

# THE PREPARATION OF THE REVISED 3C CATALOGUE OF RADIO SOURCES

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## *Summary*

New observational data are used to make a complete revision of the 3C catalogue, which should now provide a complete and reliable list for all sources with flux greater than  $9 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 178 Mc/s and for which  $\delta > -05^\circ$ . The correction of the observations for the effects of confusion is described in detail, and the analysis of these errors is verified by comparison of the original 3C measurements with new measurements now available. The new catalogue is compared with the original, and it is shown that the number counts of sources remain almost unchanged, in agreement with new observations by Scott and Ryle.

1. *Introduction.*—Recent observations at Cambridge with new radio telescopes have made possible a revision of the 3C catalogue of radio sources (Edge *et al.* 1959). The new catalogue (Bennett 1962) should provide a complete and reliable list of all sources north of  $\delta = -05^\circ$  with flux density greater than  $9 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 178 Mc/s, apart from some limitations for sources of low surface brightness. Although far more extensive lists will shortly become available, for example from the aperture synthesis observations of Scott, Ryle and Hewish (1961), it will not be possible for several years to produce a list with uniform coverage of the sky to a lower limit of flux density, and the present list should therefore fill a need for a reliable finding list of radio sources.

The positional accuracy of most of the sources is comparable with that of the original list, while the lobe ambiguities have been removed. Where more accurate positions are available, they have been included. The flux densities are considerably more reliable than those of the original list.

The new observational material is described in Section 2, which includes details of the accuracy and coverage of the revised catalogue. An analysis of errors in the kind of observations needed for catalogues of radio sources is given in Section 3, and the effect of these errors on the previous catalogues 3C and MSH (Mills, Slee and Hill 1958) is discussed in Section 4, which also gives the relation between number and flux density for the revised 3C sources.

## 2. *The observational material*

(i) *Survey material.*—The new list is based on observations at 178 Mc/s initiated by Miss Leslie (1961) and now continued to provide complete coverage of the sky north of  $\delta = -05^\circ$ . These observations include both “total power” measurements with an aerial which produces a fan beam  $4^\circ.6$  in  $\delta$  and  $13'.6$  in  $\alpha$ , and interferometer measurements at a spacing of  $469 \lambda$ , using approximately

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the same primary polar diagram. They are referred to here as the PRRL surveys. Additional information used to check the accuracy of the observations, and to provide more detailed evidence for certain areas of the sky, was derived from the high resolution observations of Scott, Ryle and Hewish (1961). The areas of sky covered in this way are  $\delta = 02^\circ$  to  $07^\circ$ ;  $17^\circ$  to  $34^\circ$ ;  $40^\circ$  to  $44^\circ$ ;  $48^\circ$  to  $54^\circ$ . The observations of 64 sources by Elsmore, Ryle and Leslie (1959) were used to normalize the flux density scales. Use has also been made of two Cambridge surveys at 38 Mc/s (Costain and Smith 1960, Kenderdine and Baldwin, in preparation), and at 408 Mc/s (Long, Elsmore and Haseler, in preparation), the MSH survey at 85 Mc/s (Mills, Slee and Hill 1958, Mills and Slee 1957), the survey at 1390 Mc/s by Westerhout (1958) and observations at 960 Mc/s by Harris and Roberts (1960).

Information on the angular diameter of many of the sources has been provided in advance of publication by Palmer (Allen *et al.* 1962), and by Moffet (1961) and Maltby (1961).

(ii) *Coverage*.—By making observations over an extensive period, it has been possible to avoid the effects of solar radiation and obtain an effectively uniform coverage of the whole sky north of  $\delta = -05^\circ$ . The limit of flux density for “point” sources is approximately  $9 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 178 Mc/s, although in areas close to the plane of the Galaxy the limit of reliable measurement is somewhat greater, reaching 18 units where the background temperature exceeds  $1000^\circ \text{K}$  as shown on the contour map of Turtle and Baldwin (1962).

Extended sources with diameters up to  $1^\circ$  have been included. An analysis of observational errors is made in this paper, leading to limits of accuracy which are quoted in the catalogue itself (Bennett 1962).

(iii) *Angular diameters*.—For the more extended sources the angular diameter is derived from the total power observations, with an E–W beam width of  $13' \cdot 6$ . The diameters of sources unresolved by this beam width were obtained from the  $469\lambda$  interferometer, and the results interpreted in terms of a Gaussian brightness distribution, unless better information was available from the observations mentioned above.

3. *Errors in determining flux density*.—The errors in determining the flux density of a radio source arise partly from difficulties in calibration and non-linearities in the recordings, neither of which will be considered here, and partly from the presence of weak confusing radio sources in the reception pattern and from receiver noise. The analysis of “confusion” for the interferometer is fairly straightforward and is presented below. The additional difficulties which arise in the total power observations, whether of “point” or extended sources, are more complicated, but the magnitude of the errors can be determined experimentally. Both analyses may be verified by examination of the errors now revealed in the original 3C catalogue.

(i) *Confusion effects in interferometer recordings*.—The effect of noise and confusion on an interferometer recording may be represented as the addition with random phase to the vector representing the source of a “confusion” vector whose amplitude is distributed as the observed record amplitudes (Ryle 1958). For a source of flux density  $S$  and a confusion vector  $\sigma$  with relative phase  $\phi$ , the observed flux density  $S'$  is given by

$$S'^2 = S^2 + \sigma^2 + 2S\sigma \cos \phi.$$

If the confusion vector is small, we can write

$$S' = S \left\{ 1 + \frac{1}{2} \frac{\sigma^2}{S^2} + \frac{\sigma}{S} \cos \phi - \frac{1}{2} \frac{\sigma^2}{S^2} \cos^2 \phi \right\}$$

discarding terms of higher order than  $\frac{\sigma^2}{S^2}$ .

There is, therefore, on the average, a small positive error  $\frac{1}{4}(\sigma^2/S)$ , and a larger error,  $\sigma \cos \phi$ , whose sign depends on the phase  $\phi$ . This latter term may be taken, approximately, as representing the random error in the flux density of an individual source, the probable error being  $\sigma/\sqrt{2}$ . Since the mean value of this error averaged over a large number of sources is small, the first term is the important one when making counts of sources falling in different ranges of flux density.

A source recorded with an apparent flux density  $S'$  is more likely to have originated from one of the weaker more numerous sources with a confusion vector having a positive value of  $\cos \phi$  than from one of the less numerous stronger sources with a negative confusion vector; when counting the number of sources down to a given flux density an error is therefore introduced, which itself depends on the true number-flux density relationship. This error may be expressed as an equivalent error in the mean apparent flux density for sources of a given flux density, and is additional to the small positive error derived above. Its magnitude is considerably smaller than the errors encountered in the flux densities of individual sources and its derivation is given in the Appendix.

The appropriate mean value of  $\sigma$  may be derived from a statistical analysis of the record amplitudes (Scheuer 1957, Hewish 1961), so the magnitude of the probable error for individual sources and for source counts may be calculated. For the 3C survey, the value of  $\sigma$  is  $2.2 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 159 Mc/s. The mean error  $\frac{1}{4}(\sigma^2/S)$  is thus  $0.12 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  for a source of flux density  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ . Using the expression derived in the Appendix, with the value  $-1.8$  for the index in the source count-flux density relationship (Scott and Ryle 1961), the total error in the source count is equivalent to an error in flux density of  $0.43 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , for sources having  $S \simeq 10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ .

The corresponding value of  $\sigma$  for the PRRL interferometric survey is  $1.4 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 178 Mc/s and the associated errors appropriate to source counts are respectively  $0.05 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  and  $0.17 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ . These errors in this survey even if uncorrected are therefore of little importance for sources having  $S > 10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ .

(ii) *Confusion effects in total power recordings.*—The errors to be expected in a total power, or pencil beam, system are more difficult to compute because of the difficulty of expressing mathematically the procedure by which the records are analysed. The major problem in the analysis of the records for radio sources is the specification of the mean level of the record in the vicinity of the source; which is complicated by the presence of structures having a scale larger than the width of the polar diagram. For a source known to be of small angular size, and whose position is known, the flux density could be obtained by fitting the polar diagram to the record. The random confusion error is then simply obtained from the statistical fluctuation of the record. This procedure is not available for extended sources.

The method of analysis adopted in the PRRL survey for sources apparently unresolved by the fan beam was to measure the maximum deflection above a base line determined in the neighbourhood of the expected zeros of the polar diagram (Fig. 1). This procedure tends to overestimate the flux density, as has been discussed by Miss Leslie (1961). The mean error depends on the length of record over which the most negative deflection is sought—about a half to one beam width in most cases—and so varies somewhat from one observer to another. The effect is, in general, worse for weak sources, when the expected position is less well-defined and a greater length of record is scanned for the most negative deflection.

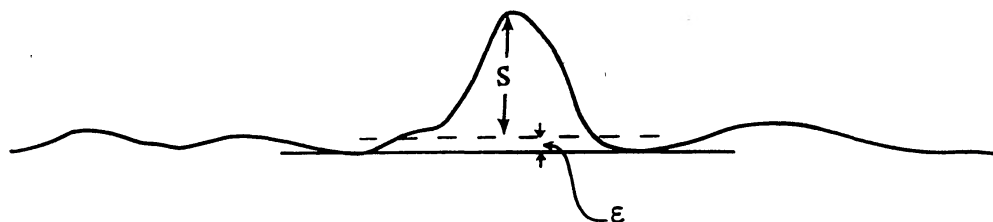


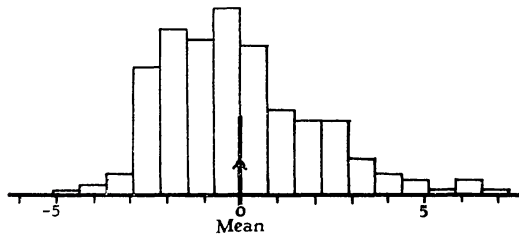
FIG. 1.—Illustrating the method adopted for the analysis of the total power records. The amplitude of the source was measured relative to a line drawn through nearby minima of the record (full line) rather than relative to the mean level of the surrounding record (dotted line) leading to an over-estimation of the flux by an amount  $\epsilon$ .

An exact analysis of this problem is difficult, and it is preferable to resort directly to the statistics of the records. A record from the PRRL survey, in a region of high galactic latitude and containing no strong sources was first smoothed by the use of a convolution function appropriate to the aerial beam. A mean curve was drawn such that the convolved record included equal areas above the curve and below it, the regions near sources of flux density greater than  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  being omitted. The deflection from this mean curve was measured, and also the most negative deflection within an interval of length (i) one-half and (ii) one beam width, for a sufficient number of points to define the distributions. Fig. 2 shows the results of the investigation as histograms. Fig. 2 (a) shows the probability distribution of the record amplitude, which has semi-interquartile range of  $1.4 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , as may be seen from the integrated probability curve, 2 (b). Fig. 2 (c) and (d) show the distribution of the most negative deflections, which have mean values  $-0.8 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  (one-half beam width) and  $-1.5 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  (one beam width). The mean error can be expected to lie in this range.

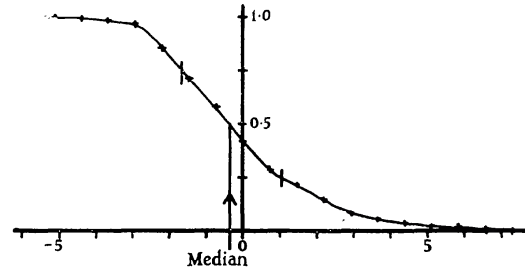
Extended sources, resolved by the primary polar diagram, will suffer from somewhat larger errors in the determination of the baseline. A source about one degree in size, occupying four beam widths on the record, may be attributed a flux density in error by about 8 units. In addition, most of the extended sources occur close to the galactic plane, where analysis is made difficult by galactic structure, and the errors may then be increased due to the presence of gradients and curvature in the background emission.

(iii) *Experimental verification of the corrections.*—Observations of sources with the full synthesis resolving power of the 178 Mc/s interferometer may be used to determine the errors in the PRRL interferometer observations directly since

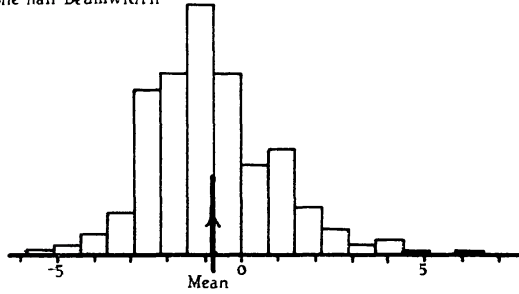
(a) Distribution of record deflections



(b) Integrated distribution of record deflections



(c) Distribution of most negative deflection within one half beamwidth



(d) Distribution of most negative deflection within one beamwidth

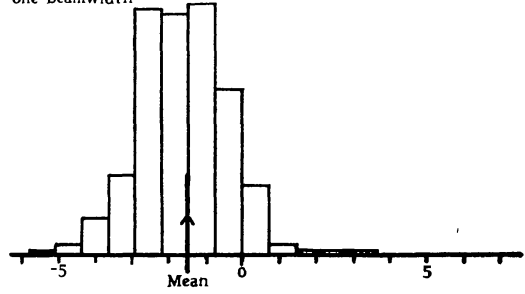


FIG. 2.—Distributions of deflections on PRRL total power records.

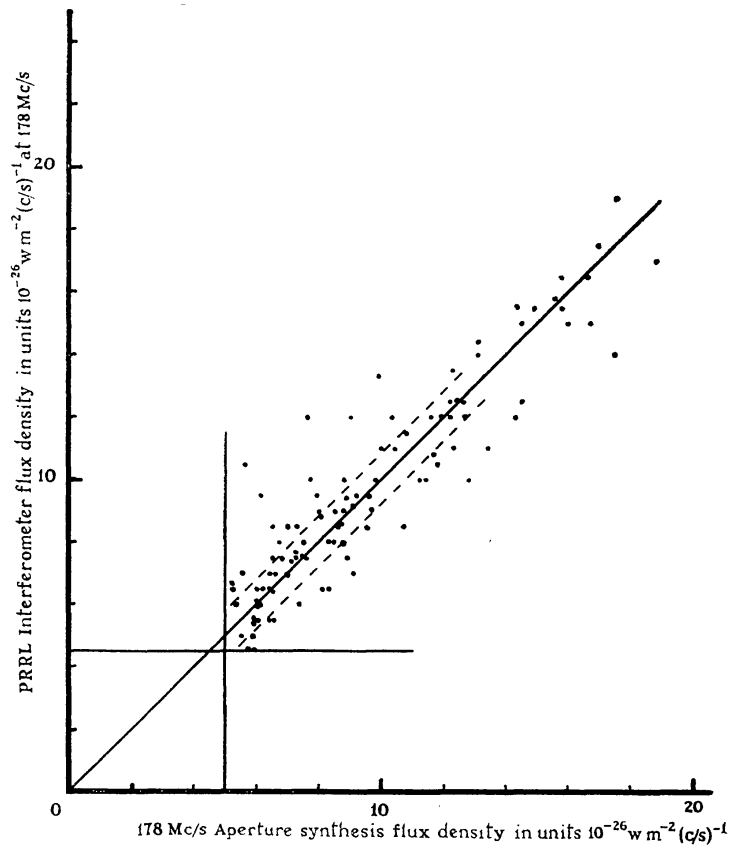


FIG. 3.—PRRL interferometer flux densities plotted against those obtained by aperture synthesis.

both are made with the same interferometric spacings. A comparison was therefore made of individual sources in the areas so far covered by the aperture synthesis interferometer, and the results are plotted in Fig. 3. It appears that the random error (p.e.) for sources with low flux density is  $0.8 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ . The flux densities are not appreciably overestimated in agreement with the calculated mean error of  $0.05 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  for the PRRL survey.

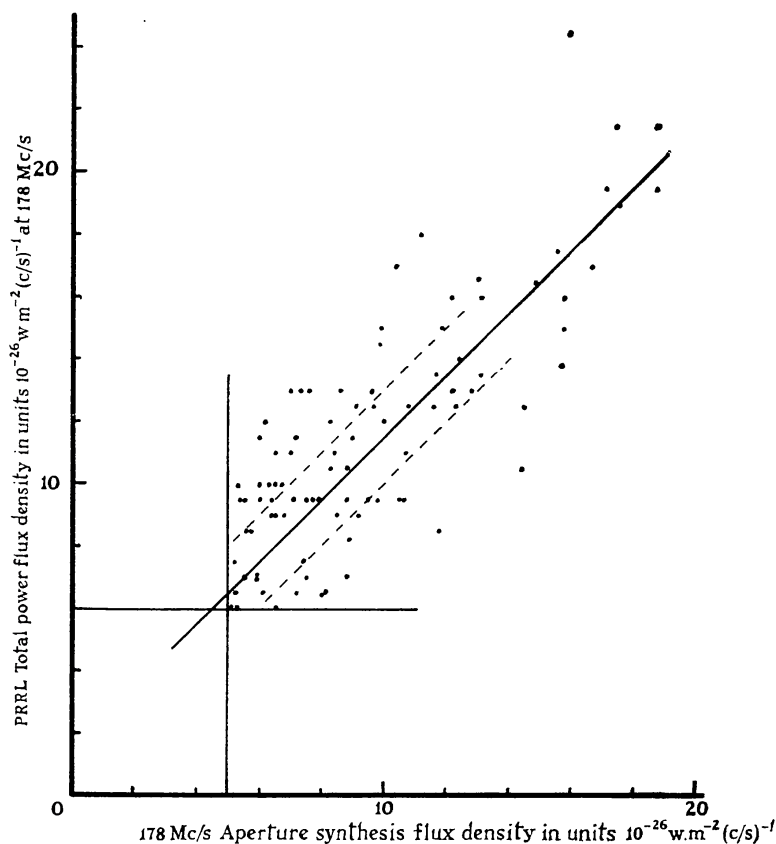


FIG. 4.—PRRL total power flux densities plotted against the interferometer flux densities obtained by aperture synthesis. Sources known, from independent evidence, to be partially resolved by the  $469\lambda$  interferometer have been omitted.

A similar analysis was made using the high resolving power observations to check the PRRL total power measurements. In this case it is necessary to consider the effect of extended sources which would be either not observed, or observed as having reduced flux density, with the high resolution system. The angular diameter measurements at Jodrell Bank and at the California Institute of Technology have shown that the effect of partial resolution should be small for all but a few of the sources so that this analysis may be used to check the theoretical mean error calculated above. The results of this comparison are shown in Fig. 4. The observations are in better accord with the larger value of the mean error, predicted above, of  $1.5 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , so this value, which is close to the values used by PRRL, is taken as the correction to be applied. The observed random error (p.e.) is  $1.5 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , in good agreement with that to be expected from the observed record deflections.

Another comparison which reveals the magnitude of errors in 3C is the comparison between the original flux density at 159 Mc/s and the new values at 178 Mc/s for sources over the whole area. In Fig. 5 the new values are plotted against the old values. A similar figure was plotted by Bennett and Smith (1961),

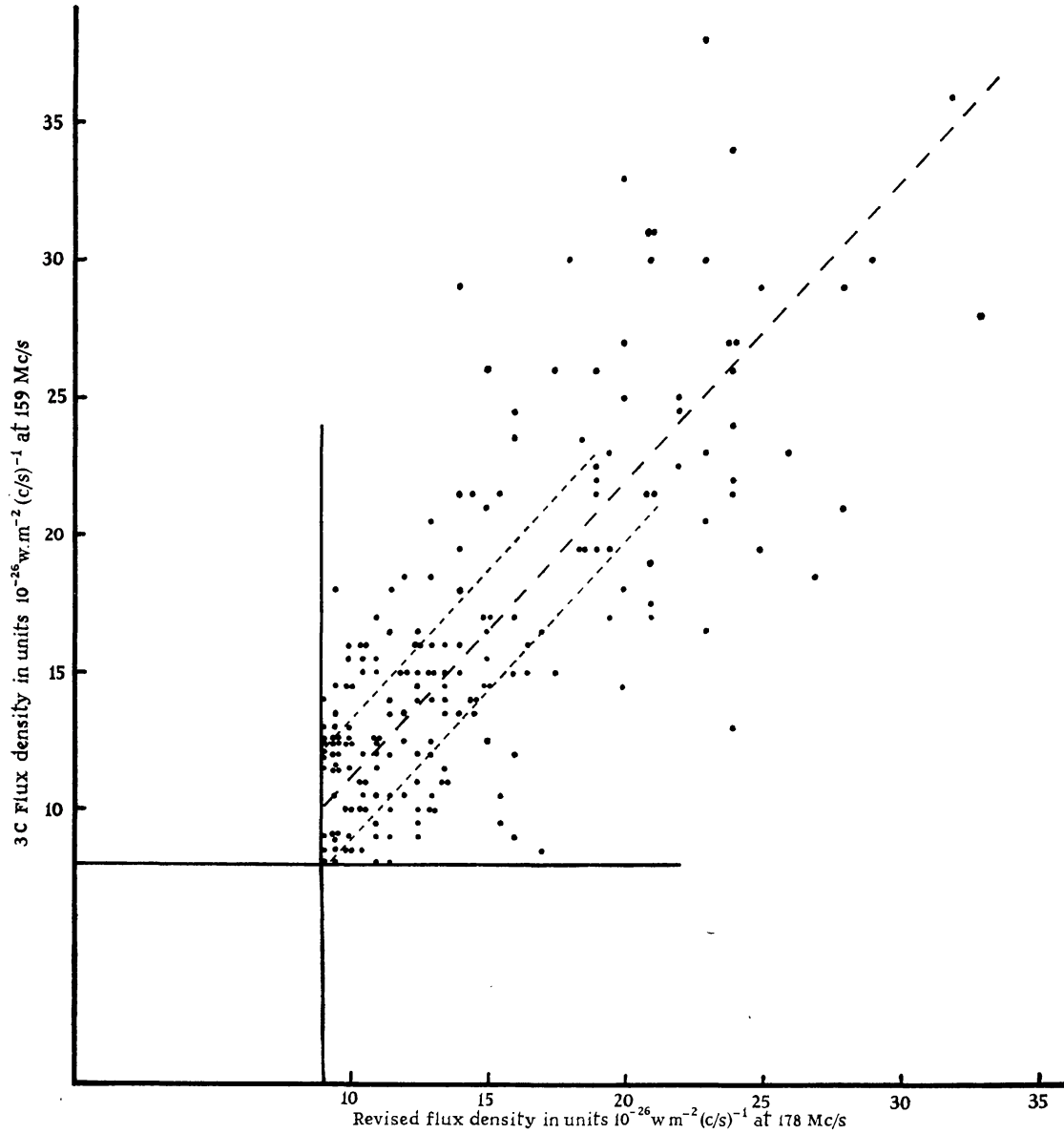


FIG. 5.—The original 3C flux densities plotted against the revised values. The dashed line is the predicted mean line, taking into account the difference in the observing frequency and the small mean error in flux density of the 3C survey calculated in Section 3 (i).

but the present analysis is made with more precise values for the new 178 Mc/s flux densities and covers a larger number of sources. The dashed line in Fig. 5 represents the correction to the 3C flux densities predicted by the theory of Section 3 (i). It can be seen that the observed points fall closely around the predicted curve. The dotted lines are drawn at  $2.0 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  either side of the mean predicted curve, representing the predicted combined probable error.

(iv) *The flux densities for the revised list.*—As shown above, the errors in flux density are larger for total power measurements than for interferometric measurements having the same primary resolution. It is therefore desirable to use the interferometer flux densities in those cases where the source is known to be of sufficiently small angular size for the effect of resolution by the interferometer to be negligible. The measurements at Jodrell Bank (Allen *et al.* 1962) and at the California Institute of Technology (Maltby and Moffet 1962), together with those of Miss Leslie (1961), show that the majority of sources in high latitudes are not appreciably resolved by the  $469\lambda$  interferometer. Therefore, in order to make use of the greater accuracy of the interferometer flux densities, these are quoted for all those sources which are not appreciably resolved by the  $2200\lambda$  spacing of the Jodrell Bank interferometer, or in the observations of the California Institute of Technology.

For all other sources, total power fluxes, corrected by subtracting the systematic mean error of  $1.5 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , found above, are quoted.

(v) *The effect of errors on the measurement of diameters.*—For sources of angular diameter not resolved by the primary polar diagram, an estimate of the angular diameter can be obtained from the PRRL survey, from the ratio of the apparent flux density measured with the interferometer to that measured with the total power system. This estimate is based on the assumption that the source has a Gaussian brightness distribution: if this is not so, the method still gives an estimate of the scale of structure of the source. The random errors, due to confusion, in the two fluxes are largely uncorrelated (because there are several interferometer lobes within the primary reception pattern) so the errors to be expected in the ratio are easily calculated from the known errors in the fluxes. After the systematic error has been allowed for, the combined random error is about  $1.7 \times 10^{-26} \text{ w. (c/s)}^{-1} \text{ m}^{-2}$  (probable error) so that for a source of flux density  $15 \times 10^{-26} \text{ w. (c/s)}^{-1} \text{ m}^{-2}$  the error in  $\gamma$ , the ratio of the fluxes, is about  $\pm 0.11$ . If such a source has a diameter of about  $3'$  arc, this error in  $\gamma$  corresponds to an error in measurement of  $\pm 0.6$  (probable error), or about  $\pm 1.6$  with 90 per cent confidence of the diameter lying within the quoted range. If the diameter were small, giving an expected  $\gamma$  of unity, an upper limit of about  $2.4$  could be set, again with 90 per cent confidence. These results agree closely with the estimates made by Miss Leslie (1961).

#### 4. *The changes in the catalogue, and in the source counts*

(i) *Sources added and sources removed.*—As a result of the revisions of flux density there are a number of changes in the 3C catalogue near the lower limit of flux density. The revised list is intended to be complete to  $9 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 178 Mc/s, corresponding to  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 159 Mc/s, the frequency of the original survey. In the 3C catalogue there are, in the area under consideration, 307 sources above  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  and 129 below. Of the 307 sources 93 do not appear in the revised catalogue, usually because of an overestimation of the flux density. In many cases, several sources are present, near the 3C position or its lobe-shifts, on the PRRL records. Of the 129 below  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , 22 appear in the revised catalogue because their revised density is above the limit.

Of the sources above  $10 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ , 12 which still appear have been moved in declination only (“lobe-shifted”, as described in the 3C catalogue),

and 38 in right ascension only. 11 have been "lobe-shifted" in both coordinates. The proportion of sources involved is less than the estimate in the 3C catalogue.

90 sources not listed in 3C have been added. A number of these, mostly near the lower limit of flux density, were missed by the 3C survey, but most of the additional sources are in areas not covered by 3C: either north of declination  $+71^\circ$  or in the area obscured by solar interference or side lobes of strong sources. A number of sources of appreciable angular extent, which were resolved by the 3C interferometer, have been added in the region of the galactic plane, also several partially resolved sources, a few of which are in quite high galactic latitudes. The total number of these is small, in agreement with the results previously quoted.

These changes have been made in a way which preserves as closely as possible the original numbering of the 3C catalogue.

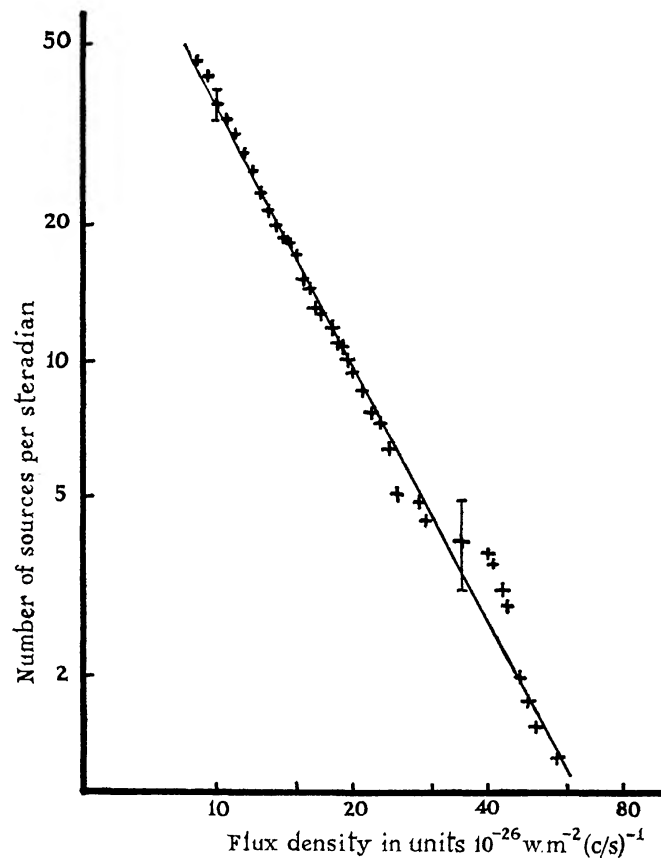


FIG. 6.—Source count for the revised 3C. The vertical lines indicate the statistical uncertainty.

(ii) *The source counts.*—The new list has been used to derive a  $\log N - \log S$  curve for the whole area with  $|b^{\text{II}}| > 20^\circ$ . The results are shown in Fig. 6. The best straight line drawn between flux densities  $10$  to  $50 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  has a slope of  $-1.9$  and is in good agreement with that obtained by Scott and Ryle (1961) from observations extending to  $2 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ . The slope obtained from the 3C results was  $-2.0$  without any allowance being made for the presence of extended sources or for the overestimation of small flux densities.

The source counts of Mills, Slee and Hill (1958) gave a slope of  $-1.8$  before correction. In a recent paper (MSH 1960), a correction on the same lines as in Section 3 is made, which leads to a slope of  $-1.5$ . It is, however, clear from the comparison of catalogues by Bennett and Smith (1961) and from recent more detailed work on the same lines, that the MSH catalogue (a) lists as extended a number of sources of comparatively high flux density which are, in fact, groups of small-diameter sources; (b) is seriously incomplete, at the lower values of flux density (below about  $12 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 85 Mc/s). The MSH small-diameter sources above  $12 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$  at 85 Mc/s, with flux densities corrected as suggested (MSH 1960), do in fact provide a slope very close to that of the revised 3C catalogue.

It has been argued that the interferometer surveys have wrongly discriminated against the extended sources, which might appear as point sources when at a great distance while not appearing among the high intensity sources. The present survey, however, now emphasizes the conclusion of Miss Leslie (1961) that there are few sources with brightness temperature between  $100^\circ\text{K}$  and  $10^4^\circ\text{K}$ , for which such selection effects would have occurred. Sources with a brightness temperature below  $100^\circ\text{K}$  are not recorded with significant flux density by the interferometer even if they are at a great distance, and consequently are not relevant to the source counts. The total-power records do indeed show many features with brightness temperatures in the range  $20\text{--}50^\circ\text{K}$  and size of the order of  $1^\circ$ ; these show some degree of concentration towards the galactic plane and are presumably galactic in origin.

#### APPENDIX

*Effect on source counts of errors in measuring flux density.*—The observed flux density of sources of given true flux density has errors whose distribution may be obtained from the observed record amplitudes by the method indicated in Section 3 (i) above: let this distribution be denoted by  $p(\eta)$  where  $\eta$  is the error. If the relation between number and flux density for the sources is of the form  $N(S) \propto S^{-\nu}$ , where  $N(S)$  is the number of sources having flux density greater than  $S$ , then the number,  $n(S) dS$ , in a flux range  $dS$  is proportional to  $S^{-(\nu+1)} dS$ . The observed number density  $n'(S)$  is then given by

$$n'(S) = \int n(S + \eta) p(-\eta) d\eta,$$

the integral being evaluated over the whole range of  $\eta$ . Writing

$$n(S + \eta) = n(S) \times (1 + \eta/S)^{-(\nu+1)}$$

and expanding by the binomial theorem gives

$$\begin{aligned} n'(S) &= n(S) \left[ \int p(-\eta) d\eta - \frac{\nu+1}{S} \int \eta p(-\eta) d\eta + \frac{(\nu+1)(\nu+2)}{2S^2} \int \eta^2 p(-\eta) d\eta + \dots \right] \\ &= n(S) \left[ 1 + \frac{\nu+1}{S} \left\{ \text{mean error in flux} = M \right\} \right. \\ &\quad \left. + \frac{(\nu+1)(\nu+2)}{2S^2} \left\{ \text{mean square error in flux} = \Sigma^2 \right\} + \dots \right]. \end{aligned}$$

From the analysis in Section 3 (i) we have

$$M = \frac{1}{4}\sigma^2/S \text{ to terms in } \sigma^2$$

and, to the same order, the mean square error is the mean value of  $\sigma^2 \cos^2 \theta$ , that is,

$$\Sigma^2 = \frac{\sigma^2}{2}.$$

Inserting these values and integrating gives for  $N'(S)$ , the observed number of sources with flux density greater than  $S$ :

$$N'(S) = N(S) \left[ 1 + \frac{\nu(\nu+1)}{\nu+2} \frac{\sigma^2}{4S^2} + \nu(\nu+1) \frac{\sigma^2}{4S^2} + \dots \right].$$

If the proportional error is small, this error in the number of sources counted may be described in terms of an equivalent error in flux density, writing  $N'(S+\delta S) = N(S)$  and using the relation:

$$\frac{\delta S}{S} = \frac{1}{\nu} \frac{\delta N}{N}, \quad \delta S = \left[ \left( \frac{\nu+1}{\nu+2} \right) + (\nu+1) \right] \frac{\sigma^2}{4S}.$$

As the observed numerical value of  $\nu$  is about 1.8 (Scott and Ryle 1961), the second term, which represents the effect of the population law on the error, is nearly four times as large as the first term, which represents a direct over-estimation of the fluxes of individual sources.

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