IDENTIFICATIONS FROM THE WSRT DEEP SURVEYS

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1. INTRODUCTION

The WSRT yields samples of radio sources which are well suited for systematic identification work for the following reasons:

a) The surface density is high: at 1415 MHz an average of 10 to 30 sources can be detected within 0°.55 from the field centre; at 610 MHz the numbers are 40 to 100 within 1°.0. In any given field, most sources will fall within the boundaries of plates for the present generation of optical telescopes.

b) The positional accuracy is, on the whole, rather high. One can thus propose identifications based on positional agreement only, avoiding selection effects present when selecting "on type".

The purpose of the present paper is to discuss the identification data available at present, either already published or in press. Completeness and reliability of the various samples will be reviewed, together with the statistical properties. The basic parameters of the various surveys are listed in Table 1, which should be largely self-explanatory. The percentage of identifications in Column 8 is the raw percentage; Column 9 gives the contamination which will be discussed in Section 2. The numbers given here do not always agree with those given by the authors, because we have included only those sources for which the map flux density, S, $> 6\sigma$, and the distance from the field centre is less than 0°.55 at 1415 MHz or less than 1°.0 at 610 MHz.

2. COMPLETENESS AND RELIABILITY

High positional accuracy is now becoming more easily obtainable; also efforts are being made to find non-blue QSO's. Identification work has therefore been put on a much more quantitative basis than it was until recently. Descriptions of possible methods for doing this have been given by Richter (1975) and Condon et al. (1976). De Ruiter et al. (in press), using WSRT data, use these methods to derive a likelihood ratio LR as a measure of the reliability of an identification. The LR

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Table 1

Surveys with Identifications

No.	Authors	Freq. (MHz)	N	S_{lim} (mJy)	Plates	m_{lim}	ID %	CP %
1	De Ruiter et al., 1976	1415	462	3 - 9	III a-J	22.5	27	4
			39	6 - 9	III a-J	24.0	49	6
2	Katgert & Spinrad, 1974	1415	53	7	PSS	20.5	26	1
			32	7	098-02	22.0	43	9
3	Jaffe & Perola, 1975	1415		4 - 5	III a-J	22.5		
	$\delta > 20$		40				28	6
4	$\delta < 20$		34				29	12
5	Katgert et al., 1973	1415	166	6 - 10	PSS	20.5	18	1
6	Valentijn et al., 1977	610	88	6	III a-J	22.5	35	17
7			38	16			26	4
8	Katgert, 1977	610	226	16 - 29	PSS	20.5	17	3

is defined as the ratio of the probabilities of an object at a given distance from the source position being either the correct identification or the first contaminating object.

These methods are of great use per survey, but they are less practical when comparing surveys, especially as some of the surveys to be discussed have been done at 610 MHz and therefore have much lower positional accuracy. In this case a simpler approach seems useful: by reducing each survey to a single number, one can compare at a glance the identification reliability of the various surveys. The number chosen is the average search area:

$$A = (2.7)^2 \pi / n \sum_n (\sigma^2_{\alpha_{rad}} + \sigma^2_{\alpha_{opt}})^{1/2} (\sigma^2_{\delta_{rad}} + \sigma^2_{\delta_{opt}})^{1/2} .$$

Including all objects within 2.7σ of the source position means that in this respect the sample will be 98.6% complete. σ_{opt} has been taken to be 1 arc sec in both coordinates; as quoted by all authors. This mean search area for each survey has been plotted against the mean density of objects on the plates used for the identifications (Fig. 1). Lines of equal percentage of contamination CP (in terms of the total radio sample) have also been drawn in. The densities of objects for some representative plate types have been marked on the right. The numbering of the surveys corresponds to that of Table 1.

The main survey (1) has been identified on III a-J plates with a limiting magnitude of 22.5. De Ruiter et al. quote an a posteriori reliability of the identifications of 85%, corresponding to a contamination rate of ca. 4.5% (their lower limit to the LR, 1.8, implies this value). This rate is in good agreement with the expected CP of 4% obtained from Fig. 1. For a subsample of survey (1) (m_{lim} = 24.0), CP

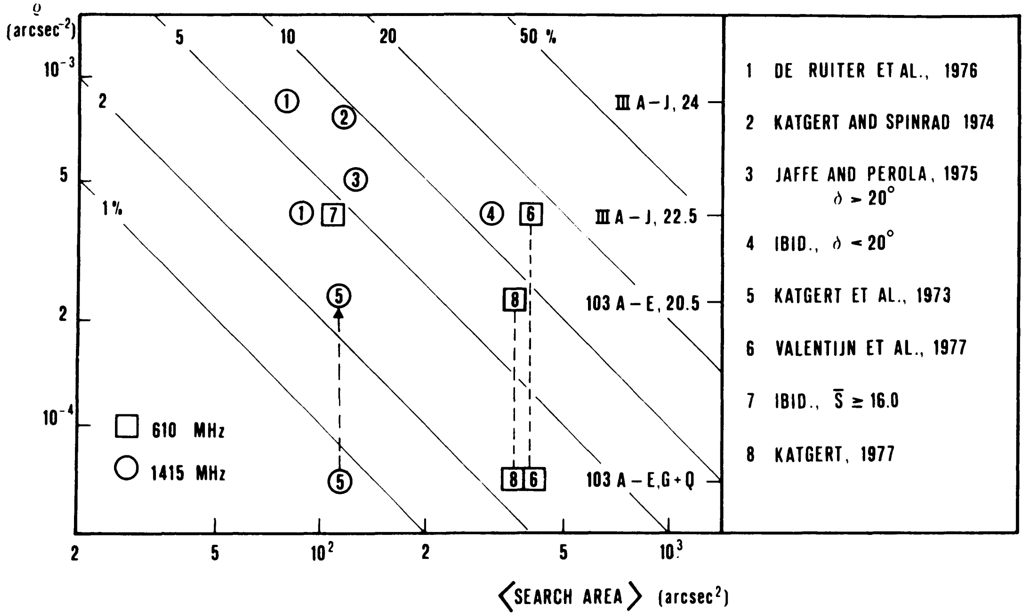

Fig. 1. Contamination for the various surveys. For a description see the text.

is 6% (3-4 sources). De Ruiter et al. find a contamination of 2% (1 source) at the cost of some (slight) loss in completeness: they set the same limit to the LR as for the total sample; due to the higher density of objects this effectively narrows down the search area. It should be noted that, as for this subsample only differential identifications have been done (i.e. $m > 20$), ρ in Fig. 1 here is really $\Delta\rho$; in Table 1 integral values have been listed for homogeneity. We have subjected the stellar and unclassified objects from survey (1) to a number of tests to see if they could be mainly responsible for the contamination, but they behaved in all respects like the galaxies and objects known to have blue-excess. We will henceforth assume they are good identifications, i.e. have a reliability of 85% as a class.

For survey (2), insofar as deep plates have been used for the identification work, CP is disappointingly large (9%). As the identification percentage is also high, the total reliability should still be acceptable (ca. 80%).

The difference in CP between (3) and (4) reflects the declination difference, as the error in declination is proportional to cosec δ.

In survey (5), Katgert et al. attempted to include normal colour objects also (lower point in Fig. 2). However, the identifications are only complete for galaxies and blue QSO's. It now seems that identification on position would have been sufficiently reliable (upper point).

On the other hand, surveys (6) and (8), when identified on position only, have an uncomfortably high CP (upper points in Fig. 1). Both surveys can usefully be re-defined to include only PSS type-identifications (lower points). As survey (8) was not yet finalized, this was done, and number 6 in Table 1 refers to the restricted case. For survey (6), the numbers in Table 1 refer to the published material.

Fig. 1 proves to be useful in deciding beforehand if it is worth while to obtain deep plates for any given survey. For WSRT 610 MHz surveys this will generally not be the case; for 1415 MHz surveys, it will be. Fig. 1 also indicates how to bring down CP, which one can do in two ways: a) confine oneself to lower densities, and b) go to smaller mean search areas. One can normally do this by setting higher limits in S, as on an average the faintest sources have the largest search area, at least at 610 MHz. Survey (7) is such a subsample of survey (6). At 1415 MHz, for surveys (2) and (5), this does not work, for here the extended sources have the largest errors and mostly a high map flux.

It should be stressed that either re-definition can be applied without loss of positional completeness. Of course, going back to identification by type one loses the neutral or red QSO's, but this seems unavoidable.

3. IDENTIFICATION STATISTICS

We have used the identifications for various statistical investigations. Survey (1) has been used as the primary source of statistics because of its size, and the other surveys have been used for confirmation. The most interesting results come from the magnitude distribution for stellar objects. This is given by De Ruiter et al. for all objects; they note that there is no clear indication of a cut-off at faint magnitudes, viz. that any lack of stellar objects may be caused by the difficulty of classifying identifications and therefore compensated by ?-objects. However, one obtains an interesting result by dividing the stellar objects into two classes of flux density, $S < 60$ mJy and $S > 60$ mJy. One obtains two congruent curves, the one for low S being shifted towards fainter magnitudes by ca. 1^m relative to the one for high S. Keeping in mind the limited numbers (22 in each sample), one can tentatively conclude:

a) that the presence of a considerable number of faint-magnitude QSO's is a reflection of the bi-variate luminosity function; the nearness of bright galaxies (most of the sources concerned lie within $0^\circ\!.5$ of an NGC galaxy) need not be invoked to explain this effect.

b) that there is some indication that the cut-off is also present at lower flux densities, but at fainter magnitudes. This cut-off would be real if the unclassified objects are faint galaxies.

The QSO's from the other surveys tend to follow an intermediate curve, except for some incompleteness for $m > 20$; the numbers are too small to draw any conclusions. The magnitude distribution for galaxies in all surveys is normal; a relative lack of galaxies at m = 20 in survey (1) is not found for other surveys and must therefore be a chance fluctuation.

For survey (1), the identification percentages of the various types are: Galaxies, 10%, QSO's, 10%, Unclassified, 7%. These proportions are confirmed by the other surveys. For surveys (1a) and (2), with deeper plates, the percentages become: Galaxies, 28%, QSO's, 11%, Unclassified, 7%. Clearly the increase in identification rate is due to galaxies only. Again dividing the sources into low S and high S classes, it can also be noted that the brighter sources tend to be identified more frequently with QSO's: of all the sources with $S > 60$ mJy, 17% are stellar objects; at $S < 60$ mJy, 7% are. The difference is significant at the 2.6σ level; the identification content of the other 1415 surveys tends in the same direction. The difference could be made up if most or all of the low S unclassified objects are QSO's. No difference in identification content has been found between resolved and unresolved sources.

We have also looked at the colours of all stellar objects with $m \lesssim 20.5$. There are 31 such objects; 21 are blue, 9 are neutral or red, 1 is invisible (possibly variable). All of the brighter ($m < 16.5$) objects are neutral-to-red and at least two of them have been found to have normal stellar spectra. Assuming that only the fainter ones are QSO's, we estimate that of the order of 20% of all QSO's at the flux density levels concerned should be indistinguishable from normal stars.

4. CONCLUSIONS

WSRT surveys at 1415 MHz are well-suited for identification work on deep plates; at densities of about $4 - 8 \times 10^{-4}$ objects arc $\sec^{-2}$ the reliability should still be of the order of 80%. At 610 MHz this reliability is only reached when one confines oneself to the Palomar Sky Survey and uses colour and type information. There is evidence for a dependence on 1415 MHz flux density of the QSO mean magnitudes. There may also be a (flux-dependent) cut-off in magnitude. The fraction of sources that can be identified with QSO's appears to decline with flux density. An estimated 20% of QSO's at present flux density levels have stellar colours.

REFERENCES

Condon, J.J., Balonek, T.J. and Jauncey, D.L., 1975, Astron. J. 80, 887.
Jaffe, W.J. and Perola, G.C., 1975, Astron. Astrophys. Suppl. 21, 137.
Katgert, J.K. and Spinrad, H., 1974, Astron. Astrophys. 35, 393.
Katgert, P., Katgert-Merkelijn, J.K., Le Poole, R.S. and Laan, H. van der, 1973, Astron. Astrophys. 23, 171.
Richter, G.A., 1975, Astron. Nachr. 296, 65.
Ruiter, H.R. de, Willis, A.G. and Arp, H.C., 1976, submitted to Astron. Astrophys. Suppl.
Valentijn, E.A., Perola, G.C. and Jaffe, W.J., 1977, submitted to Astron. Astrophys. Suppl.
Willis, A.G., Oosterbaan, C.E. and Ruiter, H.R. de, 1976, Astron. Astrophys. Suppl., in press.

DISCUSSION

Arp: I would like to comment that of the 21 Quasars noted as blue on the Sky Survey Prints, my multichannel scans showed them to be noticeably redder, on the average, than 3CR Quasars.

Jaffe: Are the 3 stars you identified actually radio sources, or is it reasonable to assume that they are chance contaminations?

J. Katgert: Probably contamination.

Condon: Are the radio sources identified with stellar objects more compact than average?

J. Katgert: No.