THE MOLONGLO RADIO SOURCE SURVEYS AT 408 MHz

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One of the basic programs undertaken with the 1 mile Cross-type radio telescope at the Molonglo Radio Observatory has been a systematic survey of the sky south of +18° declination. Commencing in late 1967, the survey has been continuing at a low priority until it is now complete to a declination of -85°, except for some small areas affected by interference or instrumental problems which are being re-observed. A program of 'deep surveys' is also being undertaken; this involves multiple observations within narrow strips at selected declinations. The signal-to-noise ratio is some three to five times better than in normal surveying and the confusion limit is approached.

The radio telescope output is stored on magnetic tapes in digital form and on paper faximile charts in analogue form. These are analysed and catalogues prepared as time permits. The present status is shown in the table below.

Molonglo Catalogues

Catalogue	Declination	Area sr	Number of Sources	Reference
MC1	-20°	0.21	1545	Davies *et al.*, 1973
MC2	+11°	0.11	609	Sutton *et al.*, 1974
MC3	+17°	0.15	657	Sutton *et al.*, 1974
MC4	-70°	0.23	1340	Clarke *et al.*, 1976
MC5	+11°	0.14		In Preparation
1 Jy Catalogue	South of +18°	8		In Preparation
Deep Survey 1	-20°	0.020	373	Robertson 1976(a)
Deep Survey 2	-62°	0.0055	95	Robertson 1976(b)

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Four catalogues of small areas totalling about 0.69 steradians have been published (MC1, 2, 3 and 4). These contain sources down to a level of about 0.2 Jy, depending on the declination and the instrumental sensitivity at the time of the observations. The catalogues range in source density from about 5000 to 7400 sources per steradian. Several more catalogues of this kind are planned in astronomically interesting areas and areas in which the instrumental sensitivity is high. In addition, a catalogue is currently in preparation of the whole area accessible to the instrument, excluding a 6° wide strip along the Galactic plane. This catalogue is complete to 1 Jy and extends somewhat lower in most areas; it will contain approximately 1000 sources per steradian. The very small 'deep survey' areas are restricted to sources less than 1 Jy and are complete to between 80 and 90 mJy; they contain about 20000 sources per steradian. All flux densities in the Molonglo catalogues are given in the Wyllie (1969) scale.

An opportunity to sample the reliability and completeness of the MC series of catalogues is afforded by the first 'deep survey' which overlaps MC1. There are 140 MC1 sources in the area of overlap and the catalogues are compared in the table below on the assumption that any discrepancies reflect errors in MC1.

A Test on a Sample of MC1 Sources

Flux Density (Deep Survey) Jy	Total Source Numbers	MC1 Completeness $\frac{\text{Sources in MC1}}{\text{Total Numbers}}\times 100$ %	MC1 Reliability $\frac{\text{MC1 Sources Confirmed}}{\text{Sources in MC1}}\times 100$ %
> 0.5	54	98	100
> 0.25	129	89	99
> 0.15	238	57	95

One may conclude that the MC1 catalogue is reliable and reasonably complete above 0.25 Jy and the completeness falls off rapidly at lower flux densities. The reliability also decreases, but is still 95% for the whole sample. Later catalogues have been truncated at a higher signal-to-noise ratio and should be correspondingly more reliable.

The catalogues have been used to make source identifications, to determine spectra in conjunction with higher frequency data and to examine the distribution of sources in depth (source counts) and their distribution on the celestial sphere.

SOURCE COUNTS

The differential source counts for MC1 have been presented by Mills *et al.* (1973). Robertson (1976a, b, c) has now included MC2, MC3 and the deep surveys, improving the statistics at medium flux densities and extending the counts to much lower levels. His results are shown in Figure 1; the so-called convergence of the counts at low levels is confirmed and the region of turn-over well defined.

It is particularly significant that all the measurements have been made with a single radio telescope, except for about seventy of the strong sources from the 'all sky' catalogue of Robertson (1973). The rather large statistical uncertainties just below 10 Jy should be much reduced soon by using the Molonglo 1 Jy catalogue.

The counts expected from two simplified cosmological models are also shown in Figure 1 (Robertson, paper in preparation). There is little difficulty in fitting the counts at low flux densities with a uniform density non-evolving model but, as is well known, the number of sources with high flux densities is then far too small to be explained plausibly as a chance fluctuation in a Universe containing a completely random distribution of sources.

Numerous models can be proposed in which the number of radio sources was greater when the Universe was several times smaller than it is now, possibly as the result of a period of rapid source formation. Thereafter the rate of source production and/or the luminosity of individual sources decreased rapidly to the present level. The second curve is representative of this class of model. There is sufficient freedom in the choice of undefined parameters to fit the counts well. However, before one can accept this kind of result as representing the real Universe it is necessary to examine the possibility that physical source groupings may permit the high flux density results with reasonable plausibility in a non-evolving or slowly evolving Universe. Information about source groupings is also, of course, intrinsically important.

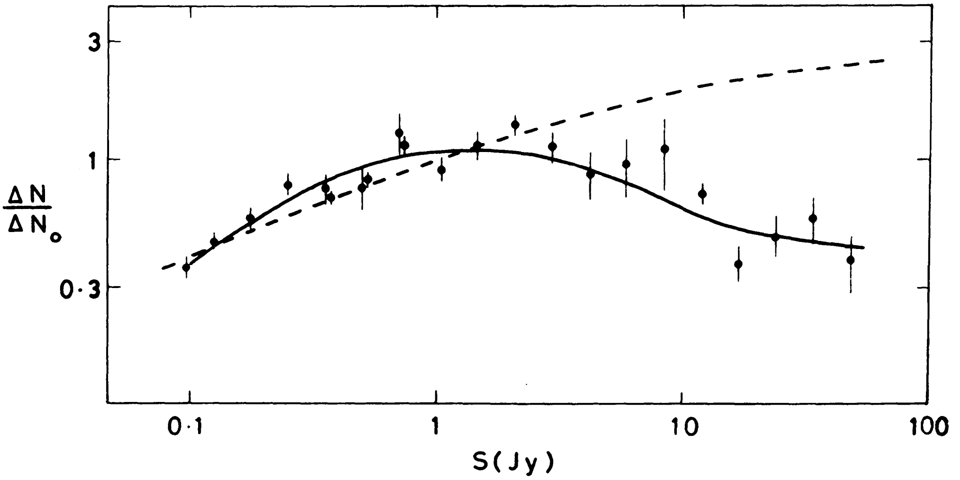

Figure 1. Combined differential source counts. Theoretical curves for a non-evolving model (dashed) and an evolving model are shown.

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SOURCE GROUPINGS

As they are produced, all Molonglo catalogues are examined for small scale clustering using simple 'binning' analysis. No significant non-randomness has been found for the MC series at the most common flux density of 0.2 Jy to 0.5 Jy, and this result has been confirmed for MC1 by a more sophisticated power spectrum analysis (Webster, 1976). The deep survey catalogues do show signs of small scale clustering but at a low significance level (5%-10%) which, in view of the large number of tests performed, cannot be given much weight.

Visual examination of the distribution of strong sources in the 'all sky' catalogue of Robertson (1973), indicates a certain amount of pairing and statistical analysis confirms that this is probably marginally significant for source separations less than two or three degrees. The implication is that some widely separated doubles are catalogued as individual sources at high flux densities whereas similar pairs, when more distant, weaker and closer, might be catalogued as single sources. The selection effect is of the right kind, but totally inadequate in magnitude, to account for the form of the high flux density counts.

In contrast to the above very weak evidence, there is strong evidence for large scale anisotropy in the Molonglo catalogues, but it is not yet firmly established whether this is caused by a real anisotropy in the source distribution or by systematic calibration errors. Intercomparing the MC series at 1 Jy and above, where all the catalogues are believed to be accurate, complete and reliable, it is found that there are no significant differences between MC1 and MC4 or MC2 and MC3, but both MC2 and MC3 have a substantially higher source density than the others. A comparison of MC1 with MC2 and MC3 combined gives, for sources $\geq$ 1 Jy:

MC1	$895 \pm 66\ sr^{-1}$
MC2 + MC3	$1217 \pm 69\ sr^{-1}$

The ratio is 1.36 and the formal significance 0.1%. At lower flux densities the ratio and the significance decrease, which may reflect a greater homogeneity for the weaker sources or, perhaps, some incompleteness in MC2 and MC3, for which the radio telescope sensitivity was much reduced.

Murdoch (1976a, b) reached essentially the same conclusion and, in addition, compared the two portions of MC2 and MC3 which are in the North and South Galactic Hemispheres. Above 0.5 Jy the catalogue source density in the northern hemisphere exceeds that in the southern by a factor of 1.23 at a significance level of 1%. Although the Virgo cluster is included in the area of high source counts it is not in a particularly dense region.

Both these indications of large scale anisotropies are subject to calibration uncertainties. The antenna gain of the Molonglo instrument is a function of declination and the internal calibration is slightly dependent on temperature, so that small diurnal variations do occur. However, it seems impossible for calibration differences to be large enough to account for the observed results. Nevertheless the uncertainties reduce the statistical significance of the indicated anisotropies; for example, if the standard error in the relative calibration of the MC1 and MC2 + MC3 catalogues was as high as 5%, the significance of the anisotropy would be reduced from the 0.1% level to the 1% level. The importance of very accurate relative calibrations over the whole sky is clear and further calibration programs are planned to improve the present situation.

Despite these uncertainties, the present results do suggest that radio sources are not randomly distributed throughout the Universe. If this is so, the source counts at high flux densities may provide little or no information about source evolution unless the relationship of the local source density to the mean can be established in other ways.

Finally, another possible large scale anisotropy should be mentioned. Robertson (1976c), in comparing his deep surveys with the Cambridge 5C surveys, found that the Molonglo catalogues contain more sources than the Cambridge, above equivalent levels, by a factor of 1.29. The formal significance is about 1% but, in view of the increased probability of calibration discordances between two quite different catalogues, this indication of anisotropy is very weak.

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DISCUSSION

Grueff: Supposing that the clustering found at about 1 Jy is real, have you any idea about the angular size involved?

Mills: There appears no clustering below a few degrees and the significant differences in source density occur between catalogues about 35° apart in declination and between portions of the same catalogue about 90° apart in R.A.

Wall: You commented that MC2 and MC3 were "statistically undistinguishable", but that MC1 differed in source density from MC2 + MC3 at a significance of 0.1%. Is this not an invalid statistical procedure in that it is "a posteriori" statistics?

Mills: This question illustrates the subjective nature of significance tests. The actual procedure was to compare first MC1 with MC2 + MC3 to check whether these two well separated sky regions of approximately equal area had the same source density. The internal comparison MC2 with MC3 followed and MC4 was also checked, but the latter catalogue is regarded as atypical because it includes the Magellanic Clouds; it is not used for the source counts. I believe that the conclusions in the paper are valid.

Ekers: The MC2 and MC3 surveys pass through the region of the Virgo cluster. Can you estimate from your identifications how many sources are associated with this cluster?

Mills: There is no particular excess in the Virgo cluster region, either of radio sources or of galaxy identifications, but there may be in the 1 Jy catalogue in the vicinity of the Hercules cluster. Comparison of strong sources between Molonglo at 408 MHz and Arecibo at 430 MHz suggests no evidence for declination dependence of the calibration except possibly for a small error in the periodic term of the calibration curve. This suggests a possible calibration error in MC2 and MC3 of about 2%, that would affect the counts by 3% which is negligible compared to the 40% difference with MC1.

THE 5C6 AND 5C7 SURVEYS

A.J. Kus and T.J. Pearson

We have recently completed two new deep surveys at Cambridge: 5C6 and 5C7. They lie at $\delta=32°$, $b=-27°$ and $\delta=27°$, $b=30°$; and being similar in their observational properties they are ideal for the study of the isotropy of faint sources. The two source counts at 408 MHz are in excellent agreement with each other, but the source density is slightly higher than in 5C2 and 5C5, in agreement with the new results from Molonglo and Westerbork. At 1407 MHz the source counts agree with each other and with 5C5, and the combined count from all three surveys shows that convergence continues down to the survey limit at about 2 mJy.

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The 5C counts agree with the Westerbork 1 survey but are lower than the corrected Westerbork 3 counts.

The spectral index distributions derived from 5C5, 5C6 and 5C7 are all similar, with median $\alpha(408,1407) \simeq 0.80 \pm 0.03$.

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