

The local radio luminosity function of galaxies at 843 MHz

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Summary. Following the investigation of the radio luminosity function by Harnett, two samples of galaxies have been observed with the Molonglo Observatory Synthesis Telescope at 843 MHz. These comprise 176 E and S0 galaxies from the sample by Sadler, and 21 galaxies with $\delta \leq -45^\circ$, a subset of Harnett's sample. The resulting local radio luminosity function (LRLF) has been extended to radio powers of $\sim 10^{18} \text{ W Hz}^{-1} \text{ sr}^{-1}$. At such low luminosities, the irregular galaxies apparently begin to dominate the LRLF. Spirals on the other hand, continue to be confined to radio powers in the range $10^{19-22} \text{ W Hz}^{-1} \text{ sr}^{-1}$. E and S0 galaxies appear unimportant to the LRLF at low radio luminosities but behave like similar standard candles above powers of $\sim 10^{22.5} \text{ W Hz}^{-1} \text{ sr}^{-1}$.

The radio properties of S0 galaxies depend on their absolute optical luminosities and hence their masses. The most massive appear similar to radio ellipticals, but at lower optical luminosities comparable to those of spirals, S0 galaxies resemble early-type spirals closely both in their detection rate and correlation between radio and optical luminosities.

1 Introduction

There have been several radio surveys of optically bright galaxies to determine the relationship between their radio and optical properties and also to determine the radio luminosity function at low radio powers (Hummel 1980; Harnett 1982, hereafter referred to as H82 and references therein). These have provided considerable data on the properties of spiral galaxies, but until recently, the optically complete samples with spectroscopic data have not been sufficiently deep to provide good statistics for the majority of E and S0 galaxies. Also, for spirals of low radio luminosities ($P_{843} < 10^{20} \text{ W Hz}^{-1} \text{ sr}^{-1}$, $H_0 = 90 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the derived luminosity function is seriously affected by the sensitivities of the various telescopes. In order to improve the situation, we have observed two independent samples of galaxies with the Molonglo Observatory Synthesis Telescope (MOST) at 843 MHz. The results reveal some interesting features in the radio

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properties of bright galaxies. In addition, they have been useful in improving the reliability of the local radio luminosity function at very low radio powers.

2 A complete sample of galaxies with $\delta < -45^\circ$

A complete sample of 294 bright galaxies was selected from the catalogue by de Vaucouleurs, de Vaucouleurs & Corwin (1976; RC2) and observed by H82 at 408 MHz. A subset of this sample, consisting of 28 galaxies south of -45° and within 1.84 sr, was observed with the MOST at 843 MHz during the period 1981–86. The V/V_m test for a uniform distribution (Schmidt 1968) indicates completeness of the sample to a limiting magnitude of $B_T^\circ = 10.8$ ($\langle V/V_m \rangle = 0.51 \pm 0.07$). As there are seven galaxies in the 843-MHz sample outside this limit, we will concentrate on the 21 galaxies constituting the complete sample.

The operation of the MOST and the procedure for real-time mapping have been described by Mills (1981) and Durdin, Large & Little (1984). In short, the visibility data are processed in the MOST by a hardwired multibeamer to produce a set of 64 simultaneous fan beams spaced 22 arcsec apart. Using time-multiplexing of the beams, it is possible to obtain synthesized maps for field sizes of $23n \times 23n \text{ cosec } |\delta| \text{ arcmin}^2$, where $n=1, 2$ or 3 . The rms thermal noise in a good 23-arcmin map synthesized for a full 12 hr is now ~ 0.3 mJy, although it was somewhat greater for the early maps used in the present study. The synthesized beam has a half-power width of $43 \times 43 \text{ cosec } |\delta| \text{ arcsec}^2$. Maps were processed on the Sydney University Computing Centre Cyber 825 computer using programs described by Crawford (1984) and Reynolds (1986). Of the 21 galaxies, 15 are spirals, five are ellipticals or lenticulars and the other is an irregular. Descriptions of the individual galaxies have been given elsewhere (Harnett 1984, 1987; Harnett & Reynolds 1985). For the present purpose, we have summarized in Table 1 the relevant optical and radio parameters for the one irregular and 14 spiral galaxies detected from the sample of 21.

Most of the distances of spirals in Table 1 are derived from 21-cm linewidths using the revised B -band Tully–Fisher relation (Bottinelli *et al.* 1983, 1984a, b). Thus a homogeneous distance scale commensurate with the adopted value of 8.5 kpc to the centre of the Galaxy has been used. The corresponding value of H_0 is somewhat controversial, but de Vaucouleurs (1983) has

Table 1. Detected spiral and irregular galaxies.

NGC	Type	D(Mpc)	B_T°	M_B	S_{843} (mJy)	M_{843}
1313	SBd	4.19	9.35	-18.8	360	-15.4
1433	SBa	9.2	10.39	-19.4	60	-15.2
1559	SBcd	10.9	10.50	-19.7	500	-17.9
1566	SABbc	7.08:	9.88	-19.4	310	-16.5
1672	SBb	11.7	10.62	-19.7	350	-17.6
2442	SBb	14.4	10.41	-20.4	360	-18.1
3059	SBbc	8.02	10.80	-18.7	236	-16.4
4945	SBcd	3.87	8.25	-19.7	8300	-18.6
Circinus	Sb:	3.65	8.62	-19.2	2300	-17.2
6215	SAC	3.44	9.97	-17.7	580	-15.6
6221	SBc	10.3	9.73	-20.3	420	-17.6
6300	SBb	8.75	9.87	-19.8	116	-15.8
IC 4662	Im	2.5	10.79	-16.2	30	-11.6
6744	SABbc	4.45	8.54	-19.7	150:	-14.6
7090	SBc	6.25	10.61	-18.4	35	-13.8

Distances are from Bottinelli *et al.* (1984a,b) except for NGC 2442 (de Vaucouleurs 1979a) and the Circinus Galaxy (de Vaucouleurs 1979b).

suggested that these measurements indicate a value of $H_0=85$ or $95 \text{ km s}^{-1} \text{ Mpc}^{-1}$ depending on the model used for galactic extinction. For consistency, we take $H_0=90 \text{ km s}^{-1} \text{ Mpc}^{-1}$ in this paper when distance estimates from redshifts are required.

The radio properties of spirals have been extensively discussed in the literature on the basis of much larger samples than ours (e.g. Hummel 1980; H82). In particular, these studies have shown that the radio and optical luminosities of the detected spirals are well correlated, although such a correlation applies only to those spirals where conditions favourable to non-thermal radio emission exist. As discussed by Hummel (1981) and H82, this depends very much on the detailed morphology of the galaxies. The sensitivities of the available radio surveys are not sufficient to decide if the majority of the undetected spirals form a separate class with negligible non-thermal radio emission.

3 A complete sample of E and S0 galaxies

A southern sample of E, E-S0 and S0 galaxies based on the Uppsala catalogue (Nilson 1973) was studied recently by Sadler (1984 a, b). This is the only large sample of such galaxies with fully determined optical properties and consists of 248 galaxies brighter than $B=14.0$ mag within a solid angle of 2.76 sr. These galaxies have also been observed by Sadler (1984c) using the Parkes radio telescope with a detection limit of 30 mJy at 2700 MHz. In order to provide better detections and to supplement our data on spirals, we have observed this sample at 843 MHz using the MOST. Although the V/V_m test had indicated earlier that the sample is reasonably complete for $B_T < 13.8$ (Sadler 1984b), similar tests made by us using the corrected magnitudes indicated that the sample is only complete to $B_T^c = 13.0$. We have therefore restricted our study to the 176 galaxies with $B_T^c \leq 13.0$ in the sample by Sadler (1984 a, b). Of these, 49 are ellipticals, 13 are E-S0 and 114 are of type S0.

In view of the large number of galaxies involved, it was impractical to obtain full synthesis maps of each field. Instead, we used multiple-field observations with the MOST to map fields of $23 \times 23 \text{ cosec } |\delta| \text{ arcmin}^2$ around 10–15 galaxies in each 10-hr observing session. A full description of this mode of observation and the procedure used for data reduction will be given elsewhere (Subrahmanya, in preparation). Briefly, a group of fields is observed in rapid succession by tracking each field for 4 min then moving the telescope to the next field, all under computer control. Each field is thus observed at about eight independent hour angles and the data are used to synthesize a map in much the same way as a normal synthesis observation (e.g. Durdin *et al.* 1984). The sparse hour angle coverage results in strong sidelobes in the synthesized ('dirty') map, however, and the dynamic range of the CLEANed maps (typically 60) is inferior to that of a full 12-hr synthesis. From an inspection of these maps, we have adopted a detection limit of $S_{843} = 20 \text{ mJy}$ (determined by confusion in the large effective area of the dirty beam rather than by the thermal noise which is about 1 mJy for an 8×4 min observation). The parameters of the detected galaxies are summarized in Table 2. We did not observe Fornax A and Centaurus A; their inclusion in our calculations was not warranted because of their extremely strong radio emission. Of the 30 galaxies listed in Table 2, there are nine new detections. On the other hand, two detections listed by Sadler (1984c), NGC 3250 and 3268, were not confirmed by the 843-MHz observations. It is interesting to compare the optical luminosities of the detected ellipticals with those of radio galaxies or the brightest members of clusters. For instance, in the 3CR complete sample, the mean absolute magnitude $\langle M_B \rangle$ of 3CR galaxies with available accurate photometry and with $z < 0.5$ is -20.60 (Laing, Riley & Longair 1983), compared to $\langle M_B \rangle = -20.87 \pm 0.39$ for the first-ranked cluster members (Sandage 1973, adjusting for $H_0 = 90 \text{ km s}^{-1} \text{ Mpc}^{-1}$). It is generally believed that this $\langle M_B \rangle$ is a characteristic of radio galaxies with $P > 10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$ and that at lower luminosities radio and optical powers may be correlated (see for example Auriemma

Table 2. Detected E and S0 galaxies.

Source	Type	D(Mpc)	B_T°	M_B	S_{843} (mJy)	M_{843}
013-G12	S0	53.9	12.7	-20.96	215	-20.44
NGC 641	E	68.9	12.8	-21.39	150	-20.58
NGC 1399	E	14.4	10.4	-20.40	920	-19.16
NGC 1533	S0	6.1	11.6	-17.33	18	-13.02
NGC 1553	E	12.5	10.1	-20.40	10	-13.93
NGC 1947	S0	11.1	11.4	-18.83	20	-14.43
NGC 2640	S0	8.3	10.6	-19.00	50	-14.80
NGC 2663	E	21.7	10.4	-21.28	3300	-21.43
NGC 3136	E	15.6	9.8	-21.16	20	-15.16
NGC 3258	E	28.3	12.2	-20.06	115	-18.36
263-G48	S0	28.9	11.7	-20.60	50	-17.50
NGC 3557	E	30.6	11.0	-21.43	495	-20.11
322-G08	S0	30.0	12.8	-19.59	15:	-16.28
NGC 4696	S0	30.0	11.1	-21.29	5000	-22.58
NGC 4751	S0	18.9	12.4	-18.98	20	-15.58
323-G93	S0	36.1	12.6	-20.19	30	-17.43
NGC 5090	E	35.6	12.6	-20.15	13730	-24.05
NGC 5140	S0	40.0	12.4	-20.61	25:	-17.46
IC 4296	E	38.3	11.4	-21.52	11490	-24.02
NGC 5419	S0	44.4	11.7	-21.54	480	-20.89
137-G45	E	35.6	12.2	-20.55	20	-16.96
NGC 6407	S0	50.0	11.9	-21.59	30	-18.14
NGC 6438	E-S0	24.4	12.4	-19.54	50	-17.14
IC 4765	S0	50.6	11.9	-21.62	19	-17.67
NGC 6730	E	44.4	12.7	-20.54	80	-18.95
NGC 6758	E	36.7	11.9	-20.92	60	-18.22
NGC 6776	S0	60.0	12.2	-21.69	30	-18.53
NGC 6861	E	31.1	11.6	-20.86	30	-17.11
NGC 6868	E	31.1	11.2	-21.26	100	-18.41
IC 4991	S0	64.4	12.2	-21.85	70	-19.61
NGC 6958	E	30.6	11.9	-20.53	25:	-16.87
NGC 7002	E	82.8	12.8	-21.79	17	-18.62
NGC 7049	S0	23.9	11.4	-20.49	50	-17.09
NGC 7057	S0	56.1	13.0	-20.75	15:	-17.64
NGC 7213	S0	19.4	10.8	-20.64	100	-17.39
IC 1459	E	18.9	10.7	-20.68	1060	-19.89

et al. 1977). By comparison, the mean absolute magnitude of the 17 detected ellipticals in our sample is $\langle M_B \rangle = -20.6 \pm 0.5$, implying that there is no appreciable change in the M_B of ellipticals even at radio luminosities as low as $10^{20} \text{ W Hz}^{-1} \text{ sr}^{-1}$. A similar conclusion was also reached by Windhorst *et al.* (1985) on the basis of the ellipticals detected in a deep radio survey.

On the other hand, the 18 detected S0 galaxies have a much wider range of optical luminosities, as seen from the range of absolute magnitudes (-17.1 to -21.7) for the detected S0 galaxies listed in Table 2. The majority of detected S0 galaxies, however, show a correlation similar to that of the spirals. In order to illustrate this, we have plotted in Fig. 1 the absolute radio and optical magnitudes of the detected S0 and S galaxies in our present samples. Also shown for comparison are the mean values of absolute radio magnitudes for each range of 1.0 mag in absolute optical magnitude for the spirals detected by Hummel (1980) and H82. In order to convert these average values to 843 MHz, a mean spectral index of 0.7 has been used. It can be seen from the figure that the detected S0 galaxies are indeed very similar to the spirals in the correlation between radio and optical luminosities. Since the only exceptions are the strongest radio sources in our sample

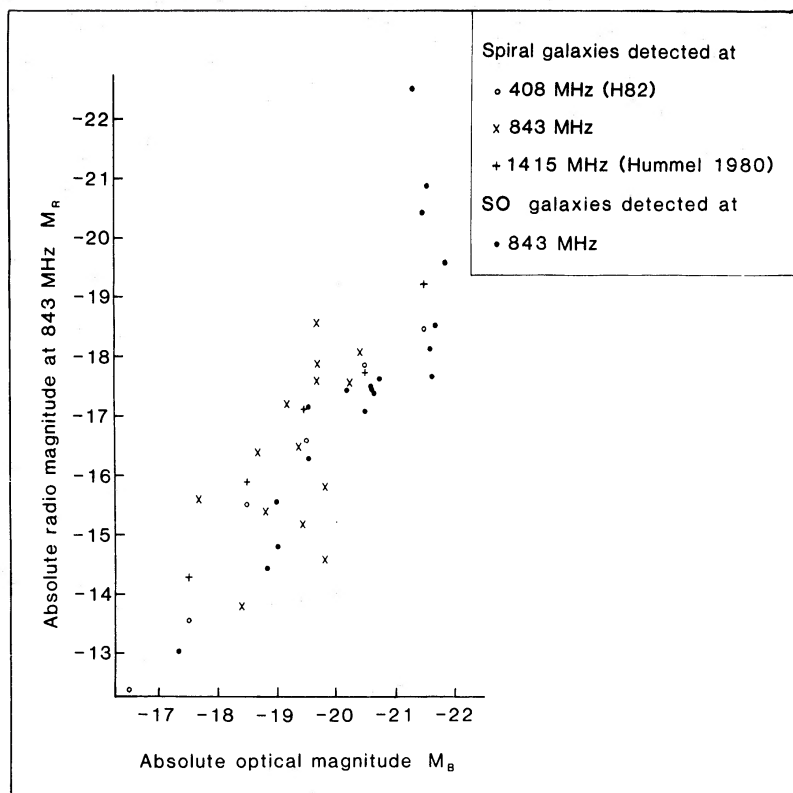


Figure 1. Absolute radio and optical magnitudes of S0 and spiral galaxies detected at 843 MHz and mean values of absolute radio magnitudes for each 1.0-mag range of absolute optical magnitude for spirals detected by Hummel (1980) and H82.

(O13–G12 and NGC 5419) and their absolute magnitudes are similar to those of the detected ellipticals, it is possible that the most luminous S0 galaxies resemble the radio ellipticals. Furthermore, we have estimated the rate of detection of S0 galaxies in our sample as ~ 30 per cent which is very similar to that of early-type spirals obtained by H82.

Interpretation of the detection rate of S0 galaxies is difficult in view of the well-known classification problem. In particular, edge-on spiral and E0 galaxies may sometimes be mistaken for S0 galaxies in optical plates which are less sensitive or have overexposed images of nuclei and discs. Hummel & Kotanyi (1982) noted that some 15 to 20 per cent of the listed S0 galaxies could be subject to misclassification. We have inspected the images of all the detected S0 galaxies on SRC-J and ESO-B plates. While we cannot rule out the possibility of some misclassifications, the majority of detected galaxies are thought to be classified correctly. Thus, although our rate of detection may be somewhat uncertain, the possibility of a correlation between optical and radio luminosities should not be affected seriously by misclassification of some of the S0 galaxies. We have started a programme of mapping the undetected S0 galaxies with the MOST in full synthesis mode and hope to address this question more confidently in a future paper.

4 The radio luminosity function

Since the observed galaxies represent a nearby sample (most of the distances are within 50 Mpc) the effects of cosmological evolution are negligible. Hence these data are useful in providing a direct estimate of the local radio luminosity function (LRLF) at very low luminosities. We define the LRLF as the number of galaxies per Mpc^3 which have radio luminosities within ± 0.5 mag of a

Table 3. The radio luminosity function at 843 MHz.

a) The 408-MHz and 843-MHz sample of spiral and irregular galaxies

Range of absolute radio magnitude	$\rho(P) \times 10^{-4}$ (Mpc ⁻³)	Number of galaxies
-12	239.9	2
-13	102.3	3
-14	61.66	2
-15	74.13	15
-16	44.67	20
-17	51.29	31
-18	30.90	29
-19	6.761	11
-20	0.8511	2

b) The 843-MHz sample of E and S0 galaxies

Range of absolute radio magnitude	$\rho(P) \times 10^{-6}$ (Mpc ⁻³)		Number of galaxies	
	E	S0	E	S0
-14	288.4	794.3	1	1
-15		478.6	0	1
-16		162.2	0	1
-17	70.80	91.20	3	5
-18	23.99	16.22	3	2
-19	18.20	2.754	2	1
-20	9.128	5.888	2	2
-21	5.495	2.042	2	1
-22			0	0
-23		2.884	0	1
-24	15.85		1	0

given radio magnitude. In order to construct this function, the samples described in the previous sections have been supplemented by the detected spirals and irregulars from the 408-MHz surveys by Cameron (1971a) and H82. The 408-MHz flux density limit was taken as 40 mJy and all detected sources with larger integrated flux densities were included in our analysis, except where confusion or sidelobes affected the observations. In addition, the distances for the 408-MHz samples were revised to conform with the homogeneous distance scale described in Section 2. The LRLF was calculated essentially as described by Cameron (1971b). The quoted errors are estimated simply by assuming Poisson statistics for the number of galaxies detected in each magnitude bin. The results are presented in Table 3 and Fig. 2. Also plotted in Fig. 2 is the luminosity function for E and S0 galaxies determined by Meier *et al.* (1979) from observations of bright galaxies associated with radio sources in the 3CR and B2 surveys. A spectral index of 0.7 has been used to convert the luminosities to 843 MHz. As noted earlier, both E and S0 galaxies seem to behave like similar standard candles at the higher radio luminosities corresponding to the data of Meier *et al.* (1979) shown in Fig. 2. Hence we are justified in treating them together as was done by the earlier authors.

In the case of E and S0 galaxies, the break in the LRLF at $P_{843} \approx 10^{23.3} \text{ W Hz}^{-1} \text{ sr}^{-1}$ was first

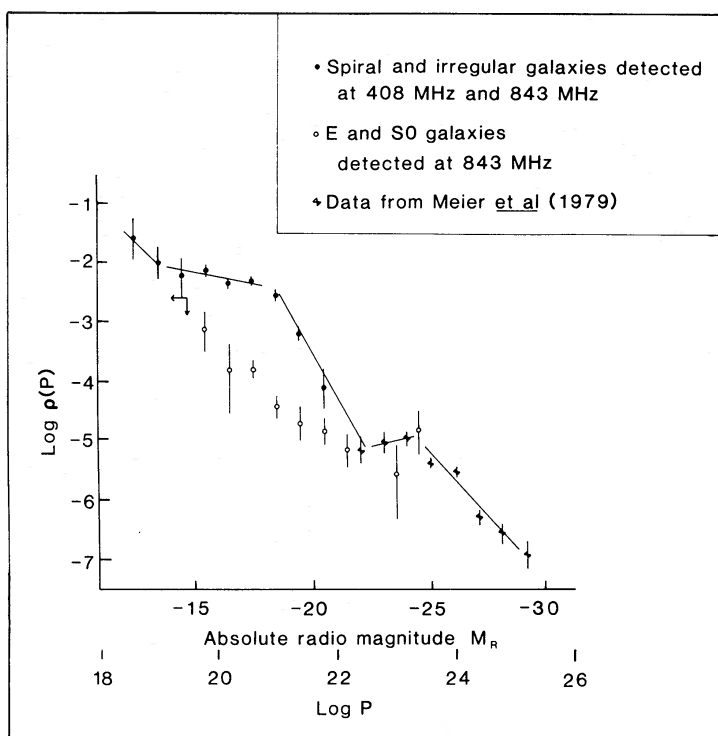


Figure 2. The local radio luminosity function (LRLF) for galaxies detected at 843 MHz and the radio luminosity function for E and S0 galaxies from Meier *et al.* (1979).

pointed out by Auriemma *et al.* (1977). Below this, the LRLF rises steeply before flattening noticeably at $P \approx 10^{21} \text{ W Hz}^{-1} \text{ sr}^{-1}$. At the lowest luminosities it again appears to rise steeply. Also, at such low radio powers, spirals become much more important than ellipticals in the total LRLF, although the contribution of spirals to the LRLF appears to be confined to radio powers in the range $10^{19-22} \text{ W Hz}^{-1} \text{ sr}^{-1}$, in agreement with the original result of Cameron (1971b). More recent work including the present observations has led to many new detections of radio emission from spirals, but there is no significant change in the observed range of their radio luminosities. In view of the strong correlation between radio and optical luminosities, this may simply reflect the observed range of optical luminosities of spirals.

At the lowest radio luminosities, the irregulars apparently begin to dominate the LRLF, but their statistics are poor in the available optically complete samples. Our radio sensitivity is inadequate to allow us to comment directly on the contribution of E and S0 galaxies to the LRLF at such low luminosities. Nevertheless, since we have found S0 galaxies to be similar to spirals in the sense of correlation between radio and optical powers, they too are probably not important at very low luminosities. In addition, we made a tentative estimate of the *optical* luminosity function for the E and S0 galaxies within our sample for $M_B < -18.5$. By comparing this with our cumulative LRLF, we can obtain an upper limit to the cumulative LRLF of these galaxies at the lowest luminosities. This is indicated in Fig. 2 by a pair of orthogonal arrows. From this, it can be seen that E and S0 galaxies are unlikely to contribute significantly to the LRLF in the region apparently dominated by the irregulars.

5 Conclusion

If S0 galaxies are a transitional type as suggested by Hubble (1936), one should expect their properties to be intermediate between those of ellipticals and spirals. It has generally been

claimed that the radio properties of S0 galaxies are different from those of both E and S galaxies and that they are very much harder to detect than either of these types (Hummel & Kotanyi 1982, and references therein). Our observations of S0 galaxies suggest to the contrary, that their detection rate and radio–optical correlation resemble those of spirals or ellipticals, depending on their optical luminosities and hence their masses. The most massive S0 galaxies appear similar to the detected ellipticals which have a roughly constant optical luminosity, whereas at lower optical luminosities comparable to those of spirals, the S0 galaxies resemble the early-type spirals very closely in their detection rate as well as the correlation between radio and optical luminosities. In this context, it is also interesting to note the recent evidence for spiral structure in the host galaxy of a well-known double-radio source 3C 33 (Simkin & Michel 1986). It may be that the mass of a galaxy and not its morphological type is the decisive factor in establishing the level of nuclear activity.

The LRLF shown in Fig. 2 reflects the extent to which direct determination is possible from the existing optical catalogues. Our results for ellipticals and S0 galaxies at the lowest radio luminosities may have been somewhat affected by the radio sensitivity, but the main limitation arises from the possibility of optically fainter galaxies contributing at the lowest radio luminosities considered by us. A substantial improvement in the quality of the observational luminosity function at low radio powers may not be possible until deeper optical samples become available.

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