

THE SOURCE COUNTS FROM THE 4C SURVEY

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Summary

The source counts derived from the fourth Cambridge catalogue of radio sources (4C) are presented and are combined with previously published results to give the number/flux density ($\log N/\log S$) curve over the range of flux density $0.27 < S < 35 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$.

The correction necessary to take account of confusion is determined by a Monte Carlo process and the corrections for angular diameters of sources and source clustering are also discussed.

On the assumption that the form of the source counts can be explained by density variation with epoch, forms of this density variation are derived which would be consistent with the latest derivation of the luminosity distribution function.

1. *Introduction.* The form of the number–flux density relation for radio sources has already been discussed as a method of investigating different cosmological models (Davidson 1962a, 1962b, Davidson & Davies 1964, Oort 1961, Hoyle & Narlikar 1961, 1962, Sciama 1963, Scott 1963, Ryle & Clark 1961). The most extensive data on source counts so far published (Scott & Ryle 1961) is based on the revised 3C catalogue (Bennett 1962b) supplemented by preliminary results from the 4C survey for a limited area of sky. The present paper contains a more precise determination of the number–flux density relation using the larger area of sky now covered by the 4C catalogue, $20^\circ \leq \delta < 40^\circ$ (Pilkington & Scott 1965) and $-7^\circ < \delta < 20^\circ$ and $40^\circ \leq \delta < 80^\circ$ (Gower *et al.*, in press). In addition to the better statistical accuracy obtainable from the larger number of sources observed, the new data should be more suitable for the determination of source counts for two reasons. Firstly, a computer programme was used to find the positions and fluxes of sources from the final synthesized output, thus improving the homogeneity of the results by eliminating any human bias that may occur in fitting by hand, and secondly, over the region $17^\circ < \delta < 42^\circ$ the majority of sources were observed twice in overlapping sets of observations.

Section 2 describes the observations to be used in determining the $\log N/\log S$ relation. As well as the new 4C observations these include the 3C source counts of the sky north of $\delta = -05^\circ$ (Bennett 1962a), and the results from the north polar survey (Ryle & Neville 1962).

In section 3 the techniques for estimating the effects of any errors on the final source counts from 4C are described. The Monte Carlo method used gives directly the necessary corrections to be made to the source counts to allow for flux errors caused by confusion, random and systematic errors introduced by the source fitting programme, and the number of sources missed as a result of obscuration of weaker by stronger sources. The systematic flux errors found are

smaller than the random errors which occur in the observation of individual sources and no correction has therefore been applied to the 4C catalogue.

Since the observations used in compiling 4C were made with a 469λ baseline interferometer, sources with angular extent greater than $2'$ arc or double sources with separations greater than about $1' \cdot 5$ arc will be received with reduced intensity. The corrections derived to allow for this effect are found to be small. Clustering of sources on an angular scale of $1'$ to $30'$ arc would also affect the source counts but present observations reveal no clustering down to about $25'$ arc; sufficient clustering on a scale greater than about $1'$ arc to affect the 4C source counts seems unlikely and would be detected in the analysis of source diameters.

In section 4 the final form of the $\log N/\log S$ curve is presented using the data described in section 2 corrected as described in section 3.

In section 5 the effect of the dispersion of intrinsic luminosities of radio sources is considered, and an attempt is made to take account of this dispersion in establishing the true $\log N/\log S$ for sources of a particular luminosity.

2. Observational data

(a) *Previous results.* Bennett (1962a) has published source counts for the revised 3C catalogue, which was compiled from total power and interferometer measurements at 178 Mc/s and 159 Mc/s and covered $4 \cdot 54$ steradians of sky more than 20° from the galactic equator. After correcting the source counts for the effects of random errors in the flux measurements of individual sources, he found that the observed $\log N/\log S$ (number-flux density) relation could be fitted by a straight line having a slope of $-1 \cdot 9 \pm 0 \cdot 3$ for sources having flux densities at 178 Mc/s, S_{178} , greater than $10 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$ the limiting flux density to which the survey was analysed.

Scott & Ryle (1961) used the source counts from the first four areas of sky synthesized by the 178 Mc/s interferometer combined with the 3C data to show that the $\log N/\log S$ relation can be fitted by a straight line of slope between $-1 \cdot 68$ and $-1 \cdot 93$ over the range $100 > S_{178} \geq 2 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$.

The form of the $\log N/\log S$ relation has been extrapolated below $2 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$ by Hewish (1961) who used Scheuer's (1957) statistical method to analyse the synthesis output in one of the areas of sky used by Scott & Ryle as mentioned above. He showed that the number counts for sources having S_{178} less than about $1 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$ must fall below the numbers expected from extrapolation using the power law derived for higher flux densities. His typical curves show that the $\log N/\log S$ slope must have changed from $-1 \cdot 8$ at high flux densities to flatter than $-1 \cdot 0$ at $0 \cdot 1 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$.

This change of slope has been confirmed by Ryle & Neville (1962) whose source counts, derived from observations with a $4 \cdot 5'$ arc pencil beam, of a circular area of sky 7° in diameter centred on the north pole, show a $\log N/\log S$ slope of $-1 \cdot 3 \pm 0 \cdot 3$ for $1 \cdot 0 > S_{178} \geq 0 \cdot 27 \times 10^{-26} \text{ w.m}^{-2}(\text{c/s})^{-1}$.

A decrease in slope of this kind must occur at some flux level for the integrated emission from extragalactic radio sources to be finite, and the equivalent temperature of this integrated emission is a useful parameter for checking extrapolations of the source counts. Turtle *et al.* (1962) estimated a temperature of about 20°K to 35°K at 178 Mc/s and more recent measurements (Bridle in preparation) suggest a value of 18°K to 28°K at this frequency. Hewish'

results are compatible with these values, the maximum contribution for sources with $S_{178} > 0.1 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ being 12°K and extrapolations for weaker sources adding a further contribution of the order of 10°K .

(b) *Present results.* The 4C catalogue of radio sources will, when completed, cover the whole area of sky between declinations -07° and $+80^\circ$ and include all sources having an observed intensity at 178 Mc/s, $S_{178} \geq 2 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$. The present analysis of source counts has been confined to regions more than 20° from the galactic equator and covers an area of 3.63 steradians between declinations $+4^\circ$ and $+80^\circ$. Small areas corresponding to the times of transit of the few most intense radio sources have been omitted from the analysis to avoid possible confusion with side-lobe responses. The regions which may be affected are given in the introduction to the catalogue (Pilkington & Scott 1965, Gower *et al.*, in press). As well as covering a much larger area of sky than that considered by Scott & Ryle (1961) the new data are improved for two reasons.

Firstly, all the source positions and fluxes have been obtained using a computer programme in which a theoretical response curve is fitted by a least squares process to the output maps, thereby improving the homogeneity of the results and eliminating any bias that might occur in fitting by hand. Secondly, the majority of the sources in the region $17^\circ < \delta < 42^\circ$ were observed in each of two independent sets of overlapping observations. In addition to reducing the random errors in the source positions and intensities, the two sets of observations are valuable in distinguishing the side-lobe responses of intense sources. Over the rest of the sky the amount of overlap was less but sufficient to be useful.

It is nevertheless necessary to consider the effect on the derived $\log N/\log S$ plot of confusion which, for the weaker sources, leads to a systematic over-estimation of the flux densities. This effect and also that arising from the obscuration of weak sources by ones of great intensity has been investigated directly by a Monte Carlo analysis which is described in the following section.

The flux scale adopted in the 4C catalogue, and used throughout the present paper, is based on the spectral work of Conway, Kellermann & Long (1963) and represents an 8% increase on the flux densities as quoted in the Revised 3C catalogue. In plotting the source counts of the 3C survey and the Ryle–Neville survey the flux densities have accordingly been increased by 8%.

3. Possible sources of error in the 4C data

(a) *Confusion.* The most important source of error in the measurements of the flux densities of the weaker sources is that due to confusion. The noise level in these observations is much less than the confusion level and can be ignored (Scott, Ryle & Hewish 1961). Provided the probability distribution of the record amplitude is known, the expected distribution of errors in measured flux density for sources of a given intensity, can, in principle, be computed. The necessary computations would be difficult, however, since allowance would also need to be made for the effects introduced by the source fitting programme, which will compute the flux density from the best fit of the theoretical response curve with sources whose observed response may be considerably affected by confusion. To determine the necessary correction to the source counts, allowance would also need to be made for those sources which are missed through being too close to a more powerful source. In the present case, these difficulties

have been avoided by using a Monte Carlo analysis. In this analysis, a large number of sources of known flux density having an idealized response curve were added to the final synthesized output maps used to compile the 4C catalogue. Each source was added to the map in a position unaffected by any previous addition so as to provide an independent sample for estimating the effect of confusion. The flux densities of the added sources were distributed in approximately the same way as those of observed radio sources down to a lower limit of $1 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ (Scott, Ryle & Hewish 1961, Ryle & Neville 1961, Hewish 1961). The fluxes of these sources were then computed from the

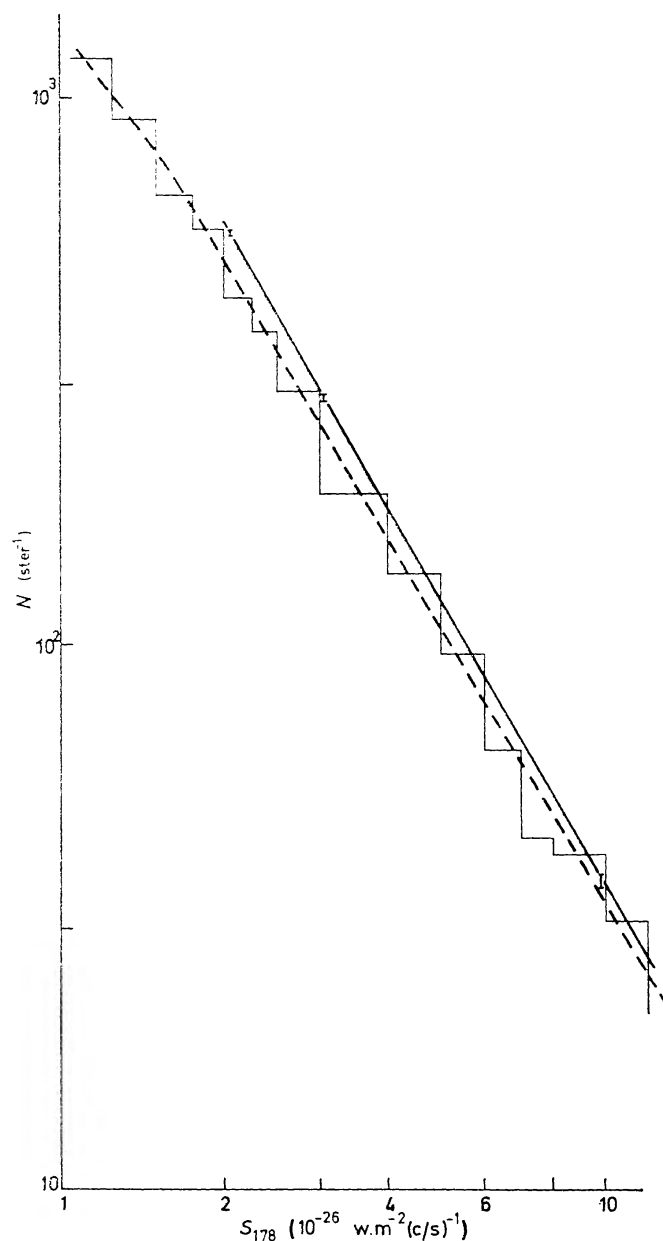


FIG. 1. The results of the Monte Carlo analysis of errors in the source counts due to confusion. The source counts of the added population of sources are shown as a stepped line to which the dotted line is the best smooth fit. The thicker upper line shows the source counts obtained by measuring the flux densities of the added sources using the same methods as were used in compiling the 4C catalogue. The figure shows a progressively greater overestimation of the number of weaker sources.

output maps using exactly the same techniques as were used for compiling the 4C catalogue and their new number/flux density distribution was found. A comparison of this number/flux density distribution with that originally added to the maps gives directly the corrections to be applied to the source counts to allow for all the effects of confusion.

Fig. 1 shows the results obtained from adding about 1200 sources to the final synthesized output maps. This shows that the effect of confusion is to increase the number of sources observed, down to the values of S_{178} given below by the amounts shown.

S_{178} $10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$	Percentage increase
2	13
3	13
5	10
7	8
10	5

These corrections represent the combined effects of confusion on the source counts. One of these effects will be the omission from the 4C catalogue of weaker sources which occur too close to a stronger source to be separately detected. Provided radio sources are distributed randomly, the Monte Carlo analysis will take this effect into account automatically, since as many sources will tend to be missed in the Monte Carlo analysis as were missed in the compilation of the 4C catalogue. For sources with $S_{178} \geq 2 \times 10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$ this effect causes about 7% of the sources to be missed.

(b) *The effect of source angular diameters and source clustering.* The 4C catalogue is derived from observations made with an interferometer having a fringe spacing of 7.5 arc, so that sources having an angular extent greater than about 2' arc will be received with reduced intensity. A similar effect will also occur in the case of a double source having a separation of components exceeding about 1.5 arc.

Sufficient information on the surface brightness distribution of sources with $S_{178} \geq 15 \times 10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$ in the Revised 3C catalogue of radio sources is now available to derive their distribution of γ , the ratio of observed to true intensity. Provided that a similar distribution of surface brightness can be assumed for the less intense sources, these results can readily be extrapolated to lower values of flux density. For values of $S_{178} \geq 4 \times 10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$ the effect of source diameters is small and at the limit of the 4C survey ($S_{178} = 2 \times 10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$) amounts to a reduction in the numbers of sources observed of less than 1%. These results are confirmed by more recent measurements using a high resolution pencil beam system. (Crowther & Caswell, in preparation.) The corrections derived have been applied to the source counts in the range $2 \leq S_{178} < 10 \times 10^{-26}\text{w.m}^{-2}(\text{c/s})^{-1}$ when plotting the complete $N/\log S$ relation.

Sources of very low luminosity ($P_{178} < 10^{23}\text{w}(\text{c/s})^{-1}\text{ster}^{-1}$), and in particular the class of normal galaxies, have been excluded from this analysis. These sources generally have a low surface brightness and will not be detected at all in

the interferometer observation of the 4C survey. The few sources of this type listed in the 3C catalogue away from the galactic plane have similarly been omitted from the source counts.

Source clustering on a scale 1' to 60' arc could affect the source counts by altering the effects of confusion. From the work of Holden (in preparation) a low upper limit can be set to clustering on any scale down to 25' arc and sufficient clustering on a scale greater than about 1' arc to affect the present results seems unlikely, and would be detected in the analysis of source diameters.

4. *The log N/log S relation.* The final form of the log N/log S relation at 178 Mc/s over the range $0.27 \leq S_{178} < 35 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ is shown in Fig. 2. Data from the revised 3C catalogue for 4.54 steradians of sky have been used for $S_{178} \geq 10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$, data from the 4C catalogue for 3.63 steradians of sky for $2 \leq S_{178} < 10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ and the results of the Ryle–Neville survey covering about 0.01 steradians for sources with

$$2 > S_{178} \geq 0.27 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}.$$

Data from 3C and the Ryle–Neville survey have had their flux densities increased by 8% as mentioned in section 2. The slope of the curve is about -1.80

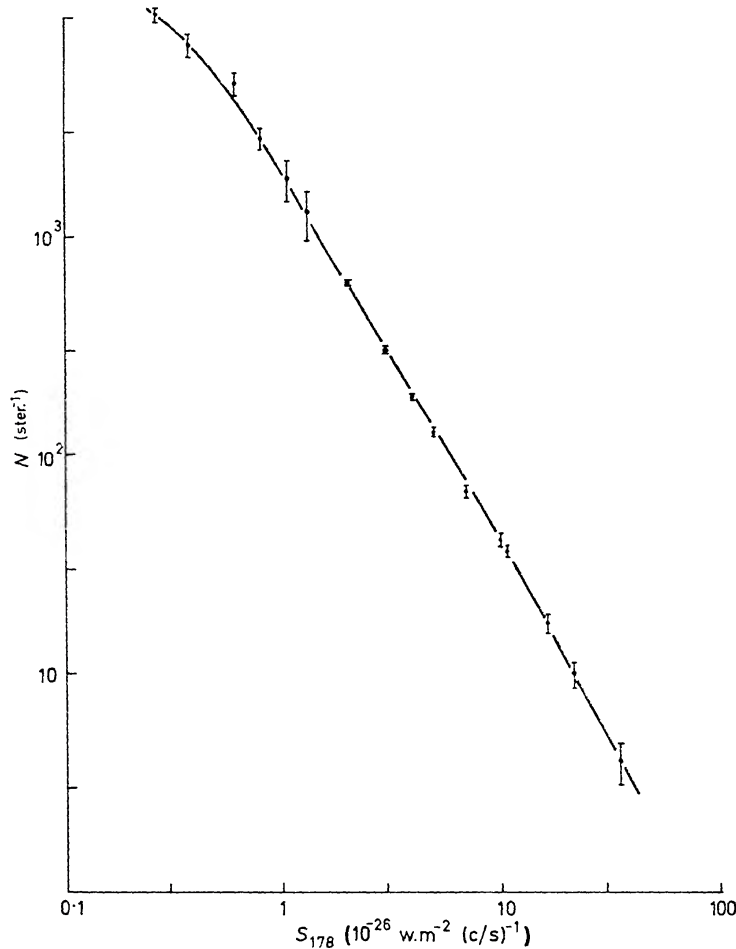


FIG. 2. *The final log N/log S curve for the flux density range $0.27 \leq S_{178} \leq 35 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$. Revised 3C data has been used for $S_{178} \geq 10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$, 4C data for $10 > S_{178} \geq 2 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ and Ryle–Neville results for $2 > S_{178} \geq 0.27 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$.*

at high flux densities changing to -1.66 over the range of flux density 2 to $10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ and then to less than -1.3 in the range covered by the Ryle–Neville survey. Hewish's results show that this decrease in slope must continue at least down to $0.1 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$.

The 4C curve shown has been corrected for confusion and for the angular diameters of sources as described in section 3 parts (a) and (b) respectively.

5. *The effect of a dispersion in radio luminosity.* An examination of the distribution of radio luminosity of the more intense sources by Longair & Scott (1965) has indicated a very wide dispersion, 50% of sources having a power at 178 Mc/s, P_{178} , outside the range $10^{25} < P_{178} < 10^{27} \text{w.}(\text{c/s})^{-1} \text{ster}^{-1}$. Their curve showing the distribution of radio luminosities, $n(P)$, for sources with flux density greater than a given limit, is shown in Fig. 3. Any variation in the mean spatial density or luminosity of sources with distance or epoch will be smoothed by this dispersion and it is interesting to consider the effect of this smoothing on the observed $\log N/\log S$ relation.

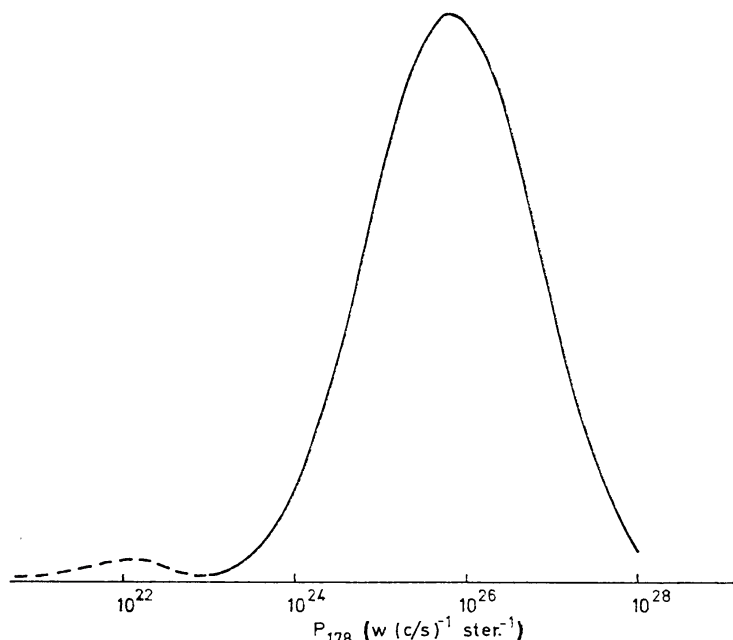


FIG. 3. The observed radio luminosity distribution for sources having $S_{178} \geq 15 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$.

The origin of the observed $\log N/\log S$ curve has been considered by a number of authors. Davidson and others have considered it as being due to a variation of number density (ρ) with epoch: Oort and others have discussed the source counts in terms of a variation of intrinsic luminosity (P) with epoch. Hoyle & Narlikar have suggested that the effect could be attributed to a large-scale non-uniformity in spatial distribution. This non-uniformity would, however, need to cover a large fraction of the observable universe (Clarke, Scott & Smith 1963). Moreover, the recent derivation of the luminosity distribution makes it unlikely that such an explanation can be accepted, since, in deriving their curve, Hoyle & Narlikar made no allowance for the dispersion in P and their curve must be convolved with the luminosity distribution of sources in order to represent the true $\log N/\log S$ curve.

If evolutionary effects are important it is difficult to make a precise analysis, since, in addition to any variation of the spatial density, ρ , the form of luminosity distribution will itself be a function of distance. If, however, it is assumed that the observed $\log N/\log S$ is caused only by changes in the density of sources, the luminosity distribution being independent of epoch, variation of ρ with distance can be found which are consistent with the observed source counts. If all radio sources were of a single power, the variation of ρ with distance could, of course, be deduced directly from the source counts. However, the observed wide dispersion in intrinsic luminosities makes direct deduction impossible since sources at very different distances will be received with the same flux density.

To investigate what forms of ρ variation are compatible with the source counts presented in section 4, and the luminosity distribution, the source counts resulting from chosen models of the ρ variation can be compared with the observed counts. It is convenient to represent this variation by an equivalent $\log N/\log S$ distribution for sources of a single power. $P_{178} = 10^{26} w. (c/s)^{-1} \text{ ster}^{-1}$ was chosen as representing a median luminosity for a bright radio source. This model $\log N/\log S$ can then be convolved with the dispersion of luminosities to give the observable source counts resulting from the model. Simple, straight line approximations to this equivalent $\log N/\log S$ were chosen since the wide dispersion in luminosities will smooth out any complex variations.

Suppose, for example, that the $\log N/\log S$ for sources having

$$P_{178} = 10^{26} w. (c/s)^{-1} \text{ ster}^{-1}$$

was as shown in Fig. 4 (a). This model represents a sharp decrease in source

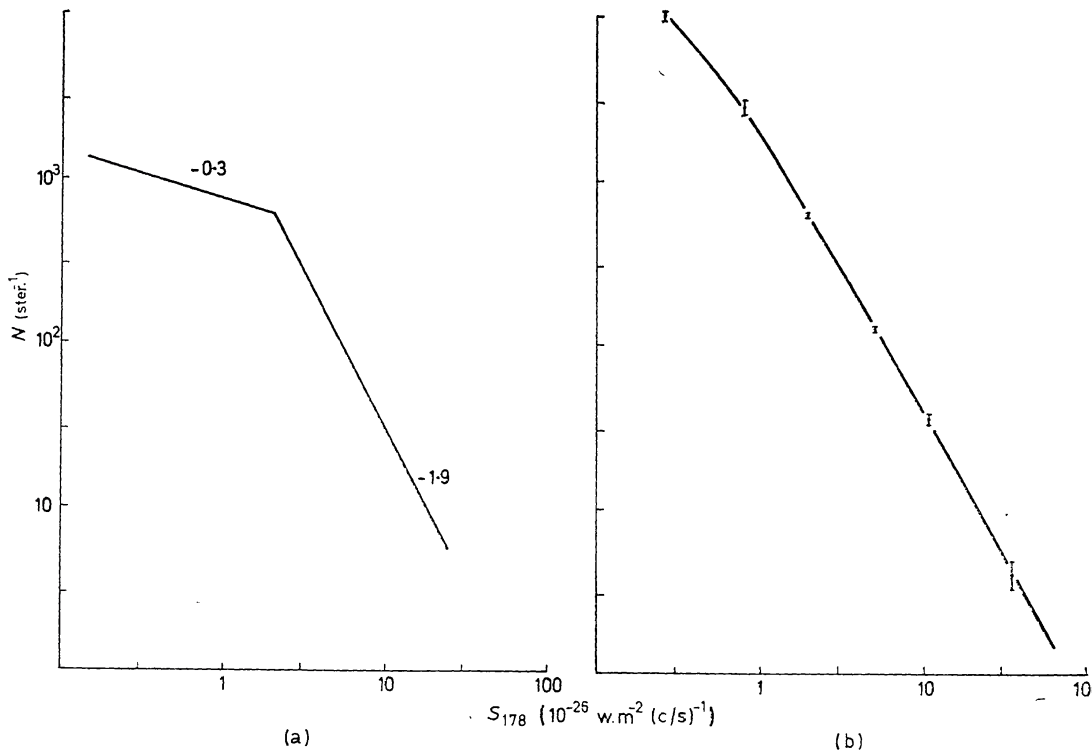


FIG. 4. (a) A model $\log N/\log S$ curve for sources having $P_{178} = 10^{26} w. (c/s)^{-1} \text{ ster}^{-1}$. Slopes are given against the lines on the figure. (b) The model shown in Fig. 4 (a) after convolution with the luminosity distribution shown in Fig. 3. The observed points with error limits have been transcribed from Fig. 2.

density for distances given by $z > 0.7$. When convolved with the luminosity distribution of bright radio galaxies, the final $\log N/\log S$ would have the form shown in Fig. 4 (b), in good agreement with that observed. The integrated emission from this computed $\log N/\log S$ would be 23°K down to

$$0.01 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$$

and a further 2°K to zero flux density. Measurements of the background temperature over a range of frequencies may be used to set upper limits on the integrated extragalactic emission for various assumed values of source spectral index. The recent measurements of Bridle (in preparation) suggest an upper limit of between 18°K and 28°K for a source spectral index of 0.8 , consistent with the value of 25°K derived above.

The form of the luminosity distribution used in this analysis is shown in Fig. 3. The distribution for the small percentage of sources having

$$P_{178} < 10^{23} \text{w.}(\text{c/s})^{-1} \text{ster}^{-1},$$

which are excluded from the present analysis as explained in section 2, is shown dotted. These sources should, in any case, be omitted when considering the total integrated emission since they will generally have a lower spectral index than the value of 0.8 assumed for the radio galaxies and their contribution will not be included in the estimated maximum extragalactic emission. The total integrated emission including that from normal galaxies, must, nevertheless, be less than 80°K at 178 Mc/s which represents the observed minimum sky temperature (Turtle & Baldwin 1962).

It should be noted that a variation in the density of normal galaxies with distance corresponding to that assumed for the radio sources would give rise to an integrated component, for these sources alone, of about 150°K , considerably above the maximum permissible total integrated emission of 80°K . It would appear unlikely, from this evidence, that normal galaxies can be distributed in the same way as the more powerful radio galaxies and indeed no evidence for such a spatial variation has been detected.

A range of models, representing different variations of ρ with distance, have been considered in order to find those models which most closely fit the observed $\log N/\log S$ distribution. The best models are found to have slopes between -1.8 and -2.0 at high flux densities. For slopes steeper than this, the flux density at which the cut-off appears would need to be greater than

$$10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$$

so that the effect of the cut-off on the observed dispersion of luminosities for bright sources with $S_{178} > 15 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$ would already be very marked. A cut-off in the range 5 to $10 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}$, necessary for an initial slope of -2.0 , is already approaching the maximum allowable.

The $\log N/\log S$ slope of the models for weak sources needs to be flatter than about -0.7 though the exact value in the range 0 to -0.7 has only a small effect on the computed $\log N/\log S$ curve in the range

$$S_{178} \geq 0.27 \times 10^{-26} \text{w.m}^{-2}(\text{c/s})^{-1}.$$

Fig. 5 shows three representative models of the $\log N/\log S$ for sources having $P_{178} = 10^{26} \text{w.}(\text{c/s})^{-1} \text{ster}^{-1}$ compared with the $\log N/\log S$ predicted for a uniform Euclidean universe ($N \propto S^{-1.5}$) and for an Einstein-de Sitter universe. All the models require a rapid decrease in source density at a distance corresponding to

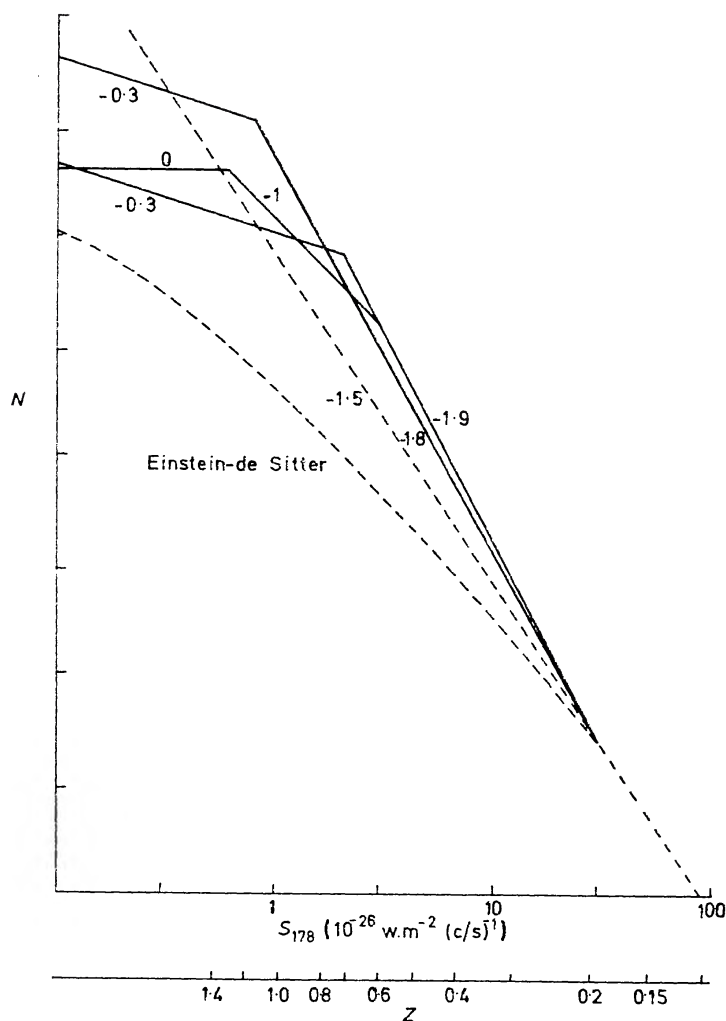


FIG. 5. Full lines show the best models for the $\log N/\log S$ of sources having $P_{178} = 10^{26} w. (c/s)^{-1} \text{ster}^{-1}$. Slopes are given against the lines on the figure. Dotted lines show the expected curves for an Einstein-de Sitter universe and a uniform Euclidean universe. All models are normalized to the same number of sources at $30 \times 10^{-26} w. m^{-2} (c/s)^{-1}$. The scale of z shown has been calculated for an Einstein-de Sitter universe.

$0.7 < z < 1.2$, at which distance the source density must be a factor 10 ± 3 greater than that expected for an Einstein-de Sitter universe.

In relating these results to the variation of source density with time it may be found more appropriate to consider models in which the spatial density in nearby regions is more nearly constant, the steep slope of the $\log N/\log S$ plot being produced by a very large increase in the density of sources at an early stage in the evolution of the universe. In this case, however, the variations of ρ with distance must necessarily be very much more marked than in any of the models considered here, which represent the smallest variations of ρ which are consistent with both the observed luminosity distribution and the source counts.

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