1976A&A....52..219W

Astron. & Astrophys. 52, 219–226 (1976)

ASTRONOMY
AND
ASTROPHYSICS

On the Counts of Radio Sources Adjacent to nearby Galaxies

A. G. Willis
Sterrewacht Leiden, Huygens Laboratorium, Wassenaarseweg 78, Leiden, The Netherlands

Received March 2, revised April 30, 1976

Summary. Counts of radio sources having integrated flux densities $\geqq 100$ mJy[1] at 1415 MHz and lying at distances of less than 33′ from the positions of sixty nearby galaxies have been computed. These counts are compared with those found in previously published surveys. No significant excess of sources near the galaxies is found. In particular, no evidence was found to support the claim of Tovmasyan (1968) that there exists a significant excess of sources at distances of less than 15′ from galaxy positions. The negative result of the present paper agrees with those of de La Beaujardière et al. (1968), de Jong (1974) and Arp et al. (1975).

Key words: radio source counts — galaxies

1. Introduction

Radio emission from strong radio galaxies usually has a double structure, with the radio emitting regions symmetrically located on either side of the associated optical object, usually a giant elliptical galaxy. Many quasars have a similar radio structure. The detection of satellite radio sources lying outside the optical image but physically associated with spiral galaxies would thus indicate the existence of a common link in the evolution of spirals, ellipticals and quasars. Indeed, one class of spirals, the Seyferts, already has some optical properties in common with quasars [see van den Bergh (1975) for a review], while at least one spiral, NGC 4258, has ejected considerable radio emitting material from its nuclear region (van der Kruit et al., 1972). Several authors (de Jong, 1965, 1966; Tovmasyan, 1968; Arp, 1973) have claimed to detect such satellite radio sources. However, de La Beaujardière et al. (1968), de Jong (1974) and Arp et al. (1975) found no significant evidence for such associations.

Tovmasyan (1968) has made the strongest claim that there exist radio sources having physical associations with adjacent galaxies. He observed 272 galaxies, mainly spirals, with the Parkes radio telescope at a frequency of 1410 MHz. He found that within 15′ of the assumed galaxy position the number count of sources with flux densities $\geqq 300$ mJy exceeded by a factor of approximately two the value at larger distances.

Except for the observations of de La Beaujardière et al. (1968), data from the other studies are summarized in Arp et al. (1975). Only Tovmasyan's data show more than a $1\,\sigma$ excess in the number of sources found relative to the number expected from $\log N - \log S$ counts. The excesses of $1\,\sigma$ or less cannot be considered statistically significant. De La Beaujardière et al. detected 16 sources stronger than 300 mJy, a number in good agreement with the 13 they expected from 4 C counts extrapolated to 1415 MHz.

Tovmasyan studied the areas around 272 galaxies at 1410 MHz. De La Beaujardière et al. observed 135 galaxies at 1415 MHz. Unfortunately it is not possible to compare their data on satellite radio sources directly with those of Tovmasyan because the area they observed around each galaxy is declination dependent. They made right ascension strip scans of length 6 min in time. Further they give no quantitative information on the positions and flux densities of the sources they detected. The total number of galaxy fields observed by the other workers is only 25, of which 16 were studied at frequencies close to 1400 MHz and 9 at 2295 MHz. One must avoid frequency dependent selection effects that would appear if the sources associated with the galaxies had, say, unusually flat or steep radio spectra. Thus a direct test of Tovmasyan's results can only be made on a sample of galaxies observed at a frequency close to the one he used. Arp et al. (1975) showed that the excess found by Tovmasyan might not yet be noticeable in the small sample of 16 galaxies studied by de Jong at 1400 MHz.

Recently a catalogue of background sources detected in 96 fields surrounding objects observed by the Westerbork Synthesis Radio Telescope at 1415 MHz has been completed [Willis et al. (1976), hereafter

---

[1] 1 mJy $= 10^{-29}$ Watt m^{-2} Hz^{-1}

called WOR]. Many of the fields surround nearby galaxies. Before we use the radio sources for cosmological studies it is necessary to investigate the possibility that a significant number of them are associated with the galaxies. I have therefore selected a specific sample of sources from the catalogue with which to test the hypothesis that normal galaxies have satellite radio sources.

2. Observations and Source Sample

The sample selected for the study consists of sources detected in 60 fields, all but one of which surround galaxies, mainly spirals, listed in the Shapley-Ames (1932) catalogue. Such galaxies have magnitudes brighter than $m_{pg}=13$. The field centres are all located within a few arcminutes of the position of the galaxy. While IC 342 is not listed within the Shapley-Ames catalogue I have included the field around this galaxy in the sample because it is one of the original galaxies around which de Jong (1965) claimed an excess of radio sources. The source sample consists of those sources having integrated flux densities $\geqq 100$ mJy and lying within 33′ of their field centres. Reasons for these particular selection criteria are set out in the following paragraphs.

A complete description of the original observations and the reduction procedure is given in WOR. The most important effect upon the present investigation is attenuation from the primary beam power pattern of the individual telescopes comprising the Westerbork array. At 1415 MHz this primary beam pattern has a half power width of 36′. Because of this attenuation the distance from the field centre out to which a source of given intrinsic flux density can be detected progressively decreases as the flux density of the source decreases. Further, the field of view is effectively bounded by a radius of 33′ because the value of the attenuation function becomes very uncertain beyond this distance due to pointing errors of dishes in the array. Thus it is not possible to derive accurate intrinsic fluxes beyond a radius of 33′.

Because I wish primarily to test the hypothesis that there is an excess of sources within 15′ of galaxy positions, it is adequate to limit the analysis to those sources having intrinsic integrated flux densities of $\geqq 100$ mJy and lying within 33′ of the field centres. Sources stronger than 100 mJy can in most cases be detected out to a radius of 33′ so we are assured of an adequate sample of control sources with accurately measured intrinsic flux densities beyond a radius of 15′. The excesses claimed by earlier workers all appeared above the 100 mJy level so the sample easily suffices to test their claims.

A possible objection to the present analysis is that the previous studies were all conducted with single dish antennae whereas the present data are taken from a survey made with an aperture synthesis telescope composed of interferometers. Thus the present observations might discriminate against extended sources that would be detected in the single disk surveys. As part of his analysis of Westerbork 1415 MHz source counts in the 5 C 2 region, Katgert (1976) gives detailed calculations which show, however, that resolution effects do not exert an influence on Westerbork source counts at flux density levels exceeding 100 mJy, the limit for the present investigation. Our source counts are in excellent agreement with those of Katgert (1976) [see Section 3(b)]. Further, Fomalont et al. (1974) have used the NRAO 92 m paraboloid to remeasure flux densities of sources stronger than ~280 mJy that were detected in the first Westerbork survey (Katgert et al., 1973). The flux densities determined by Fomalont et al. (1974) agree very well with those measured at Westerbork. Thus there is no evidence that Westerbork counts of sources stronger than 100 mJy are biased by resolution effects.

Note that we rejected from the WOR catalogue and the sample discussed here sources lying within the optical image of a galaxy. Such sources are indeed usually associated with particular parts of the galaxy such as the nuclear component (van der Kruit, 1971) or H II regions (Israel et al., 1975). What I am testing here is the hypothesis that there exist satellite radio sources outside the optical image of a galaxy which are, however, physically associated with the galaxy. Thus, although fields surrounding M 31 and M 33 were included in the WOR catalogue, I have rejected these fields from the present sample. The optical images of these two very nearby galaxies have such large angular sizes that they cover almost an entire radio field and most of the radio sources detected lie within the optical galaxy. Further, because the primary beam attenuation limits the field of view to a uniform angular size we can only look for an excess of radio sources as a function of angular distance from a galaxy rather than as a function of intrinsic distance. Any satellite radio sources associated with M 31 or M 33 might well lie at an angular distance beyond the 33′ radius from the field centre that defines our boundary.

Because of some instrumental effects occasionally present at the field centre in early Westerbork observations, the field centres were not placed at precisely the positions of the galaxies, but a few arcminutes away. The search area bounded by a radius of 33′ is thus not quite symmetrically located with respect to the galaxy position. This slight offset does not affect the detection sensitivity within 15′ of any of the galaxies in the sample and so cannot influence the conclusions.

3. Results

a) *Results from the Present Investigation*

Table 1 lists the sources in the sample. The organization of the table is as follows:

1976A&A....52..219W

Column 1: name of the galaxy near the field centre.

Column 2: its Hubble type.

Columns 3 and 4: position (epoch 1950.0) of the galaxy as given by either Gallouët and Heidmann (1971) or Gallouët et al. (1973).

Columns 5 and 6: offset (in arc s) of the observed field centre relative to the position of the galaxy in the sense field centre minus galaxy position.

Column 7: name of the source in WOR.

Column 8: the integrated flux density of the source in mJy.

Column 9: the position angle (0° to 180°) of the major axis of the source, if it was resolved.

Column 10: the position angle (0° to 360°) of the direction vector from the galaxy to the source.

Column 11: the distance (in arcmin) between the source position, listed in WOR, and the galaxy position given in Columns 3 and 4.

The table shows that the number of sources detected per field ranged from zero to five. The mean number of detections was 1.62. One cannot directly conclude that those galaxies around which large numbers of sources, four or five, were found have an excessive number of radio sources associated with them. If the population from which the source sample was selected is randomly distributed in position over the sky then the number of radio sources detected per field should obey a Poisson distribution. Figure 1 shows a histogram of the number of fields in which a particular number of sources was found. Also plotted is the expected Poisson distribution based on a mean number of sources per field of 1.62 and normalized to a sample of 60 fields. The observed distribution agrees very well with the expected one. Thus the sample could have come from a population of sources randomly distributed in position over the sky. Then the detection of as many as four or five sources per field is not unexpected.

Table 1. Radio sources detected in galaxy fields

(1) Galaxy	(2) Type	(3) α 1950.0	(4) δ	(5) Δα	(6) Δδ	(7) Source Name	(8) S_{int}	(9) PA_1	(10) PA_2	(11) DIST
NGC 147	E	00 30 27.6	48 13 48	−9	+164	0027+48W1	188	124	296	27.2
						0032+47W1	219		128	30.9
NGC 185	E	00 36 11.4	48 03 44	−52	+120	0038+48W1	255	36	67	25.5
						0038+48W2	198	42	86	28.0
NGC 628	Sc	01 34 00.5	15 31 38	+126	+147	0132+15W2	127	90	229	25.5
NGC 891	Sb	02 19 24.6	42 07 12	+35	+133	−				
NGC 1058	Sc	02 40 22.9	37 07 47	−171	+91	−				
IC 342	Sc	03 41 57.4	67 56 26	−40	+261	0336+67W1	300	27	254	30.5
NGC 1569	I	04 26 05.3	64 44 23	−43	+154	0428+65W1	248		33	33.4
NGC 2403	Scd	07 32 02.9	65 42 42	+33	+216	0728+65W1	167	0	240	22.9
						0735+65W2	168		52	24.9
NGC 2608	Sc	08 32 15.3	28 38 47	−180	−87	0832+29W1	121		353	27.2
						0832+28W1	254	139	203	3.4
NGC 2681	Sa	08 49 57.8	51 30 09	+13	+136	0848+51W2	230		241	13.0
NGC 2685	So	08 51 40.4	58 55 30	+236	+298	0853+58W2	109		137	22.6
NGC 2782	Sb	09 10 53.8	40 19 15	+125	+247	−				
NGC 2798	S	09 14 09.7	42 12 40	+280	−79	0913+42W4	166		350	13.0
NGC 2841	Sb	09 18 35.0	51 11 20	−45	+157	−				
NGC 2903	Sc	09 29 20.2	21 43 14	+95	+189	0927+21W2	222		283	22.0
						0929+21W1	481		176	17.2
						0929+21W2	105		24	7.2
						0929+22W2	127	18	10	29.0
						0930+22W1	135	116	30	30.2
M 81	Sb	09 51 30.0	69 18 17	−20	+213	−				
NGC 3077	I	09 59 21.5	68 58 31	+73	+242	0956+68W1	104	125	236	21.2
						0957+69W1	130	119	296	13.5
						0958+69W2	347	126	350	35.6
NGC 3184	Sc	10 15 16.8	41 40 34	−174	−34	1014+42W1	122	60	329	23.2
NGC 3227	Sb	10 20 46.6	20 07 07	+89	+266	1019+19W1	385		244	21.0
						1020+19W1	133		192	20.8
						1020+20W1	115		6	26.4
						1022+20W3	1248	132	54	31.8
NGC 3310	I	10 35 39.1	53 45 56	+17	+91	1036+53W2	120	76	40	10.7
NGC 3348	E	10 43 27.5	73 06 14	+31	+42	1042+73W1	630	114	352	31.1
						1044+73W1	118	44	12	29.6
NGC 3359	SBc	10 43 20.7	63 29 12	+16	+139	1039+63W1	111		283	27.3
						1044+63W2	116		126	12.2
NGC 3432	Sc	10 49 42.5	36 53 07	+23	+222	1047+37W1	144		317	30.8
						1048+36W3	113		204	25.1
						1051+36W2	286		86	26.4
NGC 3516	E	11 03 22.9	72 50 22	+2	+70	1057+72W1	130	128	271	26.0
						1058+72W1	1524	139	249	24.1
						1104+72W1	347		111	4.4
						1105+73W1	219	66	14	30.9
NGC 3556	Sc	11 08 36.3	55 56 39	+108	+222	1110+55W1	100		104	19.3
NGC 3642	Sc	11 19 25.1	59 20 59	+76	+90	1115+59W1	150		247	28.7
NGC 3675	Sb	11 23 24.7	43 51 40	−110	−168	1121+43W2	149	159	246	23.0
						1121+43W3	370	133	222	26.2
NGC 3726	Sc	11 30 37.9	47 18 26	+31	+115	1128+47W1	142	151	264	16.8
NGC 3898	Sa	11 46 36.0	56 21 47	+42	+101	1146+56W3	151	7	165	8.1
						1149+56W1	102	0	43	31.4
NGC 3953	Sb	11 51 12.9	52 36 28	+148	+118	1153+52W2	237	45	111	21.4
NGC 3992	Sb	11 55 00.6	53 39 16	−37	−109	1157+53W2	304		135	31.0
NGC 4051	Sb	12 00 36.3	44 48 39	−16	+40	1159+44W2	227	135	299	15.6
NGC 4088	Sc	12 03 02.8	50 49 10	−126	+60	1159+50W1	116		270	33.0
						1200+51W1	143	26	306	25.3
						1202+51W1	234		341	29.3
						1203+50W1	271	136	152	16.7
NGC 4151	Sb	12 08 00.0	39 40 52	−13	+87	1209+39W3	309	6	93	22.5
NGC 4157	Sb	12 08 33.5	50 45 40	−8	+148	1207+50W1	221	73	316	19.1
						1208+51W1	251	85	9	24.2
						1209+51W1	221	73	33	22.4
						1211+50W1	110		113	27.4
						1211+50W2	109		90	29.0
NGC 4214	I	12 13 08.4	36 36 29	−171	−48	1211+36W1	274	126	251	16.6
						1214+36W2	199		137	25.8
						1214+36W3	126	178	46	29.7
NGC 4258	Sb	12 16 29.2	47 35 01	−27	+175	−				
NGC 4319	S	12 19 34.4	75 35 55	+26	+218	−				
NGC 4321	Sc	12 20 22.9	16 06 01	−24	+137	1221+16W1	679		36	23.2
						1221+16W2	109	150	49	25.1
NGC 4473	E	12 27 16.7	13 42 23	−176	−68	1227+13W2	326		52	3.4
NGC 4472	E	12 27 14.3	08 16 39	+21	−90	1227+08W1	108		179	9.5
						1228+08W1	102	90	66	19.8
NGC 4490	Sc	12 28 09.6	41 54 55	+93	+83	1228+41W2	199		168	29.0
NGC 4621	E	12 39 30.9	11 55 14	+73	−49	1237+11W1	120		244	31.1
						1240+11W1	194	54	144	21.4
NGC 4631	Sc	12 39 41.0	32 48 49	+122	−192	1240+33W1	240		18	27.6
NGC 4656	I	12 41 31.6	32 26 31	+13	+125	−				
NGC 4670	Sb	12 42 50.3	27 24 00	+114	+205	−				
NGC 4725	S(B)b	12 48 00.8	25 48 38	+141	−177	1246+25W1	111		273	15.8
						1249+25W2	290		85	20.4
NGC 4736	Sb	12 48 31.6	41 23 35	+35	+44	1247+41W1	156		336	26.0
NGC 4826	Sb	12 54 16.5	21 57 04	−188	−220	−				
NGC 5055	Sb	13 13 35.1	42 17 48	+38	+120	1311+41W1	216	38	223	29.0
						1315+42W1	117		66	19.8
M 51	Sc	13 27 45.7	47 27 16	+138	+249	1330+47W3	207		70	31.1
NGC 5383	SBb	13 55 00.8	42 05 34	+86	+87	1355+42W1	132	79	18	7.2
M 101	Sc	14 01 27.8	54 35 34	−6	+52	1358+54W2	185	136	250	27.7
						1401+55W1	132		359	27.8
						1403+54W2	105	26	117	24.2
NGC 5548	S	14 15 43.4	25 21 57	−35	+92	1413+25W1	564	140	273	28.5
						1416+25W7	139		47	23.6
NGC 5866	E	15 05 07.4	55 57 18	+69	+183	1504+56W1	161		312	12.1
						1504+55W1	165		222	7.0
NGC 5907	Sb	15 14 36.6	56 30 24	+25	−74	1516+56W1	539	160	151	26.4
NGC 6946	Sc	20 33 47.7	59 58 59	−36	−53	2031+60W1	207	63	307	24.3
						2032+59W1	131	83	235	15.4
						2036+59W1	102		129	22.8
NGC 7331	Sb	22 34 47.2	34 09 31	+42	+189	2233+33W1	144		232	28.1
						2233+33W4	146	155	234	18.0
						2234+34W1	148	20	209	4.9
NGC 7626	E	23 18 10.4	07 56 36	−10	−100	2318+08W1	168	90	4	17.4
						2318+08W2	440	32	44	16.0
						2320+07W1	1176		92	28.1
NGC 7640	SBc	23 19 43.1	40 34 14	+81	+205	2317+40W1	112		301	33.1
						2322+40W1	349		109	32.3

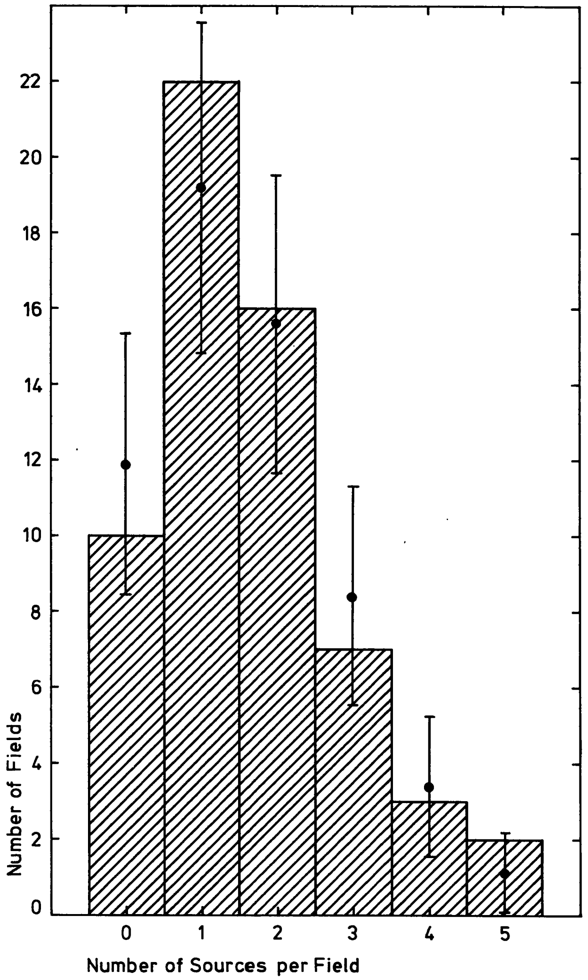

Fig. 1. A histogram (shaded bars) of the observed number of fields as a function of the number of sources per field. The dots indicate the number of fields expected from a Poisson distribution having a mean of 1.62 sources per field and normalized to the total sample of 60 fields. Their error bars denote the 1 σ expectation range over which an observed distribution would deviate from the one expected because of sampling errors

This result tells us nothing, however, about the possibility that the observed distribution is derived from two different populations, one of true background sources randomly distributed about the sky and another of satellite sources that, say, are randomly ejected from galaxies and are found predominantly within 15′ of the galaxies' positions. Such a combined distribution would very likely exhibit Poisson characteristics.

We must therefore check if our observed distribution has a mean value significantly different from that of a sample of sources believed to be true background sources at cosmological distances. Such a comparison is, of course. identical to comparing the radio source counts in areas near the galaxies with counts of sources in regions of the sky far enough from the galaxies for the sources to be considered unassociated background objects.

I have therefore counted sources in three different zones in the field surrounding the galaxies: 1) the whole field out to a radius of 33′ from the field centre, 2) the area lying within 15′ of the position of the galaxy and 3) the area beyond 15′ of the galaxy but within 33′ of the field centre (i.e. zone 1 minus 2). There were enough sources in the sample that accurate differential counts could be computed in three ranges: 1) $100 \leqq S \leqq 200$ mJy, 2) $200 < S \leqq 300$ mJy and 3) $300 < S \leqq 400$ mJy. There were too few sources detected above 400 mJy to compute an accurate differential count but these sources were, of course, included in the integral count. The results are shown in Table 2, which contains the following information:

Column 1: the flux density intervals, in mJy, for the differential count.

Column 2: the number of detected sources having flux densities within the interval specified in Column 1.

Column 3: the differential source count (number sterad^{-1} Jy^{-1}).

Column 4: the integral source count (number sterad^{-1}) having flux densities above the lower limit of the interval listed in Column 1.

The errors in the counts given in Table 2 are formal sample size errors. The counts of source found within 15′ of the galaxy position have been corrected for the area obscured by the optical image of the galaxy. I estimated the average galaxy to have a radius of 4′. The size of a galaxy's optical image was determined from its appearance on either the Palomar Sky Survey prints or deep III a–J prints (H. C. Arp, private communication) without respect to any particular isophote level. Errors introduced into the counts by this procedure are at most eight percent of the count. This value is small compared to the sampling errors of the counts in zone 2 and can be neglected.

Before comparing the counts in the different zones, first note that a 1 σ difference between two measurement m_1 and m_2 is defined as $\sigma_{m_1-m_2}=\sqrt{\sigma^2_{m_1}+\sigma^2_{m_2}}$ where σ_{m_1} and σ_{m_2} are the errors in the individual measurements.

Table 2. Source counts around all galaxies in the sample

	(1) $S_{\text{int}}(S)$	(2) n	(3) $dN/dS\,(\pm\sigma)$	(4) $N(S)\,(\pm\sigma)$
Zone 1:	$100 \leqq S \leqq 200$	58	3.42 (0.45) 10^4	5.67 (0.58) 10^3
	$200 < S \leqq 300$	22	1.27 (0.27) 10^4	2.25 (0.36) 10^3
	$300 < S \leqq 400$	8	4.60 (1.63) 10^3	9.78 (2.37) 10^2
	$400 < S < \infty$	9	—	5.18 (1.73) 10^2
Zone 2:	$100 \leqq S \leqq 200$	11	3.30 (0.99) 10^4	4.50 (1.16) 10^3
	$200 < S \leqq 300$	2	6.00 (4.24) 10^3	1.20 (0.60) 10^3
	$300 < S \leqq 400$	2	6.00 (4.24) 10^3	6.00 (4.24) 10^2
	$400 < S < \infty$	0	—	—
Zone 3:	$100 \leqq S \leqq 200$	47	3.51 (0.51) 10^4	6.05 (0.67) 10^3
	$200 < S \leqq 300$	20	1.45 (0.32) 10^4	2.54 (0.43) 10^3
	$300 < S \leqq 400$	6	4.35 (1.78) 10^3	1.09 (0.28) 10^3
	$400 < S < \infty$	9	—	6.53 (2.18) 10^2

It can then be seen that there are no statistically significant differences between the results for the three zones in either the differential or the integral counts. The largest difference, $\sim 1.8\,\sigma$, is found between the 200 mJy integral counts of zone 2 and those of zone 3. There is certainly no relative excess of sources within a radius of 15′; while the differences are not significant there is actually a slight deficit of sources relative to the number beyond this radius.

Thus there is no excess of sources within 15′ of the position of all the galaxies in the present sample. One must, consider, however, the possibility that an excess of sources might exist around some particular type of galaxy. Because the satellite sources of de Jong (1965, 1966), Tovmassian (1968) and Arp (1973) all occur around spiral galaxies, a separate count was computed for the sources lying in the fields surrounding the 46 spiral galaxies in the sample. The results are shown in Table 3, which has a format similar to that of Table 2. While the differences are not significant, the counts of sources near the spirals are actually slightly lower than those of sources from the total sample. As was the case for the total sample, the counts for the spiral sample are lowest in zone 2, the region within 15′ of a galaxy position. The 100 and 200 mJy integral counts in zone 3, the area beyond 15′ are again larger than those in zone 2, this time by about $2\,\sigma$.

One additional test can be made to check on a possible association between the radio sources and the central galaxies. It is known that, when resolved, the outer components of true double radio sources tend to be extended parallel to the major axis of the source, with a standard deviation of about 12° (Harris, 1974). The major axis is defined to be a line joining the high brightness heads of the outer components. Usually, the optical object lies within a few arcs of the major axis. Thus, if a resolved source in the present sample were associated with the galaxy at the field centre one might expect some correlation between the position angle along which the source is resolved and that of the direction vector between the source and the galaxy. Therefore the major axes of the resolved sources were plotted against the position angles of the direction vectors (thus a direction vector is effectively defined to be the major axis of a "radio source" consisting of the resolved source and the galaxy). As can be seen from the plot shown in Figure 2 there is no correlation. A similar plot, utilizing just those resolved source lying within 15′ of the galaxy positions, produces an identical result (Figure 3).

Table 3. Source counts around spiral galaxies

	(1) $S_{\mathrm{int}}\,(S)$	(2) n	(3) $dN/dS\,(\pm\,\sigma)$	(4) $N(S)\,(\pm\,\sigma)$
Zone 1:	$100 \leqq S \leqq 200$	42	$3.20\,(0.49)\,10^4$	$5.22\,(0.63)\,10^3$
	$200 < S \leqq 300$	17	$1.28\,(0.31)\,10^4$	$2.03\,(0.49)\,10^3$
	$300 < S \leqq 400$	5	$3.75\,(1.68)\,10^3$	$7.51\,(2.37)\,10^2$
	$400 < S < \infty$	5	—	$3.75\,(1.68)\,10^2$
Zone 2:	$100 \leqq S \leqq 200$	6	$2.35\,(0.96)\,10^4$	$3.13\,(1.11)\,10^3$
	$200 < S \leqq 300$	2	$7.82\,(5.53)\,10^3$	$7.82\,(5.53)\,10^2$
	$300 < S \leqq 400$	0	—	—
	$400 < S < \infty$	0	—	—
Zone 3:	$100 \leqq S \leqq 200$	36	$3.46\,(0.58)\,10^4$	$5.83\,(0.75)\,10^3$
	$200 < S \leqq 300$	15	$1.42\,(0.37)\,10^4$	$2.37\,(0.47)\,10^3$
	$300 < S \leqq 400$	5	$4.73\,(2.12)\,10^3$	$9.46\,(0.30)\,10^2$
	$400 < S < \infty$	5	—	$4.73\,(2.12)\,10^2$

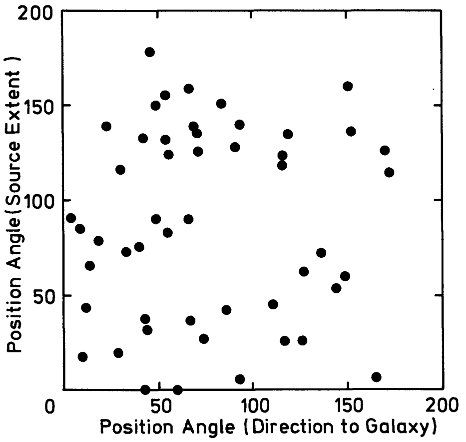

Fig. 2. The position angles along which resolved sources are extended plotted against the position angles of the direction vectors from the galaxies to the sources. To produce this plot 180° has been subtracted from those vector position angles having larger values

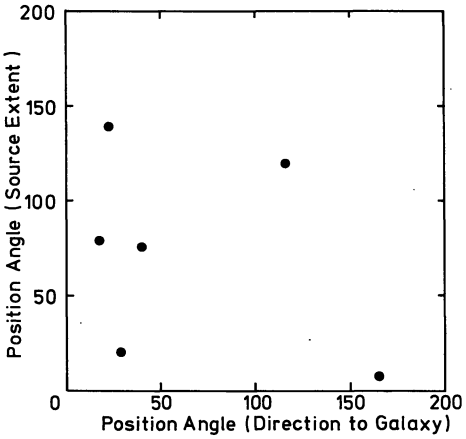

Fig. 3. A plot similar to that of Figure 2 is shown for just the resolved radio sources found within 15′ of galaxy positions

b) Comparison with Other Surveys

Tovmasyan (private communication) points out that only two of the galaxies that he listed as having possible satellite radio sources are brighter than eleventh magnitude. Since 19 of the 46 spirals in the present sample have magnitude brighter than 11 he suggests that any radio source associated with these brighter, and thus closer, galaxies would be at larger angular distances than 15′. In the previous section it was shown that the

Table 4. An intercomparison of source counts from the present survey with those of Katgert et al. (1973)

	Zone 1		Zone 2		Zone 3		Katgert et al.	
S_{int}	n	$dN/dS\,(\pm\,\sigma)$	n	$dN/dS\,(\pm\,\sigma)$	n	$dN/dS\,(\pm\,\sigma)$	n	$dN/dS\,(\pm\,\sigma)$
$124 \leqq S \leqq 193$	28	2.35 (0.44) 10^4	7	3.04 (1.15) 10^4	21	2.23 (0.49) 10^4	15	4.02 (1.04) 10^4
$193 < S \leqq 300$	26	1.40 (0.28) 10^4	2	5.61 (3.96) 10^3	24	1.63 (0.33) 10^4	13	2.00 (0.55) 10^4
$300 < S \leqq 465$	9	3.14 (1.05) 10^3	2	3.64 (2.57) 10^3	7	3.08 (1.16) 10^3	6	4.80 (1.96) 10^3

source counts indeed tend to be highest in zone 3, the area beyond 15′.

Before this source count excess can be considered significant, the counts must be compared with those from areas of sky believed to be essentially free of any sources that might be associated with nearby galaxies. I therefore compared my counts with those from the first Westerbork 1415 MHz survey (Katgert et al., 1973). Table 4 shows the counts in the different zones for the complete sample of galaxies compared with the counts of Katgert et al. (1973). The flux density sampling intervals for the galaxy zones have been changed to agree with those listed in the earlier survey. The present results are not significantly different from those found in the first Westerbork survey and are actually lower than those.

One should note that five Shapley-Ames galaxies, NGC 4861, NGC 4858, NGC 4914, NGC 5005 and NGC 5033 lie within the area covered by the first Westerbork survey. There are, however, two facts which suggest that any sources having an intrinsic association with the galaxies would exert a negligible influence on the total source count from the earlier survey. Firstly, only ~4% of the total area of sky covered by that survey lies within 15′ of the galaxy positions. Secondly, all the galaxies are at distances of 33′ or more from the field centres of the first Westerbork survey. Thus the primary beam attenuation mentioned earlier ensures that any sources that might be associated with the galaxies would probably not have been detected in the survey.

A comparison was also made with Westerbork 1415 MHz counts in the 5 C 2 region (Katgert, 1976). The 5 C 2 region is a good area for intercomparison because only one Shapley-Ames galaxy, NGC 3583, lies in the area. It is at a distance of 2.1° from the original 5 C 2 field centre (Pooley and Kenderdine, 1968). Therefore primary beam attenuation ensures that any sources due to this galaxy have a negligible effect on the data. Katgert gives a differential count for the range 100 to 200 mJy. His value, 3.67 (0.95) 10^4 sterad^{-1} Jy^{-1}, agrees well with my own data in this range (Tables 2 and 3).

Finally, the present counts may be compared with those derived by Maslowski (1973) from his survey with the NRAO 92 m telescope. This survey covered 0.1586 steradians of sky (an area that is a factor 9 greater than the total area of the fields contained in my present sample). One should note that while de Jong (1974) showed that there was no excess of sources near the four bright galaxies having radio emission that are contained within the area covered by Maslowski's survey, no equivalent study has been made of the sources near the radio quiet spirals lying within the survey zone. Nevertheless Maslowski's integral counts of 1380 ± 92 and 2272 ± 120 sources sterad^{-1} for sources having flux densities greater than 300 and 200 mJy respectively agree well with the numbers obtained from the present sample (see Tables 2 and 3) when one takes the statistical uncertainties into account.

Thus the source density around the galaxies contained within the present sample agrees well with that determined from other 1415 MHz surveys covering areas of sky that are mostly at large angular distances from bright galaxies.

c) Discussion Concerning Tovmasyan's Results

It remains, then, to reconcile the normal source densities found in the present survey with the strong excess of radio sources detected within 15′ of galaxy positions by Tovmasyan (1968). The most likely explanation is that many of the Tovmasyan sources are not satellite sources lying outside the optical image of a galaxy but are sources directly embedded within the galaxy. However, one can also show, in retrospect, that Tovmasyan could not have distinguished between a true excess of sources near galaxies and a spurious excess caused by radio sources that really coincide in position with an optical galaxy but appear to be separate from the galaxy because of measurement uncertainties.

The problem originally confronting Tovmasyan in his survey to search for radio emission from optical galaxies was as follows: one searches for radio emission at a given *optical* position and detects a radio source adjacent to, but not precisely coincident with, the optical position. How does the observer then distinguish between a radio source truly coinciding with an optical galaxy but appearing to be separate from it because of measurement errors and a background source lying close to a galaxy by chance?

This problem is identical to that which occurs when one wishes to optically identify sources detected in a radio survey of a specific area of sky. One then searches near the *radio* position for possible optical counterparts and needs a criterion to distinguish between a true optical identification and a contaminating optical object found by chance close to the radio position. De Ruiter, Willis and Arp (1976) have considered this latter problem when searching for optical identifications to WOR radio sources. They show that if the location of contaminating background objects is governed by a Poisson process and the probability distribution of position differences between true radio-optical counterparts due to measurement errors is the Rayleigh distribution, then the following likelihood ratio *LR* is defined

$$LR = \frac{\text{probability}}{\text{probability}}\,\frac{\text{of having a true radio-optical association}}{\text{of finding a contaminating background object}}$$

$$= \frac{1}{2\lambda}\exp\left\{\frac{r^2}{2}(2\lambda-1)\right\} \qquad (1)$$

where

$$r = \left(\frac{\Delta\alpha^2}{\sigma_\alpha^2} + \frac{\Delta\delta^2}{\sigma_\delta^2}\right)^{1/2}$$

and

$$\lambda = \pi\sigma_\alpha\sigma_\delta\varrho\,.$$

$\Delta\alpha$ and $\Delta\delta$ are the measured position differences in right ascension and declination prespectively between the radio and optical objects. σ_α and σ_δ are the combined radio and optical measurement errors in right ascension and declination respectively. ϱ is the mean density of background objects (these are radio sources for the problem of interest in the present paper).

One can then arbitrarily state that those radio and optical objects whose position are close enough together for their likelihood ratio to be larger than some limiting value consitute a true radio-optical association. If the likelihood ratio is smaller than this limiting value the objects are defined to be a chance association. An appropriate limiting value for the likelihood ratio which ensures that almost all true radio-optical associations are detected while few spurious associations are misclassified as real ones is $LR \simeq 2$ (de Ruiter et al., 1976).

Tovmasyan only regarded a radio source as directly identified with a particular galaxy if its coordinates differed by not more than $1'.5$ to $2'.0$ from the coordinates of the galaxy. Table 1 of his 1968 paper gives a list of the 43 sources he detected whose coordinates differ by more than $1'.5$ to $2'.0$ but less than $15'$ from those of a galaxy. He claims that many of these 43 sources must be satellite radio sources.

Likelihood ratios for these 43 sources have been computed to test the alternative hypothesis that many of them are directly embedded in the galaxies but appear to be separated simply because of measurement errors in the radio and optical positions.

The values for σ_α and σ_δ used in the computations were derived as follows. Tovmasyan's radio positions had a stated accuracy of $\pm 2'$ in declination (Tovmasyan, 1966). Tovmasyan observed some sources at 408 MHz with the Molonglo Cross telescope. These radio sources had an accuracy of $0.5'$ in right ascension while the remaining sources had $2'$ accuracy in right ascension. The radio positions were compared with galaxies optical positions listed in de Vaucouleurs and de Vaucouleurs (1964) catalogue. Positions in this catalogue have an accuracy of about $\pm 0'.83$ (Gallouët and Heidmann, 1971). Thus a $1\,\sigma$ combined measurement error in the difference between one of Tovmasyan's radio coordinates and the corresponding optical coordinate is $\sigma_\alpha = \sigma_\delta = (2^2 + 0.83^2)^{1/2} = 2'.2$ ($\sigma_\alpha = 1'.0$ for those sources having the more accurate position measurements).

For the present problem ϱ is the density of background radio sources having flux densities stronger than 300 mJy. A reasonable estimate for ϱ is Maslowski's (1973) value, $1380 \pm 92\ \text{sterad}^{-1}$.

It is then found that some 10 to 17 of Tovmasyan's possible satellite radio sources have likelihood ratios greater than 2 (the exact number is uncertain because he does not state which sources have the more accurate right ascension positions). Thus these sources have a much larger probability of really being directly embedded within the corresponding galaxies than of being nearby background sources. Removal of a mean of 14 sources from Tovmasyan's original sample of 43 causes the density of the remaining ones to drop to $\sim 1700 \pm 300\ \text{sterad}^{-1}$, a value only $\sim 1\,\sigma$ larger than Maslowski's density of $1380 \pm 92\ \text{sterad}^{-1}$.

However, consider the possiblity that many of Tovmasyan's objects constitute a true population of satellite radio sources causing the source density near galaxies to be indeed much higher than the true background density. Use of the likelihood ratio test would then lead to many of the sources being erroneously identified directly with galaxies simply because of the large uncertainty in Tovmasyan's positions. Thus Tovmasyan's positions are not accurate enough for one to discriminate between the hypothesis that there exists an excess of satellite sources near galaxies and the hypothesis that the sources are really coincident with the galaxies but appear separated because of measurement errors. One needs radio and optical data whose combined position uncertainty is $\sim 0'.75$ or better before one can effectively distinguish between the two possibilities.

4. Concluding Remarks

One must conclude that the vast majority of sources in the WOR catalogue are unrelated background sources having no physical association with the galaxies at the field centre. This result is consistent with the earlier findings of de La Beaujardière et al. (1968), de Jong (1974) and Arp et al. (1975). Further, the present observations agree with those of Van Vliet et al. (1976), who found no evidence for an excessive number of sources near the strong radio galaxies and quasars that have been observed at Westerbork.

It should be noted that the present investigation has only been concerned with the study of radio sources at a uniform angular distance from galaxies. The angular size of extended radio sources associated directly with strong radio galaxies and quasars is a function of the redshift of the parent galaxy or quasar (Miley, 1971). If satellite radio sources associated with normal galaxies also had a distance dependent angular separation, their presence might not have been revealed by the simple tests carried out in this paper. In addition, the primary beam attenuation of the Westerbork telescope does not permit the detection of sources beyond a distance of $\sim 33'$ from the field centre. Thus the present investigation would miss any satellite sources that lie at greater distances from their parent galaxies.

If Arp et al. (1975) and Tovmasyan (private communication) are correct in suggesting that $\sim 12\%$ of nearby spirals have satellite sources stronger than 300 mJy, then only $\sim 6 \pm 2$ such sources would be associated with the present sample of 46 spirals. Because of fluctuations in the background source density, these few sources will not exert a detectable influence on the observed source count. However, the number of galaxy observations in the Westerbork data reservoir continually increases so it will be possible to repeat the present analysis on a much larger galaxy sample within a few years.

Calculations show that ~ 14 of the 43 sources found near galaxies by Tovmasyan (1968) are more likely to be directly embedded within the galaxies. It is desirable, however, that the positions and flux densities of Tovmasyan's sources be measured very accurately at 1400 MHz so as to distinguish between this conclusion and the alternative hypothesis that a true excess of sources occurs near the galaxies studied by Tovmasyan.

Acknowledgements. I thank Dr. H.C. Arp for bringing the problem to my attention and for commenting upon the manuscript. Prof. H. van der Laan, H.R. de Ruiter and H.M. Tovmasyan also gave helpful advice.

References

Arp, H.: 1973, *Astrophys. J.* **183**, 791

Arp, H., Carpenter, R., Gulkis, S., Klein, M.: 1975, preprint

de La Beaujardière, O., Kazès, I., Le Squeren, A.M., Nguyen-Quang-Rieu: 1968, *Ann. Astrophys.* **31**, 387

de Jong, M.L.: 1965, *Astrophys. J.* **142**, 1336

de Jong, M.L.: 1966, *Astrophys. J.* **144**, 555

de Jong, M.L.: 1974, *Publ. Astron. Soc. Pacific* **86**, 90

de Ruiter, H.R., Willis, A.G., Arp, H.C.: 1976, in preparation

Fomalont, E.B., Bridle, A.H., Davis, M.M.: 1974, *Astron. & Astrophys.* **36**, 273

Gallouët, L., Heidmann, N.: 1971, *Astron. & Astrophys. Suppl.* **3**, 325

Gallouët, L., Heidmann, N., Dampierre, F.: 1973, *Astron. & Astrophys. Suppl.* **12**, 89

Harris, A.: 1974, *Monthly Notices Roy. Astron. Soc.* **166**, 449

Israel, F.P., Goss, W.M., Allen, R.J.: 1975, *Astron. & Astrophys.* **40**, 421

Katgert, P., Katgert-Merkelijn, J.K., Le Poole, R.S., van der Laan, H.: 1973, *Astron. & Astrophys.* **23**, 171

Katgert, P.: 1976, *Astron. & Astrophys.* **49**, 221

Maslowski, J.: 1973, *Astron. & Astrophys.* **26**, 343

Miley, G.K.: 1971, *Monthly Notices Roy. Astron. Soc.* **152**, 477

Pooley, G.G., Kenderdine, S.: 1968, *Monthly Notices Roy. Astron. Soc.* **139**, 529

Shapley, H., Ames, A.: 1932, *Harvard Ann.* **88**, No. 2

Tovmasyan, H.M.: 1966, *Australian J. Phys.* **19**, 565

Tovmasyan, H.M.: 1968, *Astrofizika* (English translation) **4**, 32

van den Bergh, S.: 1975, *J. Roy. Astron. Soc. Canada* **69**, 105

van der Kruit, P.C.: 1971, *Astron. & Astrophys.* **15**, 110

van der Kruit, P.C., Oort, J.H., Mathewson, D.S.: 1972, *Astron. & Astrophys.* **21**, 169

Van Vliet, W., Harten, R.H., Miley, G.K., Albers, H.: 1976, *Astron. & Astrophys.* **47**, 345

de Vaucouleurs, G., de Vaucouleurs, A.: 1964, Reference Catalogue of Bright Galaxies, Univ. of Texas Press, Austin.

Willis, A.G., Oosterbaan, C.E., de Ruiter, H.R.: 1976, *Astron. & Astrophys. Suppl.* (in press)