THE LARGE SCALE DISTRIBUTION OF RADIO SOURCES

M. S. Longair
Mullard Radio Astronomy Observatory
Cavendish Laboratory, Cambridge

1. INTRODUCTION

In this brief survey, three topics will be described:

(i) the large scale distribution of extragalactic radio sources on the celestial sphere;

(ii) the problems of identifying optically quasars and radio galaxies in that region of the source counts where they diverge most significantly from the predictions of all uniform world models;

(iii) the problems of interpretation of the source counts, some models for the spatial distribution of sources and the most important observations for defining more precisely the evolution of the radio source population.

Nowadays, all source counts are presented in normalised, differential form, meaning that the number of sources ΔN in the flux density interval S to ΔS is normalised to the prediction of a locally Euclidean world model $\Delta N_o \propto S^{-5/2}\Delta S$. A number of recent source counts at frequencies 408, 1400, 2700 and 5000 MHz are presented in the form $\Delta N/\Delta N_o$ in Figure 1; in this diagram, the normalisation at different frequencies is arbitrary. The most recent data were presented at IAU Symposium No.74 "Radio Astronomy and Cosmology" which has just been published (Jauncey 1977).

It is well known that all the counts shown in Figure 1 contradict the predictions of uniform world models. As an example, in Figure 2, the most recent counts at 408 MHz are compared with the predictions of a uniform Friedmann world model having $\Omega = 0$; similar results are obtained for all values of Ω. The prediction is based upon a knowledge of the radio luminosity function derived from samples of sources at high flux densities for which the optical identification percentages are greater than 90%. A similar prediction is expected for counts at the other frequencies shown in Figure 1.

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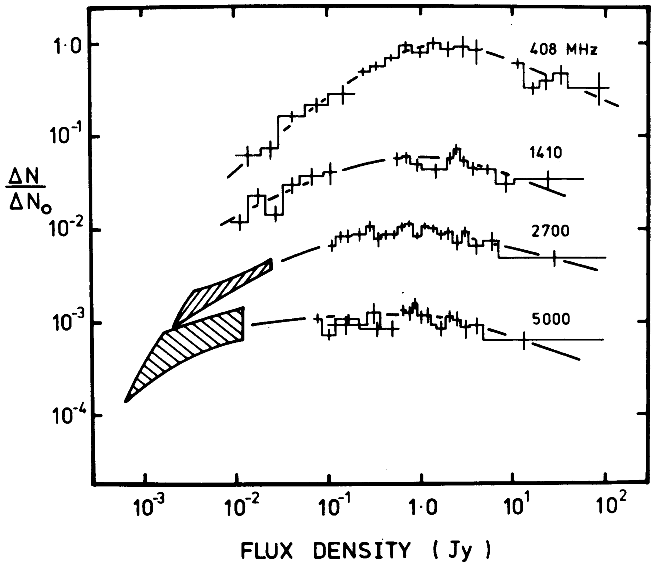

Figure 1. Differential counts of radio sources at 408, 1400, 2700 and 5000 MHz. For references, see Wall (1977). For more recent data, see Jauncey (1977).

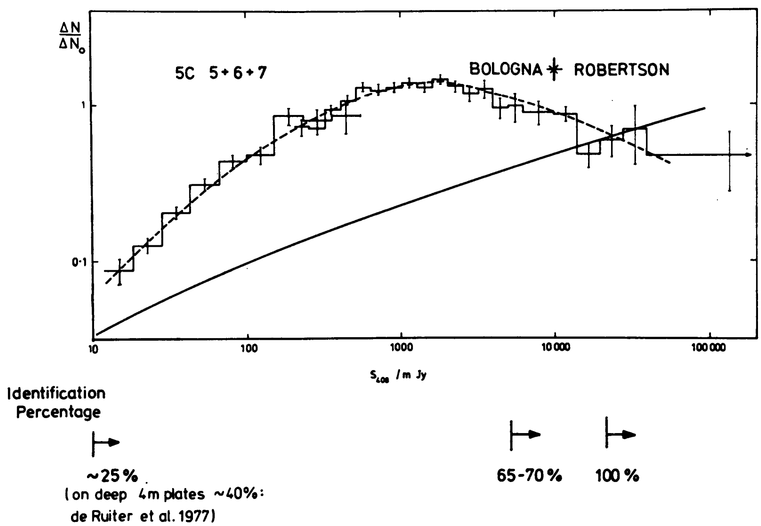

Figure 2. Comparison between the counts of radio sources at 408 MHz and the predictions of world models (Pearson 1977). The solid line is for a uniform model having $\Omega = 0$. The dashed line is the prediction of the evolutionary model described in Section 4. At the bottom of the diagram, the integral percentage identifications at different flux density levels are indicated.

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It will be noted that the maximum in the differential counts is most pronounced at low frequencies. At 2700 and 5000 MHz, the counts are much "flatter" and indeed at the latter frequency, they follow the law $\Delta N \propto S^{-5/2}\Delta S$ over a wide range of flux densities. However, because the sources counted extend to large redshifts, this result contradicts the predictions of uniform models in which the exponent of the differential distribution is significantly smaller than 5/2 as shown in Figure 2.

2. THE ISOTROPY OF THE LARGE SCALE DISTRIBUTION OF RADIO SOURCES

The source counts shown in Figure 1 are nowadays based upon very large samples of radio sources, mostly lying in directions away from the Galactic plane, and hence they provide important information about the isotropy of the Universe on a large scale. In Table 1, the numbers of sources at various flux densities and frequencies suitable for such studies are listed.

Table 1

Large surveys of radio sources

Frequency (MHz)	Survey	Flux density range (Jy)	Numbers of sources	
178	4C	2 - 10	$\sim$ 5000	PS
408	Bologna B2	$\geqslant$ 0.2	$\sim$ 9000	PS
	Molonglo	$\gtrsim$ 0.1	$\sim$ 4000	PS
	5C	$\geqslant$ 0.01	$\sim$ 1000	PS
1400	GB	$\gtrsim$ 0.1	$\sim$ 1000	PS
	Westerbork	$\geqslant$ 0.01	$\sim$ 1800	B
2700	Parkes	$\geqslant$ 0.1	$\sim$ 7500	PS
5000	Greenbank & Parkes	$\gtrsim$ 0.1	$\sim$ 800	

The surveys indicated by the letters PS have been analysed by Webster (1977) using the technique of power spectrum analysis, similar to that developed by Peebles and his colleagues for studying the distribution of galaxies on the celestial sphere. This technique is very sensitive to any anisotropies in the source distribution and Webster shows that, except on the largest scales, it is the optimum test of isotropy. The Westerbork deep surveys, marked B, have been analysed by the technique of multiple binning analysis (Willis et al 1977). (These surveys have now also been subjected to power spectrum analysis with similar results - Oosterbaan, private communication.)

According to these analyses, there is no evidence that sources are not distributed independently at random on the sky. The conversion of this result into a limit to the statistical fluctuations in the source distribution in space depends upon a knowledge of the typical distances of the sources. According to the models described below (and on general grounds), the majority of sources studied probably lie in the redshift range $1 \lesssim Z \lesssim 3$. On this basis, Webster (1977) quotes a limit to the amplitude of the fluctuations $\Delta N/N \lesssim 3\%$ on a scale of 1 Gpc, i.e. if one moves a cube of side 1 Gpc about the Universe, the variations in the number of sources counted is less than 3%. This limit is derived from the largest sample of sources studied, the Bologna B2 catalogue (see Fanti, Lari and Olori 1977), and is limited only by the finite size of the sample ($N \sim 10^4$). To obtain stronger limits, much larger surveys of sources are required, the limit to the isotropy being proportional to $N^{-\frac{1}{2}}$. In addition to the above limit, limits to the isotropy on a wide range of physical scales can be obtained down to the typical angular distance between sources (Webster 1978).

The significance of these results is twofold. First, they provide upper limits to the covariance function for the distribution of matter in the Universe on much greater physical scales than has been possible for galaxies and clusters of galaxies. Second, the obvious comparison is with the upper limits to fluctuations in the microwave background radiation. It must be emphasised that the present result refers to limits to the fluctuations in the matter distribution whereas the microwave background radiation tells us only about the radiation content observed by us now. It is well known that if there is early reheating of the intergalactic gas, the amplitude of temperature fluctuations of the background radiation can be strongly damped and hence the present limits to these fluctuations could be consistent with large fluctuations at the epoch of recombination, $Z \simeq 1500$. In some ways, the present limit $\Delta N/N \lesssim 3\%$ is therefore stronger than the limit from the background radiation because fluctuations in the matter distribution grow with time as $\Delta N/N \propto (1+Z)^{-1}$. Thus at $Z = 1500$, $(\Delta N/N)_{matter} \lesssim 0.03 \times (3/1500) \approx 10^{-4}$. Notice that at $Z = 1500$, this limit refers to scales much larger than the horizon.

3. PROBLEMS OF INTERPRETATION OF THE SOURCE COUNTS

If the redshifts of all the sources now observed were known, it would be a relatively straightforward matter to derive directly from observation the evolutionary history of the radio source population. The best method would involve a variant of the V/V_{max} technique described by Schmidt (this volume). Unfortunately, at present, distances can only be measured by first identifying the sources optically and then measuring the redshift of the optical object. The problem can be understood from Figure 2 in which the optical identification percentages at different flux density levels are given. At the very highest flux densities, $S_{408} \gtrsim 15$ Jy, optical identifications and redshifts are more or less complete. However, at lower flux densities fewer and fewer sources can be identified optically and very few redshifts are available. At the lowest flux densities, only about 25% of the sources can be identified using deep 48 inch Schmidt plates; higher percentages, $\sim$ 40%, have been reported by de Ruiter et al (1977) who obtained very deep plates with the Mayall 4-m telescope. Quasars can now be identified relatively easily because the radio positions are of high precision and, because of their strong emission-line spectra, redshifts can be measured without much difficulty. Schmidt (this volume) has described how successfully this work is proceeding. For radio galaxies, however, the situation is much less satisfactory. Even at the limits of the largest telescopes under conditions of excellent astronomical seeing, radio galaxies can only be identified to redshifts $Z \sim 1$ and it is very difficult to measure their redshifts.

A further problem in interpreting the counts even at high flux densities can be seen in Figure 2. Just at the point where the divergence between the predictions of world models and the observations becomes large ($S_{408} \approx 5$ Jy), the optical identification percentage decreases. It is certain that part of this divergence is due to the steep source count of the quasars (see Schmidt, this volume). However, the remaining unidentified sources also have a very steep source count and it is important to discover the nature of these sources.

We have recently completed a deep optical survey of the fields of unidentified 3CR radio sources which form part of a complete statistical sample of sources with $S_{178} \geqslant 10$ Jy, corresponding roughly to $S_{408} > 5$ Jy (Laing, Longair, Riley, Kibblewhite and Gunn 1978). We were lucky to have one night of excellent astronomical seeing at the Hale 200-inch telescope which enabled us to make 10 new identifications of very faint radio galaxies having $20 < m < 23$; no new quasars were found. The resulting optical identification statistics for a complete sample of 60 3CR radio sources is given in Table 2. The source counts ($N(\gtrsim S) \propto S^{-\beta}$) and V/V_{max} test for this sample are given in Table 3. For radio galaxies without redshifts of which there are 14 examples in the sample a conservative lower limit to their redshift of 0.3 has been adopted; the values of V/V_{max} for radio galaxies are therefore lower limits. It can be seen that the slope of the integral source count β and the value of $\langle V/V_{max} \rangle$ for all sources and quasars are typical of much larger samples of sources. The radio galaxies have a source count and $\langle V/V_{max} \rangle$ greater than those expected for a uniform distribution although as yet not with great statistical significance. The importance of the present work is, however, that only 4 out of 60 sources in the complete sample are either doubtful or unidentified and hence there is unlikely to be any other unknown class of source contributing to the overall source counts in addition to radio galaxies and quasars. If this result is typical for all bright radio sources, it can be seen that strong

Table 2

Optical identifications in a complete sample of 60 3CR radio sources

Type of object	Number	Percentage of total	
Quasars	23	$38\frac{1}{3}$)	
		)	$93\frac{1}{3}$
Galaxies (Certain + Confirmed + New)	33	55)	
Possible identifications with galaxies	2	$3\frac{1}{3}$	
Empty fields	2	$3\frac{1}{3}$	
	60	100	

Table 3

Source counts and the V/V_{max} test for the statistical sample of 60 3CR radio sources

	β	$\langle V/V_{max} \rangle$	σ*
All sources	1.88 ± 0.25		
Quasars	2.21 ± 0.5	0.709	3.5
Galaxies	1.59 ± 0.29	0.581	1.6
Weak radio galaxies $P_{178} < 10^{26}$ $WHz^{-1}sr^{-1}$	1.06 ± 0.42	0.52	0.2
Strong radio galaxies $P_{178} > 10^{26}$ $WHz^{-1}sr^{-1}$	1.92 ± 0.42	0.610	1.9

*σ = significance in standard deviations of difference of $\langle V/V_{max} \rangle$ from 0.5.

radio galaxies exhibit strong cosmological evolutionary changes with cosmological epoch, similar to those of quasars.

4. INTERPRETATION OF COUNTS OF RADIO SOURCES

The general features of satisfactory models of the radio source population are well known:

(i) The evolution must be strong and for the most powerful sources an evolution law similar to that of quasars is satisfactory $f(Z) \propto e^{-mt}$ where t is cosmic time and $m = 10\ H_o$ for $\Omega = 0$;

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(ii) Only the most powerful sources evolve in this manner or else the convergence of the counts at low flux densities cannot be reproduced;

(iii) A cut-off to the source distribution at large redshifts may be required in some models to achieve satisfactory convergence of the source counts.

Wall, Pearson and I (1977) have developed a fast numerical procedure for testing models of the source population and comparing the predictions of the models statistically with all the avilable observational data. This work was motivated (i) by the recent vast improvement in the statistics of the source counts, (ii) the wealth of new identification data at high and low flux densities and (iii) the need to know which are the most sensitive tests of the models.

We found that none of the many models in the literature was acceptable when subjected to a proper statistical comparison with the present source counts. We found a number of models, some of which incorporated a cut-off in the source distribution at large redshifts. I find most intriguing a model in which one uses the V/V_{max} of all sources in complete samples at high flux densities to define the variation of the exponent of an exponential evolution function M(P) as a function of radio luminosity. A best fitting model has M(P) = 11 for $P_{408} \geq 10^{27}$ $WHz^{-1}sr^{-1}$, M(P) = 0 for $P_{408} \leq 10^{26}$ $WHz^{-1}sr^{-1}$ and varies linearly with log P_{408} between these values. This gives a remarkably good fit to the overall counts (see Figure 2).

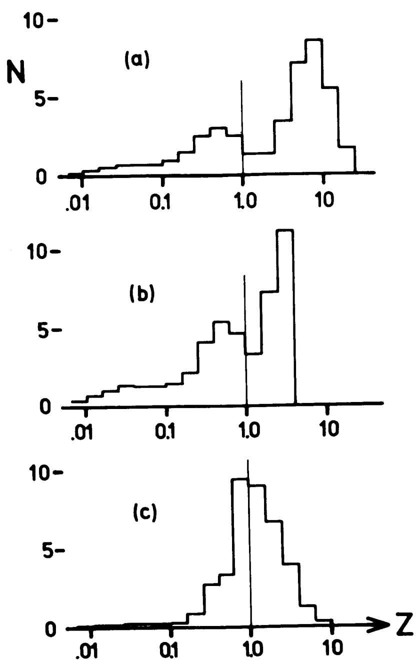

Figure 3. Predicted distribution of redshifts for sources with 10 < S_{408} < 50 mJy. The models are described in Wall, Pearson and Longair (1977). In model (b) there is a cut-off in the source distribution at Z = 3.5.

The most sensitive test of the models is the identification content of samples of faint radio sources. For example, the predicted redshift distributions for three of the models at S_{408} = 0.01 Jy are shown in Figure 3. What is at present available from observation are identification percentages for some of the 5C and Westerbork surveys which have been studied with deep 53-inch Schmidt and 4-m plates respectively. Richter (1975) finds that more than 35% of the sources are associated with red objects; de Ruiter et al (1977) find that 28% are galaxies, 11% quasars and 7% unclassifiable. These results suggest that in satisfactory models, 30-40% of the sources should have redshifts $Z \lesssim 1$. Interpreted literally, this would exclude models such as (a) and is barely consistent with model (c). These results are not yet strong enough to prove that there must be a cut-off at large redshifts as in model (b) but they are suggestive and indicate the areas in which further identification work is urgently needed.

5. FUTURE OBSERVATIONS

The importance of performing deep optical identification and redshift observations at all flux densities has been emphasised above. Particular attention should be paid to the completeness of the samples and as a first step intensive studies of complete samples of, say, 100 sources at flux densities $S \lesssim 1$ Jy are most valuable. In addition to optical identifications, the radio properties of these sources should be studied to provide further physical information about how the sources themselves change with luminosity and redshift. It is to be hoped that eventually we will obtain an overall picture of how radio-source activity has changed with cosmological epoch. This evidence will provide complementary information about the evolution of the Universe as a whole to that obtained from optical and X-ray studies of galaxies and quasars.

The above analyses have been restricted to the interpretation of low frequency surveys ($\nu \lesssim 1000$ MHz). There is no simple way of relating these results to high frequency source counts (see Wall, Pearson and Longair 1977 for details). However, we can assert with confidence that the same types of programme outlined above will be of the greatest importance at these frequencies in order to obtain a complete picture of the evolution of the radio source population at radio wavelengths.

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DISCUSSION

Zeldovich: Is the cut-off at large redshifts certain? I remind everyone that power-law evolution $f(z) = (1+z)^n$ needs a cut-off, because as $z \to \infty$, $f(z) \to \infty$. An exponential law is a remedy, but does it need a cut-off? Is the cut-off in optical QSO identifications due to observational difficulties because Ly-α is shifted into the near infrared part of the spectrum?

Longair: I emphasised that there is no unambiguous answer to this question. All we have done is to indicate how we may be able to detect a cut-off using observations of complete samples of radio sources. The present data are more easily accommodated in exponential models, which include a cut-off but I would not exclude the absence of a cut-off yet.

Schmidt: While there may be a need to introduce a cut-off in the density law to explain radio source counts, as mentioned by Dr Longair, there is at present no evidence of a cut-off for quasars from statistical samples. From the redshift distribution at B = 17.5, we can predict that quasars with $z > 3.5$ should appear in significant numbers beyond B = 19.5. Since the ultraviolet excess will not show at these redshifts, we have to rely on objective prism or grating surveys. Osmer has suggested that the Hoag-Smith 4-metre survey may be incomplete beyond B = 19.2. If so, the absence of $z > 3.5$ quasars in this survey is not (yet) a serious argument for a cut-off at this redshift.

Ostriker: It is easy to show that, in general, galaxy formation was relatively recent; if galaxies formed at $z \gtrsim 10$ the cosmic density was so high that the resulting system would have a velocity dispersion much larger than the values of ≈ 200 km s^{-1} seen in typical galaxies.

Ozernoy: Could you give an upper limit to the exponent of the evolution law for weak radio sources using the condition of convergence at small radio flux densities?

Longair: Not without quite a lot of model computations. Weak evolution is allowed, but I am most reluctant to quote any specific figure.

Silk: What is the angular scale associated with the upper limit of microwave background anisotropy that was inferred from the study of the source distribution?

Longair: Webster quotes a figure of $\Delta N/N < 3\%$ on a scale of 1 Gpc at a typical distance of 6000 Mpc, i.e. an angular scale of 10°-20°. Notice that fluctuations on these scales only came within the horizon at late epochs, $z \sim 6$.

Peebles: I might remark that the observed positive "cross-correlation" between Lick galaxy counts and 4C radio-position does not require that the 4C objects have optical brightness greater than B = 19, only that some fraction of these objects belong to groups or clouds of galaxies having some members brighter than 19.

Longair: This may certainly help resolve some of the discrepancy. It is generally the rule that radio sources are associated with galaxies in small groups as mentioned by Dr Bolton.

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