

A 20 cm VLA SURVEY OF ABELL CLUSTERS OF GALAXIES V. OPTICAL OBSERVATIONS AND SURFACE PHOTOMETRY

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ABSTRACT

We present results from a program of optical imaging of 265 radio galaxies in rich clusters. Using isophotal surface photometry, we investigate the optical properties such as the morphology, surface-brightness profiles, surface-brightness/size relationships, ellipticities, and the frequency of nonelliptical isophotes. The results are compared to a “normal” nonradio-selected sample of elliptical galaxies from the same clusters. The goal is to determine if the parent population of FR I radio galaxies can be distinguished optically from radio-quiet galaxies. The results of the analysis are that cluster ellipticals are a very homogeneous class of objects. The optical properties are consistent with a one-parameter family, where the optical luminosity is the fundamental parameter. In all tests considered, radio-loud FR I galaxies cannot be distinguished optically from radio-quiet galaxies selected from the same environment. The local density of nearby companions (<20 kpc) and the frequency of morphological peculiarities or tidal interactions are not statistically different between the radio-loud and quiet samples. There is some suggestion from comparison to published samples of non-cluster radio galaxies, that the cluster environment is not conducive to long-lived tidal interactions, and that such events may be more important to galaxy evolution in poor groups and lower density environments. Such events appear to have little influence on the formation of FR I radio galaxies in rich clusters. The results are consistent with the idea that all elliptical galaxies may at some time (or many times) contain powerful (FR I) radio sources. © 1995 American Astronomical Society.

1. INTRODUCTION

This is the fifth paper in a series describing a systematic study of a large sample of radio galaxies in Abell clusters. In Papers I–III (Zhao *et al.* 1989; Owen *et al.* 1992, Owen *et al.* 1993), the VLA C-Array survey was presented, including optical identifications, radio maps, and source parameters. In Paper IV (Ledlow & Owen 1995a), the final, complete sample was presented along with a study of the cluster properties and their relation to radio source detection and number statistics. In this paper, we report results from the optical observations and surface photometry of the complete radio sample from Paper IV.

While the morphologies and properties of radio sources have been studied in great detail both observationally (in the radio) and in sophisticated theoretical simulations, the existent database of optical observations of the parent galaxies is still quite small. One distinct advantage to the study of clusters, is that it allows us to observe a very large number of radio galaxies in similar environments and at different stages

of their evolution. Models exist to explain the physics of individual source evolution, but few studies have concentrated on the properties and evolution of radio galaxies as a population. From careful surface photometry, we can examine the structural properties of the galaxy's underlying stellar population and its relationship to the observed radio morphology. Because it is through the ISM of the galaxy that the radio source propagates, and is possibly fueled, an understanding of the optical characteristics of these galaxies may provide important clues to the origin of the radio emission and its subsequent evolution.

The lifetime of the radio source is much less than the typical lifetime of the parent galaxy. When we look at the radio sky we see sources in all stages of their development (fractional representation as a function of age is model dependent however), whereas the optical properties of the host galaxies should remain relatively unchanged over the lifetime of the radio source (except for any effects caused by the radio source itself). It is unclear what factors are responsible for producing radio sources in galaxies. Are the conditions for fueling and *turning on* the radio source a function of the immediate environment (the local conditions in the host galaxy) or are they a result of external influences from the large-scale environment in which the galaxy lives and its interaction with this medium or other objects?

It has been established that powerful radio sources are most commonly associated with elliptical galaxies. It is not

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clear, however, if the parent-elliptical radio galaxies as a population are different from their radio-quiet counterparts. What structural properties (if any) separate radio galaxies from the normal E-galaxy population? The active galactic nuclei (AGN) phenomenon appears in many different kinds of galaxies with very different observational characteristics. In recent years, unification theories have been proposed to explain a common physical basis for these objects. The placement of radio galaxies in the standard models is still under debate. Are the radio sources we see in galaxies a transient phenomenon which occur in most or all galaxies at some time or perhaps several times during their lifetime? Or is it a phase of evolution which only occurs in galaxies of specific properties? Also, what is the relationship between the optical galaxy properties and the diverse types of radio morphologies observed? What effects, if any, does the environment have on the observed radio properties? It is also unclear if the distinct morphological properties of the FR I and FR II classes (Fanaroff & Riley 1974) are indeed separate and found in totally different host systems or if there is some evolutionary connection. These unanswered questions motivate an in-depth optical study of large samples of radio galaxies in order to understand these objects as a population rather than individual curiosities.

There exists a fairly large database of elliptical galaxy surface photometry in the literature (see Kormendy & Djorgovski 1989 for a review), however, very few of these studies have concentrated on radio-selected samples. Heckman *et al.* (1986) looked at a sample of high-luminosity radio galaxies (mostly FR II's). They found that $\sim 35\%$ showed evidence of distorted morphologies such as shells, tidal bridges, and distorted isophotes. They concluded that galaxy-galaxy interactions may be important in the creation of the nuclear radio sources and in shaping their overall morphology. A similar study was done by Cólina & Pérez-Fournon (1990) and de Juan *et al.* (1994) of lower-luminosity (FR I) radio galaxies (mostly chosen from the Bologna B2 radio survey). They found that $\sim 50\%$ of their sources had nearby companions and/or exhibited peculiar optical morphologies. The common factor in any interaction model is the origin of the gas supply to the nucleus as fuel for powering the radio source. Whether this gas is supplied by gravitational or tidal interactions, or simply by the internal dynamics of the gas and stars present in the host galaxies is unclear. However, none of these studies have made any firm conclusions or comparisons between the structural properties of "normal" radio-quiet ellipticals and radio-loud galaxies. Given the large sample size from our VLA survey, we are able to address these issues on a more significant level than possible with existing samples.

In Sec. 2, we discuss the samples, the optical observations, and the data reduction techniques. In Sec. 3 we outline the selection of a control sample of radio-quiet ellipticals. In Sec. 4 and its subsections, we compare the results from the surface photometry for our radio-loud and quiet samples. Comparisons are also made to samples chosen from the literature. We discuss the effects of the external environment and galaxy-galaxy interactions on radio source properties and detection rates in Sec. 5. A discussion and interpretation

TABLE 1. Observing runs and instrument setup.

Telescope	Dates	F-Ratio/Reducer	CCD	" / pixel
1.8 meter	3/90	F8/4:1	TI 800x800	0.403
	11/90	F8/4:1	TI 800x800	0.403
	11/6 - 11/9/91	F8/1:1	TI 800x800	0.485
	11/26 - 12/02/91	F8/1:1	TI 800x800	0.485
	6/23 - 6/26/92	F8/4:1	TI 800x800	0.409
1.1 meter	3/27 - 4/2/92	F8/1:1	TI 800x800	0.363
	4/24 - 4/30/92	F8/1:1	RCA 320x512	0.713
	10/21 - 10/27/92	F8/1:1	TI 800x800	0.363

of the results is presented in Sec. 6. We summarize our conclusions in Sec. 7.

Throughout this paper, we assume $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2.1 Observations and Data Reduction

The cluster radio galaxy sample studied in this paper is discussed in detail in Ledlow & Owen (1995). The sample is statistically complete for all Abell clusters with measured redshifts less than 0.09 and 1400 MHz flux density greater than 10 mJy. We have included all radio galaxies within 0.3 corrected Abell radii (Rudnick & Owen 1977) of the cluster center position. We have supplemented this complete sample with a representative number of clusters (~ 100) with redshifts out to 0.25. All of the radio galaxies have confirmed cluster membership (Owen *et al.* 1995a). See these references for details on the sample selection and the VLA observations.

CCD observations of the radio galaxy samples were obtained at Lowell Observatory in Flagstaff, Arizona using the Perkins 1.8 m and Hall 1.1 m telescopes. All CCD images were made with a Cousins R-band filter. See Table 1 for a listing of the instrumentation and nights observed.

On photometric nights, approximately 20 Landolt equatorial standards were observed (Landolt 1973) to determine extinction, the zero point, and to transform the observations to the standard Cousins (R_C) scale (Cousins 1976). In many cases, the night was usable but nonphotometric. For these data, the calibration was determined at a later date by taking exposures of the field during photometric conditions, and bootstrapping the calibration by comparing aperture magnitudes of the brightest objects in the field. A majority of these calibration observations were made with the 61 cm telescope at Capilla Peak Observatory of the University of New Mexico with a 320×512 RCA CCD. Duplicate observations and comparison with published values indicates that our calibration is accurate to within 0.03–0.05 mag.

Most optical measurements of radio galaxies reported in the literature are given in the Johnson B or V bands. Coleman *et al.* (1980) derived mean colors for galaxies of different Hubble types (also see Frei & Gunn 1994). Coleman *et al.* found for ellipticals, $V - R = 0.85$ and $B - V = 1.1 - 1.4$ over the redshift range applicable to our sample ($z < 0.2$). However, they quoted the R magnitudes in the Johnson- R system. Bessel (1979) finds the transformation from the Cousins to Johnson system via the equation:

$$(V - R)_C = 0.73(V - R)_J - 0.03 \quad (V - R)_J < 1.0. \quad (1)$$

This gives us the relation $(V-R)_C=0.59$. These color indices will be used to compare our results to published photometry of other samples. Although some errors are introduced by assuming a standard color, the results of our spectroscopy of these objects (Owen *et al.* 1995) indicated that color variations are small. When possible, however, an effort was made to find objects in common between our sample and published data to find the transformation between magnitude systems.

Standard data reduction methods were used for bias removal, dark count, and flatfielding. At least once with any given instrumentation setup a series of long dark frames were obtained. In most cases, the dark count was negligible over the typical exposure times of the observations. On the 1.8 m, dome flats were produced by illuminating a flat screen with a tungsten lamp and correcting filters to approximate the color of our bandpass. On the 1.1 m, a median of several twilight-sky frames were combined. Typically, these flat-fields were successful in flattening the image to better than 1%. An additional flat-field correction was made by combining several of the object frames (which were not contaminated by bright objects) using a median filter and sigma clipping to remove the objects from the field. This *sky flat* is a much better approximation to the flat-field response of the chip because it uses the same optical light path as the observations. In some cases, when there were not sufficient frames from our object observations, blank regions of sky were observed (Christian *et al.* 1985) several times and combined as mentioned above. This method also proved useful during one run on the 1.1 m using the RCA CCD. These images were contaminated by interference fringes from night-sky emission lines in the *R* band. The sky flat was very successful in removing these fringes.

Observations for the program objects consisted of 3–5 pointings within each field each shifted approximately 20'' from the other. Typical exposure times were 3 and 10 min each for the 1.8 and 1.1 m telescopes. A reference image was chosen and relative shifts for the other frames were calculated to align all of the images. The registered frames were then coadded. This procedure produces a final frame with an increased sensitivity (equal to the sum total of the exposure times when the data are sky-noise limited) and rejects bad or errant pixels which are present on the single frames (such as cosmic rays).

2.2 Optical Surface Photometry

Elliptical profiles were fit to each radio galaxy using the techniques discussed in Jedrzejewski (1987). In brief, given an initial value for the centroid of the object, the light distribution is sampled along a first-guess elliptical path. This produces a one-dimensional intensity distribution as a function of the eccentric anomaly, and is evaluated as a harmonic expansion in a Fourier series of sine and cosine components. A least-squares fit is performed to determine the first- and second-order coefficients of the harmonic series, and the parameters of the fit (position angle, ellipticity, centroid) are adjusted until the largest harmonic amplitude is less than 4% of the rms residuals of the intensity within that isophote.

Once a suitable fit is obtained, the third- and fourth-harmonic amplitudes are calculated. The amplitude of these coefficients (A4 and B4, normalized to the semimajor-axis length) measure the deviation of the fitted isophote to a true ellipse. In general, we have fit isophotes to within a few counts of the sky background level. The distance between isophotes was chosen to geometrically increase by 10% with each successive fit in order to keep the S/N at reasonable values in the outer regions of the surface-brightness profile. We allowed the centroid, ellipticity, and position angle of the isophotes to vary with each iteration.

Because these objects are located in crowded fields, it was nearly always necessary to remove several confusing sources from the frame before performing the isophotal fits. In most cases, aperture masks were defined to flag pixels with INDEF values to eliminate stars and small galaxies. In many of the images, however, large/bright objects were located near the radio galaxy. For these objects, we fit models to the confusing sources, and subtracted them from the image. The isophotal fits were monitored closely for any residual contamination from nearby objects.

We have adopted the magnitude system given in Owen & Laing (1989) and Owen & White (1991). In this system, we measure the luminosity enclosed within an isophote with mean *R*-band surface brightness equal to 24.5 mag arcsec⁻² in the rest frame of the galaxy. The transformation to the rest frame includes corrections for cosmological dimming [$\propto(1+z)^4$], a *K* correction, and galactic absorption estimated from maps in Burstein & Heiles (1981). An isophotal magnitude ($m_{24.5}$) was calculated by integrating over the measured surface-brightness profile out to a radius corresponding to our surface-brightness limit ($r_{24.5}$). By making the transformation to the rest frame of each cluster, we can compare the intrinsic properties of these galaxies over the entire range in redshift.

The surface-brightness profiles were fit with both a de Vaucouleurs (1959) $r^{1/4}$ and a power-law function. The inner points of the profile which fell within two seeing diameters were deleted before the fit. The seeing was not measured individually for each frame, so a conservative estimate of 2'' was adopted for all the data. In most cases the seeing was probably much better. This method introduces some bias in comparing galaxies at very different redshifts because the exclusion of the inner 4'' of the profile corresponds to different physical distances within each galaxy. Only those objects which had at least ten valid measurements along the profile have listed values in the tables.

In addition to the isophotal parameters, we have calculated two aperture magnitudes. We have used the metric apertures defined by Gunn & Oke (1975) and Sandage (1972). Transformed to our cosmology, these apertures have radii of 13.1 and 29.1 kpc, respectively.

The results of the isophotometry are presented in Tables 2 and 3. Table 2 (this table can also be found in the AAS CD-ROM Series, Vol. 5, 1995) lists the structural parameters for the statistically complete sample of 188 radio galaxies with $z < 0.09$. In Table 3, we list these parameters for the more distant $0.09 < z < 0.25$ sample.

TABLE 2. Results of surface photometry for $z < 0.09$ sample.*

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_c	$c_{24.5}$	$\theta_{24.5}$	σ_{pt}	$\sigma_{r,1/4}$	plerp	N	Notes
0014	0012-241	15.22	15.19	15.39	-21.97	-22.00	-21.80	11.07	0.61	0.149	49	0.2626	0.2534	-3.54	12	
0027	0022-209B	14.91	14.28	14.71	-21.87	-22.50	-22.07	25.27	12.42	0.294	118	0.0195	0.0363	-1.85	23	θ twists 50°
0074	0036-226B	15.05	14.65	14.87	-22.17	-22.57	-22.35	22.95	8.30	0.059	44	0.0441	0.0328	-2.04	12	
0075	0037+209	15.10	14.49	14.49	-22.03	-22.63	-22.63	27.93	30.53	0.456	92	0.0416	0.0278	-1.52	26	disturbed spiral at 65kpc, E-gal at 22kpc
0077	0037+292	14.83	14.20	13.94	-22.70	-23.33	-23.59	49.50	23.07	0.501	120	0.0364	0.0114	-1.76	29	cD, disk isoph (?)
0085	0039-095B	15.06	14.86	15.14	-21.84	-22.04	-21.60	12.91	1.55	0.288	156	0.0444	0.0683	-2.81	16	
-	0039-095A	13.82	13.13	13.08	-23.08	-23.77	-23.66	36.33	16.04	0.397	144	0.0731	0.0416	-1.78	28	
-	0039-097	14.71	14.45	14.66	-22.28	-22.54	-22.33	20.08	5.79	0.096	100	0.0461	0.0256	-2.16	19	
0102	0046+011	14.87	12.81	14.66	-22.29	-24.35	-22.50	23.30	8.18	0.235	18	0.0228	0.0376	-2.04	20	θ twists 30°
0104	0047+241	15.58	15.38	15.60	-22.22	-22.42	-22.20	16.94	0.88	0.111	157	0.3257	0.3136	-3.50	13	nearby int. system at 16kpc
-	0047+242A	15.82	15.60	15.85	-21.98	-22.20	-21.95	15.39	1.17	0.273	33	0.0994	0.0758	-3.20	13	θ twists 35°
0114	0050-220	14.89	14.51	14.78	-22.08	-22.47	-22.11	20.97	7.29	0.150	23	0.0241	0.0261	-2.05	19	distorted spiral at 15kpc, $M \sim -20.7$
0117	0053-102A	15.20	14.94	15.22	-21.64	-21.90	-21.62	14.17	4.08	0.113	120	0.0328	0.0245	-2.26	16	
-	0053-102B	13.86	13.38	13.32	-22.98	-23.46	-23.52	34.98	13.11	0.454	17	0.0320	0.0046	-1.90	28	θ twists 50°
0119	0053-015	13.48	13.07	12.97	-22.86	-23.27	-23.37	46.20	14.60	0.100	95	0.0490	0.1280	-1.85	29	
-	0053-016	14.07	13.7	13.92	-22.27	-22.57	-22.42	25.10	6.30	0.050	40	0.0410	0.0840	-2.10	23	
0126	0057-145B	14.61	14.32	14.68	-22.21	-22.50	-22.14	15.90	3.46	0.142	1	0.0454	0.0214	-2.37	17	E-gal at 11kpc, $M \sim -21.0$
0133	0100-221A	14.03	13.47	13.34	-23.01	-23.57	-23.70	53.33	21.23	0.494	18	0.0349	0.0093	-1.76	31	cD, 2 nuc., distorted gal. at 31kpc
0154	0108+173	14.13	13.53	13.78	-23.08	-23.67	-23.42	37.59	13.86	0.134	72	0.0479	0.0185	-1.90	24	θ twists 25° , 4 gal within 20kpc, 2 spirals
0160	0110+152	13.73	13.25	13.43	-22.65	-23.13	-22.95	36.03	14.98	0.370	97	0.0406	0.0141	-1.79	29	2 nuclei
0168	0112-000	14.49	14.23	14.44	-21.90	-22.16	-21.95	21.23	5.11	0.318	19	0.0161	0.0296	-2.22	22	
0179	0119+193	14.66	14.46	14.66	-22.19	-22.40	-22.20	19.48	3.69	0.262	32	0.0279	0.0222	-2.39	20	
0193	0122+084	13.20	12.83	12.85	-23.40	-23.77	-23.75	49.41	23.71	0.253	59	0.0203	0.0299	-1.69	31	cD, distorted nucleus
0194	0123-016A	12.13	11.77	11.92	-22.23	-22.59	-22.44	26.79	9.58	0.360	112	0.0314	0.0142	-1.77	34	distorted gal at 18kpc, $M \sim -18.5$
-	0123-016B	11.31	10.98	10.60E	-23.06	-23.38	-23.76E	-	-	-	-	-	-	-	-	Dumbell
0225	0136+185	14.47	13.53	13.92	-22.93	-23.87	-23.49	43.35	18.62	0.288	102	0.0430	0.0172	-1.81	26	3 E-gal within 20kpc, $M \sim -21$
-	0135+185	15.26	14.84	15.21	-22.15	-22.56	-22.20	22.66	5.49	0.145	111	0.0374	0.0308	-2.25	18	θ twists 40°
0240	0139+073B	14.70	14.17	14.56	-22.45	-22.98	-22.60	27.39	8.71	0.183	26	0.0148	0.0371	-2.06	22	θ twists 45° , structure in halo
-	0139+073A	15.10	14.94	15.16	-22.04	-22.21	-21.98	17.10	2.89	0.033	34	0.0511	0.0278	-2.54	16	interacting pair at 33kpc, E-gal at 22kpc, $M \sim -21$
0257	0146+138	14.99	14.69	14.79	-22.46	-22.77	-22.67	31.87	9.94	0.473	118	0.0163	0.0331	-2.06	24	distorted faint E at 10kpc

*Table 2 is also presented in its complete form in the AAS CD-ROM Series, Volume 5, 1995.

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_c	$c_{24.5}$	$\theta_{24.5}$	σ_{pl}	$\sigma_{r-1/4}$	plexp	N	Notes
0262	0147+360	11.42	11.05	12.28	-22.78	-23.16	-21.93	20.24	8.07	0.328	72	0.0351	0.0089	-1.74	33	
-	0149+359	11.88	11.46	11.10	-22.33	-22.75	-23.11	44.60	29.50	0.400	40	0.0650	0.1580	-1.34	38	
0278	0154+320	15.28	14.69	15.06	-22.73	-23.32	-22.95	29.78	5.51	0.200	41	0.0469	0.0184	-2.39	19	S0 and E at 14kpc, $M \sim -21$, -20.5
0415	0304-122	14.95	14.29	14.14	-22.76	-23.42	-23.58	52.63	33.34	0.314	-17	0.0450	0.0205	-1.64	27	filament in halo?, double nuclei
0419	0306-237	14.83	14.62	14.82	-22.45	-22.66	-22.46	20.95	3.65	0.109	113	0.0556	0.0273	-2.47	18	
0423	0308-123	15.09	14.51	14.80	-22.67	-23.25	-22.97	36.45	14.37	0.487	105	0.0202	0.0143	-1.93	24	2 nuclei, sep = 11kpc
0428	0313-192	16.00	15.79	16.06	-21.32	-21.52	-21.26	14.16	1.58	0.706	82	0.1146	0.0884	-2.75	19	Seyfert, disturbed at large radii to West
-	0314-192	15.19	14.93	15.13	-22.12	-22.38	-22.19	21.52	5.09	0.235	107	0.0322	0.0145	-2.30	19	θ twists 25°
0496	0431-133	12.94	12.35	12.20	-22.77	-23.36	-23.51	49.20	26.55	0.521	-6	0.0285	0.0031	-1.56	37	cD, 4 faint gal in halo
-	0431-134	14.04	13.29	14.04	-21.62	-22.37	-21.59	17.60	5.40	0.060	140	0.0490	0.0740	-2.03	23	
0514	0445-205	15.44	15.17	15.43	-22.07	-22.34	-22.08	22.16	3.69	0.283	-20	0.0323	0.0198	-2.50	18	
-	0446-205	15.48	15.03	15.30	-22.03	-22.48	-22.21	25.20	9.19	0.159	82	0.0298	0.0136	-2.04	19	Boxy?
0576	0717+559	13.84	13.19	13.96	-22.25	-22.90	-22.14	22.31	6.28	0.053	98	0.0445	0.0286	-2.05	23	
0578	0720+670	15.31	14.93	15.18	-22.64	-23.02	-22.77	25.32	4.84	0.091	81	0.0894	0.0602	-2.43	17	interacting with spiral/S0(?), sep=12kpc
-	0719+670	15.26	14.38	14.76E	-22.69	-23.57	-23.19E	-	-	-	-	-	-	-	-	Dumbell
0595	0745+521	15.00	14.52	14.00	-22.38	-22.86	-23.38	57.80	61.10	0.600	120	0.1460	0.1990	-1.33	32	
0623	0803-008	14.36	13.77	13.70	-23.64	-24.24	-24.30	61.33	21.40	0.087	170	0.0338	0.0161	-1.88	26	4 nuclei in common halo, cD
0628	0806+354b	14.98	14.41	14.46	-22.91	-23.48	-23.43	54.91	29.52	0.528	34	0.0212	0.0379	-1.72	29	disky isoph, θ twists 20° faint gal at 10kpc
0690	0838+290	14.69	14.15	13.86	-23.02	-23.56	-23.85	56.40	31.40	0.350	60	0.0600	0.0740	-1.68	27	cD, E-gal at 30kpc, $M \sim -21$ + several fainter
0754	0906-094	14.65	14.01	14.66	-22.16	-22.81	-22.13	16.19	2.81	0.078	124	0.0357	0.0114	-2.50	16	
0757	0909+479	14.45	14.21	14.14	-22.24	-22.48	-22.55	30.10	9.46	0.177	61	0.0133	0.0291	-2.00	24	E at 14kpc, $M \sim -20.1$
0763	0909+162	15.67	14.91	15.18	-22.20	-22.97	-22.70	37.93	19.16	0.465	10	0.0365	0.0233	-1.81	24	disky isoph, distorted gal at 23kpc
0858	0940+060	15.60	15.24	15.38	-22.36	-22.72	-22.58	31.10	8.35	0.391	-25	0.0339	0.0175	-2.20	20	2 nuclei, interacting?
1066	1037+054	14.56	13.87	13.96E	-22.84	-23.53	-23.44E	-	-	-	-	-	-	-	-	2 nuclei, interacting?
1142	1058+107	12.84	12.60	12.98	-23.03	-23.27	-22.88	20.73	3.87	0.290	-67	0.0498	0.0167	-2.25	25	Dumbell, East nuc. elongated
1145	1059+169	15.74	15.55	15.77	-21.59	-21.78	-21.56	14.32	1.53	0.291	59	0.0447	0.0225	-2.92	14	
1185	1108+289B	13.88	-	14.09	-21.73	-	-21.52	14.35	4.71	0.329	9	0.0720	0.0437	-2.00	23	spiral-slightly distorted
-	1108+289A	13.89	13.76	13.97	-21.72	-21.85	-21.64	15.18	3.38	0.153	41	0.0286	0.0109	-2.22	22	θ twists 20°
-	1108+289C	13.26	12.72	13.18	-22.35	-22.89	-22.43	23.14	7.41	0.317	175	0.0475	0.0193	-1.94	27	
1187	1108+398	14.99	14.50	14.49	-22.67	-23.16	-23.17	37.61	1.98	0.220	91	0.0356	0.0283	-1.91	23	

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_e	$c_{24.5}$	$\theta_{24.5}$	σ_{PI}	$\sigma_{r/4}$	plexp	N	Notes
1190	1108+411	15.00	14.45	14.50	-22.67	-23.22	-23.17	42.57	16.33	0.256	4	0.0270	0.0182	-1.91	24	θ twists 25° , 2 E-gal within 20kpc
-	1108+410A	15.36	14.27	15.29	-22.31	-23.40	-22.38	22.90	5.39	0.360	2	0.0302	0.0382	-2.34	19	galaxy at 12kpc distorted
-	1108+410B	15.07	14.41	14.25	-22.61	-23.27	-23.42	49.09	23.64	0.431	-17	0.0447	0.0195	-1.76	27	possible interaction?, asymmetric shape
1213	1113+295A	13.70	13.40	13.59	-22.77	-23.07	-22.88	26.26	5.59	0.151	90	0.0484	0.0176	-2.21	23	Disk, probably spiral
-	1113+295B	14.47	-	14.50	-22.00	-	-21.97	16.82	3.26	0.275	130	0.0424	0.0171	-2.38	19	
-	1113+295C	14.02	13.59	13.95	-22.45	-22.88	-22.52	25.44	8.63	0.383	160	0.0223	0.0365	-1.96	25	E-gal, sep=17kpc, $M \sim -22.5$
1238	1120+013	14.94	14.24	14.34	-22.51	-23.21	-23.11	44.71	35.80	0.132	64	0.0315	0.0361	-1.58	25	disky isoph at mid radii
1257	1124+355	13.42	13.31	13.76	-22.33	-22.44	-22.00	13.57	1.86	0.433	41	0.0970	0.0700	-2.56	22	Seyfert 2, interacting
1291	1129+562	14.93	14.20	14.50	-21.82	-22.54	-22.24	29.15	36.26	0.403	101	0.0403	0.0201	-1.43	25	3 E-gal within 16kpc, $\sim$ same mag
1307	1130+148	16.27	15.99	16.35	-21.54	-21.82	-21.46	13.43	1.34	0.046	161	0.1959	0.1718	-3.12	12	gal at 16kpc disturbed
1308	1130-037	13.83	13.45	13.47	-22.74	-23.12	-23.10	33.40	14.00	0.160	120	0.1450	0.1070	-1.82	25	3 faint gal in halo
1314	1131+493	13.15	12.84	12.79	-22.57	-22.88	-22.93	34.50	12.20	0.200	120	0.0680	0.1000	-1.84	28	
-	1132+492	13.82	13.62	13.65	-21.90	-22.10	-22.07	21.30	5.60	0.100	40	0.0910	0.0290	-2.07	23	halo has structure
-	1132+493	12.91	12.44	12.60	-22.81	-23.28	-23.13	33.82	11.91	0.459	95	0.0218	0.0175	-1.83	32	
1318	1133+551	14.49	14.14	14.45	-22.39	-22.74	-22.43	23.15	5.78	0.418	145	0.0205	0.0206	-2.21	22	
1334	1136-040	14.48	14.16	14.26	-22.38	-22.71	-22.61	29.06	8.51	0.287	186	0.0132	0.0194	-2.05	24	large halo, cD like
1367	1142+198	12.40	11.77	11.79	-22.32	-22.95	-22.93	43.60	17.40	0.440	140	0.0740	0.2390	-1.60	37	E-gal, $M \sim -21.0$, sep=20kpc
-	1141+202B	12.02	11.42	11.54	-22.69	-23.29	-23.18	42.04	16.46	0.241	-20	0.0193	0.0117	-1.64	37	E-gal, $M \sim -21.2$, sep=32kpc
1371	1142+157	15.00	14.47	14.32	-22.31	-22.84	-22.99	37.81	20.97	0.329	45	0.0184	0.0275	-1.74	25	
1412	1153+736	15.69	15.16	15.43	-22.12	-22.66	-22.38	25.92	9.40	0.394	133	0.0736	0.0529	-2.04	20	θ twists 25°
1436	1157+565	14.72	14.36	14.74	-22.46	-22.82	-22.43	29.08	13.92	0.412	153	0.0151	0.0205	-1.86	24	superimposed spiral (?), not disturbed
1452	1200+519	14.66	14.08	14.15	-22.48	-23.06	-22.99	37.30	19.50	0.400	63	0.1050	0.0750	-1.74	24	disturbed spiral at 20kpc
1526	1219+140	15.70	15.55	15.77	-22.00	-22.16	-21.93	12.97	1.98	0.064	69	0.1167	0.0992	-2.78	11	
1541	1224+091	15.89	15.76	15.96	-22.06	-22.19	-21.99	13.47	1.36	0.218	91	0.2278	0.2212	-3.08	11	
1552	1227+120	14.94	14.12	14.53	-22.90	-23.71	-23.31	29.54	12.13	0.334	77	0.0546	0.0318	-1.94	21	2 E-gal sep=15kpc, East unusual shape
-	1227+119	14.67	14.11	14.28	-23.16	-23.72	-23.55	30.51	8.66	0.427	116	0.0602	0.0373	-2.14	22	2 E-gal sep=22kpc
1569	1233+169	14.61	14.08	14.25	-23.05	-23.59	-23.41	34.67	8.59	0.276	115	0.0607	0.0324	-2.14	22	Dumbell
-	1233+168	15.20	14.42	14.85E	-22.46	-23.25	-22.81E									S0 at 20kpc
1589	1238+188	14.85	14.55	14.66	-22.60	-22.91	-22.80	28.63	7.32	0.252	56	0.0419	0.0138	-2.18	21	nearby interacting pair
1609	1243+267	14.97	14.51	14.58	-23.00	-23.46	-23.38	41.21	14.46	0.245	22	0.0159	0.0197	-2.00	23	int w/ E-gal at 17kpc (?)

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_c	$e_{24.5}$	$\theta_{24.5}$	σ_{pl}	$\sigma_{r,1/4}$	pl exp	N	Notes
1631	1250-150A	14.29	13.46	13.90	-22.17	-23.00	-22.56	36.40	18.25	0.206	132	0.0129	0.0216	-1.72	27	E-gal, $M \sim -22.5$, sep=25kpc
-	1250-150B	14.25	13.91	14.57	-22.21	-22.55	-21.89	21.06	6.00	0.296	103	0.0138	0.0206	-2.12	22	distorted spiral at 25kpc, $M \sim -20.3$
1644	1254-171	13.69	12.55	12.49	-22.81	-23.95	-24.01	65.29	49.39	0.491	133	0.0398	0.0132	-1.44	35	cD, distorted S0 at 25kpc, $M \sim -21.8$
-	1255-170	14.42	13.68	13.80	-22.08	-22.82	-22.70	37.70	25.04	0.381	165	0.0283	0.0134	-1.61	28	D/S0 - emission lines
1656	1256+281	12.98	12.74	13.40	-21.93	-22.17	-21.51	12.60	2.50	0.050	90	0.1750	0.0990	-2.26	21	disturbed spiral and E at 22kpc, $M \sim -20$
-	1257+282	12.13	11.32	10.99	-22.78	-23.59	-23.92	61.00	26.20	0.150	60	0.0810	0.1200	-1.36	37	E-gal at 21kpc, $M \sim -21$
1668	1301+195	14.43	13.85	13.87	-22.79	-23.37	-23.36	36.58	17.53	0.210	72	0.0582	0.0291	-1.80	24	cD, disky isoph (?), disturbed gal in halo
1749	1327+378	13.80	13.24	13.27	-23.16	-23.72	-23.69	46.35	18.23	0.224	111	0.0229	0.0160	-1.81	28	cD
1775	1339+266A	14.59	13.71	13.99E	-22.87	-23.75	-23.47E	-	-	-	-	-	-	-	-	A&B sep=27kpc
-	1339+266B	14.59	13.62	13.99E	-22.87	-23.84	-23.47E	-	-	-	-	-	-	-	-	see above
1795	1346+268A	14.33	13.73	12.86	-22.78	-23.38	-24.25	92.10	93.00	0.600	12	0.0660	0.1580	-1.32	37	cD
-	1346+268B	15.66	15.49	15.80	-21.42	-21.59	-21.28	11.43	1.12	0.079	189	0.0460	0.0270	-3.06	11	brightest of 5 gal in line
1825	1355+208A	14.40	14.04	13.97	-22.74	-23.10	-23.17	43.87	22.09	0.385	161	0.0089	0.0207	-1.74	27	unusual feature W of nucleus
-	1355+208B	14.52	14.05	14.14	-22.62	-23.09	-23.00	37.64	14.22	0.462	45	0.0106	0.0221	-1.88	27	boxy?
1827	1355+219	14.45	14.01	14.31	-22.84	-23.28	-22.98	30.74	9.56	0.156	207	0.0387	0.0096	-2.05	22	E-gal at 16kpc, elong $\rightarrow$ radio gal
1828	1355+185B	14.86	14.58	14.84	-22.26	-22.54	-22.27	20.22	3.06	0.393	32	0.0591	0.0339	-2.54	20	boxy, probably an S0
1831	1356+282	14.63	14.10	14.28	-22.44	-22.98	-22.79	32.11	10.09	0.610	-28	0.0182	0.0207	-2.13	20	S0?, boxy
1836	1359-113	13.23	12.82	12.74	-22.73	-23.14	-23.22	41.50	13.80	0.350	25	0.1170	0.0380	-1.78	30	
1890	1415+084	14.70	14.29	14.33	-22.21	-22.62	-22.58	32.20	16.50	0.400	25	0.0390	0.0670	-1.80	26	cD, 3 gal within 40kpc, none <20kpc
1898	1418+253	15.15	14.13	14.86E	-22.48	-23.51	-22.78E	-	-	-	-	-	-	-	-	2 gal sep=10kpc
1899	1419+179	15.19	14.45	15.24	-21.58	-22.32	-21.54	20.48	7.88	0.237	56	0.0185	0.0408	-1.98	20	E-gal at 6kpc, $M \sim -20$
1913	1424+169	14.29	14.06	14.32	-22.44	-22.67	-22.41	20.67	2.70	0.322	121	0.0541	0.0253	-2.60	20	
-	1424+167	14.54	14.32	14.53	-22.19	-22.41	-22.20	19.60	3.65	0.211	130	0.0605	0.0294	-2.41	19	
1939	1435+249	16.31	16.00	16.29	-21.63	-21.94	-21.65	18.44	5.51	0.289	122	0.0378	0.0280	-2.27	14	
-	1435+250	16.02	15.72	16.02	-21.93	-22.22	-21.92	19.89	7.54	0.381	116	0.0541	0.0809	-2.13	16	θ twists 20°
1991	1452+188	14.24	13.61	13.49	-22.71	-23.33	-23.46	44.11	26.95	0.409	9	0.0440	0.0193	-1.63	29	
2028	1507-077	14.81	14.17	14.13	-22.83	-23.47	-23.51	42.77	25.04	0.240	71	0.0173	0.0182	-1.71	25	2 galaxies within 26kpc, $M \sim -21$
2029	1508+059	14.26	13.48	12.78	-23.35	-24.13	-24.83	96.00	55.50	0.600	24	0.1340	0.0370	-1.55	34	cD
2033	1508+065	14.60	14.12	14.05	-23.18	-23.66	-23.73	49.49	20.82	0.528	37	0.0356	0.0223	-1.98	21	2 gal, sep=9.5kpc, distorted nearby spiral
2040	1510+076	14.78	14.44	14.88	-21.62	-21.95	-21.51	13.84	2.42	0.216	137	0.0287	0.0261	-2.48	18	

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	$c_{24.5}$	$\theta_{24.5}$	σ_{pl}	$\sigma_{r,1/4}$	plexp	N	Notes	
2052	1514+072	13.17	12.43	12.05	-22.64	-23.38	-23.76	60.93	48.58	0.347	-21	0.0290	0.0039	-1.38	37	cD, elongated nucleus
2063	1520+087	13.21	12.61	12.55	-22.65	-23.24	-23.30	46.14	33.29	0.333	153	0.0296	0.0049	-1.48	34	cD
2079	1525+290	14.75	14.10	14.43E	-22.52	-23.17	-22.87E	-	-	-	-	-	-	-	-	slightly distorted
2089	1530+282	16.34	16.11	16.45	-21.21	-21.44	-21.09	12.46	1.25	0.216	3	0.0341	0.0452	-3.05	12	bright nucleus
2092	1531+312	15.91	15.31	15.46	-21.41	-22.01	-21.86	27.96	40.42	0.206	3	0.0312	0.0277	-1.42	21	
2142	1556+274	16.36	15.81	16.30	-21.66	-22.21	-21.72	17.82	4.44	0.167	63	0.0260	0.0244	-2.40	14	
2147	1559+161	13.24	12.82	12.85	-22.63	-23.05	-23.02	34.55	13.75	0.582	11	0.0349	0.0079	-1.77	33	cD-like
2149	1600+540	15.23	14.96	15.22	-22.14	-22.41	-22.15	19.75	4.74	0.155	43	0.0636	0.0346	-2.40	17	elongation SW of nucleus toward small E-gal
2151	1602+178A	13.76	13.25	13.75	-22.19	-22.70	-22.20	20.74	8.16	0.015	86	0.0543	0.0325	-1.90	23	int w/ bright spiral, θ twists 35°
-	1602+178B	13.46	13.08	13.27	-22.49	-22.87	-22.68	28.24	9.12	0.355	146	0.0430	0.0217	-1.91	28	θ twists 75°, boxy
2152	1603+165	13.64	13.25	13.51	-22.34	-22.73	-22.47	24.71	7.51	0.254	-64	0.0216	0.0203	-2.01	26	
2162	1610+296	12.86	12.64	12.73	-22.78	-23.00	-22.91	24.65	7.34	0.402	1	0.0401	0.0156	-1.95	29	
-	1610+297	13.68	13.52	13.72	-21.96	-22.12	-21.92	16.61	2.45	0.396	-5	0.0339	0.0117	-2.40	24	
2184	1619+503B	14.88	14.62	14.99	-22.03	-22.28	-21.91	17.89	4.63	0.275	-10	0.0450	0.0199	-2.24	19	E gal, $M \sim -20.5$, sep-7.5kpc
2199	1626+396	12.45	11.93	11.68	-23.06	-23.58	-23.83	57.80	24.60	0.500	30	0.1950	0.0870	-1.59	37	3 bright nuclei, Dumbell, cD
2205	1630+129	15.85	15.44	15.82	-22.14	-22.55	-22.18	23.11	8.08	0.093	117	0.0344	0.251	-2.11	16	S0/Spiral at 13kpc
2241	1657+325B	15.05	14.67	14.82	-22.14	-22.52	-22.37	25.81	9.70	0.116	112	0.0912	0.0691	-1.97	20	structure in halo, shell?
-	1657+325A	15.16	14.92	15.12	-22.03	-22.27	-22.07	21.25	4.33	0.297	149	0.0573	0.0314	-2.33	19	spiral features, θ twists 30°, boxy?
2248	1701+771	14.84	14.49	14.576	-22.48	-22.83	-22.74	30.43	12.33	0.250	-15	0.0103	0.0250	-1.95	22	
2249	1707+344	15.31	14.83	15.32	-22.46	-22.94	-22.45	21.52	5.38	0.359	139	0.0543	0.0313	-2.28	18	Galaxy at 10kpc, $M \sim -20$
-	1708+344	15.63	15.04	15.70	-22.14	-22.73	-22.06	21.68	5.05	0.165	83	0.0489	0.0279	-2.30	16	$\sim$ same mag galaxy at 16kpc
2250	1709+397B	14.85	14.45	14.72	-22.44	-22.84	-22.57	26.71	6.32	0.238	98	0.0237	0.0171	-2.22	21	2 galaxies (Sp,E) within 20kpc
2255	1712+640	15.56	14.91	15.44	-22.19	-22.84	-22.31	24.93	6.76	0.043	31	0.0445	0.0316	-2.22	17	1 of 5 gal in line, S0 at 20kpc
-	1712+641	15.60	15.44	15.62	-22.16	-22.31	-22.13	18.31	2.33	0.206	161	0.0602	0.0305	-2.77	14	
-	1713+641	15.14	13.40	14.70	-22.62	-24.35	-23.05	35.58	14.45	0.418	66	0.0274	0.0162	-1.92	23	
2256	1706+786	14.52	13.27	13.22E	-22.53	-23.78	-22.83E	-	-	-	-	-	-	-	-	double-nuc E at 21kpc, $M \sim -23$
-	1705+786	15.06	14.69	14.87	-21.99	-22.36	-22.18	24.82	9.37	0.108	14	0.0123	0.0308	-2.00	21	
-	1706+787	15.09	14.47	15.09	-21.96	-22.58	-21.96	20.58	5.51	0.065	180	0.0449	0.0607	-2.23	19	
-	1703+787	15.58	15.45	15.69	-21.47	-21.59	-21.36	12.36	1.27	0.190	82	0.0916	0.0675	-2.95	14	several brighter E's in field
2293	1800+576	15.60	14.97	15.57	-21.88	-22.51	-21.90	20.16	7.60	0.542	114	0.0684	0.0510	-2.02	20	1 of 2 interacting pairs in cluster, boxy

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_e	$c_{24.5}$	$\theta_{24.5}$	σ_{pt}	$\sigma_{r,1/4}$	plexp	N	Notes
2304	1820+689	15.07	14.68	14.53	-22.92	-23.32	-23.47	51.16	18.60	0.022	-66	0.0386	0.0636	-1.93	24	
2311	1849+702	15.94	15.62	15.85	-22.13	-22.45	-22.22	23.03	5.76	0.240	69	0.0273	0.0524	-2.33	17	structure in halo to SW
2331	2055-079	15.74	14.87	14.98	-22.02	-22.89	-22.78	27.50	12.73	0.116	74	0.0470	0.0279	-1.92	19	faint structure in halo, nearest gal=40kpc
2361	2136-145	14.61	14.27	14.90	-22.47	-22.81	-22.18	19.99	6.58	0.472	93	0.0253	0.0414	-2.13	21	
2372	2142-202	14.35	13.95	14.09	-22.60	-23.00	-22.86	25.42	8.47	0.481	3	0.0219	0.0285	-2.04	24	cD
2382	2149-158B	14.66	13.94	14.42	-22.60	-23.32	-22.84	30.76	10.50	0.198	123	0.0254	0.0325	-1.99	22	~ mag E-gal at 15kpc
-	2149-158C	14.91	14.58	14.82	-22.32	-22.68	-22.44	19.18	3.97	0.076	88	0.0577	0.0341	-2.40	17	
2399	2154-080A	14.56	14.04	14.29	-22.51	-23.03	-22.78	31.12	7.70	0.203	55	0.0402	0.0091	-2.11	23	E-gal at 19kpc, $M \sim -20.8$
-	2154-080B	14.74	14.28	14.62	-22.33	-22.78	-22.44	23.71	7.01	0.113	11	0.0225	0.0224	-2.11	20	E-gal at 18kpc, $M \sim -21$
2401	2156-203	14.56	14.29	14.44	-22.43	-22.70	-22.54	27.46	6.54	0.038	44	0.0318	0.0220	-2.17	21	E-gal at 12kpc, $M \sim -19.3$
-	2155-203	14.04	13.51	13.59	-22.87	-23.41	-23.33	45.09	14.68	0.128	113	0.0268	0.0091	-1.89	27	θ twists 75° , S0 at 35kpc, $M \sim -21$
2402	2155-100	15.16	14.51	14.52	-22.58	-23.23	-23.22	40.69	14.05	0.355	59	0.0707	0.0406	-1.94	24	
2412	2201-216	15.06	14.17	14.76E	-22.45	-23.33	-22.75E	-	-	-	-	-	-	-	-	
2415	2203-058	14.97	14.53	14.69	-22.10	-22.54	-22.38	28.03	15.75	0.125	146	0.0242	0.0101	-1.79	22	
-	2202-057	15.14	14.74	15.34	-21.93	-22.33	-21.73	15.73	2.87	0.120	134	0.0487	0.0423	-2.52	16	5 gal in halo, interacting?
2420	2207-124	15.06	14.48	14.06	-22.75	-23.33	-23.76	68.15	40.95	0.631	41	0.0115	0.0177	-1.63	32	cD
2448	2229-086	14.46	13.98	13.82	-23.34	-23.82	-23.98	53.40	18.80	0.2250	60	0.0980	0.0420	-1.92	27	E-gal at 11kpc but much fainter
-	2228-087	14.88	14.36	14.39	-22.92	-23.44	-23.41	41.80	15.50	0.300	40	0.0920	0.0660	-1.92	22	
2462	2236-176	14.56	14.03	13.79	-22.85	-23.38	-23.62	53.50	36.60	0.250	130	0.0570	0.0850	-1.60	28	
2495	2247+106B	15.25	14.44	14.01	-22.43	-23.23	-23.66	52.58	39.62	0.545	229	0.0358	0.0141	-1.54	29	cD-like, some asymmetric features
2524	2300+174	15.55	15.17	15.54	-22.23	-22.62	-22.24	20.36	2.77	0.174	46	0.0686	0.0448	-2.70	16	
2538	2305-201B	14.99	14.60	14.70	-22.80	-23.20	-23.09	32.20	7.95	0.070	56	0.0558	0.0251	-2.23	19	disturbed S0/spiral to SE
-	2305-201A	15.74	15.40	15.84	-22.06	-22.39	-21.96	17.77	1.56	0.096	212	0.1318	0.1063	-3.06	13	stellar appearance (N-gal?)
-	2306-201	15.76	15.59	15.83	-22.03	-22.20	-21.97	17.47	1.41	0.092	46	0.0989	0.0669	-3.14	12	
2566	2313-207	15.28	14.74	14.68	-22.47	-23.01	-23.07	42.33	16.75	0.421	156	0.0331	0.0100	-1.82	25	2 nuclei
2589	2321+164	14.88	14.65	14.97	-21.37	-21.60	-21.28	14.33	4.32	0.092	98	0.0468	0.0247	-2.15	18	
2593	2322+143a	14.86	14.04	14.99	-21.40	-22.22	-21.27	12.48	2.92	0.102	45	0.0349	0.0071	-2.35	17	
-	2322+143b	14.48	14.22	14.49	-21.78	-22.04	-21.77	18.30	4.96	0.184	72	0.0270	0.0078	-2.15	21	interacting pair (S+E) at 15kpc
2597	2322-123	15.25	14.78	14.73	-22.59	-23.06	-23.11	37.91	12.88	0.625	-43	0.0441	0.0183	-1.97	26	cD, high ϵ , almost spiral-like
2622	2332+270	14.47	13.92	14.18	-22.72	-23.26	-23.01	35.68	14.38	0.383	55	0.0358	0.0100	-1.87	26	

3. THE COMPARISON SAMPLE

As discussed in the Introduction, detailed isophotometry allows us to examine the structure, brightness, and intrinsic optical properties for our sample of radio galaxies. The pertinent question concerning its interpretation is: Can radio galaxies be distinguished from radio-quiet elliptical galaxies by their optical properties? If so, are these differences a prerequisite to forming a radio source, or are they the result of the radio sources' influence on the host galaxy? In order to address these questions, a suitable control sample of radio-quiet elliptical galaxies must be studied in an identical manner as the radio-loud sample.

It is possible that the global environment in which the host galaxies reside (i.e., high or low galaxy density) has an effect on the observed optical properties (de Carvalho & Djorgovski 1992). An independent study of noncluster ellipticals is not appropriate for this work but will be addressed via published results from the literature and in a future paper.

A control sample was chosen using the CCD frames from our complete cluster sample ($z < 0.09$). Each frame was inspected for elliptical galaxies of comparable magnitude to the identified radio galaxy. This criterion was used for several reasons. Because redshifts are not available for all of the galaxies on the frame, choosing galaxies with similar apparent magnitudes reduces the possibility of including background or foreground objects. Also, it is important to use a sample of objects which span the same range in optical luminosity as the radio-loud sample in order to separate out any dependence on optical luminosity from the isophotal parameters (i.e., size, ellipticity, and surface brightness). Using these criteria, 50 elliptical galaxies were chosen from the CCD frames from all cluster members with $z < 0.09$.

An identical procedure was used to fit elliptical isophotes and calculate magnitudes as for the radio galaxy sample. The adopted cluster redshift was used in each case. Equatorial coordinates were calculated for each object by calculating an (x, y) offset from the radio galaxy on the frame, converting to seconds of arc, and transforming to right ascension and declination using the measured position of the radio galaxy. The results from the surface photometry of the control sample is presented in Table 4.

4. COMPARISON BETWEEN RADIO-LOUD AND RADIO-QUIET SAMPLES

In this section, we summarize the analysis of the optical surface photometry of the radio galaxy and control samples. The goal is to discern if differences exist in the population of galaxies which contain radio sources and those which are classified as radio quiet. The investigation will compare the optical properties such as the optical luminosity (a measure of mass), ellipticity (a measure of the internal dynamics and the Hubble classification), surface-brightness/size relationships (which define the structure of the galaxy's light distribution), and the overall morphology and local environment. Reference and comparison will be made to other samples of elliptical galaxies found in the literature to supplement this analysis. (Kormendy 1977; Schneider *et al.* 1983; Schombert

TABLE 2. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_e	$e_{24.5}$	$\theta_{24.5}$	σ_{pl}	$\sigma_{r,1/4}$	plexp	N	Notes
2626	2333+208	14.12	13.55	13.59	-22.84	-23.41	-23.37	36.20	17.87	0.379	153	0.0707	0.0399	-1.72	27	Dumbell, boxy?
2634	2335+267	12.61	12.09	11.88	-23.06	-23.58	-23.79	54.20	26.60	0.400	40	0.1020	0.1130	-1.58	35	cD
2637	2336+212	15.06	14.79	15.04	-22.40	-22.67	-22.42	20.73	4.29	0.093	155	0.0577	0.0280	-2.38	17	disturbed small E-gal SE of nuc.
2656	2342-042	14.63	14.07	13.99	-22.97	-23.54	-23.62	46.78	18.58	0.349	167	0.0586	0.0297	-1.85	26	unusual nucleus-almost double
2660	2342-261	14.09	13.48	13.93	-22.62	-23.23	-22.78	28.11	9.50	0.423	144	0.0451	0.0206	-1.95	25	3 gal within 23kpc, brightest ~ -21
2665	2348+058	14.28	13.35	13.54	-22.62	-23.56	-23.37	48.04	26.18	0.386	83	0.0320	0.0075	-1.65	30	cD

*This table can also be found in the AAS CD-ROM Series, Vol. 5, 1995.

TABLE 3. Results of surface photometry for $0.09 < z < 0.20$ sample.

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_c	$e_{24.5}$	$\theta_{24.5}$	σ_{μ}	$\sigma_{r,1/4}$	plexp	N	Notes
0055	0031+060	16.00	15.02	15.30E	-22.98	-23.97	-23.68E	-	-	-	-	-	-	-	-	
0069	0035+180	16.46	15.57	15.96E	-22.73	-23.62	-23.23E	-	-	-	-	-	-	-	-	
0084	0039+211	15.57	15.02	15.15	-22.76	-23.31	-23.19	34.28	17.20	0.173	106	0.0851	0.0667	-1.92	21	
0098	0043+201	15.44	14.72	14.71	-22.92	-23.64	-23.54	51.40	25.60	0.460	165	0.0570	0.0620	-1.75	25	
0115	0053+261A	17.54	16.97	17.25	-22.49	-23.06	-22.78	22.06	1.15	0.218	124	0.4699	0.4859	-3.73	11	
-	0053+261B	17.42	17.12	17.34	-22.61	-22.91	-22.69	20.85	1.61	0.191	62	0.1602	0.1503	-3.27	12	$A_c > 0.5$
0217	0134-083	15.97	15.47	15.46	-23.21	-23.71	-23.72	39.98	9.21	0.297	48	0.0464	0.0203	-2.32	19	
0224	0135-071	16.56	16.24	16.46E	-22.88	-23.20	-22.98E	-	-	-	-	-	-	-	-	
0501	0439+083	17.45	17.12	17.46	-22.04	-22.37	-22.04	16.68		0.354	84	-	-	-	<10	
0591	0738+441	15.68	15.28	15.27	-23.02	-23.42	-23.43	42.80	11.88	0.332	6	0.0403	0.0187	-2.14	21	
0610	0756+272	15.47	14.99	14.97	-22.68	-23.16	-23.18	38.99	19.28	0.104	19	0.0269	0.0095	-1.85	21	
0614	0758+181	16.30	15.69	15.70	-22.89	-23.51	-23.49	44.90	21.13	0.270	3	0.0341	0.0264	-1.92	20	
0618	0810+665	16.67	16.07	16.22	-22.40	-23.00	-22.85	43.20	21.90	0.350	60	0.0610	0.0630	-1.89	12	
0643	0816+526	18.30	17.79	17.94	-21.59	-22.10	-21.95	21.80	13.50	0.340	85	0.0520	0.0420	-1.98	11	
0646	0818+472	16.88	16.58	16.76	-22.06	-22.36	-22.18	20.60	3.80	0.300	85	0.0310	0.0240	-2.56	11	
0725	0857+628	14.94	14.56	14.50	-23.11	-23.49	-23.55	48.94	14.88	0.451	-77	0.0112	0.0366	-2.01	25	
0731	0854-034	17.30	16.97	17.21	-22.31	-22.63	-22.39	22.69		0.161	144	-	-	-	<10	
0739	0901+474	16.85	16.11	16.16	-22.76	-23.50	-23.45	41.24	18.05	0.172	150	0.1383	0.1240	-1.98	17	
0756	0908+487	15.85	15.30	15.37	-22.82	-23.38	-23.31	41.86	15.88	0.320	64	0.0390	0.0182	-1.99	21	
0761	0908-103	15.90	15.41	15.50	-22.18	-22.67	-22.59	33.02	9.86	0.221	99	0.0418	0.0310	-2.09	20	
0849	0938+215	17.47	16.87	17.11	-22.89	-23.49	-23.25	33.86	5.61	0.352	3	0.0854	0.0785	-2.68	14	
0869	0943+026	16.36	16.09	16.30	-22.32	-22.60	-22.39	22.71	2.82	0.039	101	0.0609	0.0643	-2.85	12	
0933	1005+006	15.76	15.49	15.73	-22.43	-22.70	-22.45	19.81	2.45	0.231	175	0.0467	0.0589	-2.81	14	
0950	1011+500	17.28	16.68	16.72	-22.86	-23.46	-23.42	39.72	9.15	0.050	155	0.1385	0.1203	-2.37	14	
1024	1025+040	15.03	14.27	13.74	-22.63	-23.39	-23.92	75.88	65.22	0.281	122	0.0120	0.0214	-1.47	31	$z < 0.09$
1030	1028+313	16.30	16.09	16.20	-23.39	-23.61	-23.49	31.24	4.93	0.205	45	0.0613	0.0818	-2.71	13	
1064	1036+015	15.78	15.23	15.18	-23.14	-23.69	-23.74	47.27	19.72	0.228	-65	0.0221	0.0196	-1.96	21	
1234	1119+216	16.84	16.33	16.60	-22.65	-23.16	-22.89	27.99	7.36	0.298	85	0.0884	0.0755	-2.37	14	
1346	1138+060	15.29	14.71	14.57	-22.88	-23.46	-23.60	49.47	23.79	0.363	6	0.0271	0.0182	-1.80	25	
1361	1141+466	15.85	15.08	14.99	-22.73	-23.50	-23.59	50.26	18.55	0.535	-41	0.0533	0.0276	-1.94	25	

TABLE 3. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_e	$c_{24.5}$	$\theta_{24.5}$	σ_M	$\sigma_{r,1/4}$	plexp	N	Notes
1366	1141+676	15.90	15.31	15.09	-22.72	-23.32	-23.54	52.98	31.69	0.458	95	0.0270	0.0102	-1.72	25	
1425	1155+266	16.53	15.91	16.42	-21.98	-22.60	-22.09	24.61	4.83	0.163	40	0.0509	0.0477	-1.99	15	
1446	1159+583	15.50	14.88	14.84	-22.84	-23.46	-23.40	48.50	22.40	0.400	130	0.0810	0.0950	-1.86	22	
1455	1201+282	17.19	16.53	17.20	-21.86	-22.52	-21.85	17.86		0.100	152	-	-	-	<10	$z < 0.09$
1459	1201+026	15.10	14.51	14.53	-22.71	-23.30	-23.29	45.95	18.31	0.316	70	0.0340	0.0141	-1.89	24	
1462	1202+153	16.08	15.66	15.65E	-23.07	-23.49	-23.50E	-	-	-	-	-	-	-	-	
1484	1207+722	16.15	15.49	15.30	-22.60	-23.26	-23.46	51.11	25.21	0.476	56	0.0513	0.0270	-1.80	24	
1516	1216+055	14.58	14.01	13.72	-22.97	-23.54	-23.83	60.41	35.11	0.360	-61	0.0112	0.0151	-1.66	29	$z < 0.09$
1529	1221+615	17.74	17.05	17.13	-22.66	-23.35	-23.27	39.20	28.08	0.401	138	0.0841	0.0758	-1.82	16	
1544	1225+636	15.92	15.37	15.28	-23.23	-23.79	-23.87	64.84	40.11	0.210	53	0.0448	0.0343	-1.69	23	
1559	1231+674	15.21	14.58	14.23	-23.20	-23.83	-24.18	73.20	46.30	0.560	10	0.0850	0.1270	-1.64	28	
1562	1232+414	17.30	16.98	17.06	-22.58	-22.90	-22.82	25.00	6.00	0.250	140	0.0450	0.0550	-2.44	11	
1608	1243+336	16.13	15.33	15.65	-22.77	-23.57	-23.25	37.19	18.40	0.390	93	0.0497	0.0351	-1.92	19	
1614	1243+699	17.70	17.02	17.03	-22.72	-23.40	-23.39	46.85	16.09	0.100	57	0.0425	0.0361	-2.15	15	
1620	1247-012	15.11	14.64	14.47	-22.65	-23.12	-23.29	49.59	22.91	0.324	36	0.0217	0.0329	-1.81	25	$z < 0.09$
1667	1300+321	16.97	16.43	16.37	-22.52	-23.06	-23.12	50.69	34.19	0.143	95	0.0619	0.0819	-1.75	19	
1674	1300+677	15.98	15.37	15.44	-22.39	-23.00	-22.93	40.02	20.50	0.279	40	0.0380	0.0201	-1.82	21	
1684	1306+107A	15.20	14.64	14.76	-22.70	-23.26	-23.14	35.92	20.61	0.327	78	0.0341	0.0129	-1.79	22	$z < 0.09$
	1306+107B	16.01	15.38	15.94	-21.89	-22.52	-21.96	23.08	14.17	0.361	4	0.0680	0.0888	-1.87	17	$z < 0.09$
1731	1320+584	16.93	15.94	16.23E	-22.96	-23.95	-23.66E	-	-	-	-	-	-	-	-	
1761	1330+579	17.97	17.06	16.70	-22.38	-23.30	-23.66	71.90	56.33	0.419	111	0.0280	0.0393	-1.64	21	
1763	1333+412	17.14	16.36	16.34E	-23.24	-24.02	-24.04E	-	-	-	-	-	-	-	-	
1790	1344+543	17.21	16.79	17.02	-21.47	-21.89	-21.66	24.04	7.85	0.368	184	0.0794	0.0805	-2.20	15	
1880	1410+227	16.66	15.26	16.48	-22.41	-23.81	-22.60	30.21	6.81	0.108	6	0.0822	0.0840	-2.40	14	
1893	1412+745	17.67	17.00	17.00	-22.44	-23.10	-23.10	29.98	19.25	0.515	223	0.2384	0.2477	-1.91	15	
1940	1433+553	16.05	15.47	15.17	-22.99	-23.57	-23.87	58.50	38.80	0.350	72	0.1010	0.0590	-1.68	23	
1942	1435+038	17.25	16.45	16.57	-23.05	-23.85	-23.72	38.57	10.05	0.324	39	0.2076	0.1956	-2.33	15	
1960	1442+195	17.04	16.60	16.58	-22.78	-23.21	-23.23	39.43	18.02	0.370	92	0.0502	0.0650	-2.01	17	
1971	1445+149	17.46	17.08	17.22	-22.64	-23.02	-22.87	25.78	3.63	0.096	184	0.1354	0.1250	-2.89	10	
2036	1508+182	15.98	15.39	15.49	-22.60	-23.20	-23.09	39.03	26.20	0.464	41	0.0181	0.0278	-1.76	22	

TABLE 3. (continued)

Abell	IAU Name	m_{GO}	m_S	$m_{24.5}$	M_{GO}	M_S	$M_{24.5}$	$r_{24.5}$	r_c	$\epsilon_{24.5}$	$\theta_{24.5}$	σ_{pt}	$\sigma_{r,1/4}$	plexp	N	Notes
2091	1531+104	17.29	16.88	17.26	-21.66	-22.07	-21.68	17.96		0.158	212	-	-	-	<10	
2141	1555+356	17.05	16.20	16.19	-22.34	-23.20	-23.20	49.51	31.03	0.466	46	0.0393	0.0277	-1.76	21	
2214	1636+379	16.56	15.97	15.74	-22.85	-23.44	-23.67	50.70	26.00	0.400	85	0.0860	0.0590	-1.84	19	
2219	1638+468	17.96	17.27	17.88	-22.12	-22.81	-22.20	20.52		0.132	118	-	-	-	<10	
2220	1638+538	15.34	14.71	14.47	-23.20	-23.83	-24.07	57.20	27.60	0.150	100	0.1380	0.0500	-1.79	24	
2225	1638+558	17.54	17.13	17.20	-22.98	-23.39	-23.32	33.75	5.25	0.349	0	0.1252	0.1174	-2.71	13	
2289	1753+580	17.74	17.05	17.18	-22.70	-23.39	-23.26	35.27	8.37	0.360	135	0.1666	0.1595	-2.42	14	
2306	1826+747	16.07	15.49	15.46	-22.86	-23.44	-23.47	37.60	15.70	0.270	16	0.1340	0.0820	-1.94	18	HI EXT
2316	1857+799	18.02	17.63	17.99	-22.15	-22.56	-22.18	20.77		0.345	44	-	-	-	<10	
2345	2124-124	16.83	16.10	16.89	-21.91	-22.64	-21.85	16.62	1.48	0.289	164	0.1723	0.1665	-3.18	11	
2365	2140-188	17.60	17.21	17.42	-22.25	-22.63	-22.42	25.18	3.01	0.371	28	0.2194	0.2222	-2.93	12	
2395	2152+085	16.62	16.30	16.43	-22.70	-23.02	-22.89	30.37	4.04	0.287	-1	0.0554	0.0401	-2.73	15	
2522	2259+137	17.24	16.73	16.89	-22.42	-22.93	-22.77	29.09	5.54	0.172	-19	0.1586	0.1483	-2.54	13	
2607	2327+110	16.65	16.17	16.45	-22.07	-22.54	-22.26	25.94	12.84	0.056	58	0.0435	0.0359	-1.98	14	
2617	2330+091	16.70	16.32	16.69	-22.79	-23.17	-22.80	27.48	2.77	0.091	84	0.2245	0.2106	-2.97	12	
2627	2334+236	15.99	15.51	16.01	-22.87	-23.35	-22.85	16.08	2.67	0.060	81	0.4585	0.4860	-2.84	11	
2672	2352+261	18.16	17.83	18.11	-22.45	-22.79	-22.50	19.95		0.030	21	-	-	-	<10	

TABLE 4. Results of surface photometry for control sample.

Abell	Name	z	RA(1950)	DEC(1950)	m _{GO}	m _S	m _{24.5}	M _{GO}	M _S	M _{24.5}	r _{24.5}	r _c	c _{24.5}	θ _{24.5}	σ _p	σ _{r,1/4}	plxp	N	Notes
0114	C1	0.0587	00 51 15.8	-22 00 23	15.70	15.55	15.83	-21.27	-21.42	-21.14	10.97	0.80	0.210	73	0.1678	0.1415	-3.29	12	Spiral at 39kpc
0119	C2	0.0444	00 53 42.6	-01 31 36	13.46	12.72	12.60	-22.90	-23.62	-23.76	53.20	31.29	0.499	42	0.0284	0.0068	-1.59	34	dist spiral @ 25kpc
0160	C3	0.0444	01 10 23.5	15 11 27	14.25	-	14.27	-22.12	-	-22.11	18.37	3.05	0.059	89	0.0866	0.0511	-2.42	19	
0168	C4	0.0448	01 12 43.1	-00 01 26	14.51	-	14.70	-21.86	-	-21.68	17.22	3.36	0.213	26	0.0226	0.0152	-2.35	19	E @ 10kpc ~ -20.8, Δθ=35°
2524	C5	0.0797	23 00 43.4	17 25 11	15.36	15.02	15.18	-22.42	-22.76	-22.60	25.39	8.23	0.168	130	0.0345	0.0369	-2.16	18	
0576	C6	0.0381	07 17 15.6	55 53 36	14.17	(12.90)	14.33	-21.92	(-23.19)	-21.76	17.74	2.84	0.233	170	0.1012	0.0795	-2.43	21	S0 at 11kpc, possibly dist
0582	C7	0.0581	07 24 34.6	42 00 55	16.11	15.56	16.02	-20.96	-21.51	-21.04	18.34	14.56	0.020	111	0.0262	0.0324	-1.70	17	nearest gal=37kpc
2052	C8	0.0348	15 14 17.6	07 14 20	14.24	14.06	14.39	-21.57	-21.75	-21.42	12.31	1.42	0.123	127	0.0329	0.0571	-2.73	18	E-Gal, ~ -19.5 @ 9kpc
1291	C9	0.0531	11 29 29.7	56 14 20	15.29	14.80	15.37	-21.46	-21.94	-21.37	14.80	4.98	0.167	-61	0.0478	0.0771	-2.16	17	S0 @ 17.5kpc, ~ -20.5, D-gal?
1314	C10	0.0338	11 32 19.2	49 12 51	13.61	12.99	13.49	-22.11	-22.73	-22.23	22.49	7.11	0.021	-54	0.0109	0.0354	-1.97	25	Distorted? E @ 18kpc
1367	C11	0.0214	11 41 26.6	20 14 58	13.53	-	13.35	-21.18	-	-21.36	15.38	5.43	0.411	-9	0.0115	0.0289	-1.92	28	radio gal @ 32kpc
2256	C12	0.0581	17 04 01.5	78 47 44	15.17	(14.15)	15.16	-21.88	(-22.90)	-21.89	18.33	2.79	0.156	101	0.0571	0.0323	-2.57	17	-
1631	C13	0.0465	12 50 20.0	-15 04 32	14.73	14.46	14.82	-21.74	-22.00	-21.64	14.88	1.72	0.083	-3	0.1140	0.0840	-2.73	17	int w/radio gal @ 26kpc?
1890	C14	0.0570	14 14 56.4	08 28 02	14.68	14.28	14.44	-22.23	-22.62	-22.47	28.09	13.31	0.319	28	0.0215	0.0141	-1.84	24	gal at 9kpc, ~ -19.5, boxy
1899	C15	0.0538	14 19 20.3	17 58 47	14.35	13.98	14.30	-22.42	-22.79	-22.48	23.33	5.26	0.125	62	0.0608	0.0278	-2.21	21	gal @ 5kpc, ~ -21.0, Δθ = 25°
1913	C16	0.0528	14 24 07.7	16 58 51	14.66	14.47	14.71	-22.07	-22.26	-22.02	17.43	3.72	0.057	13	0.0806	0.0513	-2.37	17	very round E
2040	C17	0.0451	15 10 10.4	07 38 19	15.57	15.17	15.74	-20.82	-21.22	-20.65	10.84	1.20	0.081	96	0.1028	0.0792	-2.84	14	3 gal ~ -18.6 within 20kpc
2052	C18	0.0348	15 14 18.3	07 11 16	14.09	13.79	14.13	-21.72	-22.02	-21.68	17.00	3.29	0.198	61	0.0928	0.0574	-2.29	22	assym. halo, boxy, Δθ = 30°
2152	C19	0.0372	16 03 10.3	16 34 36	14.06	13.90	14.10	-21.92	-22.08	-21.88	16.64	4.77	0.382	135	0.0422	0.0362	-2.09	23	elong → RG @ 31kpc, Δθ = 35°
2247	C20	0.0384	16 55 47.7	81 39 45	14.78	-	14.99	-21.35	-	-21.14	9.82	1.02	0.075	68	0.0785	0.0530	-2.90	15	RG @ 20kpc, ε l
2256	C21	0.0581	17 07 17.3	78 42 25	14.11	13.48	13.22	-22.94	-23.57	-23.83	61.08	30.13	0.191	123	0.0182	0.0138	-1.68	30	2 gal within 25kpc, Δθ = 40°
2256	C22	0.0581	17 07 17.8	78 42 19	14.22	13.59	13.49	-22.83	-23.46	-23.55	46.91	24.55	0.247	57	0.0228	0.0085	-1.72	28	2 gal within 28kpc, Δθ = 25°
2256	C23	0.0581	17 03 22.6	78 44 21	15.49	15.31	15.56	-21.56	-21.74	-21.49	13.85	2.25	0.385	9	0.0305	0.0431	-2.63	17	assym. @ low r, Δθ = 25°
2372	C24	0.0576	21 42 27.2	-20 14 20	14.94	14.56	14.91	-22.01	-22.39	-22.04	19.72	7.61	0.247	-19	0.0230	0.0409	-2.05	19	gal @ 15kpc, ~ -20.5, structure?
2399	C25	0.0604	21 54 58.9	-08 01 55	14.64	(14.02)	14.50	-22.43	(-23.05)	-22.57	26.63	6.16	0.352	108	0.0130	0.0364	-2.17	23	E @ 26kpc, interacting?

TABLE 4. (continued)

Abell	Name	z	RA(1950)	DEC(1950)	m _{GO}	m _S	m _{24.5}	M _{GO}	M _S	M _{24.5}	r _{24.5}	r _e	c _{24.5}	θ _{24.5}	σ _{pl}	σ _{r/4}	plexp	N	Notes
1307	C26	0.0834	11 30 27.1	14 50 05	16.67	16.58	16.83	-21.14	-21.22	-20.98	9.75	-	0.111	102	-	-	-	< 10	
2593	C27	0.0421	23 21 56.1	14 21 53	16.31	15.87	16.53	-19.95	-20.39	-19.73	7.32	1.03	0.233	58	0.0694	0.0528	-2.84	11	high ε nuc, Δθ = 35°
2660	C28	0.0524	23 42 34.2	-26 06 07	15.25	15.16	15.36	-21.47	-21.56	-21.36	12.95	3.20	0.188	68	0.1433	0.1232	-2.30	15	high ε nuc, Δθ = 25°
0074	C29	0.0654	00 36 29.9	-22 36 26	15.27	(14.77)	15.25	-21.95	(-22.45)	-21.97	19.34	3.66	0.0229	11	0.0356	0.0236	-2.44	18	dist. E @ 16kpc, ~ -20.4
0102	C30	0.0632	00 46 02.7	01 09 02	15.46	(14.79)	15.41	-21.70	(-22.67)	-21.75	19.70	5.20	0.337	21	0.0203	0.0436	-2.23	19	
0104	C31	0.0818	00 47 03.0	24 11 30	16.48	15.98	16.59	-21.32	-21.82	-21.22	13.25	1.70	0.085	46	0.0672	0.0423	-2.89	11	dist. spiral @ 19.8kpc, ~ -21
0104	C32	0.0818	00 47 02.3	24 13 33	16.37	16.13	16.39	-21.43	-21.67	-21.41	17.85	2.75	0.126	79	0.1084	0.0879	-2.64	14	nearest gal=RG @ 41kpc
1638	C33	0.0620	12 52 06.0	19 13 39	15.12	(14.52)	15.17	-22.00	(-22.60)	-21.95	17.56	3.08	0.191	95	0.0272	0.0385	-2.49	17	
0428	C34	0.0669	03 13 56.2	-19 15 56	15.09	14.88	15.05	-22.23	-22.44	-22.96	21.22	-	0.166	209	-	-	< 10		nearest gal ~ 50kpc
0763	C35	0.0851	09 09 53.9	16 12 42	16.50	16.45	16.63	-21.38	-21.43	-21.25	11.37	-	0.252	-32	-	-	< 10		nearest gal @ 37kpc
0104	C36	0.0818	00 46 59.7	24 12 14	16.12	15.79	16.17	-21.68	-22.01	-21.64	17.86	2.83	0.267	29	0.0771	0.0737	-2.62	15	gal at 8kpc, ~ -18.5
1371	C37	0.0670	11 42 43.9	15 45 52	15.02	14.56	14.42	-22.28	-22.74	-22.88	44.13	29.27	0.351	139	0.0124	0.0319	-1.63	27	4 gal within 14kpc
1436	C38	0.0642	11 57 41.7	56 32 30	15.98	15.69	16.23	-21.20	-21.49	-20.95	10.62	2.11	0.036	122	0.0635	0.0592	-2.57	11	asymm shape, faint gal ~ 20kpc
1609	C39	0.0891	12 43 53.1	26 42 30	15.50	15.12	15.19	-22.46	-22.85	-22.78	34.00	15.52	0.117	28	0.0221	0.0279	-1.90	20	asymm @ large r, Δθ = 40°
1638	C40	0.0620	12 51 57.5	19 11 59	15.19	14.88	15.08	-21.92	-22.24	-22.04	24.48	8.30	0.279	28	0.0250	0.0473	-2.06	21	very faint gal @ 10kpc, Δθ = 40°
1795	C41	0.0724	13 46 38.1	26 48 29	16.50	(15.75)	16.69	-20.96	(-21.71)	-20.77	10.23	1.60	0.304	70	0.0671	0.0711	-2.78	11	dist spiral @ 26kpc, E at 16kpc
1828	C42	0.0620	13 55 51.9	18 35 20	14.86	14.58	14.78	-22.26	-22.54	-22.34	23.50	4.34	0.313	13	0.0371	0.0383	-2.39	21	round nuc, Δθ = 30°, boxy?
1898	C43	0.0750	14 18 19.7	25 23 04	15.38	15.10	15.28	-22.16	-22.44	-22.26	21.29	5.23	0.092	52	0.0213	0.0200	-2.31	17	faint structure in halo
1939	C44	0.0883	14 35 00.9	25 04 45	16.97	16.73	17.09	-20.97	-21.22	-20.85	13.05	-	0.143	115	-	-	< 10		disky appearance
2061	C45	0.0777	15 19 27.6	30 53 12	16.08	15.62	15.71	-21.80	-22.26	-22.17	28.16	17.13	0.443	76	0.0086	0.0289	-1.79	22	E @ 13.5kpc ~ -20, Δθ = 40°
1609	C46	0.0891	12 43 48.1	26 42 16	16.12	16.05	16.19	-21.84	-21.91	-21.77	15.47	0.69	0.161	94	0.4203	0.4185	-3.67	11	boxy, large halo, bit asymm
2089	C47	0.0734	15 30 42.1	28 13 50	16.85	16.45	16.91	-20.70	-21.10	-20.64	13.04	2.45	0.333	50	0.1105	0.0937	-2.56	13	diffuse nuc, 1 gal @ 28kpc
2255	C48	0.0808	17 11 57.0	64 05 38	15.53	15.02	15.38	-22.22	-22.73	-22.38	24.14	5.80	0.042	61	0.0588	0.0394	-2.30	17	odd-shape E @ 30kpc ~ -22
2255	C49	0.0808	17 12 09.5	64 07 05	14.87	14.23	13.80	-22.88	-23.52	-23.95	69.09	40.33	0.272	59	0.0310	0.0134	-1.61	29	faint gal @ 30kpc
2311	C50	0.0899	18 50 00.6	70 17 48	15.58	15.19	15.17	-22.48	-22.88	-22.90	37.56	13.56	0.070	124	0.0304	0.0535	-2.01	21	nearest gal @ 75kpc

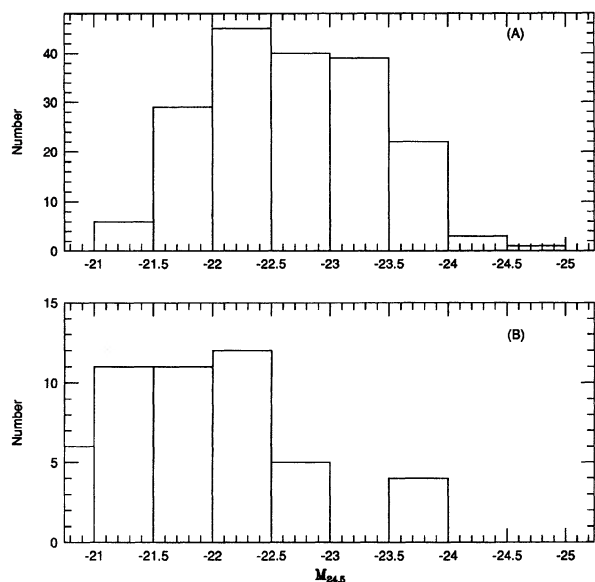


FIG. 1. The optical absolute magnitude distributions for the radio galaxy sample (A) and control sample (B).

1986, 1987; Smith & Heckman 1989; Owen & Laing 1989; Owen & White 1991; Porter *et al.* 1991; and Zirbel 1993).

4.1 Relationships Between Magnitudes

We have defined, from the surface photometry, the parameters which may be important in understanding the structure and characteristics of radio galaxies and ellipticals as a class of objects. Previous studies have examined which parameters (and how many) are required to accurately define this class (Djorgovski & Davis 1987; Okamura *et al.* 1988). Okamura *et al.* argue that the luminosity is the defining property. Djorgovski & Davis (also Dressler *et al.* 1987) studied the surface brightness and stellar velocity dispersion (normal ellipticals). However, most studies have concluded that the optical luminosity is the fundamental parameter.

In Fig. 1(A) and 1(B), we show histograms of the distribution in optical absolute magnitude of the radio galaxy and control samples. The radio galaxy sample has a broad peak centered near -22.50 . This magnitude is interestingly very near M^* (the break in the optical luminosity function) in the $M_{24.5}$ R-band system ($M_R^* \sim -22$). Thus a majority of the galaxies detected in our radio survey have luminosities from M^* to 1 mag brighter. Although luminous galaxies, these are not typically the brightest galaxies in the cluster. *cD* galaxies have absolute magnitudes ≥ -23.5 . Approximately 3% of the galaxies are fainter than M^* . No galaxies fainter than -21.0 had radio powers above our detection limit. However, the luminosity distribution is somewhat reflective of the optical luminosity function for elliptical galaxies (Binggeli *et al.* 1988). The distribution in Fig. 1(A) does not imply that M^* type galaxies have a higher probability of radio emission, but that there are simply more of them present in clusters as compared to brighter galaxies. For galaxies with magnitudes fainter than M^* , however, the lack of detected

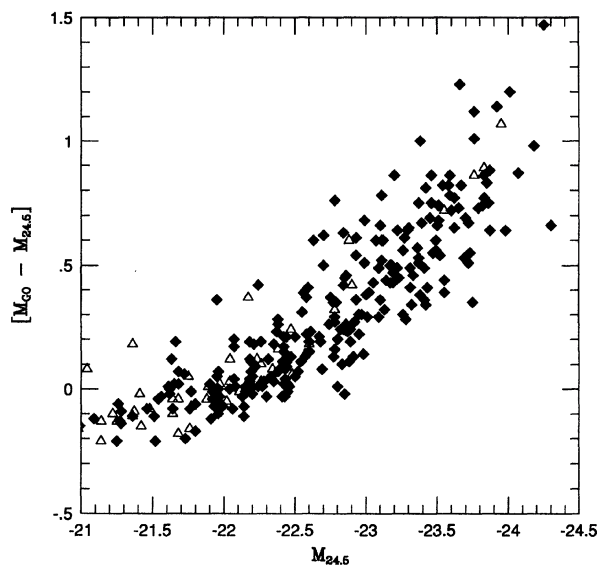


FIG. 2. The difference in absolute magnitude at a radius of 13 kpc and at the 24.5 mag arcsec $^{-2}$ isophote. The radio galaxies are plotted as solid diamonds, the control sample objects as open triangles.

objects does suggest that these galaxies are very rarely radio emitting (at least at powers $>10^{22}$ W Hz $^{-1}$) because the luminosity function continues to rise to fainter luminosities. Thus radio galaxies appear to be luminous cluster galaxies but are not always the brightest cluster member. Our control sample extends to fainter magnitudes than the radio-loud sample, but spans the same range to -24.0 .

In calculating the magnitudes, we have extracted the luminosity at the Gunn–Oke radius and at a radius corresponding to a surface brightness of 24.5 mag arcsec $^{-2}$ in the rest frame of the galaxy. A comparison of these two magnitudes relates the luminosity within the inner portion of the galaxy to the extended luminosity in the outer halo. In Fig. 2 we plot $[M_{GO} - M_{24.5}]$ vs $M_{24.5}$ for each sample. One should notice that for galaxies with $M_{24.5}$ fainter than M^* the mean difference in magnitudes is ≤ 0 . There is a distinct increase in this difference with increasing luminosity. For the fainter galaxies in the sample, the 13 kpc radius falls outside the 24.5 surface-brightness limit. Galaxies a magnitude or more brighter than M^* are therefore much larger and more diffuse. For the *cD* galaxies it is likely that we are not sampling the entire halo as they are often detected to surface-brightness levels of 26–27 mag arcsec $^{-2}$ or fainter. For a few cases in which we could not fit isophotes down to the 24.5 mag arcsec $^{-2}$ level, we have used Fig. 2 to estimate $M_{24.5}$ from the Gunn–Oke aperture magnitude.

From the plot in Fig. 2, one can also see the change of elliptical classification with increasing luminosity. These classifications have been defined by Matthews *et al.* (1964). This classification follows from normal ellipticals around -21.0 to giant ellipticals at magnitudes ~ -22.5 , to large-extended *D* galaxies at or near -23 to the largest *cD* galaxies with haloes exceeding 100 kpc. It is also possible that *N* galaxies appear in this diagram. They are characterized by very bright starlike nuclei with steep-brightness profiles,

somewhat like quasar host galaxies. However, it should be noted that a steep-brightness profile does not necessarily define an N galaxy. Many of the low-luminosity galaxies in our sample have steeper than average surface-brightness profiles with apparently normal nuclear magnitudes. Some of these galaxies may be good candidates for tidal stripping from galaxy–galaxy interactions in which stars from the outer halo has been removed from the galaxy.

The magnitude relationship in Fig. 2 covers a range of 3.5 mag or a factor of 25 in luminosity but all galaxies appear to follow a simple relationship. The relationship seen in Fig. 2 appears consistent between the radio-loud and quiet samples. A chi-squared test between the two distributions shows that these two samples are inconsistent with having been drawn from the same parent sample at only a 32% significance.

4.2 Surface-brightness Profiles

Along with the idea that elliptical galaxies can be characterized by a set of parameters which define a fundamental plane (with luminosity as the fundamental parameter), the implication is that the structure of all ellipticals should be similar. From the surface-brightness profiles, we have calculated fits to a $r^{1/4}$ law and a best-fit power-law exponent.

Tonry (1987) and Kormendy & Djorgovski (1989) have shown that most galaxies are well fit by a $r^{1/4}$ law over the inner parts of the galaxy, but many exhibit systematic departures from this relation at larger radii. D and cD type galaxies with extended haloes have an additional light component not predicted by this brightness distribution. These galaxies have a tendency to flatten at large radii and thus have shallower profiles. Because of the surface-brightness limit of our photometry ($24.5 \text{ mag arcsec}^{-2}$), in most cases we are not sampling the entire halo of highly extended galaxies which extend to much fainter surface-brightness levels. Thus, even the cD galaxies in our sample are reasonably well-fit by $r^{1/4}$ laws down to the 24.5 surface-brightness level.

Owen & Laing (1989), in their report of surface photometry of FR I and FR II-type radio galaxies, found that 80% of their sample fit $r^{1/4}$ laws better than power-law fits. As compared to their cluster sample (Owen & White 1991), they found an opposite trend. A majority of the cluster radio galaxies had smaller residuals to power-law profiles.

From our radio galaxy sample [of which Owen & White (1991) is a subset], for $z < 0.09$, 63% fit $r^{1/4}$ laws best, 26% fit power laws, 3% fit both equally, and another 8% fit neither very well. From the control sample, we find 55% fit $r^{1/4}$ laws, 39% fit power laws, and 6% fit neither within a standard deviation of 0.12. Given the sample sizes, these percentage values are not found to be statistically different from a χ^2 significance test. The shape of the surface-brightness profiles are indistinguishable between our radio-loud and control samples. Owen & Laing (1989) did however find systematic differences in these fits between radio galaxies of different morphologies, suggesting that FR I and FR II-type sources may exist in different types of ellipticals.

The power-law exponents derived from plots of surface brightness versus $\log(r)$ are listed in Tables 2 and 3 for both

samples. To supplement the above comparison based on best-fit models, we can compare the steepness of the profiles directly. For the radio galaxy sample we find a mean value of -2.08 ± 0.03 . For the control sample, $pl_{\text{exp}}(\text{ave}) = -2.26 \pm 0.07$. This would imply that the radio galaxies had shallower profiles, a result which was found by Smith (1988) and Zirbel (1993). However, we expect that the optical luminosity is correlated with the derived power-law exponents. Thus any luminosity differences between the two samples may skew this result. If we separate the radio galaxy group into cD 's (Schombert 1986), brightest cluster ellipticals (BCE) (cross referenced with Porter *et al.* 1991), and nonbrightest cluster ellipticals (non-BCE), the mean values for these subgroups are

$$(cD \text{ galaxies}) \quad pl_{\text{exp}}(\text{ave}) = -1.66 \pm 0.04,$$

$$(BCE) \quad pl_{\text{exp}}(\text{ave}) = -1.81 \pm 0.04,$$

$$(non-BCE) \quad pl_{\text{exp}}(\text{ave}) = -2.20 \pm 0.04.$$

We see the progression from normal cluster ellipticals to the larger and more extended D and cD classes. The control sample is consistent with non-BCE radio galaxies (see Fig. 1). Any apparent differences in the shape of the profiles can be attributed to differences in optical luminosity.

4.3 The Surface-brightness/size Relationship

Also listed in Tables 2 and 3 are the effective radii derived from fits to a $r^{1/4}$ law. As discussed in the previous section, $r^{1/4}$ laws do not fit all elliptical galaxies equally well, so the definition of a half-light radius is obviously not valid in galaxies with extended haloes beyond that predicted by this scaling law or those with truncated outer profiles. Nevertheless, previous work by Schneider *et al.* (1983), Schombert (1986), and Kormendy & Djorgovski (1989), have indicated that brightest cluster ellipticals do follow a similar relation between the surface brightness measured at the effective radius (μ_e) as do less luminous galaxies (Kormendy 1977). This relation is often referred to as the fundamental plane, and has been investigated as a possible indicator of evolution in the galaxy population with epoch. Assuming that the $r^{1/4}$ scaling law has not changed with epoch, any differences seen in the relation between samples of galaxies at high and low redshifts may result from evolution in the stellar population of the galaxies (Hoessel *et al.* 1980). Likewise, a similar comparison between radio-loud and radio-quiet galaxies may allude to any differences in their histories and formation. Often, other variables are included in this plane, such as the stellar velocity dispersion, or metallicity indicators (Mg II index). However, from our spectroscopy, we have found no correlation between the Mg II index and optical luminosity (Owen *et al.* 1995b). It is generally agreed that the optical luminosity, however, is the fundamental parameter.

It is unclear how radio galaxies fit into this scenario. If radio galaxies, as a class, have different optical properties from normal, radio-quiet galaxies, one might expect some difference in the relation. It is also possible that the presence of a radio source in a galaxy may alter the properties of its host as the radio jets propagate through the ISM. Powerful

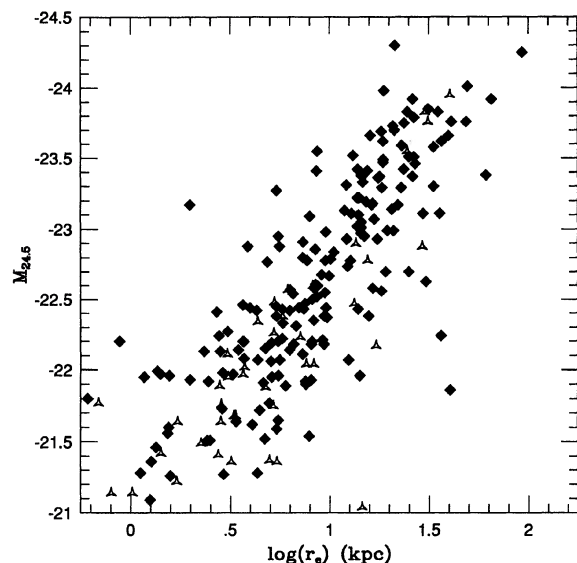


FIG. 3. M_{Ks} is plotted vs $\log$ of the effective radius (r_e) determined from an $r^{1/4}$ law fit to the surface-brightness profile. Symbols are same in Fig. 2.

radio galaxies (FR II's), and some low-power sources, often have emission-line regions, and may have enhanced star formation. Thus the placement of radio galaxies in the fundamental plane is important to understand their status in the elliptical galaxy hierarchy.

There is also some evidence to suggest that field and cluster ellipticals inhabit their fundamental planes differently (de Carvalho & Djorgovski 1992). de Carvalho's results indicated that the noncluster ellipticals exhibit more intrinsic scatter than the cluster ellipticals. This scatter was highest with regard to metallicity and stellar population measures. The cluster ellipticals appeared to have more homogeneous properties. They interpreted these results to mean that within any given cluster, the member galaxies formed early and in a similar fashion. Noncluster ellipticals, on the other hand, were found to be more heterogeneous, and their properties may depend strongly on individual histories. This study, however, did not distinguish between radio-loud and quiet galaxies. We will address the issue of cluster/noncluster radio galaxies further in a future paper.

In Fig. 3, we have plotted M_{Ks} vs $\log(r_e)$ for both samples. There is obviously a linear relation in this log-log plot, but there is a fair amount of scatter. There are many more bright galaxies in the radio loud sample, but the two datasets appear consistent. A χ^2 test reveals that these two samples are different at only at a 78% significance. The correlation between the isophotal (near total) luminosity and the half-light radius supports our finding that the surface-brightness profiles are consistent between both samples.

In Fig. 4, we have plotted μ_e vs r_e for several subsamples. We have divided the cluster radio galaxies into cD -type galaxies, BCEs, and non-BCEs. Also plotted are the calculated values for the control sample and a fit to a small sample of nearby galaxies from Kormendy (1977). From this plot, we see that all the samples essentially lie within the same relative plane. However, it is evident that fits to the individual

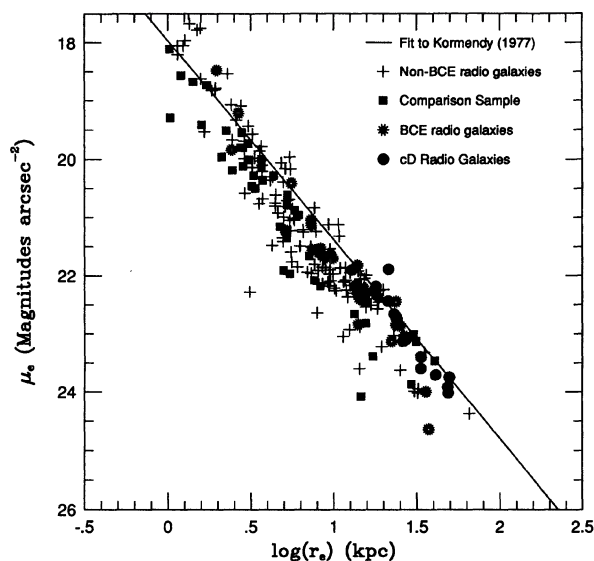


FIG. 4. The fundamental plane of elliptical galaxies; the surface brightness measured at the effective radius (r_e) vs $\log r_e$. The symbols are labeled on the plot.

samples are likely to have different slopes. The cD galaxies, as expected, are found in the region with larger effective radii and higher surface-brightness levels. There is no obvious difference in this plot between the BCE and non-BCE cluster radio galaxies. This is an important point. Very often, the difference in luminosity between the BCE and the next brightest cluster member is only a few tenths of a magnitude. It is easy to assume from the literature that BCE galaxies are somehow unique or special in properties from other cluster galaxies. Status as the brightest galaxy in a cluster does not necessarily imply some unique formation process, but there is some evidence that the cD galaxies do form differently than the other cluster members. In other words, only a small fraction of BCE galaxies are actually cD 's, and non- cD BCE properties do not appear to be different from other cluster radio galaxies in our sample when the difference in luminosity is taken into account.

We have found the following fits to the data for the various subsamples:

$$\begin{aligned} (cD \text{ radio galaxies}) \quad \mu_e &= 18.24(\pm 0.37) + 3.32 \\ &(\pm 0.27)\log R_e, \end{aligned} \quad (2)$$

$$\begin{aligned} (BCE \text{ radio galaxies}) \quad \mu_e &= 17.84(\pm 0.25) + 3.83 \\ &(\pm 0.21)\log R_e, \end{aligned} \quad (3)$$

$$\begin{aligned} (\text{non-BCE radio galaxies}) \quad \mu_e &= 17.77(\pm 0.11) \\ &+ 4.10(\pm 0.13)\log R_e, \end{aligned} \quad (4)$$

$$\begin{aligned} (\text{Control sample}) \quad \mu_e &= 18.08(\pm 0.17) + 3.94 \\ &(\pm 0.22)\log R_e. \end{aligned} \quad (5)$$

The fit derived by Kormendy (1977) (transformed to our system) for normal noncluster ellipticals is

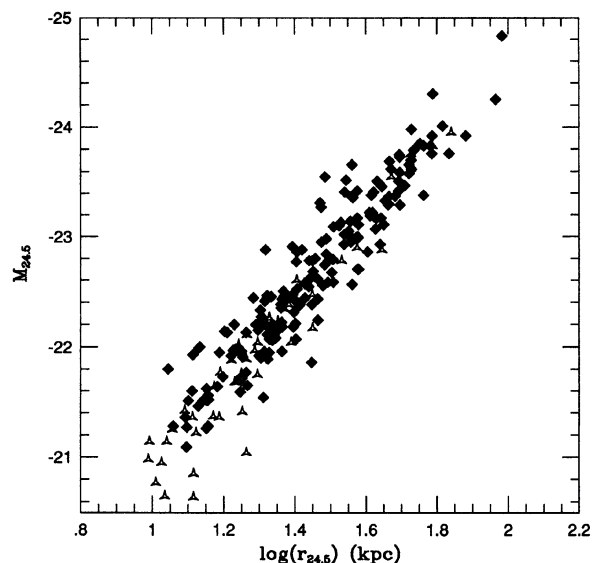


FIG. 5. $M_{24.5}$ vs $r_{24.5}$ (the radius at the 24.5 mag arcsec $^{-2}$ isophote). Symbols are the same as in previous plots.

$$\mu_e = 17.96(\pm 0.17) + 3.42(\pm 0.39)\log R_e. \quad (6)$$

We see a progression in these relationships from the non-BCE, to the BCE, and cD samples in which the relationship becomes progressively flatter (i.e., shifted towards larger effective radii at the same surface-brightness level). The control sample is consistent with the non-BCE and BCE radio galaxies. Within the errors in the fits, all samples are essentially consistent with one another. The cD galaxies and the nearby non-cluster sample (Kormendy 1977) are nearly equivalent. The other three cluster subsamples also have nearly identical slopes. Thus, selection based on radio properties does not appear to affect the relationships within the fundamental plane.

4.4 Isophotal Sizes of Radio Galaxies

In this section, we will examine whether radio galaxies are more extended than radio-quiet objects with the same M_{GO} or $M_{24.5}$. Smith (1988) and Zirbel (1993) examined this relationship using their samples of mostly noncluster radio galaxies and found a significant difference in that the radio galaxies had shallower surface-brightness profiles than normal noncluster ellipticals. The effect was found to be strongest for more luminous galaxies. Measured from the 22 mag arcsec $^{-2}$ isophote, they claimed that radio galaxies were $\sim 9\%$ larger. At the 24 mag arcsec $^{-2}$ isophote, this factor increased to 25%. Given the similarities in the surface-brightness profiles between our radio-loud and control samples, such a result seems surprising.

We have plotted in Fig. 5 the isophotal magnitude $M_{24.5}$ vs $\log(r_{24.5})$ for both samples. We see that the two datasets appear to follow the same linear relationship. A χ^2 test between the two samples indicates no difference above a 55% significance.

In Zirbel's analysis, she compared the isophotal sizes measured between galaxies of equivalent 16 kpc (using $H_0=50$) aperture magnitudes. The claim, is that this normalization eliminated the luminosity dependence on the isophotal radii. Referring to Figs. 2 and 5, we see that while there is a linear relationship between the isophotal magnitude and radius, the difference between a fixed aperture and an isophotal magnitude shows a luminosity dependence. In addition, the scatter or dispersion increases with optical luminosity. The problem arises because for fainter galaxies, the 16 kpc aperture contains nearly the total light of the galaxy, whereas for brighter galaxies, the same aperture may only contain 50% of the total luminosity (see Fig. 2). We therefore do not expect a linear relationship over the total range in optical luminosity for $M_{16 \text{ kpc}}$ and $r_{24.5}$.

Zirbel compared the radio galaxy properties to a normal galaxy sample selected from Schombert (1986, 1987). Schombert's work was a study of the three or four brightest cluster members in a large sample of Abell clusters. Schombert calculated average surface-brightness profiles for the non-BCE galaxies factored by their 16 kpc V magnitude. The average profiles were calculated over coarse 1 mag bins. The inferred $M_{16 \text{ kpc}}$ /isophotal-size relationships for Zirbel's control sample were extrapolated from these average profiles.

Zirbel's radio galaxy sample consisted of mostly powerful radio galaxies from the 3CR sample. We suspect that there is an optical luminosity offset between Zirbel's radio galaxy sample and the non-BCE averaged profiles. Because the averaged profiles were derived from non-BCE galaxies, the magnitude/size relationship (see Fig. 5) will be shifted along the L_{opt} axis for the brighter galaxies from Zirbel's sample. From Sec. 4.2, we found that the average power-law exponent fit to the surface-brightness profiles of BCE and non-BCE galaxies differ by about 20%. In addition, many of the 3C galaxies are found in D to cD -like host systems. Thus, comparing these galaxies to non-BCE ellipticals, will by definition, result in a bias towards finding larger galaxies.

We have compared the actual measured size of our radio galaxies and control sample to the size predicted from Schombert's average profiles at the 24.5 mag arcsec $^{-2}$ isophotal level using the same aperture magnitude. In Schombert (1987), the average profiles are calculated for a 16 kpc aperture using $H_0=100$. Transformed to our adopted cosmology, this corresponds to 21.3 kpc. We have calculated aperture magnitudes for our samples using this equivalent aperture. We used Eq. (1) to transform Schombert's absolute magnitude bins and the surface-brightness level to our magnitude system. The values were also transformed to $H_0=75$ for extrapolating the inferred $r_{24.5}$. In Fig. 6 we show the comparison of our measured data to the fit from these average profiles. Over the magnitude range $-21 < M < -22.5$, the fit is consistent with both our radio-loud and control samples. The ratio $\Delta R_{24.5}$ (ratio of the actual size to that predicted from the averaged profiles) calculated over this range is 1.04 ± 0.04 for both our samples. For brighter galaxies in both samples, the relationship is skewed to larger radii with $\Delta R_{24.5} = 1.12 \pm 0.03$. This value is considerably less than found by Zirbel (1.25). The origin of the discrepancy can be

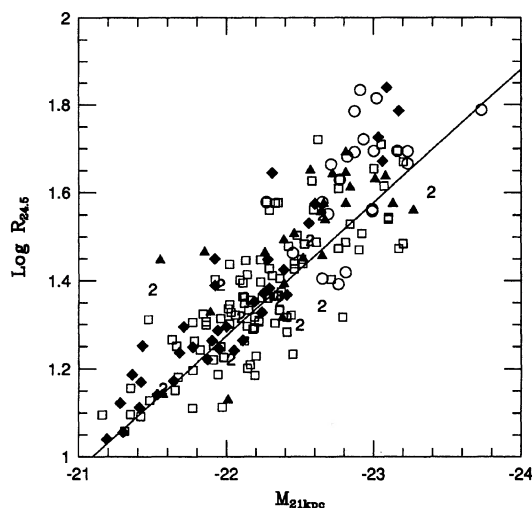


FIG. 6. The logarithm of $r_{24.5}$ is plotted vs the absolute magnitude within a 21 kpc aperture. The solid line is an interpolation of the averaged surface-brightness profiles from Schombert (1986, 1987). Solid triangles=BCE radio galaxies, open squares=NBCE radio galaxies, open circles= cD radio galaxies, solid diamonds=control sample, 2's show the placement of the FR II's from our sample.

seen in Fig. 7, where we have plotted $M_{24.5}$ vs $M_{21 \text{ kpc}}$. Consistent with the above findings, at ~ -22.5 , the tight linear relationship begins to show more scatter with a dispersion which is consistent with the $\sim 10\%$ increase in $\Delta R_{24.5}$.

The higher values found by Zirbel and Smith are consistent with a bias in optical luminosity between their objects and the control sample. An additional error is likely drawn from using profiles averaged over such coarse magnitude bins. Also, as noted above, the dispersion in Fig. 2 increases steadily with optical luminosity, suggesting that errors from the average surface-brightness profiles will be much higher for brighter galaxies. There is no evidence that the magnitude/size relationships are significantly different between the radio-loud and radio-quiet samples.

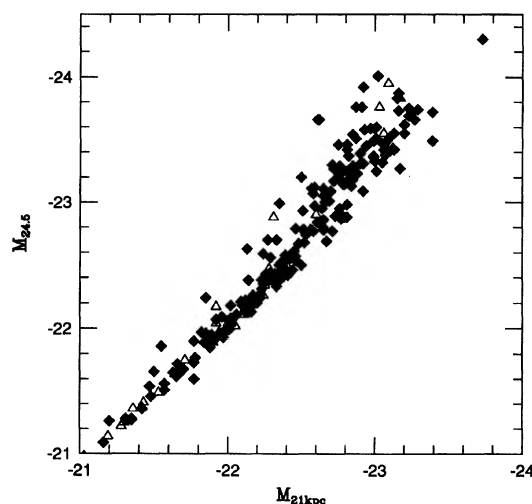


FIG. 7. $M_{24.5}$ vs $M_{21 \text{ kpc}}$. Symbols are the same as in previous figures.

4.4.1 Ellipticity

Previous isophotometric studies have examined the shape and structure of elliptical galaxies and its implication on gas dynamics in models of galaxy formation. (Hoessel & Schneider 1985; Kormendy 1985; Lauer 1985a; Djorgovski 1985; see Kormendy & Djorgovski 1989 for a review). The ellipticity (which is the basis for the different Hubble classifications; $E0-E9$), however, is not necessarily a good indicator of the dynamical history of the individual galaxy because of the number of possible models which project to the same shape (Porter *et al.* 1991). This is due in part because of the dependence on galaxy inclination or the projected viewing angle on the sky (Kormendy & Djorgovski 1989). The observed ellipticity correlates with this angle in the sense of flattened galaxies (high ϵ) being close to edge-on, and rounder ellipticals viewed face-on. We thus expect more scatter in the derived values for the ellipticity. Since the distribution of projected angles should be random in a complete sample, there should not be any bias which prefers one range in values over the other. However, intrinsically, ellipticals do appear to have a preferred shape of $E3.8$ (Binney & de Vaucouleurs 1981).

The most comprehensive studies to date of the shapes of elliptical galaxies are from Porter *et al.* (1991), who examined the properties of 175 brightest cluster ellipticals (BCE) (from the Abell catalog) and Djorgovski (1985) and Djorgovski & Davis (1987) in their study of normal (noncluster) ellipticals. Porter reported that BCE galaxies exhibit a monotonic increase in ellipticity with radius. We find an identical result for the BCE radio galaxies which fall in our sample, but also that $>90\%$ of all radio galaxies follow this trend. The structure of the non-BCE galaxies is a bit different however. While the overwhelming majority do show an increase in ellipticity with radius, the ellipticity increases much less smoothly. There are frequent turn-over points at which the ellipticity remains constant or decreases over some distance in the inner profile and then increases steadily beyond. This trend was seen by Owen & White (1991), but can now be quantified with a much larger sample.

It has been reported that radio galaxies as a class are rounder than radio-quiet ellipticals (Disney *et al.* 1984; Calvani *et al.* 1989). Calvani *et al.* additionally claimed to have found a significant radio-power/ellipticity correlation. The suggestion is that the shape of the light distribution must be related to the shape of the gravitational potential within the galaxy. Presuming that a central radio source is fueled by gas accretion from stellar mass loss within the galaxy (or from cold gas of unknown origin), the lack of angular momentum implied by a round interior might increase the efficiency at which material is channeled to the galaxy core. However, one would therefore expect a significant correlation with the central velocity dispersion (σ) or surface brightness (which is an indicator of the available angular momentum and the depth of the potential) and the radio power. However, no such correlation is found when the dependence of σ on the optical luminosity is removed (the Faber-Jackson relation) (Calvani *et al.* 1989). It is therefore difficult to understand the relationship between a round interior and the probability for a galaxy to have radio activity.

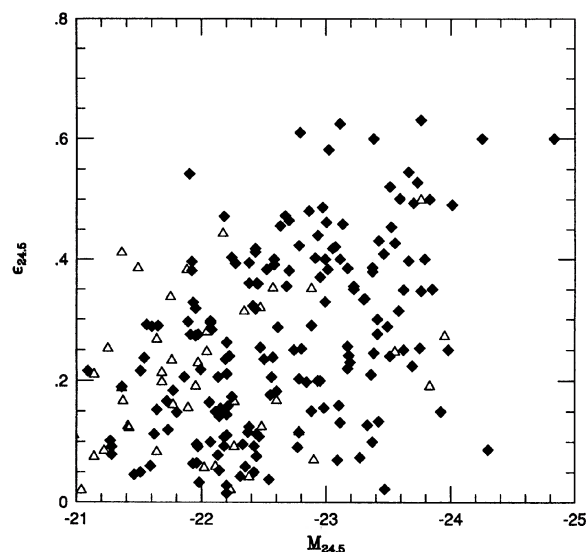


FIG. 8. The ellipticity measured at the 24.5 mag arcsec⁻² isophote is plotted vs $M_{24.5}$. Symbols are the same as in Figs. 2, 3, 5, and 7.

Calvani *et al.* also claimed to have found no correlation between optical luminosity and ellipticity. Because of the fairly strong optical luminosity dependence of the FR I/II break (Owen & Ledlow 1994; Ledlow & Owen 1995b), a positive $M_{\text{opt}}-\epsilon$ correlation might explain the dependence of ϵ on the radio power. In Fig. 8 we have plotted $\epsilon_{24.5}$ vs $M_{24.5}$ for our two samples. While there is substantial scatter in the diagram, there is a trend (correlation coefficient=0.45) for ellipticity to increase with optical luminosity.

In Fig. 9 is plotted the ellipticity versus the radius in kpc for several subsamples of the radio-loud group and our control sample. The radio subsamples are segregated by optical luminosity, so differences between them are indicative of the $M_{\text{opt}}-\epsilon$ dependence shown above. Plotted points range in ra-

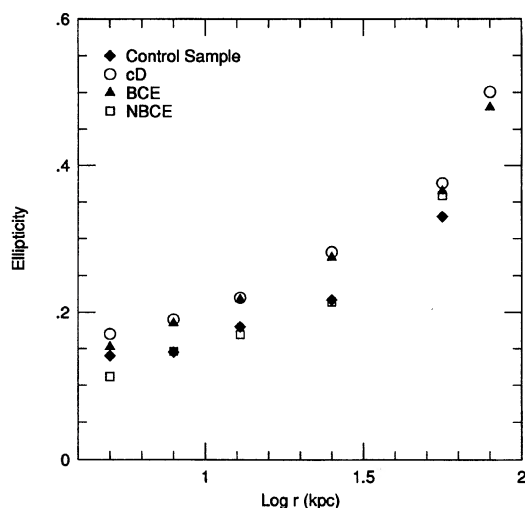


FIG. 9. The ellipticity measured over a range in radii from 5 to 80 kpc. The different points are labeled on the plot.

dus from 5 to 80 kpc. Error bars have not been plotted to avoid confusion. The standard deviations in each bin are between 0.08 and 0.13 with a mean of 0.1. For the 5 kpc bin, we have only included galaxies with $z < 0.05$ to avoid problems with seeing (see Sec. 2.2). The bins at the largest radii only include the BCE and *cD* radio galaxies because of insufficient numbers of sources in the other subsamples. With typical 0.1 dispersions in ellipticity, clearly all the samples are consistent. As a function of the optical luminosity, the NBCE and control samples show a slower increase in ϵ with radius than do the brighter galaxies. Note, however, that there are no significant differences in shape between the radio-loud and quiet galaxies at any radius.

We can use Fig. 9 to compare to other samples from the literature as well. In Fig. 5 from Porter *et al.* (1991) are plotted the median ellipticities as a function of radius for Porter's BCE sample and Djorgovski's (1985) sample of 199 ellipticals chosen from the CfA redshift survey. Our radio galaxies which overlap with Porter's BCE sample have identically derived parameters, suggesting no bias in the way we have fit the axial ratios. Additionally, our NBCE and control samples match the ellipticity values as well as the slope of Djorgovski's normal ellipticals very well.

We have looked for correlations between the total 1400 MHz radio power and the ellipticity for all radii plotted in Fig. 9. We find no radio power/ellipticity correlations in any of the bins. The only apparent difference between our samples and those of Disney *et al.* and Calvani *et al.* are that our galaxies are all found in rich clusters. These other studies have been derived from catalogs of noncluster selected galaxies. Unless noncluster ellipticals are somehow different, either at formation or in their evolution, it is difficult to reconcile our results with Disney and Calvani's findings. We find no differences between the radio-loud and quiet samples or any relationship between the ellipticity and the radio power.

4.4.2 Isophotal shapes—Non-elliptical isophotes

It has been shown (Lauer 1985b; Jedrzejewski 1987; Bender *et al.* 1987) that departures from elliptical isophotal structure may be indications of tidal disruption of the stellar distribution within elliptical galaxies. In relation to our fitting procedure (see Sec. 2.2), the first and second harmonics of the Fourier fit to the surface brightness describe a constant intensity ellipse. Higher-order terms measure deviations from true ellipticity. In particular, the amplitudes of the fourth sine and cosine components (as a function of polar angle or eccentric anomaly) are a measure of how the surface brightness deviates from the average within the isophote as a function of polar angle. Normalized to the semimajor-axis length and the slope of the surface-brightness profile, these quantities define a radial deviation, and thus can be examined as a function of radius within the galaxy. Large negative B4 amplitudes result from boxy shaped isophotes. Positive amplitudes are found for pointed or disk-shaped isophotes. Therefore, it is thought that these measures may be useful in identifying subtle distortions in the surface brightness which may have resulted from tidal interactions or galaxy mergers.

Bender *et al.* found that many of the radio galaxies in

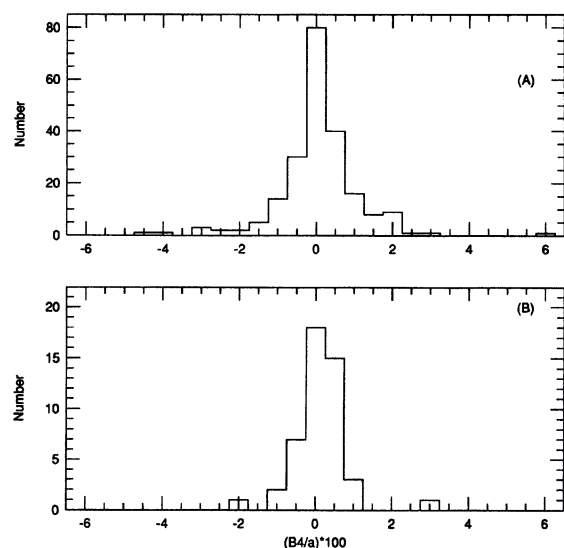


FIG. 10. Histograms of $(B4/a)*100$ for the radio galaxy sample ($z < 0.2$) (A) and the control sample (B). $(B4/a)*100$ is the percentage deviation from a true elliptical isophote measured at the effective radius (r_e).

their sample had boxy-shaped isophotes. Only a very small fraction of the radio-loud ellipticals had disk isophotes. Their interpretation was that the disk-like systems may form a link to the S0 class, which have been found to have lower radio powers and a lower detection rate at a given optical luminosity (Hummel *et al.* 1983; Sadler *et al.* 1989). González-Serrano *et al.* (1993) in a study of B2 radio galaxies also found about 1/3 of their objects to exhibit departures from ellipticity. Many of these galaxies also exhibited tidal tails or dust lanes. Note, however, that none of these studies have examined these trends for a rich cluster selected sample of galaxies.

We have examined the radial profiles of B4 and A4 for each of the radio and control sample galaxies. The normalized amplitudes have been multiplied by 100 to convert to a percentage deviation. The amplitudes were evaluated from the average of the two isophotes bracketing the effective radius (r_e). Because the normalized percentage deviation depends on the radius, the errors in A4 and B4 also change with radius. Typical errors are 0.5% at small radial distances to greater than 1% at large radii. Most of the galaxies in both samples exhibit A4, B4 profiles which oscillate about zero, with small amplitudes. Only a few galaxies in either sample actually exhibit large deviations ($>3\%$). Histograms of the distributions are shown in Figs. 10(a) and 10(b). We see that both samples have deviations symmetrical about zero, with few objects (7) outside the width of the distribution. These plots are consistent with that presented in Bender *et al.* for his sample of radio-quiet galaxies (non-rich cluster galaxies). Additionally, the A4 amplitudes have the same spread of values as B4. Boxy isophotes will typically have A4 amplitudes lower than the B4 values. Consistent with the previous results in this section, cluster ellipticals (both radio-loud and quiet) appear to have fairly homogeneous properties. There is no apparent trend in our samples for radio galaxies to have

a higher percentage of nonelliptical or boxy isophotes. These results may also suggest that despite the higher local galaxy density, cluster ellipticals undergo fewer galaxy interactions (see Sec. 5).

5. GALAXY MERGERS, INTERACTIONS, AND NEARBY COMPANIONS

In recent years, it has been suggested that the formation of radio galaxies (and perhaps all active galaxies) may be stimulated by the presence of nearby galaxies. (see review by Balick & Heckman 1982). Such close proximity could result in simply a tidal interaction or a violent merger depending on the difference in velocity, the impact parameter, and the masses of the constituent galaxies. In a merger/interaction scenario, it is presumed that through tidal forces, the dynamics and structure of one or both of the galaxies involved may be altered. Such an event may simply disturb the outer stellar distribution or may actually involve a transfer of gas or stars from one galaxy to the other. Over the lifetime of a typical close interaction (on the order of 10^8 – 10^9 yr) such disturbances can migrate to the inner few kpc of the galaxy. Thus, it is believed that such interactions may provide the necessary fuel and assist in its transport to the nuclear engine of the galaxy to form and sustain a radio source.

Previous studies have examined the environments of AGN such as quasars and BL Lac objects (Stocke 1978), powerful radio galaxies (Heckman *et al.* 1985, 1986; Prestage & Peacock, 1988) and low-luminosity radio galaxies (Colina & Pérez-Fourmon 1990; Colina & de Juan 1995). These studies suggested that the galaxy density was an important factor for the presence of radio emission, both on a large (1 Mpc) scales (Stocke 1979) and in the presence of close companions (<100 kpc). Several studies have concluded that AGNs, and in particular, radio galaxies, prefer high galaxy density regions over the typical environment in the field (Kennicutt & Keel 1984). However, work by Ledlow & Owen (1995b), Ledlow (1994), Fanti *et al.* (1982), Auremma *et al.* (1977), and others find no difference in the probability of radio emission for galaxies in clusters and those in less dense regions. Consistent with these results, it would appear that it is the immediate neighborhood of the galaxy which is most influential on the observed properties rather than its status as a cluster or non-cluster member (Dressler 1980; Stocke 1979).

Heckman *et al.* found from 1/4 to 1/3 of radio galaxies with $P_{408} > 10^{25.5}$ indicated evidence of distorted optical morphologies suggestive of mergers or tidal interactions. These disturbed features took the form of multiple nuclei, tails, shells, fans, bridges, or dust lanes. Colina found a comparable (even slightly higher) 50% of low-luminosity ($P < 10^{25}$) radio galaxies had either close companions or showed peculiar optical morphology which was not detected in more isolated galaxies. Thus the current wisdom seems to suggest that mergers/interactions are an important process in the formation or evolution of radio galaxies. However, most of the objects studied in these samples were not members of Abell clusters but were chosen from the 3C and B2 radio surveys. Given the higher velocity dispersions found in richer envi-

ronments (~ 1000 km/s) (which may limit the time-span of an encounter and the effective strength of tidal forces), and the smaller numbers of gas-rich galaxies, it is unclear if such interactions may be as likely or as important as compared to poorer groups.

Colina & de Juan (1995) examined a sample of 44 FR I host galaxies. They found that 60% of their sample showed evidence of morphological peculiarities consistent with recent gravitational galaxy-galaxy interactions. However, less than 1/3 of their sample objects reside in rich clusters. In addition, half of these cluster sources are identified with *D* or *cD* dominant galaxies, which often have nearby galaxies and extended haloes exhibiting morphological peculiarities. Thus, their galaxies are not typical of the average radio galaxy found in our complete cluster sample. Their results, however, may reinforce the suggestion that galaxy mergers or interactions are more important in less dense environments.

In order to examine the frequency of interactions, mergers, and multiple nuclei of the radio galaxies in our sample, we have used the following criteria: (1) the radio galaxy must have a companion galaxy (regardless of morphological type) within a projected distance of 20 kpc, (2) the companion galaxy must be no fainter than -20 at *R* band, (3) if a visible interaction is indicated, the galaxy is included regardless of the luminosity of the companion. In a different category, we have counted those galaxies which exhibit visible morphological peculiarities such as large ($>25^\circ$) isophotal twisting, or other disturbed morphologies. See the notes in Tables 2, 3, and 4 for a description of each source. Because the sample is selected from the centers of rich clusters and contains only elliptical galaxies, one must be cautious in interpreting the images. By definition, these galaxies lie in regions of high galaxy density. In addition, elliptical galaxies as a class form in groups much more often than galaxies in general (Davis & Geller 1976). It is for these reasons that we have restricted the projected search radius to 20 kpc. Within this distance (which lies within the galaxy in most cases), the number of chance superpositions should be small. Note, however, that we cannot separate out those galaxies in which the actual physical separation is much larger than the observed projected distance. This projected radius is also the separation used by Colina & Pérez-Fournon (1990) to study their sample of radio-jet parent galaxies from the list of Bridle & Perley (1984). The luminosity cutoff is included in order to sample all clusters to the same limiting magnitude in the optical luminosity function, and to avoid counting objects with negligible mass as compared to the radio galaxy. It is very common to see galaxies 4–5 mag fainter in the haloes of bright galaxies, but if these objects are indeed at the same redshift, their effect on the radio galaxy should be negligible. Thus, we have divided the radio galaxy sample into two subsamples; (1) those galaxies which meet the above criterion, and (2) galaxies which are more isolated or appear normal or undisturbed.

Additionally, we want to compare the frequency of nearby companions and morphological peculiarities between the radio-loud galaxies and our control sample. A rigorous treatment of the problem would require redshift information for

all of the galaxies, an estimate of the background galaxy counts (e.g., Lick counts), selection of a control sample well removed in the cluster from the radio sources, and a determination of the local galaxy density from the amplitude of the spatial two-point correlation function (B_{gg}). With a few assumptions we can simplify the comparison. Because our control sample is selected from the same clusters as the radio galaxies, and in the same redshift range, the background/foreground correction should be identical for both samples. The local galaxy density also depends on location within the cluster. For example, if the galaxy surface density within the cluster follows a King-function distribution, the probability for a galaxy to have a neighbor within some radius depends only on the distance from the cluster center. From the 182 radio galaxies used in this comparison, and our control sample of 50 radio-quiet galaxies, the mean distance from the cluster centers is $0.11 A_c$ (fraction of a corrected Abell radius) for both samples. An additional bias may result from optical luminosity differences (brighter, more massive galaxies typically have more companions). Both samples, however, span essentially the same luminosity range (see Sec. 4.1).

As a final note, without visible evidence of tidal distortions, we make no claim that galaxies with nearby companions are actually interacting systems. The purpose of this test is merely to examine the local galaxy density around radio galaxies as compared to a control sample of radio-quiet objects.

From the group of objects in Table 2, defining a complete sample for $z < 0.09$, 65/186, or 35% of the radio sources have a neighboring galaxy within 20 kpc. A few of the sources had more than one neighbor which met the selection criteria, for a total of 74 companion galaxies. Only 11 (6%) radio galaxies showed evidence for actual gas exchange or other signatures of an ongoing interaction. In most cases, the distorted morphology was observed from the companion rather than the radio galaxy. In only 35 cases, or 19%, was there evidence of optical peculiarities in the radio galaxy. We have included isophotal twists ($>25^\circ$), nonconcentric isophotes, or any other unusual features in this count. Nine (5%) of the radio galaxies are classified as Dumbell galaxies. We have used the definition of two or more roughly equal-size and magnitude galaxies within a projected radius of 10 kpc sharing a common envelope. The percentage of close companions found here for our cluster sample is comparable to the studies of Heckman *et al.* (1986), Smith & Heckman (1989), and Colina & Pérez-Fournon (1990). However, the largest portion of the sample, 121 radio galaxies, or 65%, have no close companions within 20 kpc, and only 6% actually show evidence for an interaction.

From our control sample (50 galaxies), the following results were found: percentage of dumbell galaxies=0%, number of galaxies with companions within 20 kpc=30%, percentage of galaxies with disturbed morphology in the control object or its companion=10%. The zero detection of dumbell galaxies in the control sample is at least partly explained by the lack of any *cD* galaxies in this sample. While not completely rigorous, this comparison is illuminating. Given these ratios, and using a 2×2 contingency test to approxi-

mate a χ^2 probability distribution, we find no statistical difference in the fraction of galaxies with close neighbors or the frequency of optical morphological peculiarities between the radio-loud and quiet samples.

From these results, we conclude that the interaction with other galaxies or the proximity of nearby galaxies is not common in the majority of cluster radio galaxies. We have found statistically identical results for a random sample of radio-quiet ellipticals. Thus, while it is not obvious that nearby galaxies affect radio source formation, it is possible that the properties of an established radio source might be affected by close passage or the proximity of a nearby galaxy. We have examined the distribution in radio power of those galaxies selected above as having close companions and those which were isolated on scales <20 kpc. We found no difference in the total radio power. A KS test showed the two samples inconsistent with the same parent sample at only 34% significance.

6. DISCUSSION

From the results in Sec. 4, we have shown that cluster FR I radio galaxies are optically indistinguishable from randomly selected radio-quiet cluster galaxies. Statistically, the measured surface-brightness profiles, the fundamental plane, the luminosity/size relationships, and ellipticities of the radio galaxy sample, the control sample, and elliptical galaxies selected from the literature, are all consistent with having been drawn from the same parent sample of objects. The optical luminosity appears to be the fundamental parameter which describes elliptical galaxies as a class.

The frequency of nearby companions within a 20 kpc projected distance and the fraction of galaxies with disturbed morphology is not significantly different for the radio-loud sample. In Paper IV, we have shown that the cluster morphology, richness, and location within the cluster also do not affect the detection rate or the total radio power of radio galaxies. These findings are also consistent with the emission-line properties of this sample. Owen *et al.* (1995a) looked for correlations between the optical luminosity, radio power, $H\alpha + [\text{N II}]$, and $[\text{O II}] \lambda 3727$ luminosities. They found that the apparent correlation between radio and emission-line luminosities was a result of the mutual dependence on the optical luminosity; in particular, the optical dependence on the radio power of the FR I/II break (Owen & Ledlow 1994). When compared to a sample of radio-quiet elliptical galaxies at the same optical luminosity, the radio galaxy emission-line luminosities were not found to be statistically different. The detected fraction of emission-line galaxies was also not affected by the radio properties (for FR I's).

Zirbel & Baum (1995) have also examined the host galaxy properties of FR I's, FR II's, and optically selected galaxies. In particular, they have looked for correlations between the optical, radio (both core and extended), and emission-line luminosities for a large sample of mostly non-rich cluster galaxies. While they found that the mutual correlations between these luminosities appear to be functionally different for FR I's and FR II's, at a fixed total radio

power, these properties are very similar between the two FR types. This is particularly interesting in light of the optical dependence of the FR I/II break. This result suggests that in the transition region very near the break, the optical, radio, and emission-line properties of the two FR types are not that different. This result very likely applies to the host galaxy properties as well. The differences between the FR types are the most obvious when one includes the most luminous FR II's (which are almost all at much higher redshift; $z \gtrsim 0.5$), which may be affected by evolution. Zirbel and Baum also find that the emission-line properties of their FR I galaxies are not distinguishable from samples of radio-quiet galaxies, consistent with the findings of Owen *et al.* (1995).

Radio-loud and quiet galaxies have also been compared in infrared colors. Eisenhardt & Lebofsky (1987) examined near-infrared *JHK* colors of a selected sample of radio galaxies from the 3CR survey and the catalog of Burbidge & Crowne (1979) over the redshift range $0.02 < z < 1.6$. Approximately 25% of their radio-loud sample was selected from Abell clusters. They found no significant difference in the optical to infrared colors of radio-selected and radio-quiet galaxies. They concluded that radio sources do not significantly alter the optical/infrared properties of elliptical galaxies. These conclusions were also found by Thuan *et al.* (1984) from infrared photometry of a sample of 40 radio galaxies from the Leiden-Berkeley Deep Survey (LBDS). Thuan *et al.* found no difference in the optical-infrared colors of the low-radio luminosity LBDS sources, strong 3CR radio galaxies and optically selected field galaxies. The colors also did not correlate with radio power.

These results have very important implications to our understanding of radio galaxies as a population. If FR I radio sources are not found in a unique subsample of elliptical galaxies, this opens the possibility that all elliptical galaxies may at some time (or many times) over the course of their evolution experience a radio-loud phase. Depending on the lifetime of the radio source, the radio-active stage may simply be a transient phenomenon which occurs in most or all ellipticals.

Because 95% of our cluster radio galaxy sample are FR I's, we are unable to address possible differences in host galaxy properties between the FR I/II classes from this sample. The results reported here are significant regarding the lack of unique optical properties (both photometric and spectroscopic) which define FR I host galaxies as compared to radio-quiet ellipticals. The significance of the optical dependence of the FR I/II break and a comparison of the host-galaxy properties of FR I and FR II's will be discussed in a future paper.

7. CONCLUSIONS

We have presented the analysis of optical *R*-Band CCD observations for 265 radio galaxies selected from Abell clusters, and a control sample of radio-quiet galaxies selected from the same environment. Our conclusions are as follows:

(1) Cluster radio galaxies trace the elliptical galaxy luminosity function very closely down to M^* . At fainter optical

luminosities, the fraction of galaxies which are radio loud decreases rapidly. Radio galaxies are not always the brightest galaxy in the cluster.

(2) The surface-brightness profiles, luminosity/size relationship, the fundamental plane, ellipticity, isophotal shapes, and emission-line properties of cluster FR I radio galaxies are not statistically different from radio-quiet cluster galaxies.

(3) The frequency of close galaxy companions (within 20 kpc) and the number of obviously interacting galaxy systems is no different with regard to the radio-loud and quiet cluster samples.

(4) From comparison of our results to those in the literature, there is some suggestion that non-rich cluster ellipticals (and radio galaxies) may have different optical properties from rich-cluster galaxies. These differences may be tied to either different evolutionary processes or may even occur at galaxy formation. We will address these issues in a future paper.

(5) The optical luminosity is the fundamental parameter which describes elliptical (radio-loud and quiet) galaxies. Any dependence of the radio power on any of the optical structural parameters can be related to a mutual dependence on the optical luminosity.

(6) Our analysis is consistent with the idea that all cluster ellipticals may at some time over the course of their evolution (or perhaps several times) experience a radio-loud phase.

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