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A Catalogue of Sources Found at 610 MHz with the Westerbork Synthesis Radio Telescope: Source Counts and Spectral Index Distributions

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Summary. Complete samples of radio sources have been used to derive 610 MHz source counts, and spectral index distributions for a sample defined at 1415 MHz. Both agree well with previous results. An extremely flat spectral index distribution found earlier is probably due to chance fluctuations. Some indication is found of a steepening of the spectral index distribution of the population that dominates at high flux densities, and of the presence of another, possibly nearer, population with flat spectral indices.

The 610 MHz source counts agree very well with those derived by Willis et al. (1977).

Key words: spectral index distributions – source counts

1. Introduction

In a previous paper (Katgert and Spinrad, 1974) data were published for a small sample of weak sources observed at 1415 and 610 MHz. One result was a spectral index distribution that had a larger dispersion and a flatter mean value than expected. Since the number of sources in the sample was small, and the result might have been a product of chance, further observations were made at 610 MHz of another and larger sample of sources previously observed at 1415 MHz (Katgert et al., 1973).

The observations consisted of four fields in the general area of this previous survey. A catalogue of the sources found in the field has been published (Katgert, 1978) and will be referred to as Paper I. To extend the statistics in order to derive more reliable source counts, sources found in four other fields, mostly observed for testing purposes when the 610 MHz system was first installed, were included in the catalogue. Note that one of these is the field from which the spectral data have already been discussed by Katgert and Spinrad, as mentioned above. Two other test fields were situated near the North Pole, in a region which has been observed at a number of other frequencies (Branson, 1967, 81.5 MHz; Ryle and Neville, 1963, 178 MHz; Halliday, 1977, 1421 and some 5000 MHz; Waggett, 1977, 408 and 1407 MHz; Pauliny-Toth and Kellermann, 1972, 2695 MHz). The fourth field, at $13^{h}06^{m}+76°30'$ was included in the catalogue just because of its good quality.

The present paper discusses the statistical properties of the sources catalogued in Paper I, such as source counts and spectral index distributions, and compares them to previous results.

It should be noted that preliminary results from sub-sets of the present catalogue have already been published (Katgert et al., 1977; Willis et al., 1977).

2. Spectral Index Distributions

The catalogue in Paper I has been used to select two samples complete at 1415 MHz.

The *first* WSRT *sample* comprises sources from field (1) of Paper I, and is therefore almost the same as the sample discussed by Katgert and Spinrad, however it has been defined more carefully and the 610 MHz flux densities have been slightly revised.

The *second* WSRT *sample* was selected from the 1415 MHz survey of Katgert et al. (1973). The 610 MHz observations of this survey comprise fields (3)–(6) of Paper I. The completeness criteria for the first and second sample are set such that:

a) An optimally low number of sources remains undetected at 610 MHz, so that corrections for detectability as a function of position relative to the field centre can be neglected.

b) The sample becomes as large as possible.

The following criteria give a good compromise: $S_{1415}>15$ mJy, $\bar{S}_{1415}$ (i.e. the *attenuated* flux density) >12 mJy, $A_{1415}<10$, $A_{610}<6.5$ (A is the primary beam attenuation). Setting more stringent limits would have meant discarding about 5 detected sources for each source for which only an upper limit is known. The criteria given above are relaxed with respect to those in Paper I. This means that a few sources are now included in the sample that are not listed as such in Paper I. They are listed in Table 1, together with some sources for which upper limits only are available at 610 MHz.

Some pertinent parameters of the distributions for the samples are given in Table 2, namely: Column 1: Sample identification. Column 2: Number of sources in sample. Column 3: Second frequency. Column 4: Limiting flux density at 1400 MHz. Column 5: Mean spectral index. Column 6: Dispersion. Column 7: Fraction of sources with $\alpha<0.5$. Column 8: Mean spectral index for all sources for which $\alpha>0.0$. Flux densities are expressed in Jy, and frequencies in MHz.

Parameters are also given for three comparison samples:

1. To compare the consistency of the WSRT data with those obtained with other telescopes, a sample of sources was selected from the 5C 5, 5C 6, 5C 7, and 5C 9 surveys, comprising all sources for which $S_{1407}>15$ mJy and the distance from the field centre less than 0.°6.

2. The spectral index distribution given by Maslowski (1977) for a sample of sources with $0.5<S_{1400}<2.0$ Jy (the GB 2 *sample*) was used to compare the spectral index distributions at intermediate and low flux densities.

3. To compare the spectral index distributions at high and low flux densities, a third comparison sample was selected from the 1400 MHz strong-source catalogue of Bridle et al. (1972).

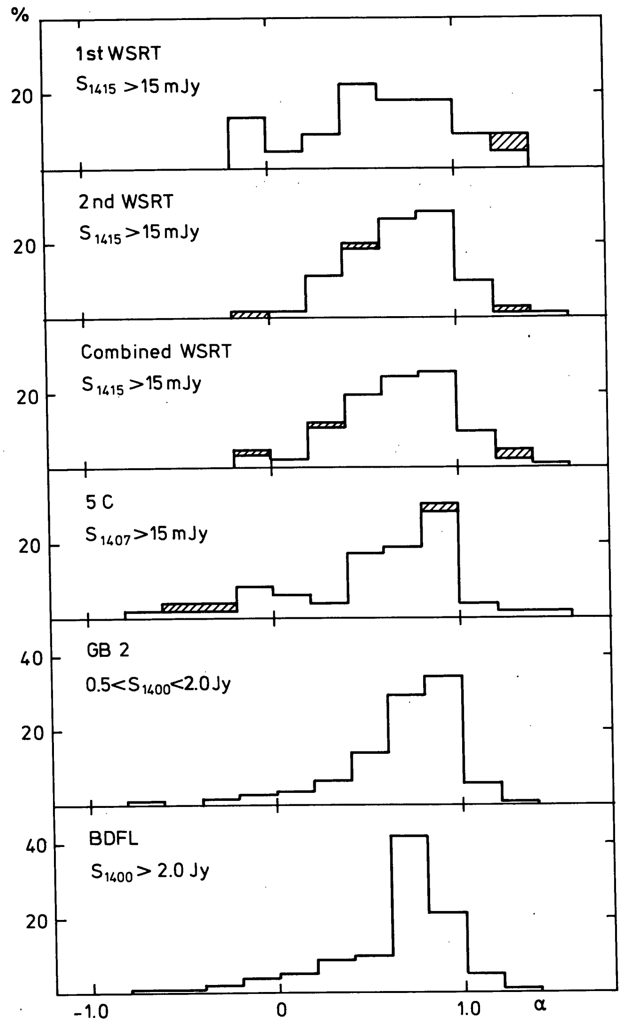

Fig. 1. Normalized spectral index distributions for the samples defined in the text. Hatching indicates upper limits. The characteristics of the distributions are summarized numerically in Table 2

Table 1. Sources to be added to the complete sample

0059+28W1	$\alpha<1.29$	1253+35W8	1305+37W5	
0059+29W1		1255+35W1	1306+36W2	
1244+35W1		1256+35W3	1308+33W3	
1245+34W2	$\alpha<0.52$	1257+35W2	1308+33W5	
1248+35W1		1257+36W1	1309+33W3	
1250+33W1		1302+37W1	1309+33W4	$\alpha<1.32$
1253+35W7		1305+36W1	1309+36W1	

50 sources from this survey were selected by Katgert et al. (1977); for these sources S_{408} was available from the B 2 survey. For a further 120 sources from the strong-source catalogue 408 MHz flux densities are available either from Parkes (ed. J. Ekers, 1969) or from Molonglo (Munro, 1971a, b, 1972; Jauncey and Hunstead, 1972; Sutton et al., 1974), or interpolated by Véron et al. (1974), mostly from all three. These latter 408 MHz data were averaged with weights inversely proportional to the quoted flux density errors, after which spectral indices were calculated and checked for consistency with other available data (mostly as given by Véron et al.). The resulting spectral index distribution was practically identical to that of the 50 sources. The data were therefore combined to give a statistically well-defined comparison sample, to be referred to as the BDFL sample.

From Table 2 the various samples can be seen to have rather similar characteristics; variations in the mean spectral index could be almost entirely due to the presence or absence of one or two objects with flat or inverted spectra, as can be seen from the values for $\langle\alpha\rangle$ obtained when only positive spectral indices are included (last column of Table 2).

There are three obvious questions we want to answer:

1. Was the result from the first WSRT sample (Katgert and Spinrad, 1974) anomalous?
2. How well do the WSRT results agree with those obtained elsewhere for comparably deep samples (5 C)?
3. How do the present results compare with those for stronger sources (BDFL and GB 2)?

To try to answer these questions, χ^2 tests were made, testing the hypothesis that two distributions have the same parent population. The combinations of distributions tested are:

1. 1st WSRT sample and 2nd WSRT sample
2. Combined WSRT sample and 5C sample
3. Combined WSRT sample and GB 2 sample
4. Combined WSRT sample and BDFL sample.

For the first and second tests the hypothesis is confirmed: in 20 and 17% respectively of all cases would random draws from the same parent population result in distributions that give worse agreement. For the third and fourth tests, however, the hypothesis is rejected at the 1 and 2% level respectively. The answers to the three questions asked above thus become:

1. The result from the first WSRT sample was not anomalous, for it compares well with the second WSRT sample.
2. The agreement between the WSRT results and those for comparably deep samples is good.
3. The WSRT results do not agree well with those for stronger sources.

This might seem somewhat surprising in view of the similarity of the characteristics given in Table 2. However, on inspection of Fig. 1, which gives the various distributions, two things may be noted:

a) the *mode* of the weak source samples (and that of the GB 2 sample) is consistently higher than that of the BDFL.

b) $\langle\alpha\rangle$ remains practically the same (it may tend to increase somewhat with decreasing flux density) because the difference in mode is balanced by a somewhat larger percentage of sources with $0<\alpha<0.6$. [$f(0<\alpha<0.6)=0.25$ for the BDFL sample, 0.24 for the GB 2 sample, but ranges from 0.32 to 0.37 for the other samples.]

It is very tempting to explain this effect as a steepening of the main population of radio sources (possibly as a result of a red-shift dependence of α) which, below S_{1400} ca. 0.5 Jy, is compensated by the increasing importance of a nearer-by population with on the average much flatter spectra; this explanation is to a certain extent borne out by a weak dependence of the identification percentage on α: for the combined WSRT samples, 32% of sources with $\alpha<0.6$ is identified, against 21% of sources with $\alpha>0.6$.

The combined WSRT samples were also used to compute the correlation between S and α *within* the sample; a value for the correlation coefficient of 0.06 was found, so there is no detectable correlation.

As there are some indications that the spectral index of radio galaxies is correlated with the absolute radio luminosity P (see

Table 2. Characteristics of the spectral index distributions

	N	ν_2	S	$\langle\alpha\rangle$	σ	$f(\alpha<0.5)$	$\langle\alpha>0\rangle$
1st WSRT	22	610	0.015	0.56 ± 0.08	0.38	0.41 ± 0.14	0.66 ± 0.07
2nd WSRT	60	610	0.015	0.73 ± 0.04	0.28	0.23 ± 0.06	0.73 ± 0.04
All WSRT	82	610	0.015	0.68 ± 0.03	0.31	0.28 ± 0.06	0.71 ± 0.03
5C	46	408	0.015	0.57 ± 0.07	0.46	0.30 ± 0.08	0.72 ± 0.05
GB2	165	408	0.5	0.66 ± 0.03	0.34	0.22 ± 0.04	0.72 ± 0.02
BDFL	170	408	2.0	0.60 ± 0.03	0.36	0.24 ± 0.04	0.66 ± 0.02

Table 3. Distribution of spectral index types

		S	C^-	c^+	P
610 MHz sample	N	12	4	2	1
	%	63 ± 18	21 ± 11	11 ± 8	5 ± 5
Véron sample	%	72 ± 5	16 ± 2	7 ± 2	5 ± 1

e.g. MacLeod and Doherty, 1972), we investigated whether the correlation is detectable in the present sample, as follows:

If one defines a parameter r such that:

$$r = m_v + 2.5 \log S_{1415},$$

and makes the assumption that the absolute magnitude M_v for radio galaxies is, to a good approximation, constant, r should be equal to the radio luminosity P plus some constant. A correlation between P and α should then show up as a correlation between r and α. No correlation was found. There are two possible explanations for this:

1. At 1415 MHz there is no correlation between M_v and α (This does not preclude correlation at other frequencies).

2. The assumption that M_v is constant is not valid. Although this assumption is known to be good for strong radio galaxies, it cannot be made for intrinsically weak radio galaxies, which may form a large fraction of the identifications in weak source samples.

Some further statistical conclusions that can be made are the following:

a) There is no indication that the spectral index distribution for resolved sources differs from that for unresolved sources. [$N=18$, $\langle\alpha\rangle=0.65$, $\sigma=0.32$, $f(\alpha<0.5)=0.28$.]

b) In a previous paper (Katgert et al., 1973) it was noted that resolved sources tended to have a higher percentage of galaxy identifications than point sources. This is to be expected if one assumes that resolved sources are on the average closer to us than point sources; but one would then also expect, other things being equal, that galaxies identified with resolved sources were on the average brighter than galaxies identified with point sources. This was not found to be the case: the magnitude distributions for the two classes of sources were very similar. A possible explanation was that a large fraction of the resolved sources might originate in clusters, in the intra-cluster gas, rather than in individual galaxies. For this explanation to be correct, one would then expect these sources to have very steep spectra ($\alpha>1.1$). However, the two most likely candidates (those where one can notice the presence of a cluster on the Palomar Sky Survey prints), 1306+36 W 2 and 1307+37 W 1 have spectral indices of 0.64 and 0.62 respectively. Also, for the *present* sample the magnitude distributions for resolved and unresolved sources are clearly different (Fig. 2). We conclude therefore that the close resemblance of the magnitude distributions in the sample of Katgert et al. (1973) is due to a chance fluctuation.

3. Individual Spectra

For a number of sources in fields (2) and (8) (the North Polar fields) there are spectral data at three or more frequencies. A number of source spectra have been published by Halliday. No data at frequencies between 178 and 1421 MHz existed at the time, but since then data at 408 (Wagget, 1977, 5C 9) and 610 MHz (present data) have become available, providing the intermediate frequency points.

Individual spectra for those sources in fields (2) and (8) that show curvature are given in Fig. 3. They are marked by Westerbork names, and by Ryle and Neville numbers, to facilitate comparison with Halliday's spectra.

The 408 MHz flux densities given by Wagget have been multiplied by 0.92: uncorrected they tend to be high relative to the other data. Waggett notes that there is an 8% difference in the 1400 MHz scale between his data and Halliday's, partly due to the use of another value for the flux density of the calibrator source, 3C 309.1 (Wagett assumes that S_{1407} is 8.1 Jy, Halliday uses $S_{1421}=7.9$ Jy; in Westerbork the value in use at the time was $S_{1415}=7.88$, very close to Halliday's value). We have assumed that the 8% difference is also present at 408 MHz; applying the scale factor to the 5C 9 data brings them into very satisfactory agreement with the other data.

Halliday's results on curvature were confirmed for all sources for which we have 610 MHz data. Three additional sources were found to show curvature: they are 0243+87W1 (RN10), 1310+89W1 + 1317+89W1 (RN48), and 1416+89W1 (RN 52). For all other sources for which flux densities at three or more frequencies are now available, the values are compatible with a straight spectrum.

There are nineteen sources in a complete sample at 610 MHz selected from the North Polar fields (see Paper I) for which spectral data are available at three or more frequencies. From these we obtain the percentage of the various types of spectra given in Table 3. These can be compared with the corresponding percentages for the strong-source sample given by Véron et al. (1974). Note that to make comparison possible, the types of spectra have been re-estimated by the author from the figures in the article of Véron et al., using the same criteria as were used for the classification of the spectral of the 610 MHz sample: the percentages of spectral types for the sample of Véron et al. are also given in Table 3: clearly the agreement is very good, and there is no evidence for a change in spectral characteristics with flux density; unless such a change is canceled by the change in selection frequency from 1400 MHz (Véron et al.) to 610 MHz. In

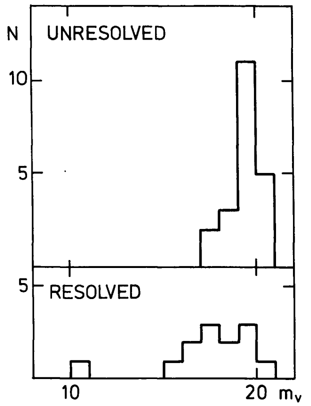

Fig. 2. The magnitude distribution of galaxies identified with unresolved sources (top) and resolved sources (bottom)

this respect it may be noted that Halliday found no evidence for such a change either, using a 20-source sample having 5 sources in common with our sample, and a 178 MHz comparison sample.

4. Source Counts

The 610 MHz source counts for a complete sample (see Paper I for sample definition) have been calculated using the method described by Katgert et al., 1973, taking due account of the variations in sensitivity between the fields. The results are given in Fig. 4 and Table 4. The normalizing count dN_0 is 900 $S^{-5/2}$ dS sterad^{-1} Jy^{-1}. For comparison the best-fit equation given by Willis et al. (1977) is also entered. Source sounts have also been determined for two sub-samples, i.e. fields (3)–(6) of Paper I on the one hand and the remaining fields [(1), (2), (7), and (8)] on the other hand. The results have also been included in Fig. 4 and Table 4.

Except in the lowest flux-density intervals, the counts for fields (3)–(6) are clearly higher than those for the other fields. This is hardly surprising, as fields (3)–(6) were situated in the general area of the first WSRT survey (Katgert et al., 1973), which also gave high values for the 1415 MHz count for $S_{1415} >$ ca. 100 mJy. In fact 68 out of the 135 sources in fields (3)–(6) were also in the sample used for the 1415 MHz source counts. Willis et al.'s best-fit count is intermediate between the two. This indicates that the difference is due to statistical fluctuations only; none of the points of the sub-sample counts deviates by more than about 1.5σ from Willis et al.'s function.

Transformations of the 1415 MHz source counts to 610 MHz have also been carried out, using the spectral index distribution of the combined WSRT sample as derived in Sect. 2, and starting from (a) the 1415 MHz source count derived by Katgert et al. (1973), (b) The equation derived by Willis et al. (1977) to fit the 1415 MHz source counts. The agreement between the result of transformation (a) (Column 8 of Table 4) and the observed 610 MHz total count is very good. The result of transformation (b) (Column 9 of Table 4) is slightly less satisfactory: it is systematically a bit low at the high-flux-density end, both compared to the observed 610 MHz source count and to the 610 MHz best-fit equation. This might mean that the equations at 1415 MHz do not give a good description of the count after all. Alternatively, it can be explained in terms of a slow increase in the effective spectral index with flux density (see also Oosterbaan, 1978). The increase should be such that at $S_{610}=0.02$ Jy, $\alpha_{\mathrm{eff}}=$ca. 0.6, at $S_{610}=1$ Jy $\alpha_{\mathrm{eff}}=$ca. 0.8. The effect might have shown up as a flux density-spectral index correlation e.g. in the combined WSRT sample as discussed in Sect. 2. That it failed to do so may simply mean that it does not stand out sufficiently against the dispersion. If it exists, it is in good agreement with the tentative conclusions for the spectral index distribution.

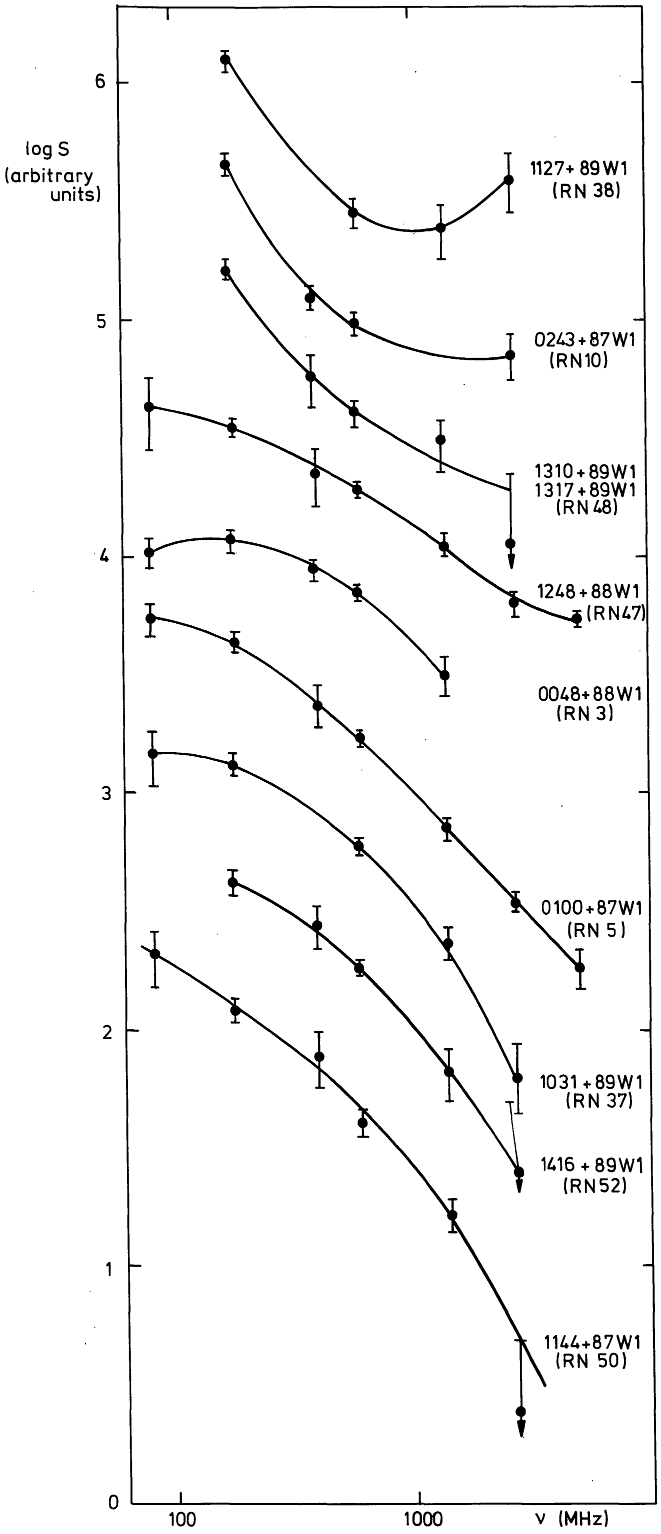

Fig. 3. Curved spectra from the North Polar fields

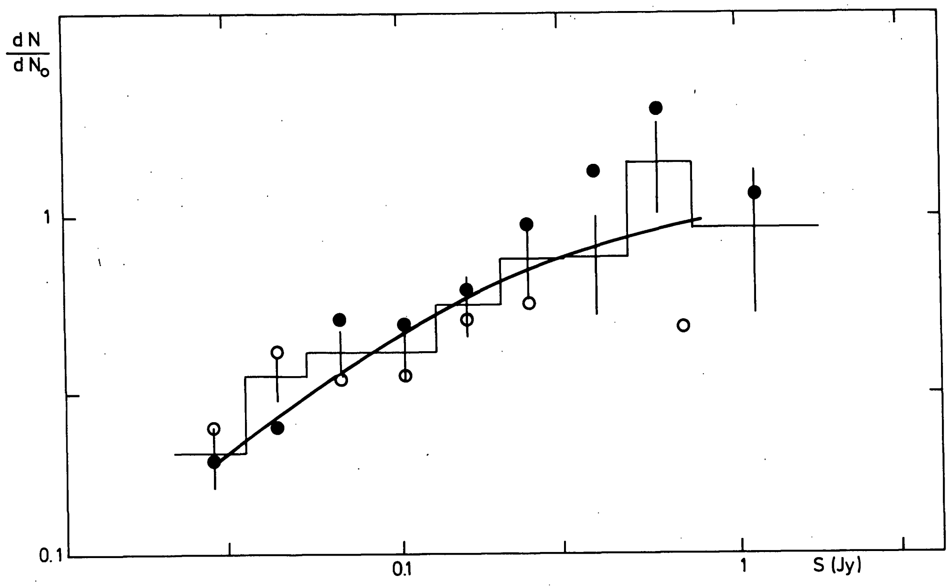

Fig. 4. The 610 MHz cource sount derived from the present sample ●-source counts for fields (3)–(6). ○-source counts for the remaining fields. For comparison the line corresponding to the equation derived by Willis et al. (1977) has been drawn in. The normalizing count is $dN_0 = 900\, S^{-5/2}\, dS$ sterad^{-1} Jy^{-1}

Table 4. $dN_0 = 900\, S^{-5/2}\, dS$ sterad^{-1} Jy^{-1}. For further explanation see text

S (mJy)	dN/dN_0 (all fields)	N	dN/dS	dN/dN_0 (3–6)	dN/dN_0 (1, 2, 7, 8)	dN/dN_0 (*a*)	dN/dN_0 (*b*)
22.0							
	0.20 (0.04)	25	$1.46\ 10^6$ (0.29)	0.19 (0.05)	0.24 (0.07)	0.21	0.18
34.1							
	0.34 (0.05)	48	$8.31\ 10^5$ (1.20)	0.24 (0.05)	0.40 (0.08)	0.26	0.25
52.9							
	0.40 (0.06)	52	$3.27\ 10^5$ (0.45)	0.50 (0.09)	0.33 (0.08)	0.29	0.35
81.9							
	0.40 (0.07)	36	$1.09\ 10^5$ (0.18)	0.48 (0.10)	0.34 (0.09)	0.44	0.43
127							
	0.55 (0.11)	27	$5.03\ 10^4$ (0.97)	0.61 (0.16)	0.50 (0.14)	0.53	0.54
197							
	0.75 (0.17)	19	$3.88\ 10^4$ (0.89)	0.95 (0.27)	0.55 (0.21)	0.79	0.64
305							
	0.76 (0.24)	10	$7.77\ 10^3$ (2.46)	1.37 (0.64)		1.29	0.72
473					0.47 (0.19)		
	1.46 (0.46)	10	$4.99\ 10^3$ (1.58)	2.06 (0.78)		1.45	0.79
733							
	0.93 (0.41)	5	$6.33\ 10^2$ (2.82)	0.92 (0.46)			0.83
1761							

5. Conclusions

The distributions of the spectral index from 1415 to 610 MHz have been investigated for samples of weak radio sources selected at frequencies near 1400 MHz. Source counts at 610 MHz have also been derived. Some indication may have been found of a steepening of the spectral index of what at high flux densities is the main population, and for the existence of a population of weak ($S_{1400} < 0.5$ Jy), flat-spectrum objects.

The 610 MHz counts, 1415 MHz counts and spectral index distribution have been shown to be consistent. The equations derived by Willis et al. to represent the counts at 610 and 1415 MHz are in less good agreement if one uses the combined WSRT spectral index distribution. This indicates either that the equation describing the 1415 MHz counts should be adjusted at higher flux densities, or that there is a slight flattening of the effective spectral index towards lower flux densities. The latter explanation agrees with the spectral index distribution results.

The 610 MHz count taken by itself is in very good agreement with that derived by Willis et al. Deviations found when dividing the sample in two on the basis of 1415 MHz source count information are consistent with chance fluctuations.

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