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A Determination of the Local Radio Luminosity Function of Elliptical Galaxies

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Summary. Four samples of radiogalaxies are combined to estimate the local ($z<0.1$) radio luminosity function (RLF) of elliptical and SO galaxies at 1415 MHz from $10^{20.5}$ to $10^{26.5}$ WHz^{-1} ($H_0=100$). The samples contain: a) galaxies not in rich clusters from the HMS catalogue observed at Westerbork; b) 5 rich clusters observed at Westerbork; c) the B 2 sources identified with galaxies in the Zwicky Catalogue ($m_p \leqq 15.7$); d) the 3CR sources identified with galaxies with $m_v \leqq 17.0$. The bivariate RLF is obtained in four intervals of optical magnitude M_p: $(-22, -21)$ $(-21, -20)$ $(-20, -19)$ $(-19, -18)$. The RLF shows a break in the slope at a power P^* between 10^{24} and 10^{25} WHz^{-1}; the data are consistent with the position of the break being independent of (or only slightly dependent on) M_p. At $P>P^*$ and up to $10^{26.5}$ WHz^{-1}, the slope seems to be independent of M_p and equal to -1.3 ± 0.2. At $P<P^*$ the slope seems to depend on M_p, being steeper for the fainter galaxies. This partly reflects the fact that for $P>10^{21}$ WHz^{-1} the brighter galaxies are closer to being 100% radio-emitting than the fainter ones. The fractional bivariate RLF shows that the probability of finding a radio source associated with an E or SO galaxy is a strong function of its optical luminosity L. At $P>P^*$ this probability scales as $L^{1.5 \pm 0.2}$, at $P<P^*$ the dependence becomes weaker with decreasing P. There is no evidence (within a factor of two) of a difference in the bivariate RLF for galaxies inside rich clusters as compared to those outside, at least for $10^{21}<P<10^{24}$ WHz^{-1}. This result is discussed in the light of other data also. From the properties of the RLF, it is shown that locally the average absolute magnitude $\langle M_p \rangle$ of radio galaxies is equal to -20.3 at $P>P^*$, and becomes fainter as P decreases below P^*, hence the need of care in the use of radiogalaxies as standard candles in cosmology. The promising connections between this kind of studies and the theory of the radio source phenomenon is briefly illustrated.

Key words: radiogalaxies — luminosity function — ellipticals — clusters

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I. Introduction

The radio luminosity function (RLF) at a given frequency is defined by Longair (1966) as the "distribution of radio luminosity among a complete sample of radio sources within unit volume at a given cosmological epoch". We shall use the symbol $\varrho(P, z)$ for the RLF defined this way, where P is the radio power at a given frequency and z is the cosmological redshift. This definition is particularly convenient when actual source counts are compared to those predicted assuming a specific cosmological model and a z-dependence of the RLF. Beside a general RLF, including radio sources of all kinds, one can define the $\varrho_i(P, z)$ of those sources which are associated with optical objects of a particular class. In this case it is sometimes preferable to define a normalized, or fractional, luminosity function

$$F_i(P, z) = \varrho_i(P, z)/\varphi_i(z),$$

where $\varphi_i(z)$ is the volume density of objects of type i at the epoch z. For instance, $F_G(P, z)dP$ will represent the fraction of all galaxies with power at a given frequency between P and $P+dP$ at the epoch z.

The second definition is more suitable when studying the correlation between the radio power and any optical property of the objects. In particular, it is well known that the galaxies associated with the most powerful radio sources belong to the elliptical class, and that there is a rather strong correlation between their optical luminosity and the probability of finding an associated radio source. To study this correlation in a quantitative way, it is convenient to use the so called "bivariate" from of the RLF, $F_{E,M}(P, z)$, which represents the fraction of elliptical galaxies with optical magnitude M as a function of the radio power P.

This paper is devoted to the determination of the „local" ($z<0.1$) bivariate RLF of the elliptical galaxies. In the past, several authors have derived the local RLF in the form $\varrho(P)$ (Longair, 1966; Caswell and Wills, 1967; Sholomitskij, 1968; Cameron, 1971; Merkelijn, 1971; Schmidt, 1972; Pfleiderer, 1973). Recently Ekers and Ekers (1973) and Colla et al. (1975) have derived a local $F_M(P)$ for the elliptical galaxies, at 5000 and 408 MHz respectively. Still our knowledge of the $F_{E,M}(P)$ at any frequency is not yet the best than can be derived from the radio observation of the local sample of elliptical galaxies, especially for value of the power at 1415 MHz below 10^{24} WHz^{-1}. (In this paper we use $H_0 = 100$ km s^{-1} Mpc^{-1}.) Two more samples of elliptical galaxies studied at 1415 MHz with the Westerbork Synthesis Radio Telescope (WSRT) are now available improving the statistics in the low power range (Jaffe and Perola, 1976; Ekers et al., 1977). In this paper we combine these two samples with that used by Colla et al. (1975) to obtain an improved determination of the local $F_{E,M}(P)$ at 1415 MHz with a reasonable statistics from $P_{1415} = 10^{21}$ to 10^{25} WHz^{-1} for the ellipticals with absolute photomagnitude $-22 \leqq M_p \leqq -18$. To improve the statistics at the bright end and to extend the range to 10^{26} WHz^{-1}, we include a sample of elliptical galaxies from the 3CR survey.

The class, which we refer to as elliptical galaxies, is not completely homogeneous, since it includes all galaxies which are not spiral and irregulars. It also contains the SO galaxies, partly because it is often difficult to distinguish them from the ellipticals, and also because even some "well" classified SO's have the radio properties normally associated with elliptical galaxies (Ekers and Ekers, 1973).

II. Description of the Samples Used in this Work

a) Ekers et al. (1977) observed individually at 1415 MHz with the WSRT the galaxies of elliptical and SO type in the Humason et al. (1956) catalogue which were classified as non-cluster objects. We shall use in this work only the 153 galaxies with absolute photomagnitude brighter than -18. The distances used are those listed in Ekers and Ekers (1973). For each of these galaxies a minimum detectable power can be established on the basis of its distance and of the minimum flux measurable in the individual observation. The total number of galaxies actually detected is 23, above a minimum detected $P_{1415} = 10^{20.6}$ WHz^{-1}.

b) Jaffe and Perola (1976) surveyed five rich clusters of galaxies (A 1656 = Coma, A 2147, A 2151 = Hercules, A 2197 and A 2199) with the WSRT at 1415 MHz. Each observation provided a full synthesis map of a field of 0°.6 radius centred on the cluster. Since the sensitivity of the telescope decreases from the centre of the map outward, the minimum power detectable from each of them is an increasing function of the angular distance from the centre of the map. So, while the number of ellipticals with $M_p < -18$, members of the five clusters, covered by the maps is approximately 380, the number of galaxies detectable decreases with decreasing power. The cluster members detected are 17, above a minimum power 10^{21} WHz^{-1}.

c) Colla et al. (1975) extracted from the B2 radio catalogue the 53 radio sources identified (on the basis of 5000 MHz positions obtained with the WSRT) with elliptical galaxies in the Zwicky and Herzog (1963, 1966) and Zwicky and Kowal (1968) catalogues, assumed complete down to $m_p = 15.7$. These sources are found in two areas of the sky with $|b| > 10°$ of 0.65 sterad (Region 1) and 0.50 sterad (Region 2), which were surveyed completely down to 0.20 and 0.25 Jy[1] respectively at 408 MHz. For all but one of these sources the 1415 MHz flux was also measured. For all the galaxies in this sample the redshifts are known and they have M_p less than -18.

d) As in Colla et al. (1975) we complement these three samples with one from the 3CR survey. It consists of the 52 elliptical galaxies of known redshift out of the 55 (or 57 if two galaxies with uncertain morphology are included) elliptical galaxies brighter than $m_v = 17.0$ identified with sources in the 3CR with galactic latitude $|b| > 10°$ and $S_{178} > 9$ Jy. Their flux at 1415 MHz is taken from Kellermann et al. (1969). 51 galaxies have $M_p < -19$, and one has $M_p = -18.8$.

It is important to note that while in the first three samples there are no galaxies with z larger than 0.1 (B2 1102+30 has the largest, 0.072), in the 3CR sample there are 8 with $z > 0.1$, the largest being 0.167 of 3C 357, all of them with $P_{1415} > 10^{24}$ WHz^{-1}. For these values of the radio power several authors (see e.g. Longair, 1966; Schmidt, 1972) have shown that the dependence of ϱ_E on z is very strong, for pure density evolution $\varrho_E \propto (1+z)^k$ with k about 6. This implies that the contribution of these objects will produce an overestimate of the local value of the F_E which could be as large as a factor of 1.5 above $P_{1415} = 10^{24}$. However, since the exact form of the evolution is not known, we have not attempted to correct for it.

The photomagnitudes used in this work were taken from the HMS catalogue for the galaxies in the first sample, and from the Zwicky catalogue for those in the second and third samples. For 47 galaxies in the 3CR sample the photoelectric blue magnitudes from Sandage (1972) were used, converting them to M_p in the Zwicky system by adding 0^m.25 (cf. Colla et al., 1975). For the remaining 6 3CR galaxies and for 5 cluster galaxies with $m_p > 15.7$, the magnitudes were estimated on the blue print of the Palomar Sky Survey, using Sandage's measurements as calibrators. The absolute magnitudes were obtained after correcting for the galactic absorption, using the formula $\Delta m_p = 0.25$ (cosec $|b| - 1$), and for the K effect, using Table 4 in Oke and Sandage (1968), which gives the correction of the apparent blue magnitude as a function of z, and assuming that the correction for the photomagnitude is not significantly different for our purpose.

The distribution in radio luminosity and optical magnitude of the galaxies in the four samples is shown

[1] 1 Jy $= 10^{-26}$ Wm^{-2} Hz^{-1}

in Figure 1, where the number of radiogalaxies of each sample is given in bins of $\Delta \log P = 0.4$ and $\Delta M_p = 1$ (i.e. $\Delta \log L_{\rm opt} = 0.4$). There are some galaxies in common in two or more samples and these are indicated.

III. Comparison between Galaxies Inside and Outside Rich Clusters

While the galaxies in sample b) all belong to the central region of Abell clusters, with typical galaxy density of order 10^2 members $\rm Mpc^{-3}$, those is sample a) belong mostly to smaller aggregates, with typical density $\leqq 10$ members $\rm Mpc^{-3}$. In order to investigate whether the probability for a galaxy to be a radio source with a certain power is influenced by the size and density of the physical group to which it belongs, we can compare the $F_{E,M}$ determined separately for the two samples. This is done in the following way. In either sample there is a number of galaxies $N(P_i, M_j)$, with magnitude in the interval $M_j \pm 0.5$, which could have been detected if their radio power were in the interval $\log P_i \pm 0.2$, and a number of galaxies $n(P_i, M_j)$ actually detected. The fractional detections, $f_{ij} = n_{ij}/N_{ij}$, represent an estimate of $F_{E,M}$. The two estimates are presented in Table 1. From this table we have obtained the two monovariate F_E for galaxies with $M_p \leqq -19$, which are shown in Figure 2. We have corrected for the different distribution of galaxies in the three optical magnitude bins by normalizing the optical luminosity distribution of sample a) to that of the cluster sample before calculating the monovariate F_E. We have not included the galaxies with $-19 < M_p \leqq -18$, because the number of them surveyed in a) is too small to be adequate. The error bars in Figure 2 are merely $n^{-\frac{1}{2}}$ percentage uncertainties. From the data in Table 1 and Figure 2, we can set a limit of at most a factor of two on the possible difference between the two F. This confirms what was found by Jaffe and Perola (1976) when comparing their estimate of the $F_{E,M}$ for the five clusters with that obtained by Colla et al. (1975) after excluding the contribution of galaxies in rich clusters to the latter. Note that the result established here is valid only for P_{1415} between 10^{21} and 10^{24} $\rm WHz^{-1}$.

IV. Determination of $F_{E,M}(P)$ with the Four Samples Combined

Since there is no compelling evidence to treat the galaxies in rich clusters differently from the rest, and since there are no galaxies in common between sample a) and b), we simply add them together. Because of the different selection of the other two samples, their combination with the first two is not so straightforward. Samples c) and d) consist of all (except for the three 3CR galaxies with unknown redshift) galaxies with apparent magnitude (in a given optical band) below a limiting m^0 that are identified with sources in a survey complete down to a limiting flux S^0 (at a given

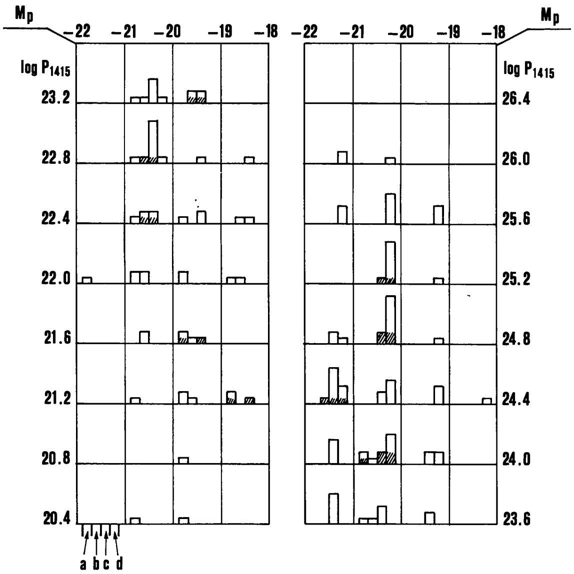

Fig. Distribution in radio luminosity and absolute optical magnitude of the radiogalaxies in the samples a)–d). The dashed boxes indicate galaxies common to two or more samples

Table 1. The bivariate fractional RLF of elliptical galaxies outside (a) and inside (b) rich clusters

M_p	−22 (a)	(b)	−21 (a)	(b)	−20 (a)	(b)	−19 (a)	(b) −18	$\log P_{1415}$ ($\rm WHz^{-1}$)
	0/4	1/1	0/45	0/28	0/69	0/104	0/35	0/260	24.4
	0/4		2/45	1/28	0/69	0/104	0/35	0/260	24.0
	0/4		1/45	1/28	0/69	0/104	0/35	0/260	23.6
	0/4		1/45	1/28	0/69	2/104	0/35	0/260	23.2
	0/4		1/45	1/28	0/69	0/98	0/35	0/250	22.8
	0/4		1/45	2/25	1/69	0/74	0/35	1/205	22.4
	1/4		2/44	2/19	2/68	0/53	1/34	1/150	22.0
	0/4		0/35	2/12	2/62	1/30	0/34	0/105	21.6
	0/1		1/15	0/3	2/56	1/10	2/27	0/50	21.2
			0/7		1/34		0/20		20.8
			1/3		1/10		0/12		20.4
			0/1		0/1		0/6		20.0

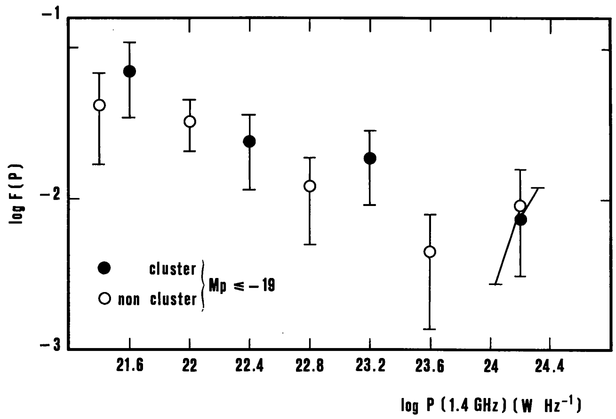

Fig. 2. Fractional RLF, given per interval $\Delta \log P = 0.4$, of the elliptical and SO galaxies with $M_p \leqq -19$, inside and outside rich clusters

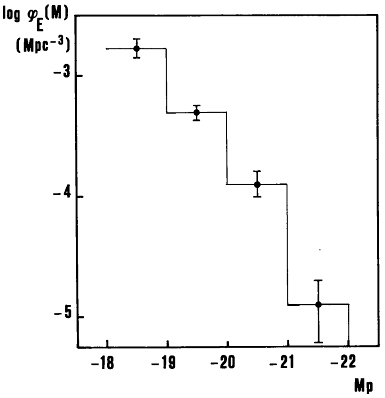

Fig. 3. Optical luminosity function of the elliptical and SO galaxies used to derive the fractional RLF

frequency) in a given area of the sky. The method of the maximum volume (Schmidt, 1968) can then be used to estimate $\varrho_{E,M}(P)$ at the frequency of the survey and in the magnitude system adopted for the selection. This is the procedure followed by Colla et al. (1975), who then obtained the fractional $F_{E,M}$ by dividing $\varrho_{E,M}$ by the average density of elliptical galaxies $\varphi_E(M)$ in the volume surveyed. However in order to be able to combine our four samples in a simple way, we have followed a different procedure.

First we choose a flux at 1415 MHz at which the two samples can be considered reasonably complete. We take $S^0_{1415}=S^0(v/1415)^{-\bar{\alpha}}$, where $\bar{\alpha}$ is the average spectral index in the v sample. The values used are $S^0_{1415}=0.093$ and 0.116 Jy for the two regions of the B2 sample, and $S^0_{1415}=2$ Jy for the 3CR sample ($\bar{\alpha}=0.62$ and 0.71 in the B2 and the 3CR samples respectively). Due to the spread in the spectral index α, some sources with $\alpha<\bar{\alpha}$, close to and above the limiting flux (we estimate about 6 in total) should be missing, while 5 galaxies have now a flux below S^0_{1415}. We shall keep these sources since they compensate for those which are missing.

Second, we estimate separately for the two samples the value of the volumes V^c_{ij} and V^d_{ij} surveyed for every bin, $\log P_i \pm 0.2$ and $M_j \pm 0.5$. For either sample there is a region of the ($\log P$, M) plane where the volume surveyed is determined only by the limiting radio flux. In this region for every bin we take as a first step the volume V_i within which sources with power P_i have a flux greater than S^0_{1415}. In fact, since the width of the bin in $\log P$ is not negligibly small, a more appropriate value of the volume, kV_i, that takes into account the dependence of F_M on P, should be used. We introduce this correction as a second step, after an estimate of $F_M(P)$ is obtained using the first choice for V. It turns out that the correction is nowhere larger than 5%. A second region of the plane is purely optically limited, and for every bin we take a volume lV_j, where V_j is the volume within which galaxies with magnitude M_j have apparent magnitude smaller than m^0, and the factor l takes into account the

Table 2. The bivariate fractional RLF of elliptical galaxies

M_p −22 … −21	−21 … −20	−20 … −19	−19 … −18	$\log P_{1415}$ (WHz^{-1})
0/4860	0/16630	0/19710		26.4
2/4770	1/16630	0/19710		26.0
3/2840	5/15820	3/19710		25.6
0/725	7/7390	1/17930		25.2
3/195	8/1875	1/7390		24.8
8/75	6/520	3/1900	1/5820	24.4
4/50	7/245	4/610	0/1705	24.0
5/40	5/185	2/345	0/722	23.6
0/20	7/162	3/273	2/452	23.2
0/8	9/95	1/231	1/378	22.8
0/4	4/72	3/164	2/321	22.4
1/4	4/64	2/127	2/214	22.0
0/4	2/47	3/90	0/144	21.6
	1/18	3/65	2/76	21.2
	0/7	1/34	0/20	20.8
	1/3	1/10	0/12	20.4
	0/1	0/1	0/6	20.0

shape of the optical luminosity function of the ellipticals (see Fig. 3). To obtain V_j two major effects need to be considered. One is the uneven effect of the galactic absorption in the area surveyed. We have estimated an average correction to V_j due to this effect, which corresponds to an effective limiting magnitude $m^0+\delta$, with $\delta_p=0.18$ and 0.25 for the B2 samples in Regions 1 and 2 respectively, and $\delta_v=0.20$ for the 3CR sample[2]. The second correction is due to the K effect, which reduces the maximum distance out to which a galaxy of a given M would still be sampled. For those bins that are limited partly in radio and partly in optical, we have computed V_j and then estimated its reduction due to the radio limit. Note that for the 3CR sample, where the optical selection was done in the visual, the volumes V_j have been computed using the visual system (where both the reddening and K corrections differ from those in the photosystem) and only as the last step M_v in the plane ($\log P$, M) has been converted to M_p, adopting an intrinsic value of the difference $M_p-M_v=1.15$ for ellipticals.

Once the quantities V^c_{ij} and V^d_{ij} are obtained, multiplication by $\varphi_E(M_j)$, the volume density of elliptical galaxies with M_p in the interval $M_j \pm 0.5$, gives the number N^c_{ij} and N^d_{ij} of galaxies surveyed. These numbers, in contrast to those for the first two samples, are subject to additional uncertainties due to:

i) The statistical uncertainty on the value of the φ_E used (Fig. 3).

ii) The inhomogeneity in the spatial distribution of the galaxies, which is a serious problem when V_{ij} is either much smaller or much larger than the volume sampled optically to estimate φ_E.

[2] Assumed galactic absorption in the visual: 0.18 (cosec $|b|-1$)

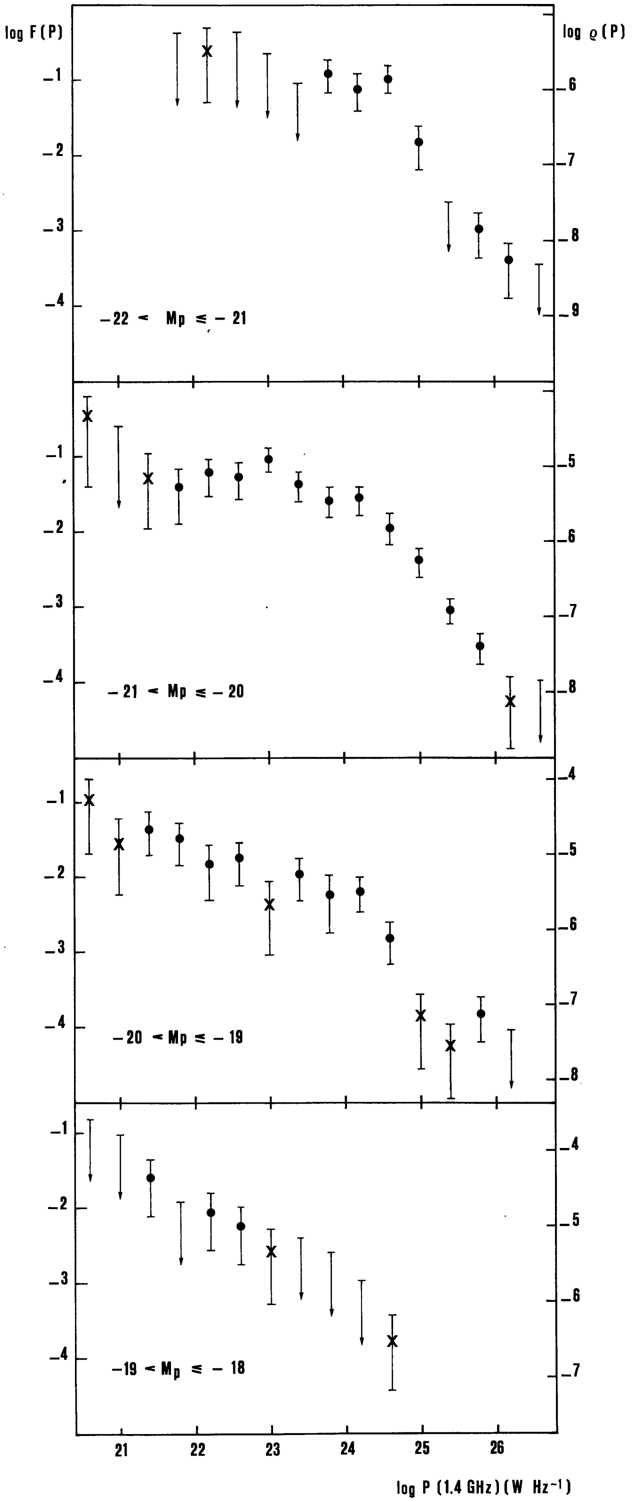

Fig. 4. The differential bivariate RLF of the elliptical and SO galaxies, given per interval $\Delta \log P = 0.4$. It can be read in the fractional form $F_{E,M}$, on the left, and in the form $\varrho_{E,M}$ (Mpc^{-3}) on the right. The crosses indicate the values obtained with $n_{ij}=1$

At this stage the four samples can be combined together, after taking care of not counting more than once the galaxies in common. Thus, we obtain for each interval of $\log P_{1415}$ and M_p two quantities, N_{ij}, the number of galaxies surveyed, and n_{ij}, the number of

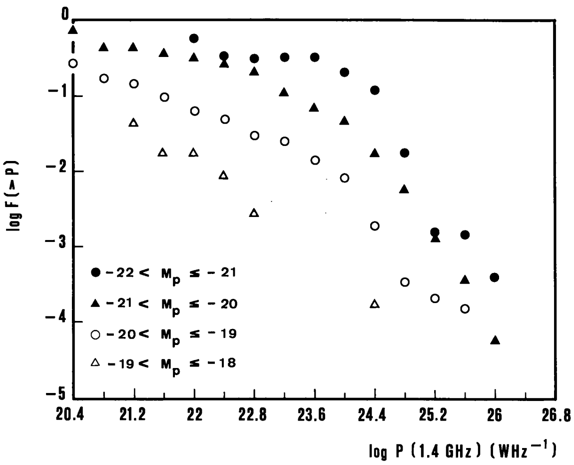

Fig. 5. The integral bivariate RLF of the elliptical and SO galaxies, in the fractional form $F_{E,M}(>P)$

galaxies detected, in any of the four samples. The estimate of $F_{E,M}(P)$ in the form $f_{ij}=n_{ij}/N_{ij}$ follows immediately and is given in Table 2. In Figure 4 the quantities f_{ij} are plotted with error bars, which merely represent the $(n_{ij})^{-\frac{1}{2}}$ percentage uncertainty. The spatial density of radioemitting ellipitcal galaxies, $\varrho_{ij}=f_{ij}\varphi_j$, is also given. In Figure 5 the integral from of F is plotted, omitting the error bars to avoid confusion.

V. The Reliability of the Present Determination of $F_{E,M}$

There are several factors affecting the reliability of the present determination of $F_{E,M}(P)$, which we list in this section.

i) Radio completeness and errors in the fluxes. Due to the limits imposed by the resolution and the sensitivity of the instrument used in a survey, low surface brightness extended components contributing a substantial fraction of the total flux of a source can be missed. This affects both the measured fluxes and the completeness of a sample. For example, DA 240 is not in the 3CR catalogue, although its flux (Willis et al., 1974) is above the limit of that survey. We estimate that the incompleteness due to this cause is probably not larger than 10% for the 4 samples used.

ii) Misidentifications. It is difficult to evaluate the incidence of misidentifications, because the identification criteria are not uniquely defined. They are of a simple objective kind for pointlike sources, but are rather subjective for extended multicomponent sources. On the other hand some identifications are likely to have been missed, as in the case of very unequal doubles, with one component below the detection limit. Our guess is that the uncertainty is less than 10%.

iii) Optical completeness. For the Zwicky catalogue, used to define the B2 sample, we estimate the degree of completeness to be at least 90%. For the 3CR sample, there is some uncertainty concerning those galaxies with $m_v \simeq 17$, for which the photoelectric magnitude are not available.

Table 3. Fit of $F_{E,M} d\log P = BP^A d\log P$

	$\log P_{1415} < 24.4$		$\log P_{1415} > 24.4$	
	A	$\log B$	A	$\log B$
$-22 < M_p \leqq -21$	$+0.16^{+0.1}_{-0.2}$	-4.9	$-1.32^{+0.3}_{-0.2}$	31.0
$-21 < M_p \leqq -20$	-0.13 ± 0.1	1.6	-1.31 ± 0.15	30.3
$-20 < M_p \leqq -19$	-0.34 ± 0.1	6.1	-1.32 ± 0.25	29.7
$-19 < M_p \leqq -18$	-0.65 ± 0.2	12.2	—	—

iv) Errors in the optical magnitudes. The r.m.s. error in the Zwicky magnitudes is estimated to be $0^m.3$ (cf. Colla et al., 1975). There also seems to be a systematic bias in the Zwicky magnitude scale. Huchra (1976) compares Zwicky magnitudes (Z) with photoelectric ones (P), and find a scale difference of $0^m.1$ per magnitude, $P - Z \propto -0.1\,Z$. This implies that a factor of 10 in optical luminosity corresponds in the Z scale to a difference of $2^m.3$ rather than $2^m.5$.

Rubin et al. (1976) have shown that the galactic extinction is probably less than assumed by us, $A_B = 0.15$ rather than 0.25. Therefore we may have overestimated the reddening correction to the absolute magnitudes, and underestimated the actual volume surveyed in samples c) and d).

v) Distance errors. Even with the redshift available, the uncertainty on the true distance of nearby galaxies ($V \lesssim 3000\,\mathrm{km\,s^{-1}}$) is not negligible. Non-Hubble motions presumably introduce a random error of about 10–20% in the distances of more than half of the galaxies surveyed in a).

vi) Optical luminosity function. The luminosity function of elliptical galaxies φ_E which is used here is the one obtained by Colla et al. (1975) from the ellipticals with velocity less than $4000\,\mathrm{km\,s^{-1}}$ in Humason et al. (1956) and with $m_b < 13$. This function is shown in Figure 3 where the bars of uncertainty are purely sampling errors. The shape of this luminosity function is close to that of the galaxies in rich clusters (Schechter, 1976) which contain a large proportion of ellipticals. The uncertainty on the shape of φ_E affects the determination of how F_E scales with M [this is irrelevant for the contributions of samples a) and b)]. Another source of uncertainty in the determination of the fractional luminosity function is the fact that φ_E is affected by local inhomogeneity. Most of the ellipticals used to determine φ_E are in the north galactic hemisphere where it is well known that there is an excess of the surface density of bright galaxies. Sandage et al. (1972) count about 2.5 more galaxies brighter than $m_p = 13$ in the north galactic cap than in the south galactic cap. Consequently the φ_E used here is probably an overestimate by a factor about 2 of the average space density of ellipticals in the volumes probed by the B2 and 3CR samples.

VI. Discussion

i) On the Form of the Local Bivariate RLF

In Figure 4 one can see rather distinctly that $F_{E,M}$ changes slope at a value of P between 10^{24} and 10^{25} $\mathrm{WHz^{-1}}$ in each of the magnitude intervals, except that we have no information beyond $10^{24}\,\mathrm{WHz^{-1}}$ for the interval $(-19, -18)$. In order to determine quantitatively how large are these changes, we have chosen to fit the data in each magnitude interval with power laws of the type

$$F d\log P = BP^A d\log P$$

above and below a value P^* of the position of the "break". The best fits have been obtained with the maximum likelyhood method, using poissonian distributions in order to make an appropriate treatment of the small and even zero number of detections is several of the bins. The values of A and B obtained this way are given in Table 3, for a value of $P^* = 10^{24.4}\,\mathrm{WHz^{-1}}$. Since the value of A that is obtained depends somewhat, especially for $P > P^*$, on the choice of P^* in the interval mentioned above, the uncertainties on A that we give in the table include also the effect of the uncertainty on the position of the "break".

The main features of $F_{E,M}$ can now be summarized as follows:

a) The position P^* of the break does not depend strongly on M_p, and actually the data are consistent with P^* being independent of M_p. We cannot esclude however that, as suggested by Rowan-Robinson (1977), there is a systematic shift of 0.4 in $\log P^*$ per $\Delta M = 1$.

b) The slope above P^* is rather poorly determined, except for the interval $(-21, -20)$. The results of the fit indicate that the slope is independent of M_p, at least up to $10^{26.5}\,\mathrm{WHz^{-1}}$, and equal to about -1.3.

c) The slope below P^* is not significantly different if two adjacent intervals of M_p are compared. What we believe is significant is the trend of A increasing as the optical luminosity decreases. This behaviour is not unexpected, since it may simply reflect the fact that below P^* the integral $F_{E,M}(>P)$ (see Fig. 5) is closer to saturation for the higher optical luminosities.

d) At $P > P^*$, where the slope is apparently independent of M_p, we can derive the dependence of F on the optical luminosity L, independent of P. We obtain

$$F \propto L^{1.5 \pm 0.2}.$$

Below P^* this dependence becomes progressively weaker as P decreases.

In Figure 6 the results of the fit are presented. For clarity we have not attempted to show in this figure the uncertainties on the values of A, B and P^*. The curves should not be taken literally to represent our knowledge of the bivariate RLF, but rather as an illustration of the properties of $F_{E,M}$ which seem to emerge from the present data. In particular they illustrate the result that the slope of $F_{E,M}$ seems to vary with M, at $P<P^*$, but to be independent of M at $P>P^*$. We can describe the last property by saying that, while the amplitude of the probability for an elliptical galaxy to be a "strong" radio source is a rather steep function of the optical luminosity L, its functional dependence on the radio power (at least up to $10^{26.5}$ WHz^{-1}) is practically independent of L.

ii) On the Spatial Density and Mean Absolute Optical Magnitude of Radiogalaxies

Our estimate of the bivariate RLF in the form $\varrho_{E,M}(P)$ is given in Figure 4. In order to illustrate the relative spatial density of radiogalaxies with different M_p, the power law fits in the four magnitude intervals are drawn in Figure 7. In this figure we also give the monovariate $\varrho_E(P, M \leqq -18)$ as obtained by adding the data points in Figure 4, and by summing the four curves. The curve obtained this way, although it is not an independent best fit to the data points in the figure, does represent a satisfactory fit. This curve is also reproduced in Figure 8, for comparison with other determinations of the monovariate $\varrho_E(P)$. The agreement with Caswell and Wills (1967) is rather good. The excess found by Merkelijn (1971) above $P=10^{25}$ WHz^{-1} is most likely due to evolutionary effects, because the sample used is much deeper than ours in the optical ($m<19$). The determination by Wall et al. (1976) is based on a sample of 3CR sources, supplemented with the samples of Caswell and Wills (1967) and of Cameron (1971) below 10^{24} WHz^{-1}. It has been obtained as the limit for $z\to 0$ of the function $\varrho(P, z)$ which best fits the luminosity distribution of the samples used and the distribution of source counts down to $S(408\ \mathrm{MHz})=12$ mJy. The excess below $P=10^{23}$ WHz^{-1} is due to the spiral galaxies, which are not included in our RLF. Rather surprisingly the slope above P^* is larger than our estimate (-1.8 instead of -1.3). We cannot esclude that the difference is due to the fact that we have neglected the effect of evolution out to $z=0.1$ and on the 8 3CR sources with $z>0.1$. Although the discrepancy is confined to a range of two decades of P, it is important to settle this point, because the two values lie on either side of the value -1.5, which is critical in the interpretation of the source counts, as illustrated in detail by von Hoerner (1973). A clarification will come when a work similar to the present one on a complete sample of B 2 sources with $0.1<z<0.2$, now in progress, will show directly the incidence of evolution on the shape of the RLF.

The bivariate $\varrho_{E,M}$ allows us to estimate the mean absolute magnitude $\langle M_p\rangle$ of radiogalaxies in the unit volume as a function of P. Above P^*, where apparently the dependence of ϱ on M and P is separable, $\langle M_p\rangle$ is independent of P and equals -20.3. Below P^*, according

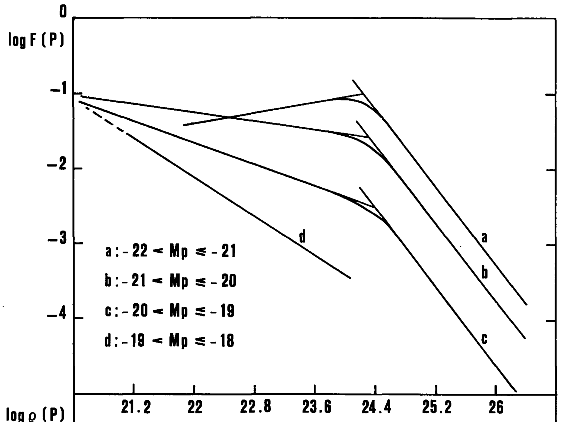

Fig. 6

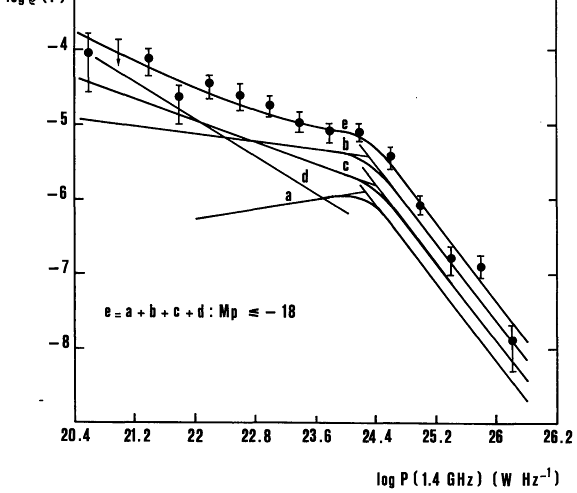

Fig. 7

Fig. 6. The bivariate fractional RLF obtained by fitting the data in Table 2 with power laws, as described in the text

Fig. 7. The points represent the density ϱ_E (Mpc^{-3}) of radiogalaxies with $M_p \leqq -18$. The curves labelled *a–d* represent the bivariate $\varrho_{E,M}$ obtained directly from the fits of $F_{E,M}$ given in Figure 6. The curve labelled *e*, representing ϱ_E, is not an independent fit to the points, but merely the sum of the other four curves

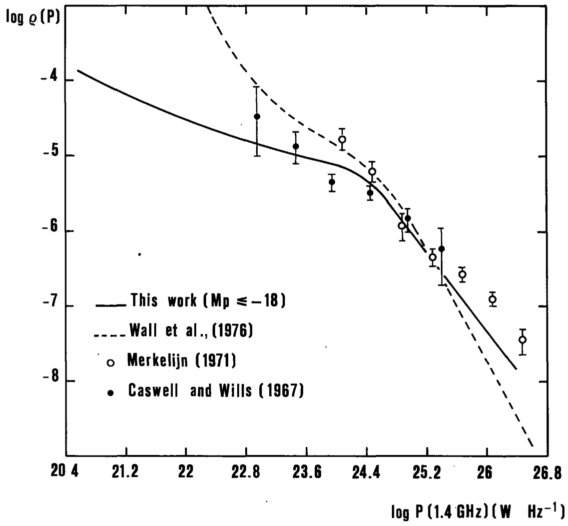

Fig. 8. The density of radiogalaxies as a function of P according to various determinations. The present work result is reproduced from Figure 7, curve labelled *e*

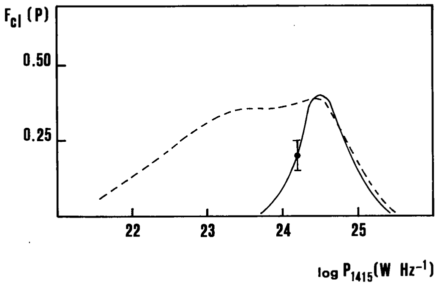

Fig. 9. The fraction of Abell clusters as a function of their "total" radio luminosity at 1415 MHz. Full line: as measured by Owen (1975); the bar indicates the degree of uncertainty. Dashed line: prediction based on our bivariate RLF

to our power law fits, $\langle M_p \rangle$ increases as P decreases by about $0^m.4$ per decade of P, because the less bright galaxies become progressively more frequent. As a consequence, the attribution of a constant $\langle M \rangle$ to radiogalaxies is only partially justified by this result. Sandage (1972) finds $\langle M_v \rangle = -21.48$ in a subsample of 3CR sources, which practically coincides with our estimate of $\langle M_p \rangle$ for $P > P^*$ (adopting $M_p - M_v = 1.15$, as in Sect. IV), as one would expect since his sample contains only sources with $P > P^*$. On the other hand for sources in a survey much deeper than the 3CR, where the volume sampled for powers below P^* is no longer negligible, one needs to estimate first the expected distribution

$$\frac{dn}{dMdz} = \left(\int_{4\pi z^2 (c/H_0)^2 S^0}^{\infty} \varrho_M(P, z) dP \right) \frac{dV}{dz}$$

and from this $\langle M_p \rangle$ as a function of z. For instance, if $S^0 = 10$ mJy, we expect $\langle M_p \rangle = -19.5$ at $z = 0.02$, -19.9 at $z = 0.08$, -20.3 at $z \gtrsim 0.30$, if evolutionary effects are neglected. This behaviour reflects the increase from $10^{21.6}$ to 10^{24} of the minimum power detectable as one goes from the smaller to the larger redshift.

We also wish to stress that, so long as there is no determination of the z dependence of the bivariate $\varrho_{E,M}$, there is no guarantee that $\langle M \rangle$ remains unchanged with cosmic epoch, and therefore the use of radiogalaxies as standard candles in cosmology is subject to this uncertainty. On the other hand, the fact that $\langle M_v \rangle$ of the 15 radiogalaxies in Table 2 of Sandage (1972) with $z > 0.1$ is not significantly different from that of the remaining sample is an indication that the M dependence of $\varrho_{E,M}(P)$ does not vary drastically in the interval from $z = 0.1$ to $z = 0.25$.

iii) *On the* RLF *of Cluster Galaxies*

As we have shown in Section III, there is no evidence up to $P = 10^{24}$ of a difference in the $F_{E,M}$ of galaxies in rich clusters with respect to the rest, although a difference of a factor 1.5–2 cannot yet be excluded. The same conclusion, with the same degree of uncertainty, is reached by Riley (1976) concerning powers above 10^{24} and up to 10^{26}. One test of the "universality" of the $F_{E,M}$ can be derived from Owen's (1975) observations of the total flux from a large number of Abell clusters, as measured with a relatively low resolution single dish telescope. In Figure 9 we plot the fraction of Abell clusters as a function of their integrated radio luminosity, determined by Owen, and compare it with a prediction. This was calculated by applying our RLF to a group of clusters with the optical luminosity function given by Schechter (1976) and a distribution of richness classes similar to that in Abell's catalogue from distance classes $D \leqq 4$. We have assumed that half of the clusters contain one very bright ($M_p \leqq -21$) cD galaxy, which are not included specifically in the Schechter luminosity function, and that half of the clusters contain 50% and the other half 75% of elliptical and SO galaxies, regardless of richness. The predicted and observed curves agree for the stronger sources, but disagree below 10^{24} WHz^{-1}; the general RLF predicts a long tail of clusters with luminosities below this value, while Owen observes a rapid dropoff. The discrepancy would be enhanced if the contribution of the spiral galaxies were included in the prediction. This discrepancy was noted by Owen, who then postulated the existence of a distinct, low luminosity type of cluster, with properties which would be different from those of the clusters studied by Jaffe and Perola (1976). The strength of this conclusion is somewhat weakened by a possible systematic effect in Owen's fluxes for the weaker clusters, all of which were close enough to be resolved by his telescope, while the higher luminosity, more distant clusters were mostly unresolved. Removing this uncertainty will require interferometric observations of some of the "weak" clusters.

Another result, which seems to indicate that the fractional RLF in rich clusters may vary with cluster type, is the following. According to McHardy (1974) powerful ($P \gtrsim 10^{24}$) radio sources are found roughly twice more frequently in clusters of Bautz-Morgan type I than in those of Types II and III. Since the absolute magnitude M_b of the brightest member is -21.26 for Type I and -20.68 for Type III (Sandage and Hardy, 1973), we have tried to explain the correlation in terms of the M dependence of F_E. If one takes into account also the contribution of the second and third members, whose magnitude difference with respect to the first member tends to decrease from Type I to Type III, it turns out that the expectation of a radio source with $P > 10^{24}$ depends weakly, if at all, on the BM type. We remark, however, that the careful study based on the actual optical luminosity function of the clusters used by McHardy in his analysis is needed to confirm the discrepancy.

The available evidence indicates that the probability for an elliptical galaxy to be a radio source depends little, or may not depend at all, on its "social" status. From this we tentatively conclude that either the environments of galaxies have little or no influence on the probability of them being radio sources, or that the environments of cluster and non-cluster radio galaxies are not too different. For a detailed discussion on this point, including also the inferences from the morphological properties of radio sources, see Jaffe (1976).

iv) The RLF *and the Theory of Radiogalaxies*

The RLF is a datum that a "complete" theory of the radio source phenomena should compare with. Since such a theory is not available yet, the RLF can provide suggestions and constraints for its development. The RLF defined in a fractional way is especially useful to explore possible correlations between the probability of radio emission as a function of power and other properties of the elliptical galaxies. The most obvious such properties are: the total optical luminosity L (which is related to the galactic mass), the ellipticity (which may be an indicator of the angular momentum), the nuclear density of stars, the contrast in brightness of the nuclear region with respect to the envelope, the colour and the gas content of the galaxy. The derivation of the local RLF as a function of the optical luminosity in a step in this direction.

A result that seems important to us is the evidence that the form of the dependence upon P of the probability of an elliptical galaxy to be a strong ($P > 10^{24}$ WHz^{-1}) radio source does not vary (or perhaps varies only weakly) with its optical luminosity, while the fraction of such galaxies which is associated with a strong radio source does increase as L increases. These facts suggest that, while the strength of the radio emission, that can be associated with a galaxy, does not depend on its total mass, either its duration, or the rate at which elliptical galaxies turn into the "active" state, are a strong function of the mass.

The "break" at P^* is also a suggestive feature of the RLF, especially when the two following coincidences are remarked. The first is that the value of P^* corresponds rather closely to the power where, according to Fanaroff and Riley (1974) the morphology of double radio sources changes from Class I (low power sources, brightness peaks nearer to galaxy than regions of diffuse radio emission) to Class II (high power sources, reverse configuration). We note also that P^* is close to the typical power of radio sources with head-tail structure, like 3C 129 and NGC 1265. The second is that, according to statistical studies like the one by Schmidt (1972), cosmical evolution affects significantly the RLF only at powers larger than about 10^{24} WHz^{-1}, that is at powers over the "break".

VII. Conclusions

The main "empirical" conclusions of the present work can be summarized as follows.

We have found no evidence of a significant difference in the probability of an elliptical galaxy inside a rich cluster of galaxies being a radio source, as compared to a galaxy outside, in the range $10^{21} < P_{1415} < 10^{24}$ WHz^{-1}.

The RLF of elliptical galaxies shows a "break" in the slope at about $P^* = 10^{24.4}$ WHz^{-1}. The position of the break seems to be independent of, or only slightly dependent on the optical luminosity of the galaxies. We estimate the slope of the RLF at $P > P^*$ to be -1.3 ± 0.2, up to $10^{26.5}$ WHz^{-1}. P^* approximately coincides with the power where the morphology of double radio sources changes from the Cen A to the Cyg A type, and where cosmic evolution starts to be important.

The probability of an elliptical galaxy to be a radio source with $P > 10^{24}$ WHz^{-1} scales with its optical luminosity as $L^{1.5 \pm 0.2}$, independent of P. Below 10^{24} WHz^{-1} the dependence upon L apparently weakens as P decreases.

The properties of the bivariate RLF yield on average value of the absolute magnitude $\langle M_p \rangle$ for radio galaxies as a function of P. For "strong" radio sources ($P > 10^{24}$) $\langle M \rangle_p$ is equal to -20.3, independent of P at least up to $10^{26.5}$ WHz^{-1}. The average optical luminosity decreases with P at P less than 10^{24} WHz^{-1}. This implies that only "strong" radio galaxies can be correctly used as standard candles in cosmology. Much caution is needed, however, because there is no guarantee that $\langle M_p \rangle$ stays constant beyond $10^{26.5}$ WHz^{-1}, and at redshifts larger than 0.1.

Further work is needed to improve our knowledge of the local RLF. Moreover it is important to establish with greater confidence to which extent the fractional RLF is insensitive to the "social status" of the galaxies. With regard to the dependence of the RLF on cosmic epoch, it is of great relevance to establish how the bivariate $F_{E,M}$ changes with z, by studying directly radio samples selected with optical limits fainter than those used in the present work.

Finally, quantitative studies on the correlation between radio and optical properties others than the monochromatic powers should also be pursued. Particularly promising (cf. Colla et al., 1975; Fanti and Perola, 1976) appears the study of how the properties of the nuclear component of a radio source correlate with those of the extended components, and with the optical properties of the galaxy.

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