR I radio galaxies, FR II galaxies prefer BM type III rather than BM type I groups. Unlike the FR I sources, FR II sources are not associated with cD galaxies; instead, in about half of the cases, the surface brightness profiles of FR II galaxies show strong disturbances. About one-quarter of the FR II galaxies have blue colors. Since group members of FR II groups also often have blue colors, galaxy interactions may be common. In addition, since the radio luminosity of FR II galaxies that are (or may be) interacting is about 4 times higher than in other FR II's (discussed in more detail in Paper II), it appears that galaxy encounters enhance the radio activity and perhaps also trigger it.

Since FR II's are found in different environments at high and at low redshifts and since the high-redshift FR II groups, as a whole, cannot evolve into low-redshift FR II groups, it implies that the conditions for forming FR II sources have changed with epoch. Furthermore, it implies that the FR II radio phenomenon must be relatively short lived (in the order of a few $\times 10^8$ yrs or less). This is discussed more in Paper IV.

In summary, powerful FR I and FR II sources are associated with different types of host galaxies, are found in different types of groups, and live at different epochs. FR I sources are associated with centrally dominant galaxies in dynamically evolved (low-redshift) systems, while FR II sources are more often associated with galaxy encounters. Finally, we speculate that the cause of the radio activity may also be different, the FR I's perhaps being fueled by cooling flows and the FR II's by galaxy encounters.

5. SUMMARY

In this paper, we have studied the large-scale environments of powerful ($P_{408\,\mathrm{MHz}} > 10^{26}$ W Hz^{-1}) radio galaxies over a range of redshifts (up to $z \sim 0.5$). Our goal was twofold: (1) to analyze the properties of radio-selected groups and determine how they differ from normal (i.e., optically selected) groups and (2) to determine those environmental properties of radio galaxies that distinguish them from other galaxies and that may affect or even give rise to the radio activity. We find the following:

1. Properties of radio-selected groups:

a. Groups that harbor powerful radio galaxies are very rare objects. Approximately one in 1000 groups harbor a radio galaxy which is more powerful than 10^{26} W Hz^{-1}.

b. Most radio galaxies are in poor groups that have three to 10 members, although some are in richer groups. The mean richness, $\langle N_{0.5}^{-19} \rangle$, is 8.6 ± 0.9. There is a possibility that up to 5% of all radio galaxies are field galaxies (and up to 13% are pairs), although our result is consistent with all radio galaxies being in groups.

c. At low redshifts, the radio galaxies are the first-ranked galaxies in $99\% \pm 1\%$ of all groups, and at high redshifts, only in $79\% \pm 8\%$. However, even at high redshifts, the rank of the radio galaxy is still relatively important.

d. Radio-selected groups display the same distributions in group richness as optically selected groups; however, poor radio-selected groups (with $N_{0.5}^{-19} < 15$) are about 1.5 times less abundant.

e. The distributions of the Bautz-Morgan classes are different for radio- and optically selected groups. Radio-selected groups are preferentially of Bautz-Morgan type I, while optically selected groups are preferentially of Bautz-Morgan types III.

f. The radio characteristics of the radio galaxies do not affect the properties of their group members. Thus, although radio-selected groups have different properties than normal groups, they can still be used to study the evolution of galaxies in groups.

2. Environmental properties of FR I and FR II galaxies:

a. FR I groups are on average richer than FR II groups. There are relatively more FR I's in rich groups and relatively less in the poorest groups.

b. FR II galaxies avoid rich groups at low redshifts, but they do exist in rich groups at high redshifts. This result does not prove an evolution in group richness; rather it implies that FR II galaxies inhabit different types of environments at high and at low redshifts.

c. Most FR II groups are of Bautz-Morgan class III, while most FR I groups are of Bautz-Morgan class I. Compared to optically selected groups, the distributions among the BM classes are very different for FR I groups but are comparable for FR II groups, although BM type III FR II groups are still relatively under abundant.

d. Groups surrounding powerful FR I's are more often of BM type I than groups surrounding less powerful radio cD galaxies which in turn are more often of BM type I than those surrounding radio-quiet cD galaxies.

e. FR I groups tend to have relatively fewer blue group members than FR II groups.

f. The magnitude distributions of group members of FR I and FR II groups seem to be comparable, although there is an indication that there may be differences among faint group members.

g. The FR I radio galaxies appear to be relatively closer to the nominal group centers than the FR II radio galaxies.

h. About twice as many FR II galaxies as FR I galaxies show either signatures of galaxy interactions and/or have a neighbor within 50 kpc.

Finally, together with the results presented in Paper I, we argue that FR I sources are associated with centrally dominant galaxies in dynamically evolved systems, while the FR II sources are more often associated with galaxy interactions.

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APPENDIX

This Appendix presents the final sample of radio sources, including galaxy names, redshifts, radio powers, absolute V magnitudes, colors, environmental properties, and radio morphology classifications in Table A1, Table A2, and Table A3.

TABLE A1

LOW-REDSHIFT DATA: DERIVED VALUES

Name (1)	z (2)	M_{V87} (3)	log P_{408} (4)	Richness (5)	$M_{rg} - M_{2nd}$ (6)	BM Class (7)	FR Type (8)	Class (9)	Neighbor (10)
3C 15	0.073	−22.95	26.35	3.5 ± 3.8[a]	2.00	I	I	E	Iso
3C 17	0.220	−22.40[b]	27.48	9.4 ± 4.3[b, c]	0.50	III	II	dE	Pin
3C 18	0.188	−23.46	27.26	−0.7 ± 0.0	...	...	...	N	Iso
3C 26	0.210	−22.53	27.10	−1.9 ± 3.6	0.80	II	...	dE	Iso
3C 29	0.045	−23.15	25.95	4.6 ± 2.5[a]	2.20	I	I	S0?	Iso
3C 33	0.060	−22.41	26.67	6.3 ± 4.2	1.30	II	IIg	E	Iso
3C 63	0.175	−22.75	27.18	11.6 ± 4.3	1.60	I	II	dE	Pin
3C 89	0.139	−23.25	26.94	15.9 ± 5.5	0.20	III	I	S0?	Iso
3C 98	0.031	−21.95	26.02	3.4 ± 2.4[a]	3.10	...	IId	E	Iso
3C 105	0.089	−21.74[d]	26.60	14.6 ± 5.1[a, b, d]	1.00	II	IId	E	Iso
3C 135	0.127	−22.47	26.80	−6.7 ± 5.6	...	...	II	N	Int
3C 184.1	0.118	−22.20[b]	26.68	2.3 ± 4.2	0.50	III	II	N	Iso
3C 196.1	0.198	−23.32[b]	27.18	11.8 ± 4.6[b, c]	1.30	I	AM	cD	Pin
3C 198	0.082	−21.70	26.23	10.7 ± 4.3[a, b, c]	0.40	III	IIn	dE	Iso
3C 218	0.065	−23.46	27.33	31.0 ± 5.5	1.50	I	I	db	Int
3C 223.1	0.108	−22.67	26.31	2.7 ± 3.2	1.20	II	II	S0?	Iso
3C 223	0.137	−22.58	26.85	0.8 ± 4.4	3.20	...	II	S0?	Iso
3C 225A[4]	...	...	...	...	1.50	I	II	S0?	Iso
3C 227	0.086	−22.20	26.77	4.3 ± 4.1	0.50	III	IIg	N	Iso
3C 236	0.099	−22.80	26.62	−0.8 ± 2.5	...	...	IId	E	Iso
3C 258	0.165	−20.75	26.27	...	...	...	...	S0?	Iso
3C 277.3	0.086	−22.55	26.27	−0.4 ± 4.1	1.00	II	II	E	Iso
3C 287.1	0.216	−22.69[b]	27.08	2.0 ± 2.6[b, c]	1.00	II	II	dE	Int
3C 303	0.141	−22.43	26.76	7.8 ± 2.9	0.20	III	II	N?	Int
3C 310	0.054	−22.10	26.53	12.2 ± 4.3	0.50	III	IIn	C	Int
3C 314.1	0.120	−22.11	26.53	3.7 ± 2.9	1.20	II	I	E	Iso
3C 315	0.108	−22.42	26.54	19.2 ± 0.0	0.50	III	I	db	Int
3C 317	0.035	−23.13	26.10	11.7 ± 4.2	1.20	II	I	db	Int
3C 326	0.090	...	26.23	4.8 ± 4.0[a, b, c]	...	...	II	...	Iso
3C 332	0.152	−22.95	26.80	6.2 ± 4.2	1.30	I	II	dE	Int
3C 346	0.161	−23.39[b]	27.05	10.0 ± 4.6[b, c]	1.70	I	I	cD	Iso
3C 348	0.154	−23.27	28.26	31.6 ± 7.4	1.50	I	I	cD	Iso
3C 353	0.030	−20.65[d]	26.72	9.0 ± 3.1[d]	1.80	I	II	E	Iso
3C 381	0.161	−22.83	27.03	8.5 ± 5.3	0.20	III	II	N	Int
3C 390.3	0.056	−22.35	26.56	14.5 ± 4.9	1.10	II	IId	N	Iso
3C 424	0.127	−21.88	26.75	17.8 ± 5.7	0.80	II	I	dE	Iso
3C 433	0.102	−22.92	27.17	12.6 ± 4.4	0.80	II	AM	db	Int
3C 445	0.056	−22.18	26.24	4.5 ± 2.5	2.10	I	IId	N	Iso
3C 452	0.081	−22.63	26.93	18.2 ± 5.4	0.90	II	IId	dE	Pin
3C 459	0.220	−23.18	27.53	2.6 ± 2.5	3.10	...	II	N	Int
4C 02.39	0.066	−20.80[b]	26.63	9.3 ± 3.4[a, c]	1.70	I	...	dE	Iso
4C 03.72	0.192	−22.83	0.00	...	1.90	I	...	cD	Int
4C 04.17	0.118	−22.99	26.12	−1.9 ± 3.5	2.20	I	...	E	Iso
4C 05.57	0.133	−22.89[b]	26.56	4.8 ± 2.7[a, c]	2.10	I	...	N	Iso
4C 12.50	0.122	−23.55	26.72	2.5 ± 3.8[2]	0.00	III	...	dE	Int
4C 14.36	0.215	−22.84[b]	26.72	0.2 ± 2.0[a, c]	...	...	...	dE	Iso
4C 20.20	0.168	−23.49[b]	26.56	7.1 ± 5.0[a, c]	1.20	II	I	dE	Iso
4C 20.25	0.132	−23.82[b]	25.99	1.2 ± 1.3[a, c]	4.20	...	II	N	Iso
4C 23.00	0.133	−20.0[e]	26.08	3.0 ± 4.4	...	...	...	C	Iso
4C 39.11	0.161	−23.75	26.78	3.5 ± 4.8	3.00	...	II	N	Iso
5C 3.100	0.071	−23.01	24.02	3.9 ± 3.6	1.50	I	...	S0?	Iso
5C 3.175	0.134	−22.37	24.46	13.8 ± 5.0	0.70	III	...	W	Int
PKS 0043−014	0.053	−21.80	26.27	2.1 ± 3.6	0.50	III	IIg	E	Int
PKS 0114−476	0.146	−23.54	26.86	0.0 ± 2.7	...	...	...	cD	Iso
PKS 0211−479	0.220	−23.20	26.92	3.3 ± 0.0	2.60	...	...	cD	Int
PKS 0214−480	0.064	−23.40	26.00	9.9 ± 6.2	2.00	I	I	E	Iso
PKS 0349−278	0.066	−22.50	26.48	11.8 ± 4.8	0.80	II	IId	cD	Int
PKS 0518−458	0.035	−21.21	26.86	0.5 ± 1.4	1.20	II	IId	N	Int
PKS 0521−365	0.061	−23.03	26.64	1.5 ± 5.0	2.60	...	I[e]	N[e]	Int
PKS 0604−203	0.164	−22.60[b]	26.97	−2.1 ± 1.6[a, c]	2.30	...	...	C	...
PKS 0719−553	0.216	−23.18	27.12	7.0 ± 5.0	2.20	I	...	cD	Iso

TABLE A1—*Continued*

Name (1)	z (2)	M_{V87} (3)	log P_{408} (4)	Richness (5)	$M_{rg} - M_{2nd}$ (6)	BM Class (7)	FR Type (8)	Class (9)	Neighbor (10)
PKS 1214+038......	0.077	−22.98	25.90	14.5 ± 5.7	1.30	II	...	E	Iso
PKS 1215+039......	0.076	−23.23	26.26	22.2 ± 7.1	1.30	II	I?	cD	Int
PKS 1216−100......	0.087	−23.56[b]	26.43	8.7 ± 3.8[a,c]	3.70	...	...	dE	Iso
PKS 1331−009......	0.081	−22.78[b]	26.26	2.8 ± 1.8[a,c]	3.80	...	...	dE	Int
PKS 1417−192......	0.119	−23.59[b]	26.45	4.0 ± 5.6[a,c]	3.00	...	...	N	Iso
PKS 1928−340......	0.098	−23.63	26.21	29.1 ± 8.5	1.20	II	I?	cD	Iso
PKS 1934−638......	0.182	−22.38	26.92	−1.1 ± 6.2	...	...	...	dE	Int
PKS 2030−230......	0.132	−22.20	26.70	8.9 ± 4.9	1.00	II	...	dE	Pin
PKS 2130−538......	0.076	−23.79	25.99	18.8 ± 5.9	2.20	I	I?	db	Iso
PKS 2300−189......	0.129	−22.55	26.68	−3.5 ± 4.2	0.80	II	...	dE	Int
PKS 2322−123......	0.082	−23.21	26.32	16.8 ± 5.6	1.80	I	I	cD	Iso

Explanation of Columns.—Col. (1). Galaxy name. Col. (2). Galaxy redshift. Col. (3). Extinction-corrected absolute V magnitude. Col. (4). Logarithm of the radio power, measured in W Hz^{-1} at 408 MHz. Col. (5). Background-corrected group richness with standard poisson errors. Col. (6). Magnitude difference between first- and second-ranked galaxy: $M^* - M_{rg}$. A high value in ΔM corresponds to a low BM class. Col. (7). Bautz-Morgan class; no intermediate types. Col. (8). Faravoff-Riley types. Col. (9). Optical structural classification (see Paper I); E = elliptical, cD = cD-like, db = dumbell, N = N galaxy, dE = disturbed elliptical, S0? = elliptical with truncated halo, C = contaminated, W = weird. Col. (10). Displays whether the radio galaxy shows signs of galaxy interactions (Int), is isolated (Iso), or may be interacting (Pin).

Notes.—(a) Small area photometered. (b) Photometry errors 0.05–0.10 mag rather than 0.01–0.03 mag. (c) No color clipping in the evaluation of the group richnesses was performed. (d) Large reddening correction. (e) Magnitude obtained by fitting surface brightness profile.

TABLE A2

High-Redshift Data: Derived Values

Name (1)	z (2)	M_{V87} (3)	log P_{408} (4)	Richness (5)	$M_{rg} - M_{2nd}$ (6)	BM Class (7)	FR Type (8)
3C 16	0.4050	−22.24	27.53	13.2 ± 6.1	1.10	II	II
3C 42	0.3950	−22.54	27.71	−4.1 ± 4.0	...	...	II
3C 67	0.3100	−22.83	27.51	−1.9 ± 5.3	...	...	II
3C 109	0.3060	−24.04	27.76	2.0 ± 5.3	2.00	I	II
3C 299	0.3670	−22.81	27.75	8.4 ± 5.3	2.80	...	II
3C 306.1	0.4410	−22.88	27.89	8.8 ± 5.3	1.70	I	II
3C 313	0.4610	−22.61	28.13	11.6 ± 8.3[a]	1.10	II	IIg
3C 320	0.3420	−23.15	27.51	17.2 ± 6.4	0.30	III	II
3C 434	0.3220	−22.56	27.21	10.4 ± 7.3	0.00	III	II
3C 435	0.4710	−22.65	27.90	33.5 ± 8.1	0.20	III	II
3C 341	0.4480	−22.26	27.90	9.9 ± 6.2	1.20	II	IIg
3C 457	0.4280	−22.18	27.82	10.3 ± 5.8	0.00	III	II
4C 01.31	0.4300	−23.52	27.57	0.0 ± 4.8[a]	...	...	II
4C 17.71	0.3140	−22.85	27.29	−4.7 ± 5.1	0.05	III	...
4C 27.51	0.3190	−21.74	27.03	21.0 ± 6.8	0.10	III	D
4C 34.42	0.4020	−23.17	27.85	1.5 ± 5.2	0.20	III	II
4C 29.44	0.3290	−23.06	27.53	70.4 ± 9.1	0.10	III	II
4C 37.29A	0.3460	−22.59	27.48	15.1 ± 5.2	1.70	I	II
4C 62.22	0.4290	−21.96	27.62	9.1 ± 5.4[a]	0.80	II	U
5C 12.251............	0.3120	−23.06	27.36	36.3 ± 7.2	0.90	II	D
5C 6.1420............	0.4480	−23.19	26.00	23.3 ± 7.2	0.90	II	II
B2 0822+34	0.4060	−22.33	27.18	0.6 ± 4.5[a]	...	...	II
B2 0847+37	0.4070	−22.75	27.03	7.3 ± 6.6[a]	...	...	IId
B2 1025+39	0.3600	−23.07	27.81	7.2 ± 5.0	1.80	I	II
B2 1104+36	0.3930	−22.86	27.18	3.2 ± 4.2	2.60	...	IId
B2 1201+39	0.4450	−22.52	27.07	6.7 ± 5.2	1.30	II	IIg
B2 1245+34	0.4090	−22.50	27.01	14.9 ± 6.4[a]	1.30	II	IIg
B2 1603+32	0.3740	−22.68	26.51	4.1 ± 5.0	2.00	I	...
B2 2347+302	0.3740	−22.75	26.97	6.2 ± 4.9	...	...	D
PKS 0229+034......	0.2730	−22.49	...	3.5 ± 4.3	1.40	I	II
PKS 0337−216......	0.4140	−22.62	27.17	2.7 ± 4.5	3.00	...	...
PKS 2152−218......	0.3060	−21.85	27.43	0.5 ± 5.0	1.50	I	C
PKS 2159−187......	0.3320	−21.72	27.20	0.4 ± 5.9	0.60	III	...

Explanation of Columns.—Col. (1). Galaxy name. Col. (2). Galaxy redshift. Col. (3). Extinction-corrected absolute V magnitude. Col. (4). Logarithm of radio power, in W Hz^{-1} at 408 MHz. Col. (5). Background-corrected richness. Col. (6). Magnitude difference between first- and second-ranked galaxy. Col. (7). Bautz-Morgan class; no intermediate types. Col. (8). FR type (Fanaroff & Riley 1974).

Note.—(a) Significant correction to −19.0 completeness limit.

TABLE A3

RADIO GALAXIES FROM HILL & LILLY (1991) THAT DO NOT OVERLAP WITH OURS

Name (1)	z (2)	M_{V87} (3)	log $P_{408\ \mathrm{MHz}}$ (4)	Richness (5)	FR Type (6)
3C 200	0.4580	−22.56	27.89	1.0 ± 6.0	IId
3C 244.1	0.4280	−22.93	28.26	25.0 ± 9.9	IIn
3C 268.3	0.3710	−21.48	27.85	8.0 ± 6.0	IIg
3C 274.1	0.4220	−22.42	27.98	10.0 ± 6.6	IIg
3C 275	0.4800	−22.76	28.18	1.0 ± 1.0	IIg
3C 295	0.4610	−23.99	28.72	29.0 ± 9.9	IIg
B2 0835+37	0.3960	−22.00	26.68	23.0 ± 8.0	C
B2 0841+44	0.4250	...	24.00	−11.0 ± 8.0	I?
B2 1301+38A	0.4700	−22.66	27.32	1.0 ± 7.0	IIg
5C 12.71	0.4360	−22.21	25.75	8.0 ± 7.0	I
5C 12.91	0.4640	−22.99	25.96	21.0 ± 9.8	IIn
5C 12.168	0.4240	−22.80	26.77	4.0 ± 6.0	I
5C 12.217	0.4280	−22.06	26.08	7.0 ± 8.0	IIg
5C 12.241	0.4870	−22.15	26.89	8.0 ± 8.0	IId
5C 12.264	0.3730	−22.84	26.00	9.5 ± 8.0	C
5C 12.304	0.4600	−22.31	26.38	23.0 ± 8.0	C
53W032	0.3700	−22.98	25.30	14.0 ± 9.0	I?
53W039	0.4020	−22.86	24.90	16.0 ± 9.0	I?
53W076	0.3900	−22.53	24.60	14.0 ± 9.0	C
55W010	0.4520	−23.13	26.00	9.0 ± 9.9	C
55W016	0.3750	−22.04	25.11	0.0 ± 7.0	I?
55W023	0.3600	−22.61	24.90	1.0 ± 7.0	I?
55W097	0.3650	−21.31	24.30	14.0 ± 7.0	I?
55W150	0.4650	−21.45	24.48	6.0 ± 9.9	I?
55W161	0.0240	−21.91	24.48	4.0 ± 9.0	I?

EXPLANATION OF COLUMNS.—Col. (1). Galaxy name. Col. (2). Galaxy redshift. Col. (3). Absolute magnitude calculated from Hill's raw magnitudes but using AEZO's empirical *K*-correction method. Col. (4). Logarithm of the radio power in W Hz^{-1} measured at 408 MHz. Col. (5). Group richness and its errors (for explanation, see AEZO). Col. (6). FR type (Fanaroff & Riley 1974).

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