THE ASTROPHYSICAL JOURNAL, Vol. 157, August 1969

RADIO SOURCES AND ELLIPTICAL GALAXIES

D. H. ROGSTAD AND R. D. EKERS
Owens Valley Radio Observatory, California Institute of Technology
Received November 13, 1968

ABSTRACT

One hundred ninety-one E and S0 noncluster galaxies with known redshift have been surveyed for radio emission at a frequency of 2640 MHz. The observations support the hypothesis that an elliptical galaxy must have an absolute photographic magnitude brighter than −20 to be a strong radio source. A comparison of the results of this survey with observations of radio galaxies in rich clusters indicates that cluster membership does not enhance the probability that an elliptical galaxy is a radio emitter. In addition to the strong radio sources, several E and S0 galaxies were found to have weaker radio emission associated with them, but their absolute radio luminosity was still on the order of 100 times larger than that for detected spiral galaxies.

I. INTRODUCTION

For some time it has been recognized that when radio sources are found in clusters of galaxies they are often identified with the brightest cluster member (e.g., Minkowski 1965). This has been further supported by the radio observations of clusters of galaxies (Fomalont and Rogstad 1966). Sandage (1964, 1965) has also noted that the elliptical galaxies identified with strong radio sources are among the brightest of all elliptical galaxies. Since in many cases Sandage's object is the brightest member in a cluster, it is not obvious whether having high optical luminosity or being the dominant member of a cluster of galaxies is an important characteristic of a strong radio source. To investigate this point we have made radio observations of all of the noncluster elliptical galaxies listed in the catalog of Humason, Mayall, and Sandage (1956, hereinafter referred to as HMS), the largest list of galaxies for which redshifts are available. For galaxies brighter than magnitude 11.6, it is essentially complete and will be an unbiased sample for an investigation of the probability of detecting radio emission. For galaxies fainter than magnitude 11.6, the sample is not complete and some bias may be introduced because selection depends on properties not independent of the probability of radio emission (e.g., compactness, presence of emission lines). However, it is believed that this bias has not seriously affected the present survey and conclusions.

The only previous extensive surveys of a similar nature are those by Heeschen and Wade (1964) and by Cameron and Glanfield (1968). Both of these surveys contained too few elliptical galaxies for any conclusions to be drawn.

The following section describes the observations and presents the results of our survey together with additional data for the galaxies with detected radio emission. The statistical properties of these galaxies are discussed in § III. Section IV contains a reanalysis of the cluster data from Fomalont and Rogstad (1966) and a comparison of the radio properties of cluster and noncluster galaxies. The main conclusions of this paper are summarized in § V.

II. OBSERVATIONS AND RESULTS

a) *Observations*

A search for radio emission was made in the direction of all the E and S0 galaxies listed in HMS with redshift less than 10000 km sec^{-1}. The S0 galaxies have been included with the E galaxies since both types are identified with strong radio sources. Also, in some cases, both E and S0 galaxies have been reclassified as Morgan D-type galaxies, and from the point of view of radio emission they seem to be closely related classes. For the remainder of this paper both groups will be referred to as elliptical galaxies. The observations of these 191 galaxies were made in 1967 and 1968 using the two 90-foot parabolas at the Owens Valley Radio Observatory as a twin-element interferometer with an east-west spacing of 100 feet at a frequency of 2640 MHz. The interferometer has been described in detail by Read (1963). Three sets of 20-minute observations were made of each galaxy; this gave an rms receiver-noise error of 0.03 flux units.[1] The interferometer output consists of fringe amplitude and phase. The amplitude is a measure of the flux density from the direction of the galaxy, and the fringe phase determines the position of the detected radio source. These two quantities were calibrated by observing standard sources every few hours.

b) Results

The results of the survey are contained in Table 1. The name of the galaxy observed is given in column (1), and its type, as listed in HMS, in column (2). The entry "em" indicates the observation of emission lines by HMS. Column (3) contains the observed flux density and its rms error. For those galaxies with flux density greater than twice the rms noise, column (4) gives the right ascension of the radio source, derived from the fringe phase, relative to the position of the galaxy given in HMS. This position is given in minutes of arc and increases to the east. Column (5) gives the apparent photographic magnitude of the galaxy taken from Table I of HMS and corrected for galactic absorption by using the formula

$$\Delta m_{\mathrm{pg}} = 0.25(\csc b - 1)\ .$$

Column (6) gives the distance to each galaxy either derived from the redshift given in HMS, assuming a Hubble constant of 100 km sec^{-1} Mpc^{-1}, or taken from Holmberg (1964) for the closer galaxies. Columns (7) and (8) give the absolute photographic magnitude and the absolute radio luminosity. The radio luminosity L was calculated by using

$$L = 4\pi r^2 \int_{10^{-7}}^{10^{11}} S_\nu d\nu\ ,$$

where

$$S_\nu = S_{2640}\left(\frac{\nu}{2640 \times 10^6}\right)^{-n}\ ,$$

for those sources with known spectral index n. For the rest of the galaxies, a mean spectral index of -0.75 was used. In this case the relation becomes

$$L = 2.55 S_{2640} z^2 \times 10^{44}\ \mathrm{ergs\ sec^{-1}}\ .$$

Because the observations were made at the high-frequency end of the range of integration, this relation is insensitive to the assumed value of the spectral index. The luminosity varies by only a factor of 2 for n between -0.3 and -1.4.

c) Confusion

At the time of these observations, we also made a special series of observations to measure the background confusion for the 90-foot antennas at a frequency of 2640 MHz. The rms value of the confusion was found to be 0.04 flux units. It should be realized, however, that the confusion error does not have a normal distribution, so in our case it

[1] One flux unit = 10^{-26} W m^{-2} (c/s)$^{-1}$.

TABLE 1 - OBSERVATIONAL RESULTS FOR 191 E AND SO GALAXIES

Name NGC (1)	Type (2)	Flux Density (3)	r_{α} (') (4)	m_{pg} (5)	Dist. (mpc) (6)	M_{pg} (7)	Log(L) (8)
68	SO	<0.18		14.4	60.1	-19.5	<40.27
71	E2	0.06(0.03)	1.5	14.6	68.2	-19.6	39.90
ANON	E4	0.06(0.03)	1.5	15.7	70.3	-18.6	39.92
80	SO	<0.14		13.8	57.9	-20.1	<40.12
83	EO	0.18(0.03)	2.3	14.2	67.4	-20.0	40.37
125	SO em	0.15(0.07)	-1.6		54.2		40.10
128	SO em	<0.14		12.7	43.8	-20.5	<39.88
185	Ep	0.11(0.05)	2.5	10.5	0.7	-13.8	36.18
194	E1	<0.06		13.3	52.4	-20.3	<39.67
221	E2	<0.06		9.5	0.7	-14.7	<35.92
227	E4	<0.06		13.5	54.2	-20.2	<39.70
375	E5	†		15.7	62.1	-18.3	
379	SO	†		13.8	55.7	-20.0	
380	E2	†		13.8	45.4	-19.5	
382	EO	†		13.8	53.5	-19.9	
* 383	SO	3.27(0.16)	1.3	13.4	50.9	-20.2	41.40
384	SO	†		14.4	46.0	-19.0	
385	E3	†		14.1	50.4	-19.5	
386	E3	†		15.5	57.5	-18.3	
388	E3	†		15.4	53.1	-18.3	
404	SO em	<0.16		11.1	1.5	-14.8	<37.02
474	EO	0.07(0.03)	-3.6	13.0	24.0	-18.9	39.06
495	SO	<0.14		13.9	43.1	-19.2	<39.87
499	SO	<0.15		12.9	45.7	-20.4	<39.95
507	E3	0.07(0.03)	1.4	12.5	51.2	-21.0	39.72
524	SO	<0.14		11.5	25.9	-20.5	<39.42
560	SO	<0.20		14.0	55.8	-19.8	<40.25
564	E3	<0.06		13.8	59.2	-20.1	<39.78
584	E3	0.09(0.03)	3.0	11.4	18.8	-20.0	38.95
596	EO	<0.12		12.1	21.0	-19.5	<39.17
636	E1	0.07(0.03)	-0.3	12.4	19.8	-19.1	38.89
720	E5	<0.10		11.3	18.1	-20.0	<38.97
736	E1	<0.06		13.3	45.3	-20.0	<39.54
* 741	EO	0.54(0.06)	-0.8	12.9	56.4	-20.8	40.76
750	EO	<0.06		13.4	52.9	-20.2	<39.68
751	EO	<0.06		13.8	52.9	-19.8	<39.68
821	E6	<0.06		11.9	18.6	-19.4	<38.77
890	SO	<0.14		12.3	41.9	-20.8	<39.84
1049	Ep	<0.06					
FORNAX	Ep	<0.06					

TABLE 1 - CONTINUED

Name NGC (1)	Type (2)	Flux Density (3)	r_{α} (') (4)	m_{pg} (5)	Dist. (mpc) (6)	M_{pg} (7)	Log(L) (8)
* 1052	E3 em	0.54(0.04)	0.4	11.6	14.2	-19.2	40.06
1199	E3	<0.08		12.8	25.2	-19.3	<39.16
1201	SO	<0.14		11.7	16.3	-19.4	<39.02
1209	E6 em	0.06(0.03)	0.7	12.6	25.0	-19.4	39.03
1332	SO	<0.14		10.9	15.1	-19.9	<38.95
1395	E2	0.06(0.03)	0.9	11.3	15.7	-19.7	38.62
* 1399	E2	0.50(0.08) †	0.0	11.1	13.0	-19.4	39.38
1404	E1	0.09(0.03)	-2.0	11.0	18.8	-20.3	38.96
1400	E1	<0.06		12.2	3.8	-15.7	<37.39
1407	EO	0.14(0.03)	-1.2	11.1	17.1	-20.0	39.06
1426	E4	<0.06		12.5	12.4	-17.9	<38.42
1439	EO	0.08(0.03)	-1.4	12.8	18.8	-18.5	38.90
1449	SO	<0.16		14.5	41.2	-18.6	<39.89
1451	E3	0.08(0.03)	6.6	14.4	38.7	-18.6	39.53
1453	E1 em	<0.06		12.8	38.6	-20.2	<39.40
1521	E3	<0.06		12.9	40.6	-20.1	<39.45
1587	E1	0.12(0.04)	0.7	13.0	38.1	-19.9	39.69
1600	E5	0.16(0.03)	0.7	12.0	47.3	-21.4	40.01
1601	SO	<0.14		14.9	48.9	-18.6	<39.98
1700	E3	<0.06		11.8	38.6	-21.1	<39.40
1889	EO	0.11(0.03)	-1.0	14.1	23.1	-17.8	39.22
2314	E3	<0.06		13.0	40.0	-20.0	<39.44
2300	E1	<0.08		11.9	21.5	-19.7	<39.02
2379	EO	<0.10		14.2	39.9	-18.8	<39.66
2549	SO	<0.20		11.9	11.6	-18.4	<38.88
2563	SO	<0.20		13.4	46.6	-19.9	<40.09
2655	SO em	<0.20		10.6	14.7	-20.3	<39.09
2672	E1	0.07(0.03)	1.0	13.0	41.0	-20.1	39.52
2673	EO	0.07(0.03)	1.0	14.2	36.7	-18.6	39.43
2685	SO em	<0.20		12.2	9.6	-17.8	<38.72
2693	E2	<0.06		13.2	50.0	-20.3	<39.63
2694	EO	<0.06		15.4	51.6	-18.2	<39.66
2723	SO	<0.14			35.3		<39.69
2749	E2 em	<0.20		13.3	40.8	-19.7	<39.97
2768	SO	<0.12		10.9	15.0	-20.0	<38.88
2831	E1	<0.06		14.7	51.0	-18.8	<39.65
2832	E2	<0.06		13.4	68.9	-20.8	<39.91
2855	SO em	0.16(0.07)	-1.7	12.3	16.5	-18.8	39.09
2865	E4	<0.12		12.0	24.4	-20.0	<39.31
* 2911	SO em	0.21(0.08)	2.5	13.5	29.8	-18.9	39.72

TABLE 1 - CONTINUED

Name NGC (1)	Type (2)	Flux Density (3)	r_α (') (4)	m_{pg} (5)	Dist. (mpc) (6)	M_{pg} (7)	Log(L) (8)
2974	E4 em	<0.10		11.7	18.0	-19.6	<38.96
2986	E2	0.06(0.03)	3.2	11.8	21.3	-19.8	38.89
3032	SO	<0.16		12.7	15.0	-18.1	<39.01
* 3078	E2	0.27(0.04)	-1.1	11.7	22.0	-20.0	40.68
3115	E7	<0.06		9.9	4.2	-18.2	<37.48
3158	E3	<0.06		13.1	70.1	-21.1	<39.92
3193	E2	<0.06		12.1	12.7	-18.4	<38.44
3226	E1 em	0.14(0.03)	2.7	12.5	12.3	-17.9	38.78
3245	SO	<0.14		11.8	12.0	-18.6	<38.76
3348	EO	0.09(0.03)	-5.2	11.9	30.1	-20.5	39.36
3377	E6	<0.12		11.3	5.9	-17.6	<38.08
3379	EO	0.12(0.04)	-3.4	10.5	7.3	-18.9	38.26
3489	SO em	<0.18		11.0	5.7	-17.8	<38.22
3585	E6	<0.06		10.8	12.3	-19.7	<38.41
3593	SO em	<0.18		11.6	4.3	-16.6	<37.97
3605	E4	<0.12		14.0	6.0	-14.9	<38.09
* 3607	SO	0.20(0.07)	-0.8	11.0	8.6	-18.7	38.62
3608	E1	0.11(0.03)	-3.5	12.1	11.2	-18.2	38.59
3613	E5	<0.12		11.7	21.5	-19.9	<39.20
3619	SO em	<0.20		12.5	17.4	-18.7	<39.24
3640	E2	<0.10		11.6	12.0	-18.8	<38.61
3665	SO	0.17(0.08)	1.2	11.9	20.1	-19.6	39.29
3718	SO em	<0.20			11.3		<38.86
3818	E5	<0.20		12.9	13.2	-17.7	<38.99
3872	E3	<0.10		13.0	30.1	-19.4	<39.41
3904	E2	0.12(0.05)	5.7	11.9	13.8	-18.8	38.81
3923	E4	<0.06		11.1	15.5	-19.9	<38.61
3962	E1 em	0.10(0.05)	5.6	11.8	16.0	-19.2	38.86
* 3998	SO em	0.22(0.07)	0.6	11.2	12.0	-19.2	38.96
4026	SO	<0.10		11.7	9.6	-18.2	<38.41
4036	SO em	<0.14		11.5	15.1	-19.3	<38.95
4105	E2 em	<0.08		11.8	16.6	-19.3	<38.80
4111	SO em	<0.14		11.6	8.3	-18.0	<38.44
4125	E6	<0.06		10.8	14.4	-20.0	<38.55
4150	SO em	0.18(0.08)	6.4	12.6	2.3	-14.3	37.45
4251	SO	<0.20		11.6	10.0	-18.4	<38.75
* 4278	E1 em	0.52(0.03)	0.4	11.2	10.0	-18.8	39.69
4283	EO	<0.15		13.1	10.6	-17.0	<38.68
4291	E2	<0.06		12.3	19.6	-19.2	<38.82
4494	E1	0.06(0.03)	-3.8	10.9	13.2	-19.7	38.47

TABLE 1 - CONTINUED

Name NGC (1)	Type (2)	Flux Density (3)	r_α (') (4)	m_{pg} (5)	Dist. (mpc) (6)	M_{pg} (7)	Log(L) (8)
ANON	SO em	<0.20			72.3		<40.47
IC3481	E3	<0.16			70.1		<40.35
4589	E1	0.09(0.03)	-4.9	11.9	20.0	-19.6	39.01
4915	EO	0.19(0.09)	3.3	13.0	30.4	-19.5	39.70
5018	E4	<0.14		12.1	27.4	-20.1	<39.47
5049	SO	0.17(0.08)	1.5	13.7	26.0	-18.4	39.51
* 5077	E3 em	0.57(0.18)	-0.2	12.5	25.1	-19.5	40.00
5087	SO	0.16(0.08)	-1.4	12.0	16.7	-19.1	39.10
* 5128	Ep em	912.00(9.12)	0.0	7.2	4.0	-20.8	41.55
5173	EO em	<0.06		13.8	25.1	-18.2	<39.03
5195	Ep em	<0.15		10.7	6.5	-18.4	<38.25
5198	E1	<0.08		13.0	25.9	-19.1	<39.18
5273	SO	0.22(0.10)	4.6	12.5	10.9	-17.7	38.87
5308	SO	<0.18		12.1	22.1	-19.6	<39.39
5322	E4	<0.12		10.9	20.6	-20.6	<39.16
5353	SO	<0.20		12.1	22.8	-19.7	<39.47
* 5485	SO	0.40(0.12)	-1.5	12.6	21.4	-19.1	39.71
5557	E1	<0.06		12.3	33.0	-20.3	<39.27
5576	E4	<0.06		12.0	15.1	-18.9	<38.59
5631	SO em	<0.16		12.5	21.4	-19.1	<39.32
5638	E1	<0.10		12.4	16.6	-18.8	<38.89
5687	E3	<0.08		12.8	22.9	-19.0	<39.07
5689	SO	0.18(0.08)	4.2	12.9	23.5	-19.0	39.45
5812	E1	0.07(0.03)	3.6	12.5	20.4	-19.1	38.92
5813	E1	0.15(0.03)	2.6	11.7	18.9	-19.7	39.18
5820	SO	<0.16		13.0	34.4	-19.6	<39.73
5831	E3	<0.08		12.5	17.0	-18.6	<38.81
5838	SO	0.26(0.09)	-2.6	11.8	14.4	-19.0	39.18
5846	EO em	<0.10		11.2	17.8	-20.0	<38.95
ANON	E2	<0.10		14.0	22.9	-17.8	<39.17
5866	SO em	<0.20		10.8	9.2	-19.0	<38.68
5898	EO	0.13(0.03)	4.5	12.3	22.3	-19.4	39.26
5903	E2	0.09(0.03)	0.5	12.4	25.4	-19.6	39.22
5982	E4	<0.06		12.3	30.7	-20.1	<39.21
ANON	SO em	<0.18			96.1		<40.67
6359	E1	0.07(0.02)	-4.6	13.6	32.0	-18.9	39.31
6482	E3	<0.04		12.7	41.4	-20.4	<39.29
6658	SO em	<0.14		13.3	45.1	-20.0	<39.91
6661	SO	0.31(0.14)	-5.7	12.4	46.1	-20.9	40.27
6702	E2	0.08(0.02)	-4.0	13.5	50.2	-20.0	39.76

TABLE 1 - CONTINUED

Name NGC (1)	Type (2)	Flux Density (3)	r_α (') (4)	m_{pg} (5)	Dist. (mpc) (6)	M_{pg} (7)	Log(L) (8)
6703	SO	<0.16		12.0	25.9	-20.1	<39.48
6927	SO	<0.14		15.0	45.2	-18.3	<39.91
ANON	E7	<0.08			46.6		<39.69
6944	E1	0.04(0.02)	-0.6	13.9	46.0	-19.4	39.38
6963	EO	0.06(0.03)	-0.2	14.9	45.5	-18.4	39.55
6964	E4	<0.10		13.9	40.4	-19.2	<39.66
ANON	E1	<0.06		14.9	94.1	-20.0	<40.18
ANON	SO	<0.14			62.7		<40.19
7242	E3	0.04(0.02)	1.3	13.6	59.7	-20.2	39.61
7252	SO em	<0.14		13.0	48.1	-20.4	<39.96
7302	SO	<0.20		13.0	27.2	-19.1	<39.62
7317	E4	0.09(0.03)	1.7	14.9	70.1	-19.4	40.10
7318	E2	0.09(0.03)	1.7	14.4	69.2	-19.8	40.09
7332	SO	<0.20		11.4	14.6	-19.4	<39.08
7343	E3	<0.06		14.1	14.9	-16.8	<38.58
7377	SO	0.16(0.07)	-3.8	12.4	35.0	-20.4	39.74
* 7385	EO	1.40(0.10)	-0.1	14.0	80.5	-20.6	41.40
7386	SO	<0.20 †		14.5	74.2	-19.9	<40.49
IC1460	SO em	<0.16		15.2	74.6	-19.1	<40.40
7457	SO	<0.14		12.0	7.9	-17.5	<38.39
7507	EO	0.08(0.03)	-5.2	11.6	16.8	-19.6	38.81
7585	SO	<0.20		12.7	34.8	-20.1	<39.84
7600	E5	0.07(0.03)	-2.6	13.0	35.3	-19.8	39.39
7611	SO	<0.14		13.5	35.8	-19.3	<39.71
7617	SO	<0.10 †		14.9	42.7	-18.2	<39.71
7619	E3	<0.10 †		12.3	39.5	-20.7	<39.64
7623	E4	<0.12		13.9	36.6	-18.9	<39.66
7625	SO em	<0.20		13.1	19.3	-18.4	<39.32
* 7626	E1	0.50(0.04)	-0.8	12.6	35.5	-20.1	40.32
7679	SO em	<0.18		13.1	53.8	-20.5	<40.17
7785	E5	<0.06		12.9	40.1	-20.1	<39.44

* - Galaxies which were positively detected.

† - Fluxes and positions corrected or omitted due to known confusion sources in beam.

is more useful to point out that in 100 observations four would give flux densities greater than 0.2 flux units. For the observations giving a flux density significantly greater than the receiver noise, phase information is available and can be used to distinguish between confusion (which would give a signal of random phase) and radiation from the galaxy. Fourteen galaxies satisfied the criterion that the flux density must be higher than 0.2 flux units and 2.5 times the quoted noise error. We also require that the phase must give a position for the radio emission within 1′.5 of the galaxy center measured on the *Palomar Sky Survey* prints. We consider these to be positive detections, and they are indicated as such by an asterisk to the left of their names in Table 1.

TABLE 2

DETECTED RADIO SOURCES

Catalog No		Flux Density (10^{-26} W m^{-2} Hz^{-1})			Spectral Index	Position (1950)		Refs †	Structure
NGC	Other	S_{1400}	S_{2700}	S_{10000}		R A	Decl *		
383	3C 31	5 0	3 27		−0 7	01^{h}04^{m}40^s	+32°09′	6	2′6 double, emission peak centered on NGC 383
741	P0153+05 4C05.10	0 9	0 54		−0 6	01 53 45	+05 23	4	
1052	. . .	0 5‡	0 54	1 0‡	−0 05	02 38 38	−08 28	3, 4	<2″ arc
1399	P0336−35		0 50		(−0 8)	03 36 36*	−35 37	2	See text
2911		. . .	0 21	. .	.	09 31 10	+10 22		
3078		0 28	0 27	0 48	+0 4	09 56 07	−26 41		
3607			0 20			11 14 15	+18 19		
3998		. .	0 22	. . .	. .	11 55 28	+55 14		
4278		0 60	0 52	0 29	−0 1	12 17 38	+29 34	3, 4	<2″ arc
5077	.	0.22	0 57	0 21	−0 8	13 16 53	−12 24		
5128	Cen A	1330	912		−0 6	13 22 24	−42 46	1	2°5 double
5485	. .	. .	0 40	. . .	. .	14 05 20	+55 14		
7385	P2247+11 4C11 71	2 5	1 4	0 27	−0 9	22 47 23	+11 21	5	2′3 double E-W
7626	P2318+07	0 8	0 5	(0 15)	−0 6	23 18 09	+07 56		

* Position from HMS

† References to other literature: 1, Cooper, Price, and Cole (1965); 2, Ekers (1968); 3, Heeschen (1968); 4, Heeschen and Wade (1964); 5, Fomalont (1968); 6, Parker and Kenderdine (1967)

‡ From Heeschen (1968)

d) *Other Data for the Detected Radio Sources*

For some of the sources found in this survey, other measurements have been made, and these additional data are given in Table 2.

Following the recent discovery by Heeschen (1968) of flat spectral components in the elliptical galaxies NGC 1052 and NGC 4278, A. Moffet and W. Sargent kindly agreed to observe some of the detected galaxies listed in Table 1 at other frequencies. These observations were made with the same telescope at 1420 and 10000 MHz, and these results are also given in Table 2.

The radio source P0336−35 has a component, located 5′ south of the radio centroid and containing 30 percent of the total flux density, which is coincident with NGC 1399 (Ekers 1968). The flux densities given in Tables 1 and 2 are based on the assumption that only this component is associated with NGC 1399.

e) Proximity of Other Galaxies

When there are two or more galaxies in the primary beam of the 90-foot antennae (19 minutes of arc to half-power points), radiation from any one of these may mask the radiation from the others. For this reason no information is given for the six galaxies near NGC 383 (radio source 3C 31), and they have been excluded from the statistics.

III. DISCUSSION OF THE NONCLUSTER GALAXIES

Although the number of positive detections made in this survey is small, we do have the advantage of having a sample of galaxies with known redshift which is unbiased for a study of radio emission. For this reason we will confine the present discussion to those aspects for which we have the best information—namely, the probability that elliptical galaxies are radio sources, and the absolute luminosities of those galaxies.

a) Absolute Luminosity

From the absolute radio luminosity L, or the upper limit, and absolute optical magnitude, it can be seen that the galaxies in this sample which are strong radio sources ($L \gtrsim 10^{41}$) do have the high optical luminosity found for radio galaxies in general, and that those which are weaker radio sources have lower optical luminosity. These weaker radio sources have lower optical luminosity. These weaker radio sources, $L = 10^{39}$–10^{41}, appear to be similar to the three sources, 3C 270, 3C 272.1, and 3C 386, discussed by Matthews, Morgan and Schmidt (1964) as members of the class of the weakest of the strong radio sources.

In Figure 1 we have plotted the positive detections from this survey with data for the radio galaxies and QSOs kindly supplied by A. Sandage, and data for the spiral galaxies from De Jong (1967). The B photoelectric magnitudes for the data from Sandage have been used since these are close to the photographic-magnitude system. The radio-magnitude scale defined by the relation $m_r = -54.6 - 2.5 \log S_{2695}$ used by De Jong (1967) has been added to the right-hand side of Figure 1 for convenience.

This figure suggests a weak correlation between absolute optical magnitude and radio luminosity for the radio-source elliptical galaxies with no obvious break between the stronger and weaker radio sources. The spiral galaxies form a well-separated class an order of magnitude fainter in radio luminosity.

b) Probability of Radio Emission

For the present paper it is convenient to define a strong radio source as one having $L \geq 1.7 \times 10^{41}$ ergs sec^{-1} since this is the limit of completeness for the cluster data discussed in the next section. This definition is also in accord with previous luminosity limits used when discussing strong radio sources. For our sample we find that 6 percent (three out of forty-eight) of the elliptical galaxies brighter than magnitude -20 are strong radio sources. Since we have detected all the elliptical galaxies that are strong radio sources from an unbiased sample, this is a direct estimate of the probability that an elliptical galaxy brighter than magnitude -20 is a strong radio source. However, since the numbers are so small, it is useful to compare this probability with that found indirectly by comparing the density of a somewhat larger sample of radio sources with the density of bright elliptical galaxies (Schmidt 1966). Such an analysis, made in the Appendix by using values appropriate to our conditions, gives a probability of 7.7 percent that a bright elliptical galaxy is a strong radio source. This is in agreement with the value found for our sample.

c) Other Properties

Taking all our data together, we find a possible correlation between radio emission and the presence of emission lines in the optical spectra. Six of the thirty-seven (16 percent) elliptical galaxies with emission lines have been positively detected, as compared with eight of the 145 (6 per cent) without emission lines.

Five out of seven of the elliptical galaxies observed by Moffet and Sargent (private communication) appear to have a flux density at 10000 Mc/s in excess of that expected for a normal-spectrum radio source, an observation which suggests that this characteristic may be a common feature of elliptical galaxies.

IV. THE CLUSTER DATA

To compare the radio properties of field and cluster elliptical galaxies, we have re-examined the results of the radio observations of Fomalont and Rogstad (1966, hereinafter referred to as FR) of clusters of galaxies from the catalog of Abell (1958).

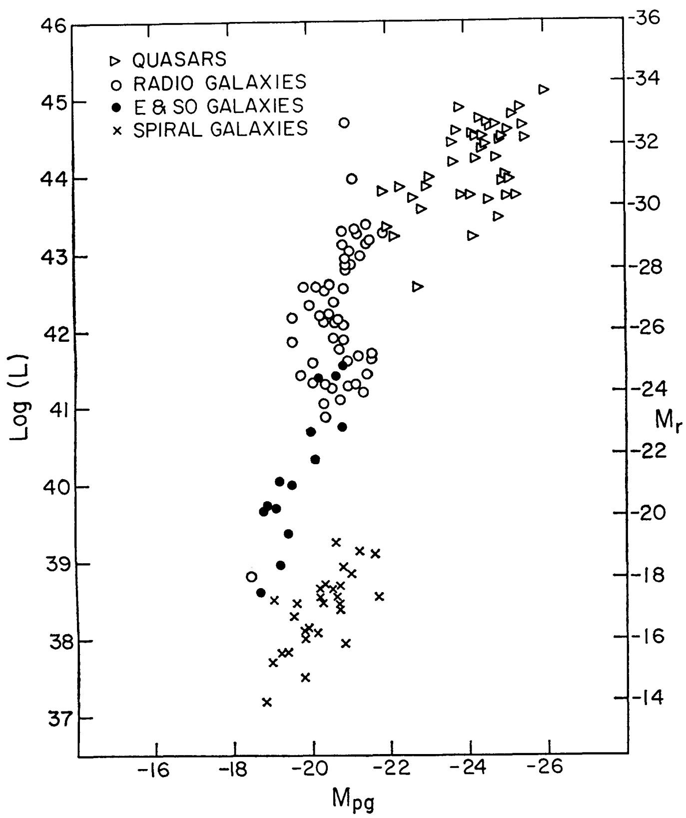

FIG. 1.—Absolute radio luminosity vs. absolute photographic magnitude for the detected elliptical galaxies, along with radio galaxies and QSOs from Sandage (private communication) and spiral galaxies from De Jong (1967).

All the clusters of galaxies of richness 0 or greater and distance 3 or less were observed by FR. For a Hubble constant of 100 km sec^{-1} Mpc^{-1}, distance 3 corresponds to 224 Mpc. It should be noted that Abell's distance scale for the clusters is based on the red-shift measurements of HMS and so is directly related to the distance scale for the non-cluster elliptical galaxies in the present observations. The limit of detection for the cluster radio observations was 0.2 flux units at 1445 Mc/s; thus any cluster members with radio luminosity greater than 1.7×10^{41} ergs sec^{-1} (assuming a mean spectral index of -0.75) would have been seen. The limit of detection is not as low where there is confusion with strong nearby radio sources, but a check of the data has shown that no clusters would have to be excluded from the sample for this reason.

The fields of all the clusters observed were reexamined on the *Palomar Sky Survey* prints, and identifications were made with individual galaxies if they were within 2 standard deviations of the radio position (the average radio-source position error was 0'.5).

a) Probability of Radio Emission for Cluster Ellipticals

To make the comparison between the probability of radio emission from cluster and noncluster elliptical galaxies, it is necessary to find the number of cluster elliptical galaxies above a given absolute optical magnitude which are strong radio sources. Since photometric data are not available for the majority of the cluster members, we have made the analysis by estimating their rank and using a mean-luminosity function for the cluster to determine their absolute magnitudes. Although it is realized that individual estimates of magnitudes made in this way will have considerable error, both from variations in the luminosity function and from errors in the estimate of rank, the method is felt to be satisfactory for a statistical discussion.

HMS give a difference of 0.84 mag between the first- and fifth-rank cluster members. The mean absolute magnitude of the brightest cluster members determined by Sandage (private communication) is -20.8 (corrected to the photometric-magnitude scale of HMS), hence the mean absolute photometric magnitude of the fifth brightest cluster member is -20.0. We can now find the probability that a cluster elliptical galaxy brighter than absolute magnitude -20.0 is a strong radio source by counting the number of identifications with cluster galaxies in the first five ranks. To ensure radio completeness down to a given absolute luminosity, it is necessary to allow for the width of the primary beam used in the observations of FR, since these galaxies are not necessarily at the center of the clusters. In order to do this in an unambiguous manner, we have counted only the identifications in a fixed spatial volume centered on the cluster. For the 14'.1 beam ($1/e$ width) used by FR, any source with radio luminosity above the completeness limit of 1.7×10^{41} ergs sec^{-1} within a radius of 500 kpc will be seen. The number of galaxies with rank of 5 or higher (referred to the whole cluster) in this volume has been calculated by assuming the galaxies have a trivariate distribution with a standard deviation of 240 kpc (Scott 1962; also see FR) and is 4.15 galaxies per cluster.

Using this method, we find that out of a sample of 460 elliptical galaxies with $\langle M \rangle_{\rm pg}$ larger than -20.0, twenty-three have $L_R > 1.7 \times 10^{41}$ ergs sec^{-1}, i.e., 5 percent.

The optical-luminosity function used was determined for clusters dominated by elliptical galaxies, and we considered only elliptical galaxies when determining the rank. However, if all types of galaxies are counted, 20 percent of the galaxies brighter than rank 5 are spirals. If it is assumed that the luminosity function is independent of galaxy type, then our probability that an elliptical galaxy is a strong radio source is increased to 6.3 percent. Our data suggest that this assumption is valid since fewer radio sources were found in clusters with bright spiral members. However, we have not attempted to push this type of analysis too far because of the difficulties in estimating the rank of different types of galaxies, and because of the possible differences in the distribution of galaxies in regular (elliptical dominated) and irregular (spiral dominated) clusters (Abell 1962).

b) Comparison of Cluster and Non-Cluster Galaxies

There is considerable latitude in the defining of a cluster, and it is possible that all galaxies are in clusters of some sort, from the very obvious compact clusters to the small groups and the diffuse irregular clusters. In this discussion we are interested in comparing the properties of radio sources in relatively rich clusters with those in poorer clusters or in no cluster at all. We will consider galaxies in groups with less than thirty members in the interval of 2 mag fainter than the second brightest member (Abell's definition of richness 0) as noncluster galaxies. The galaxies in Table I of HMS are defined as not being in groups of more than forty members. Since there is some overlap in these definitions, we have excluded the galaxies NGC 507, 1399, 1404, 2831, and 2832 from the noncluster sample by using the data on groups given in Table XI of HMS. This restricted sample of galaxies was used in the calculation of the probability of radio emission for the noncluster elliptical galaxies in § III (*b*).

The probability, $P_c = 6.3$ percent, that a cluster elliptical galaxy brighter than absolute photographic magnitude -20.0 is a strong radio source can now be compared directly with the values of the probability for the noncluster elliptical galaxies, $P_{nc} = 6$ percent for our data or 7.7 percent from the Appendix.[2] From this agreement we postulate that the probability that a bright elliptical is a radio source is the same for cluster and noncluster ellipticals, and that it is possible to account for the radio emission from clusters by the probability that individual galaxies are radio sources.

This postulate can be examined further by looking at the distribution of the number of strong radio sources against the rank of their identification. If the postulate is true, we would expect that the identifications should not all be with the first-rank cluster members, but should have a distribution with absolute optical magnitude similar to that found for radio sources in general. These distributions are given in Table 3.

TABLE 3

DISTRIBUTION OF IDENTIFICATIONS WITH CLUSTER RANK

Cluster Rank (1)	Number of Identifications (2)	$\langle M \rangle_p$ (3)	Number Predicted (4)
1.... .	8	−21 0	11
2... .	6	−20 7	4
3.... .	3	−20 5	4
4.... .	5	−20 2	1
5 .	1	−20 0	2
>5.....	1	>−20 0	2
No identification .	3		2

Columns (1) and (2) give the total number of identifications in each brightness rank for the cluster data. The mean absolute magnitudes, $\langle M \rangle_p$, for each rank, calculated from the luminosity function of Abell (private communication) and normalized to Sandage's value for rank 1, are given in column (3). These are used to obtain the predicted distribution of numbers, column (4), from the photoelectric data of Sandage used in Figure 1. The last entry in this column is the number of radio sources expected to be associated with the clusters by chance. Although this comparison is somewhat indirect, we believe this good agreement to be significant.

c) Cluster Richness

If the probability that a cluster contains a strong radio source is to be explained by the probability that individual galaxies are strong radio sources, a correlation between cluster richness and number of strong radio sources might be expected. No strong correlation has been found between these parameters (e.g., FR and Tovmassian and Moiseev [1967]). This lack of correlation can be explained since the density of galaxies at the bright end of the galactic luminosity function is not strongly dependent on richness, at least for the range in richness involved in this sample (Abell 1958). This interpretation is

[2] It should be noted that the determination of P_{nc} in the Appendix used the same cluster radio data as were used to determine P_c. However, this does not invalidate our comparison since the cluster data affect the two percentages in the opposite sense.

supported by the discovery of Sandage (private communication) that the values of the absolute magnitude of the brightest cluster members have very little dispersion and are independent of richness even down to small groups.

V. SUMMARY

The present observations of an unbiased sample of elliptical galaxies support the hypothesis that having absolute photographic magnitude brighter than about -20 is a necessary condition for an elliptical galaxy to be a strong radio source.

From a reexamination of the cluster data of FR and a comparison with the data for noncluster elliptical galaxies, we conclude that membership in a *rich* cluster does not significantly enhance the probability that an elliptical galaxy is a radio source—and as a corollary, the probability of radio emission from rich clusters of galaxies is explained by the number of bright elliptical galaxies they contain. The cluster radio source is not necessarily the brightest member, nor is it necessarily centrally located in the cluster. Also, because of the nature of the bright end of the cluster optical-luminosity function one does not expect to find a correlation of the probability of radio emission with cluster richness. A similar conclusion was reached by Wills (1966).

The number of members of the class of elliptical galaxies that are weaker radio sources has been increased. The average absolute radio luminosity of the detected ellipticals appears to be about 100 times greater than the radio luminosity of the spiral galaxies that have been detected (see Fig. 1), and they fall in the same range of absolute optical magnitude.

With the inclusion of the elliptical galaxies having weak radio emission, there may be a correlation between absolute radio luminosity and absolute optical magnitude (see Fig. 1) for radio galaxies in general. The division between the strong and weak radio sources may be artificial. However, the structure has been determined for a few of these weaker radio sources, and they are found to have single components rather than the predominantly double-component structure of the strong radio sources. It would be interesting to make further investigations of the structure of these objects.

We would like to acknowledge the use of material supplied by Drs. A. Sandage and G. Abell prior to its publication. The program of research in radio astronomy at the California Institute of Technology is supported by the U.S. Office of Naval Research under contract N00014-67-A-0094-0008.

APPENDIX

It is possible to derive an estimate of the probability that a bright noncluster elliptical galaxy will be a strong radio emitter by using the volume densities for bright noncluster elliptical galaxies, strong radio galaxies, and rich clusters of galaxies, together with the percentage of rich clusters having radio emission associated with them.

a) Bright Noncluster Ellipticals.—The HMS catalog gives a nearly complete list of noncluster E and S0 galaxies out to 38 Mpc over 63 percent of the sky. There are fifteen of these galaxies which have absolute magnitude $\langle M\rangle_{pg} \gtrsim -20.0$. Therefore the density of bright noncluster ellipticals is $D_E = 1.04 \times 10^{-4}$ Mpc^{-3}.

b) Rich Clusters of Galaxies.—Abell's catalog (1958) of rich clusters of galaxies provides a list of clusters that is probably complete down to richness 0 out to about 100 Mpc. Using the twenty clusters found in the volume between 50 and 100 Mpc, we obtain a density for rich clusters of $D_c = 1.2 \times 10^{-5}$ Mpc.

c) Strong Radio Sources Identified with Galaxies.—Following the derivation given in Schmidt (1966), we use the 3 CR catalog of radio sources (Bennett 1962) which is complete down to 9 flux units at 178 MHz over 54 percent of the sky. For our luminosity cutoff of 1.7×10^{41} ergs sec^{-1} this catalog is complete to 71 Mpc. The 3 CR radio sources found within this volume with log $_{10}$ $L \geq 41.23$ and which are identified with E-type galaxies are: 3C 40, 3C 66, 3C 75, 3C 83.1, 3C 84, 3C 264, 3C 274, 3C 278, and 3C 430, taken from the identifications of Matthews, Morgan, and Schmidt (1964). Schmidt (1966) believes this list is probably complete. This gives a volume density for strong radio sources identified with galaxies of $D_R = 1.1 \times 10^{-5}$ Mpc^{-3}.

d) Strong Radio Sources Identified with Noncluster Galaxies.—The density of radio sources identified with noncluster galaxies can be derived from the above densities by subtracting the density of radio sources associated with cluster galaxies from the complete radio-galaxy density D_R. From the reevaluation of the cluster radio data of Fomalont and Rogstad (1966) presented in § IV, we find that in 25 percent of the rich clusters one of the members is a strong radio source. Therefore, 25 percent of the rich-cluster density D_c, or 0.3×10^{-5} Mpc^{-3}, is the density of radio galaxies associated with rich clusters. Subtracting this from the radio-galaxy density D_R gives $D_{\rm RNC} = 0.8 \times 10^{-5}$ Mpc^{-3} for the density of noncluster radio galaxies.

Comparing the density of noncluster radio galaxies $D_{\rm RNC}$ with the density of bright noncluster ellipticals gives an estimate of $P_{\rm nc} = D_{\rm RNC}/D_e \times 100 = 7.7$ percent for the probability that a noncluster bright elliptical galaxy will also be a strong radio source.

REFERENCES

Abell, G. O. 1958, *Ap. J. Suppl.*, **3**, 211.

———. 1962, in *Problems of Extra-galactic Research*, ed. G. C. McVittie (New York: Macmillan Co.), p. 213.

Bennett, A. C. 1962, *Mem. R.A.S.*, **68**, 163.

Cameron, M. J., and Glanfield, J. R. 1968, *M.N.R.A.S.*, **141**, 145.

Cooper, B. F. C., Price, R. M., and Cole, D. J. 1965, *Australian J. Phys.*, **18**, 589.

De Jong, M. L. 1967, *Ap. J.*, **150**, 1.

Ekers, R. D. 1968, *Australian J. Phys. Ap. Suppl.* (in press).

Fomalont, E. B. 1968, *Ap. J. Suppl.*, **15**, 203.

Fomalont, E. B. and Rogstad, D. H. 1966, *Ap. J.*, **146**, 528.

Heeschen, D. S. 1968, *Ap. J.*, **151**, L135.

Heeschen, D. S., and Wade, C. M. 1964, *A.J.*, **69**, 277.

Holmberg, E. 1964, *Medd. Uppsala Astr. Obs.*, No. 148.

Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, *A.J.*, **61**, 97.

Matthews, T. A., Morgan, W W., and Schmidt, M. 1964, *Ap. J.*, **140**, 35.

Minkowski, R. 1965, in *Quasi-Stellar Sources and Gravitational Collapse*, ed. I. Robinson, A. Schild, and E. L. Schucking (Chicago: University of Chicago Press), p. 433.

Parker, E. A., and Kenderdine, S. 1967, *Observatory*, **87**, 124.

Read, R. B. 1963, *Ap. J.*, **138**, 1.

Sandage, A. R. 1964, in *Proceedings Padua Conference on Cosmology*, ed. L. Rosino (in press).

———. 1965, *Ap. J.*, **141**, 1560.

Schmidt, M. 1966, *Ap. J.*, **146**, 7.

Scott, E. L. 1962, in *Problems of Extra-galactic Research*, ed. G. C. McVittie (New York: Macmillan Co.), p. 269.

Tovmassian, H. M. and Moiseev, I. G. 1967, *Australian J. Phys.*, **20**, 715.

Wills, D. 1966, *Observatory*, **86**, 140.