WESTERBORK SURVEYS OF RADIO SOURCES AT 610 AND 1415 MHZ

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1. INTRODUCTION

The Westerbork Synthesis Radio Telescope (WSRT) has now been used to make source surveys at frequencies of 610 and 1415 MHz. This paper summarizes the results concerning source counts and anisotropies in the distribution of sources from those surveys not concerned with clusters of galaxies.

2. 610 MHZ SURVEYS

The 610 MHz source counts described here are a combined count derived from the work of three separate groups. Although they were originally searching for radio counterparts to unidentified 3-U X-ray sources, Harris et al. (1976) have derived a source count for all the radio sources detected in the five fields they observed. Valentijn et al. (1976) were mainly concerned with observing the Coma cluster of galaxies but have computed a source count for those radio sources detected which they consider to be unassociated with the cluster itself. These sources are either unidentified optically or identified with objects having magnitude fainter than 17.5. Katgert-Merkelijn (1976) has observed several regions. Four fields lie in the area of the first 1415 MHz WSRT survey (Katgert et al,1973), one covers the region of the second 1415 MHz survey (Katgert-Merkelijn and Spinrad,1974) and three are high declination fields mostly observed for testing purposes when the 610 MHz system was first installed on the WSRT in 1973. At 610 MHz the primary beam pattern of the WSRT has a half power width of 83 arcmin, while the synthesized antenna pattern half power width is 55" (RA) x 55"cosecδ (DEC). The completeness limits for the counts of the different groups are: Harris et al., 15 mJy; Valentijn et al., 6.3 mJy; Katgert-Merkelijn, 22 mJy. Figure 1 shows the differential count derived by combining the various observations and, to lower the statistical error, using only those sample bins found to contain more than 10 sources. The total number of sources contributing to the count is 472. The error bars on the measurements represent sampling errors proportional to $\sqrt{n}$ where n is the number of sources found within a sampling bin. An excellent least squares fit to the observed counts

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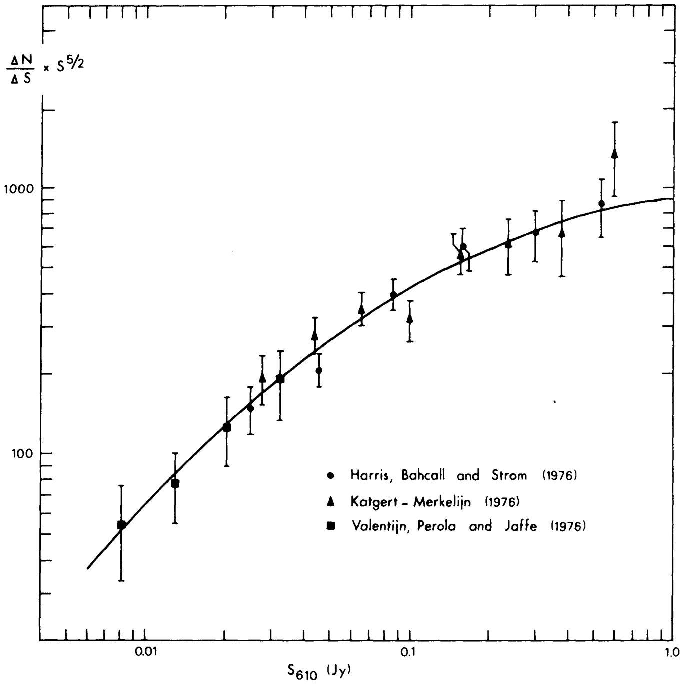

Fig. 1. WSRT 610 MHz differential counts. The solid line describes eq.(1).

is given by

$$dN/dS = 912.06\ S^{(-2.39\ -\ 0.101\ \ln S)} \qquad (1)$$

One must note, however, that there is no a priori astrophysical reason for the use of this particular type of equation. It is apparent that we are seeing strong convergence of the counts at the lower flux density levels. The slope of the differential count continually flattens, reaching a value of -1.46 at 10 mJy. Note that the fit to the counts for equation (1) did not include the Katgert-Merkelijn data point at 600 mJy because this point is strongly influenced by the count from the 1415 MHz survey 1 area (see below). An anomalously large number of sources stronger than 100 mJy is found in this region at 1415 MHz. We find a similar excess to occur at 610 MHz when the Katgert-Merkelijn integral count above 200 mJy (corresponding roughly to 100 mJy at 1415 MHz) from the four fields in the 1415 MHz survey 1 area is compared with the count of Harris et al.. Katgert-Merkelijn obtains 8300 ± 1470 sr^{-1} while Harris et al. find 5530 ± 790 sr^{-1}. The excess, 1.7σ, is not statistically significant, unlike the result at 1415 MHz, but this may be due to the small control sample presently available. This conclusion is supported by the fact that the counts from the other areas studied by Katgert-Merkelijn are also low relative to the counts in the 1415 MHz survey 1 area. Two of the other fields have some interference and thus may suffer from some incompleteness. Therefore these fields were not directly added to the control sample.

3. 1415 MHZ SOURCE SURVEYS

Seven surveys have now been completed using the WSRT at this frequency. Table 1 gives a brief description of their characteristics. Properties of the telescope common to all surveys are 1) primary beam half power width is 36 arcmin and 2) synthesized antenna pattern half power width is 23" (RA) x 23"cosecδ (DEC). Detailed descriptions of the reduction procedures employed for the various surveys are given in the references listed in Table 1. Source counts for surveys 1 to 4 are also found in the references.

Figure 2 shows the counts from survey 5 (Oosterbaan, 1977) combined with preliminary counts from the deep surveys 6 and 7 (Le Poole and Willis, 1977). The counts from these surveys have not yet been corrected for biases due to noise and resolution. Corrections for these effects, particularly the latter, will probably cause the counts to migrate upwards

Table 1 : 1415 MHz WSRT Source Surveys

Survey	Reference	Area (deg^2)	No. Sources	S_{lim}(mJy)
1	Katgert et al., 1973	25	224	7
2	Katgert-Merkelijn and Spinrad, 1974	4.5	58	7
3	Katgert, 1975, 1976	18	238	6.25
4	van Vliet et al., 1976	20	130	7.5 to 20
5	Willis et al., 1976	90	1075	3 to 10
6	Le Poole, 1977	2	60	1.5
7	Le Poole and Willis, 1977	1	50	1

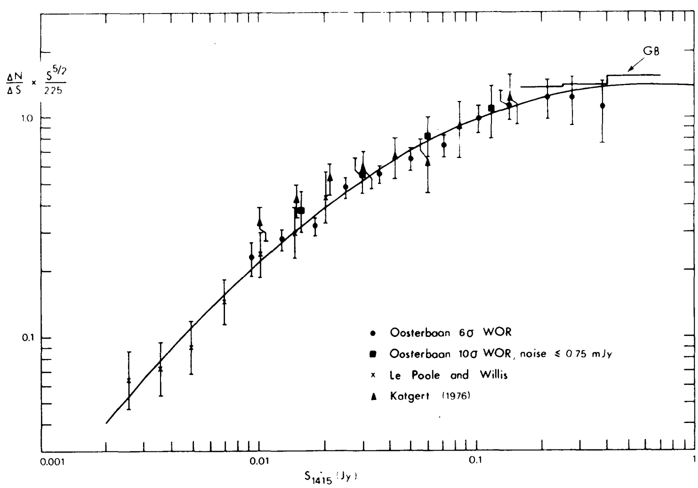

Fig. 2. 1415 MHz differential source count from surveys 3, 5, 6 and 7. The solid line describes eq. (2). For comparison, the counts from Maslowski's (1973) 1400 MHz Green Bank (GB) survey are also plotted.

since the separate count for the survey 5 sources having signal to noise ratios larger than 10 all move above the fitted line (eq. (2) below) in the direction of Katgert's (1976) counts for survey 3. The survey 3 counts have been corrected for noise and resolution bias. A fit to the counts from surveys 5, 6 and 7, which must therefore be regarded with caution, is

$$dN/dS = 310.72\ S^{(-2.59\ -\ 0.106\ \ln S)} \tag{2}$$

The counts at 1415 MHz, like those at 610 MHz, show strong convergence at low flux densities, and the slope of the differential count flattens to −1.50 by 6 mJy.

Because there are now WSRT 1415 MHz surveys composed of fields scattered over the sky (surveys 4 and 5) as well as of fields concentrated in a small area (surveys 1, 2 and 3) we can make some tests for anisotropy in the source counts on both a large and small scale.

Firstly, if radio sources are randomly distributed over the entire sky, the number of sources stronger than some limiting flux density detected within a uniform area should be poisson distributed. Thus the number of sources found within a WSRT field out to a distance of 0.55^{o} from the field centre should have this distribution. Survey 5 provides an excellent sample to test this hypothesis since the fields are reasonably well distributed over the sky. Figure 3 shows distributions of the number of sources detected per field for 85 fields from survey 5. We have plotted (a) the number of sources per field having a peak S $\geq$ 10 mJy, (b) the number having an intrinsic sky S $\geq$ 100 mJy and (c) sources contained in group (a) but not in (b). Distribution (a) essentially tests for variations in the integral count above the 10 mJy level, (b) for fluctuations in the integral count above 100 mJy and (c) for variations in the differential

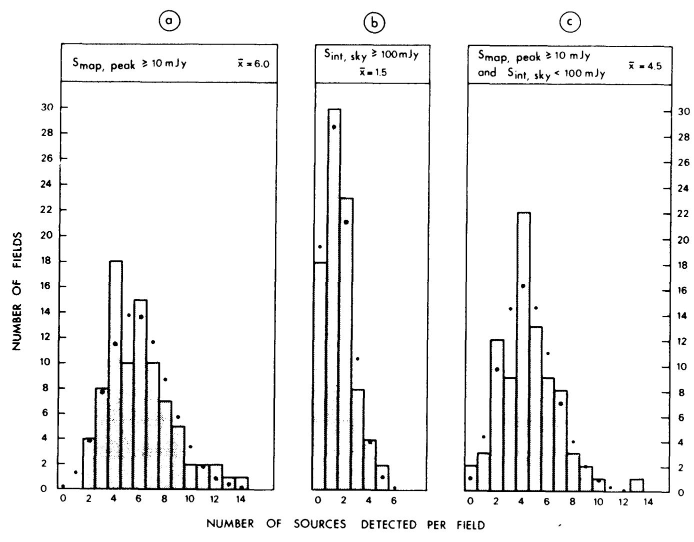

Fig. 3. Distributions of radio sources detected per field at 1415 MHz.

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count between 10 and 100 mJy. Figure 3 also lists the mean number of sources detected per field in each group and the dots show the theoretical poisson distribution expected on the basis of the observed mean number of sources. The observed distributions obviously agree very well with those expected. This is confirmed by a χ^2 test. Thus there does not seem to be any obvious evidence of large scale anisotropy. The poisson test is, however, insensitive to effects such as a gradient in the density distribution over the sky. We have divided the 85 fields into groups and searched for gradients in the number of sources detected as functions of galactic latitude, right ascension and declination. A gradient in the declination distribution would not be unexpected due to the changing resolution of the WSRT. No significant departures from random fluctuations were found in any of the groupings.

One can search for small scale anisotropy by comparing the number density of sources in each of the surveys composed of fields concentrated in a small area (1, 2 and 3 in Table 1) with the density found in control samples produced from other surveys listed in Table 1. There is certainly one significant anomaly. The survey 1 area contains too large a number of sources having intrinsic flux densities stronger than 100 mJy. 37 sources stronger than 100 mJy are found in the 14 fields from the survey 1 area which do not overlap each other. Using a control sample of 112 fields from surveys 3, 4 and 5 we find that a mean of 19.6 $\pm$ 1.6 sources is expected in 14 fields. The difference between the two samples is thus 2.8σ, which is significant at about the 0.6% level. The optical identifications, 9 galaxies and two stellar objects, are also anomalous. Accurate optical identifications of survey 5 sources stronger than 100 mJy (de Ruiter et al.,1976) lead us to expect about 4 stellar objects and only two galaxies to be identified in a 37 source sample. Thus the survey 1 identifications have about a 2σ excess of galaxies. Although these data suggest the possibility that strong sources cluster on a scale of $\sim$ 10 to 15 deg^2, more surveys of a similar size are definitely needed to confirm such a result. It is certainly not improbable that the survey 1 anomaly constitutes a "statistical mishap" with an occurrence of about 1 in 100 to 200 cases. Note that the source excess does not extend to flux densities below 100 mJy. The counts from survey 1 agree with those from the other surveys below this limit.

4. COMPARISON OF RESULTS AT DIFFERENT FREQUENCIES

Before one can accurately intercompare source counts made at two different frequencies one needs to know the two point spectral index distribution between the frequencies. This distribution has only been determined in a preliminary way for WSRT 610 and 1415 MHz samples (P. Katgert et al., this volume). We have simply scaled the counts using an effective (or δ function) spectral index,α_e. To make the WSRT 610 MHz and 1415 MHz surveys 5,6 and 7 counts presented in sections 2 and 3 compatible with each other one must change α_e from 0.6 to 0.8 as the 1415 MHz flux density increases from 2.6 mJy to $\sim$ 400 mJy. Excellent agreement between the counts is then obtained. This variation in α_e is consistent with that found by Fomalont et al. (1974). Note, however, that the corrected counts of 1415 MHz survey 3 (Katgert,1976) imply that α_e actually becomes considerably flatter than 0.6 in the 1415 MHz flux density range from ∿ 10 to 30 mJy.

A slight discrepancy is found when the WSRT 610 MHz counts are compared with the 5C2 and 5C5 counts (Pearson, 1975) made at the nearby frequency of 408 MHz. The 5C differential counts appear to be systematically lower by ∿ 20% and to exhibit less curvature over the 408 MHz flux density range from ∿ 20 to 200 mJy than do the 610 MHz counts scaled with α_e equal to 0.6. At this time one cannot say whether the disagreement is due to instrumental effects or is indicative of a real anomaly.

Although they were only derived from the WSRT data, equations (1) and (2) are found to give a reasonable mathematical description of the source counts up to S ∿ 10 Jy and ∿ 15 Jy at 1415 and 610 MHz respectively. Integration of S·dN gives an estimate of the total sky brightness temperature due to extragalactic radio sources. If we assume equations (1) and (2) to describe the counts to S = 0 Jy integration from S = 0 to ∞ yields brightness temperatures of 0.063 K and 0.651 K at 1415 and 610 MHz respectively. These integrals are not very sensitive to the lower limit. If we begin the integration at 2 mJy at 1415 MHz and 6 mJy at 610 MHz the resulting temperatures are 0.059 K and 0.599 K respectively. Using the assumption that the first two temperatures are reasonable estimates of the total brightness temperatures we compute the temperature spectral index between 1415 and 610 MHz to be 2.78. The brightness temperature at 178 MHz is then expected to be ∿ 20 K. This value is in quite reasonable agreement with Bridle's(1967) estimate of 30 ± 7 K at this frequency.

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DISCUSSION

Longair: If you omit the corrections from Westerbork 3 survey, do the numbers agree with all the other surveys?

Katgert: In view of the fact that a large percentage of the weak sources have angular sizes of the order of the beam, it would seem that a correction for resolution effects must be applied. The magnitude of the correction can be estimated only through model calculations, and it is possible that our use of (unequal) double sources has led to slight overestimation of the correction. Yet it would seem that such effects cannot really explain the higher source densities in the 3rd survey.

Pearson: Concerning the difference between the Westerbork 3 survey and the 5C surveys at 1400 MHz. The 5C source counts have not been corrected for resolution. Although these corrections are necessary, they are not significant above 10 mJy.

Katgert: It is true that corrections are important only near the flux density limit, but their effect on the counts is present also at higher flux densities, due to the effect of the envelope attenuation.

Jauncey: To increase the significance of the Westerbork results from the present 2 to 3 sigma to a more believable 5 or 6 sigma is going to require 4 times as much data from Westerbork.

Petrosian: At what flux level would you expect the normal galaxies to dominate the counts?

Willis: I expect the normal galaxies at about 1 mJy.

Longair: No. You only expect normal galaxies at about 0.1 mJy and then they will be at cosmological distances anyway.

Lynden-Bell: Since Westerbork survey 1 has too many Galaxy identifications, has there been a Galaxy count over this region to see whether there are too many optical Galaxies?

Katgert-Merkelijn: No.