A 6 cm Source Survey with the Westerbork Synthesis Radio Telescope. II: Analysis

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Received May 30; revised October 30, 1978

Summary. A catalogue has been made of 43 background sources detected in 89 fields observed with the Westerbork Synthesis Radio Telescope at 6 cm wavelength (4995 MHz). In some fields the completeness limit is as low as 4.5 mJy. The actual catalogue is presented in a companion article (Paper I) in the Supplement Series. In this paper, using the source sample, we extend the statistics of sources detected at high frequencies to fainter flux densities than was previously possible. We obtain the following results:

1. Contrary to the nearly Euclidean behavior found by Wall (1978), the exponent in the integral number–flux density relation appears to have an average value of \(-1.1\) in the range from \(-100\) mJy to 4.5 mJy.

2. The spectral index distribution agrees well with that found for the Bonn deep 6 cm surveys (~15–50 mJy).

3. The fraction of sources with optical counterparts decreases systematically with decreasing flux density.

4. The median angular size of faint 6 cm sources is less than \(\sim 8^\circ\).

Key words: radio source surveys — source counts — optical identifications — spectra — angular sizes

1. Introduction

It has been apparent for some time that sources detected in radio surveys conducted at high frequencies (e.g. 5000 MHz) have properties rather different to those of sources found in low frequency (e.g. 178 MHz) surveys. Some important properties of sources detected in high frequency surveys are:

a) The integral source count has a slope of approximately \(-1.5\), that is, it is "Euclidean" over the range of flux densities \(-2\) to 0.1 Jy (Pauliny-Toth, 1977). Thus the strong evolution seen in low frequency counts (e.g. Pooley and Ryle, 1968) is not present in the high frequency counts.

b) There is a much larger fraction of flat spectrum sources detected in high frequency surveys than in low frequency surveys (see e.g. Kellermann et al., 1969; Pauliny-Toth, 1977).

c) The flat spectrum sources are predominantly identified with quasars which appear to exhibit little or no cosmic evolution (Schmidt, 1976; Mason and Wall, 1977).

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\(^1\) mJy = \(10^{-20}\) W m\(^{-2}\) Hz\(^{-1}\)

We therefore felt it worthwhile to make an initial 6 cm source survey with the Westerbork Synthesis Radio Telescope (WSRT). The main goals of the survey were:

a) A determination of the source count at flux densities fainter than the level accessible to single dish telescopes.

b) A comparison of the optical identifications of a deep survey with the identification content of the strong source 6 cm surveys.

c) A study of the angular diameter distribution of the faint sources.

The sources detected in the survey are listed in a companion article (Paper I) published in Astronomy and Astrophysics Supplement Series. A full description of the source selection criteria and data reduction procedure is given there. Here we only note that some sources in the catalogue lie at distances from their field centers of more than 7'. The telescope pointing error (discussed in Paper I) causes the uncertainties in the flux densities of such sources to be greater than one third of the measured flux density. Such sources, therefore, cannot be used reliably for source count and spectral index studies.

2. Source Counts

We have detected enough sources (a) having flux densities above the completeness limit of their fields and (b) lying within 7' of their field centers to produce a reliable source count in two interval bins: 4.5–12.6 mJy and 12.6–35 mJy (see Table 1). The lower limit for the counts was established by noting that we have 19 fields complete to this limit and thus there should have been a reasonable chance of detecting a source this weak. The two fields having a completeness below 4.5 mJy constitute too small an area from which to expect the detection of any sources fainter than 4.5 mJy. Both the upper limit of 35 mJy and the maximum radius of 7' are quite arbitrary; however changing the upper limit boundary to a flux density of as much as 59 mJy and/or decreasing the maximum radius for a source to be included in the count to 5' both resulted in source counts which lay within the errors given in Table 1. Note that the errors listed there are merely formal statistical sampling errors; the small size of the present sample and the uncertainty in the correction factor for primary beam attenuation are most likely the dominant factors contributing to uncertainty in the source count. The source counts were computed using the area normalization procedure introduced by Katgert et al. (1973) and correcting for the finite areas subtended by the sources at the field centers. The correction was negligible for the count in the
Table 1. Westerbork 6 cm source counts

<table>
<thead>
<tr>
<th>S (mJy)</th>
<th>Number of Sources</th>
<th>ΔN/ΔS (sterad⁻¹ Jy⁻¹)</th>
<th>n/n₀^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>11</td>
<td>(7.00 ± 2.11) 10⁶</td>
<td>0.36 ± 0.10</td>
</tr>
<tr>
<td>12.6</td>
<td>12</td>
<td>(6.39 ± 1.84) 10⁵</td>
<td>0.43 ± 0.12</td>
</tr>
<tr>
<td>35.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^a Normalized with respect to an integral Euclidean count of n₀ = 60 S⁻¹.6 (Pauliny-Toth, 1977)

12.6 to 35 mJy bin and amounted to 10 ± 5% for the 4.5-12.6 mJy count, i.e. less than the sampling error.

Our differential count in the 12.6-35 mJy bin agrees reasonably well with that found at about this flux density limit in the deep Bonn surveys (Pauliny-Toth, 1977), although our normalized value is somewhat smaller than the Bonn one (0.43 vs. 0.59).

However, in making such a comparison one must be careful to consider what constitutes a “source” in either sample. Since the Bonn resolution is ~3', sources 4 and 5 and 21 and 22 in Table 2 of Paper I would just be considered two sources in a 100 m telescope survey. On this assumption, recomputation of the source count would yield normalized counts of 0.54 and 0.30 in the 12.6-35 and 4.5-12.6 mJy bins respectively. The normalized count of 0.54 then agrees well with the Bonn one.

The differential counts from our survey, normalized to the Euclidean integral count of 60 S⁻¹.6 are plotted in Fig. 1. Also plotted there are the counts from the Davis (1971) survey with the NRAO 300 ft telescope to a limiting flux density of 67 mJy. A comparison of our counts with those from the Davis survey indicates that over the range 100-45 mJy, the integral number–flux density relation must have a power law exponent of average value ~ −1.1. Thus at these low flux densities the 6 cm source counts finally show some definite departure from Euclidean behavior. However, the convergence is slower than that found for longer wavelength surveys. This is consistent with the presence of a steep spectrum population which evolves strongly and a flat spectrum population which undergoes little or no evolution.

The only previous estimate of the 6 cm count at a limiting flux density comparable to ours are the P(D) analyses of Wall and Cooke (1975) and Wall (1978). These authors placed maximum and minimum bounds on the source count to a level of ~1 mJy through an analysis of the deflection distributions in confusion limited scans with the Parkes 64 m telescope. Our 4.5-12.6 mJy count lies very near midway between the boundaries determined by Wall and Cooke (1975), but appears to be beneath the lower bound of the more recent P(D) count given by Wall (1978). Wall suggests that the 6 cm count is Euclidean to a level of ~10 mJy. Thus his proposed source count would lie considerably above our own count at this flux density level (Fig. 1). To explain his flat count, Wall finds it necessary to adopt the suggestion of Davis and Taubes (1974) that a class of flat spectrum objects begins to contribute strongly to the counts only at levels fainter than 20 mJy. If these flat spectrum objects have the compact structure characteristic of the flat spectrum sources found in the strong source 6 cm surveys they should have been easily detectable in the Westerbork survey. However, we find no evidence that the faint sources detected in our survey mainly have flat spectra (see Sect. 3). The only way we could have failed to detect Wall’s proposed population would be for these flat spectrum sources to have sufficiently large angular sizes to be well resolved by the WSRT. We therefore regard the existence of the additional proposed source population as unproven.

3. Spectral Index Distribution

We have computed a very crude spectral index distribution using all those sources in the survey (20 in total) which have been detected in Westerbork observations at other wavelengths. (In this analysis, sources 21 and 22 are counted as one source since they are blended together when seen with the lower resolution 21 cm beam.) We use the word “crude” advisedly because 8 of the 20 sources either lie at a radius greater than 7' from the 6 cm field center or are below the 6σ detection level and thus have a large error in their 6 cm flux densities. Nevertheless, the 21–6 cm spectral index distribution derived from the data given in Table 2 and shown in Fig. 2 is interesting for three reasons.

a) Seven out of the 20 sources, or 35 ± 13%, have flat spectra (α > −0.5 when S ∝ ν). This value is in excellent agreement with the results of Davis (1977) who finds that 34% of the Bonn deep survey sources have flat spectra although the large sampling error in our result cannot allow us to discriminate against the possibility that up to ~50% of the sources have flat spectra, as is the case for the 6 cm strong source surveys (Pauliny-Toth, 1977).

b) If we were indeed missing or resolving out a considerable part of the flux at 6 cm that is detected in longer wavelength 21 cm observations, we would expect the measured 21–6 cm
spectra of many of the sources to be very steep. For instance, if we were missing ~50% of the 6 cm flux from a source whose intrinsic 21–6 cm spectral index was $-0.75$, we would measure a 21–6 cm spectral index of $-1.3$. At least for those sources for which we do have 21 and 6 cm flux densities, the effect cannot be strong. The spectral index distribution (Fig. 2) that we derive from our smaller sample is not markedly different from that of Davis (1977) who studied 61 sources from the Bonn deep surveys.

There is one source in the sample where we have probably resolved out part of the flux. At 21 cm, source 1 was found by Willis et al. (1976) to have an angular extent of 19'. At 6 cm in the high resolution map it is apparently unresolved and has a very steep spectrum ($\alpha = -1.22$), so presumably a large scale component has been missed in the 6 cm observations. We note that source 2, the only other source found to have a spectral index $\alpha < -1$, must have an intrinsically steep spectrum, at least over the range 21–3 cm, since our measurements fit well with those of Rudnick and Owen (1976) at 11 and 3 cm.

c) Of the 11 sources having $S_6 < 21$ mJy, only 2 have spectral indices $> -0.5$. This is further evidence against the existence of an excessively large number of faint sources with very flat spectra as hypothesized by Wall (1978).

4. Optical Identifications

For the optical identification statistics we have a complete sample of 25 sources (excluding source 4 from the NGC 1514 field). We were able to identify 8 of these sources ($32 \pm 11\%$). Of the identifications, 4 are galaxies, 1 is obviously stellar in appearance, and 3 are too faint for their morphology to be directly determined on the Sky Survey prints. One additional source in the complete sample, number 19, could be identified on a deep Kitt Peak 4 meter IIIa-J plate kindly supplied by Dr. E. M. Burbidge. In order to compare this identification distribution with that found at 5 GHz at higher flux density levels, we exclude the two sources in the complete sample having flux densities stronger than 0.67 mJy, the identification percentage then becoming 7/23, or $30 \pm 12\%$.

It is then apparent that the identification percentage at 6 cm drops steadily from $80 \pm 8\%$ for $S_6 > 0.6$ Jy (Johnson, 1974) to $57 \pm 8\%$ for $0.067 < S_6 < 0.6$ Jy (Fanti and Padrielli, 1977; see also Condon et al., 1975) to $30 \pm 12\%$ for $S_6 < 0.067$ Jy (this paper).

How does our identification content, galaxies vs. stellar objects, compare with the identification content for the stronger source surveys? Johnson (1974) found that 53% of the identified sources in the strong source survey were stellar in appearance whereas 47% were galaxies. This distribution is not significantly different to that of Fanti and Padrielli (1977) who find 56% of their identifications to be quasars and 44% to be galaxies. At first sight, the fact that we find 4 obvious galaxies and only 1 stellar object would thus seem to imply a marked difference between the strong and weak source surveys. However, our survey identification statistics may contain a small bias: 2 of the galaxy identifications (sources 33 and 41) are with galaxies which are clearly members of the same cluster as the original radio galaxy at the field center (NGC 6037 and NGC 7385 respectively). Thus there is an excess of galaxies over the normal "background" number in some of our fields. Further, it was only possible to say directly that source 29 is identified with a galaxy because we had available a plate going to a considerably fainter magnitude level than do the Sky Survey prints (see de Ruijter et al., 1977). If sources 33 and 41 are rejected from the sample and source 29's identification is reassigned to the ? column, as it would have been if only the Sky Survey print had been available, the identification distribution is not significantly different to that found in the stronger 6 cm source surveys.

Note that the identification percentage found in this deep 6 cm survey ($32 \pm 11\%$) is, considering the errors, comparable to that found ($23\%$) in the deep Westerbork 21 cm surveys reaching similar limiting flux densities (Willis and de Ruijter, 1977).

If we split the sample of 20 sources for which we have spectra into two samples having spectral indices greater and less than $\alpha = -0.5$, we find identification fractions of 2/7 or 29% and 3/13 or 23% respectively. Thus, there is no significant difference.

5. Angular Size Distribution

Of the 26 sources lying within 7' of their field centers which constitute a complete sample, only 4 are obviously resolved (see Fig. 1 of Paper I). The remainder of the sources are unresolved, which implies that the medium East-West angular size of the present sample is $< \sim 5'$. Assuming that the sources are randomly oriented in position angle on the sky, one may multiply the East-West upper limit by a correction factor $\pi/2$ to obtain the median angular size of the sample which therefore must be less than $\sim 8'$.

Note that if we consider only the steep spectrum sources from the sample we obtain the same upper limit for the angular size. Both our own data and that of Davis (1977) indicate that only $\sim 35\%$ of faint 6 cm sources have flat spectra (see Sect. 3). Thus, since we only have 4 resolved sources out of 26 in our
sample (the median flux density of the sample equals 17 mJy), it is clear that the median angular size of even the steep spectrum sources is $<$ $\sim$ 8°.

The median angular size of steep spectrum sources is probably larger at higher 6 cm flux density levels. Fanti and Padrielli (1977) have recently used the WSRT to determine accurate positions and angular sizes of those sources from Davis' (1971) survey which are at galactic latitudes greater than $|b|$ = 20°. Utilizing those sources with flux densities $\geq$ 100 mJy (which are the ones with good signal-to-noise ratios) in the Fanti-Padrielli sample, we find (a) that the median angular size of the entire sample is $< 6°$ but that (b) the median angular size of the steep spectrum sources ($\alpha < - 0.5$) is $14° \pm 5°$. The median flux density of this latter subsample is 148 mJy. If we scale this flux density to 178 MHz, assuming an average spectral index of $\sim -0.75$, we find that the median angular size agrees well with that determined by Swarup (1975) who analyzed sources which were originally detected in low frequency surveys and have mainly steep spectra.

Since our own sample size is small and the median angular size of the Fanti-Padrielli sample does have a large error, the difference between the angular sizes of the steep spectrum sources in the two samples may be merely a statistical fluctuation. Also, the sizes of weak unequal double sources might have been systematically underestimated. For example, we would have missed one component of a double source with attenuated flux density $< 14$ mJy which has an intensity ratio between components of more than 2 to 1.

6. Conclusions

The results of the present survey may be summarized as follows:

a) The 6 cm source counts are beginning to converge in the range between 4 and 100 mJy. The rate of convergence is not, however, as rapid as that found in longer wavelength Westerbork surveys (see Willis et al., 1977).

b) The spectral index distribution of the present sample seems similar to that of sources in the deep Bonn surveys.

c) The percentage of sources with optical counterparts shows a systematic decrease as a function of decreasing flux density.

d) The median angular size of faint 6 cm sources is less than 8°. A similar result is found for just the steep spectrum sources with $\alpha < -0.5$. However, it is clearly desirable to measure the angular sizes of a larger sample of faint 6 cm sources to confirm this result.

The accuracy of most results discussed in this paper is limited by the small size of the source sample. Since new 6 cm fields are continually being added to the Westerbork 6 cm data reservoir, a more accurate analysis of a larger sample of faint 6 cm sources should be possible in the near future.

Acknowledgements. We are grateful to our colleagues who permitted us to use their data to construct the catalogue. Thanks are also due to the Westerbork Radio Observatory telescope and reduction groups for their efforts in providing high quality data. P. Katgert gave helpful advice, A.G.W. and G.K.M. respectively acknowledge the hospitality of Brandeis University and Lick Observatory during the final preparation of this paper. G.K.M. thanks the Netherlands Organization for the Advancement of Pure Research (ZWO) for a travel grant. The Westerbork Radio Observatory is operated by the Netherlands Foundation for Radio Astronomy with the financial support of ZWO.

References


