EXTENDED RADIO SOURCES. II

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Summary

Detailed observations of "extended radio sources" were reported in a previous communication. Some of these sources are probably irregularities in the galactic radio emission, but at high galactic latitudes the typical extended source consists of a group of sources of small angular diameter.

The question examined in this paper is whether these groups are astronomically significant, or whether they merely represent chance groupings of unrelated sources near the same line of sight. The question is examined in three ways: (i) by searching for optical identifications with galaxies in the same cluster, (ii) by purely statistical considerations, and (iii) by computing the clustering of radio galaxies which must be expected from the known clustering of galaxies.

I. INTRODUCTION

In the previous paper (Milne and Scheuer 1963) (paper I) we have reported observations of 21 "extended sources" from the catalogues of Mills, Slee, and Hill (1958, 1960, 1961) with greatly improved resolution. From these observations, several conclusions are obvious.

(i) In nearly every case, there is a collection of objects which accounts for a major part of the $85 \cdot 5$ Mc/s flux density reported by Mills, Slee, and Hill.

(ii) There are at least two kinds of extended source. Some are groups of sources of small angular diameter, and others contain diffuse areas of low surface brightness.

(iii) The latter type tends to avoid very high galactic latitudes.

Thus it seems reasonable to regard the diffuse sources as galactic, and we would guess that the sources MSH $15-16$, $17+01$, $20+012$ and the diffuse parts of $18-41$ and $21-06$ should be classified with the galactic extended sources, although their galactic latitudes are (excepting $18-41$) about $30°$. In addition, these five sources all lie within $40°$ of the galactic centre, but we cannot attach any significance to this fact, since the anticentre region was not accessible during the night at the time of the 1400 Mc/s observations, so that no sources between 02^h and 08^h R.A. were observed.

For the remainder of this paper, we shall regard the diffuse sources as galactic irregularities and take no further notice of them. The question with which we are concerned is whether the groups of small diameter sources have some astronomical significance or whether they are merely unrelated sources which happen to lie near the same line of sight. The answer is not obvious; three lines of evidence will be considered below.

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II. Identifications

The most satisfactory solution is to identify the component sources and thus find out whether they are at similar distances and perhaps members of the same cluster or group of clusters of galaxies.

This method will shed light on the nature of a particular extended source if *either* (a) at least two of the component sources can be identified, *or* (b) at least one component is identified with a galaxy (or a cluster of galaxies) well above the plate limit, and at least one other component source is in an unobscured region where no galaxy of comparable magnitude exists within two or three probable errors of the radio position.

Condition (a) is fulfilled only for 00−0*17*, which may represent a pair associated with the same cluster. Condition (b) is satisfied for 00−0*9*, where 3C 17 must be much more distant than the galaxy identified with 3C 15.* Condition (b) may also be satisfied for 14+0*10*, if the north-following of the two main sources belongs to a cluster of galaxies in which its position lies.

Thus the evidence from identification is scanty, but such evidence as we have does not favour the hypothesis that extended sources are groups of related objects.

III. Statistical Significance

One may compare the number of apparently extended sources, down to some limiting flux density, with the number arising by chance in a random distribution of point sources (Mills and Slee 1957).

The difficulty in this approach is that the concept of an extended source is initially subjective and its definition is very elusive. To illustrate the nature of the difficulty, suppose that we construct a synthetic "sky" by distributing point sources (with some assumed relation between numbers and flux densities) at random over a coordinate grid, and then look for groups of sources. Firstly, some arbitrary limit must be set to the size of the groups which are counted; this would generally be taken as one or two beamwidths. Suppose such a limit has been chosen; we then agree to count as "extended sources" those regions in which the total flux density is $> S$ (the limiting flux density), but no one source contributes more than, say, 80% (again an arbitrary figure) of the total. But even with these assumptions, the result is ambiguous, for the very faint (and very numerous) sources produce an almost uniform background, which does not contribute to the bumps on records which are recognized as sources, yet they are part of the total flux density of the extended source in our hypothetical calculation. Indeed, if we assume the usual relation $N \propto S^{-3/2}$, the contributions of the faint sources to the flux density diverge, unless we modify that relation by a definite cut-off (due to "cosmological" effects). Similar difficulties arise if we count extended sources down to a limiting value of "peak" flux density rather than total flux density. Doubtless, it would be possible to devise an unambiguous definition of an extended source, but it is clear that it would contain so many arbitrary parameters that it would bear little relation to the subjective processes of analysing records from a radio telescope.

* This identification has since been confirmed by C. Hazard, who obtained a very precise position by observing a lunar occultation of the source.

We therefore prefer to avoid calculations of this kind, and fortunately the new observational material allows us to apply a more objective test. In this test, no attempt is made to predict the number of extended sources that would be expected to arise in a random distribution of point sources, and therefore there is no need to simulate the process of recognizing extended sources. Instead, we test the hypothesis that groups of sources found near the positions of "extended sources" constitute a significant degree of clustering. The test involves the following steps:

(i) Calculation of the expectation of pairs of sources in a given area A of sky, in which sources are distributed at random. The pairs of sources which are to be counted must be specified by lower limits to their flux densities and an upper limit to their separation. The calculation requires a knowledge of the number of sources per steradian to any given limit of flux density.

(ii) Counting the numbers of pairs (specified in precisely the same way as in (i)) associated with all the extended sources in an area A of sky. There is a slight complication in the present work, in that there is no large region of sky in which all "extended sources" were surveyed, but this fact can be taken into account. Thus, if only half of the "extended sources" in an area of 3 steradians were examined, the numbers of pairs observed in them must be compared with calculations as indicated in (i) for an area $A = 1\cdot5$ steradians.

(iii) The results of (i) and (ii) are then compared for a variety of ways of specifying a pair. If a reasonably natural way of defining a pair can be found for which the observed number of pairs exceeds the computed number, then one may conclude that the "extended sources" represent a real clustering of sources. If no such specification of a pair can be found, the opposite conclusion must be drawn.

To avoid the uncertainties of extrapolating spectra to 85 Mc/s, the calculations will refer to 1400 Mc/s throughout.

The number–flux density relation at 1400 Mc/s is plotted in Figure 1. It represents unpublished surveys (due to Bolton and Gardner) of two small areas of sky, covering a total of 100 sq degrees. The data have been fitted by two straight lines, one of slope $-1\cdot5$ and one of slope $-1\cdot7$, each passing through the point $N = 0\cdot15$, $S = 0\cdot7$.

The specification of a pair of sources is made in the following form:

each source has a flux density $\geqslant S_1$,

the sum of their flux densities is $\geqslant S_2$ (clearly, $S_2 \geqslant 2S_1$),

their separation is less than R degrees.

Then, if

$$N(S)/N_0 = (S/S_0)^{-\beta}$$

(where $N_0 = 0\cdot15$ per sq degree, $S_0 = 0\cdot7$, $\beta = 1\cdot5$ or $1\cdot7$), the number of pairs satisfying these conditions is

$$\pi R^2 \int_{S_1}^{\frac{1}{2}S_2} N(S_2 - S)|N'(S)|\,\mathrm{d}S + \tfrac{1}{2}\pi R^2\{N(\tfrac{1}{2}S_2)\}^2 \qquad (1)$$

per square degree, provided that $\pi R^2 N(S_1) \ll 1$.

The expectation of pairs of sources is the product of the expression (1) and an area of A sq degrees of sky. To estimate A, the number of extended sources observed is divided by the number of extended sources per square degree in the MSH catalogue. The latter figure will be determined from the regions R.A. $= 22^h$ to 05^h and 09^h to 14^h, $\delta = 10°$ N. to $20°$ S., which are at high galactic latitudes.

Mills, Slee, and Hill (1958) list 13 extended sources in this region with a total flux density $\geqslant 37 \cdot 5$ (at 85 Mc/s, on the CKL scale, as in paper I), and 26 with a total flux density $\geqslant 22 \cdot 5$. The regions have a total area of 5320 sq degrees, so that there is one extended source with $S_{85} \geqslant 37 \cdot 5$ for every 5320/13 sq degrees, or one with $S_{85} \geqslant 22 \cdot 5$ for every 5320/26 sq degrees. In Table 1 of paper I, there are 11 extended
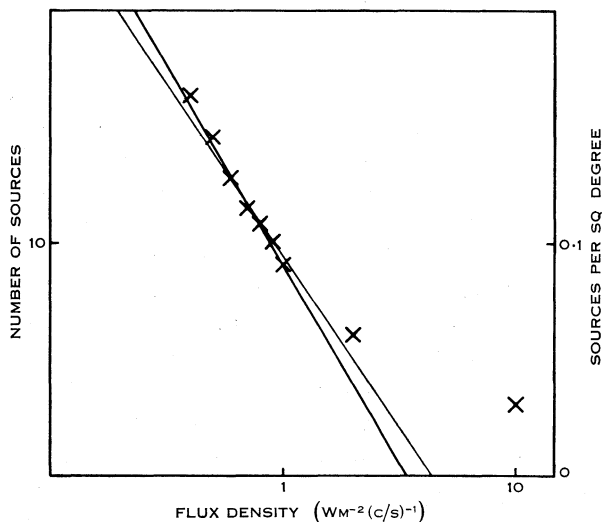

Fig. 1.—Number–flux relation at 1400 Mc/s for radio sources in two small areas of sky.

sources with a catalogued $S_{85} \geqslant 37 \cdot 5$, and 18 with $S_{85} \geqslant 22 \cdot 5$, but some of the sources (MSH 15−16, 17+01, 18−41, 20+012, 21−06) are diffuse and presumably galactic features, and others (08+03, 21+05, 14−16) may be suspected of containing such features, and should therefore be excluded from the analysis. (The inclusion of these sources would increase A, and hence the expectation of pairs, without contributing to the number of pairs observed. Numerically, though of course unjustifiably, this would only strengthen the conclusion reached in this paper.) The source 01+03 must also be omitted, because there are no 1400 Mc/s observations for this source. These exclusions leave 7 extended sources with $S_{85} \geqslant 37 \cdot 5$ and 11 with $S_{85} \geqslant 22 \cdot 5$; the corresponding values of A are $7 \times 5320/13 = 2860$ and $11 \times 5320/26 = 2250$ sq degrees respectively.

The comparison with observation is made in Table 1, for a variety of limits S_1, S_2, and R. It is clear from this table that the observed number of pairs never exceeds the expectation from a random distribution of sources. In order to avoid any possible bias in favour of this conclusion, the smaller value of A has been adopted in Table 1,

and the "observed" column contains the pairs of sources found in all the extended sources at high galactic latitudes (R.A. 21^h to 05^h and 09^h to 15^h) that were examined, not only the 11 used in computing A.

Pairs with small separation, or in which one of the sources is very faint, would be listed as normal unresolved sources in the MSH catalogues, and this is reflected in the upper part of Table 1, where fewer such pairs are found in extended sources than would be expected even in a random distribution of point sources over 2250 sq degrees.

TABLE 1

THE EXPECTATION OF PAIRS OF SOURCES IN A RANDOM DISTRIBUTION, COMPARED WITH THE NUMBER OF PAIRS IN EXTENDED SOURCES

Specification: each source has flux density $> S_1$; total flux density $> S_2$; separation $< R$

		Number of Pairs of Sources								
		$R = 30'$			$R = 45'$			$R = 60'$		
S_1	S_2	Expectation		Obs.	Expectation		Obs.	Expectation		Obs.*
		$\beta = 1\cdot5$	$\beta = 1\cdot7$		$\beta = 1\cdot5$	$\beta = 1\cdot7$		$\beta = 1\cdot5$	$\beta = 1\cdot7$	
0·5	2	23·6	22·8	4	53·2	51·4	6	94·5	91·3	8+(1)
0·5	3	11·7	10·1	4	26·4	22·7	5	47·0	40·4	7+(1)
0·5	4	7·1	5·6	2	15·9	12·7	3	28·3	22·5	3+(1)
1·0	3	4·6	3·7	2	10·4	8·3	3	18·6	14·8	3+(1)
1·0	4	3·0	2·2	2	6·6	4·9	3	11·8	8·6	3+(1)
1·0	5	2·0	1·4	1	4·5	3·1	2	8·1	5·5	2+(1)
1·5	5	1·2	0·8	1	2·7	1·7	2	4·7	3·1	2+(1)
4·0	10	0·1	0·05	0	0·2	0·1	0	0·4	0·2	(1)

* The extra (1) in the last column refers to the principal sources of 00−09, which are 61 min of arc apart.

IV. THE EXPECTATION OF ASTRONOMICALLY ASSOCIATED SOURCES

It is known that galaxies occur in clusters; is it reasonable that pairs of radio sources within the same cluster of galaxies should be observed as rarely as the previous two sections indicate? With the aid of the luminosity function for radio sources, it is possible to give an answer. The luminosity function proposed by Minkowski (1960) will be used here; it is not very different from those proposed by Bolton and by Mills.

It will be assumed that all radio galaxies occur in clusters of galaxies (this assumption cannot give too few pairs), but that the presence of one radio source in a cluster does not affect the probability that another galaxy in the same cluster will become a radio source. Let the expectation of radio sources with radio luminosity less than L be $\rho(L)$ per unit volume, and let the expectation of clusters be C per unit volume. Then the expectation $N(S)$ of sources with flux density less than $S = L/4\pi r^2$ (r = distance) is

$$N(S) = \int_0^\infty \rho(4\pi r^2 S)4\pi r^2 \, \mathrm{d}r = \frac{1}{2\pi^{\frac{1}{4}}S^{3/2}} \int_0^\infty L^{\frac{1}{2}}\rho(L) \, \mathrm{d}L. \tag{2}$$

The expectation of sources with luminosity greater than L in any one cluster is $\rho(L)/C$, so that the expectation of clusters with at least two such sources is (per unit volume)

$$C\,e^{-\rho(L)/C}\left[\frac{1}{2!}\left\{\frac{\rho(L)}{C}\right\}^2 + \frac{1}{3!}\left\{\frac{\rho(L)}{C}\right\}^3 + \cdots\right] \simeq \frac{\{\rho(L)\}^2}{2C}, \tag{3}$$

if $\rho(L)/C < 1$.

Hence the expectation of pairs of sources belonging to the same cluster and with flux density greater than S is

$$N_2(S) = \frac{1}{4C\pi^{\frac{1}{2}}S^{3/2}} \int_0^\infty L^{\frac{1}{2}}\{\rho(L)\}^2\,\mathrm{d}L. \tag{4}$$

Following Minkowski, we take

$$\rho(L) = \rho_0(L/L_0)^{-1\cdot2}, \qquad\qquad L_1 < L < L_2, \tag{5}$$

$$\rho(L) = 0, \qquad\qquad \text{for } L < L_1 \text{ or } L > L_2.$$

Then

$$N(S) = \frac{\rho_0 L_0^{1\cdot2}}{2\pi^{\frac{1}{2}}S^{3/2}} \cdot \frac{L_2^{0\cdot3} - L_1^{0\cdot3}}{0\cdot3} \tag{6}$$

and

$$N_2(S) = \frac{\rho_0^2 L_0^{2\cdot4}}{4C\pi^{\frac{1}{2}}S^{3/2}} \cdot \frac{L_1^{-0\cdot9} - L_2^{-0\cdot9}}{0\cdot9}. \tag{7}$$

As (6) shows, $N(S)$ would diverge if $\rho(L)$ followed the same power law to indefinitely high luminosities; hence the upper cut-off L_2 must be imposed in (5). The lower cut-off L_1 must be imposed because there cannot be more radio galaxies than galaxies, but in our case we should take L_1 one or two orders of magnitude higher, for when counting pairs of sources we do not consider a normal galaxy as constituting a source. Any normal galaxy with a measurable flux density would be a large bright optical object; no identifications with "normal" galaxies occur among the observations reported in paper I. Thus L_1 should be taken as a luminosity of the same order as that of NGC 1068 or NGC 4234 rather than that of NGC 224.

Equations (6) and (7) show that $N(S)$ and $N_2(S)$ are dominated by the high-luminosity sources and the low-luminosity sources respectively. Minkowski's data (Minkowski 1960, Fig. 1) show that $L_2/L_1 \gg 10^4$, and probably $L_2/L_1 > 10^6$, so that we may rewrite (6) and (7) to a very good approximation as

$$N(S) = \frac{\rho_0 L_0^{1\cdot2}}{2\pi^{\frac{1}{2}}S^{3/2}} \cdot \frac{L_2^{0\cdot3}}{0\cdot3},$$

$$N_2(S) = \frac{\rho_0^2 L_0^{2\cdot4}}{4C\pi^{\frac{1}{2}}S^{3/2}} \cdot \frac{L_1^{-0\cdot9}}{0\cdot9},$$

so that

$$\frac{N_2(S)}{N(S)} = \frac{\rho(L_1)}{C} \cdot \frac{1}{6} \cdot \left(\frac{L_1}{L_2}\right)^{0\cdot3}$$

$$= \frac{\text{Number of sources per cluster}}{6(L_2/L_1)^{0\cdot3}}, \qquad (8)$$

for, by definition of L_1, no source properly so called has $L < L_1$.

Taking $L_2/L_1 = 10^6$, (8) becomes

$$\frac{\text{Number of pairs with both sources} > S}{\text{Number of sources} > S} = \frac{\text{Number of sources per cluster}}{400}. \qquad (9)$$

From Minkowski's data, one galaxy in 10^2–10^3 is a radio source (depending on the choice of L_1), so that the number of sources per cluster is of the order of one. Since about 2000 radio sources are known, equation (9) indicates that the number of occasions on which more than one of these sources occur in the same cluster can be counted on the fingers of one hand. Furthermore, the clusters involved should be among the nearest clusters, and the sources most probably sources of low radio luminosity.

Such evidence as we have from optically identified sources is in agreement with these conclusions. Outside the local group, which contains no "radio galaxies", the only clusters in which more than one radio source has been found are the Virgo cluster (M 87, M 84, NGC 4234, NGC 4261), the Perseus cluster (NGC 1275, NGC 1265) and possibly the cluster of $\sim 14^{\mathrm{m}}$ galaxies associated with MSH 00$-$01$7$. But this direct evidence is not very strong, since there are strong selection effects which tend to prevent the identification of two sources in more distant clusters—in general, the sources would not be resolved by the primary beam of the radio telescope, so that accurate positions would not be obtained (cf. the history of radio investigations of the Perseus cluster).

V. Conclusions

(i) The groups of sources associated with extended sources at high galactic latitudes do not constitute a statistically significant degree of clustering.

(ii) The clustering of radio sources which arises merely from the known clustering of galaxies (as opposed to a causal connection between the formation of several radio sources) would not yield a number of groups of radio sources comparable with the number of extended sources. Furthermore, nearly all such groups within the range of observation would consist of intrinsically faint sources in nearby clusters, and should therefore be identifiable with bright optical objects; with one possible exception, such identifications have not been found among the sources considered in paper I.

(iii) From optical identifications, we find one pair of sources at comparable distances, and probably two cases of "optical doubles".

(iv) Some extended sources at moderate galactic latitudes are diffuse objects of low surface brightness. Their surface brightness is comparable with that of structure in the galactic background which can be seen over most of the sky on the 408 Mc/s records, and they do not seem to require a separate explanation.

VI. Acknowledgments

VII. References

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Appendix

Mills and Slee (1957) concluded that the extended sources represent significant clustering (if they are not a new type of source altogether); by studying a representative sample of the same objects we reach the opposite conclusion. A number of causes contribute to the discrepancy.

(i) In calculating the expectation of chance "blends" of sources with total flux density greater than S, Mills and Slee counted only pairs in which each source has a flux density greater than $\frac{1}{2}S$. Thus their estimates may be too low.

(ii) Some extended sources at quite high galactic latitudes appear to be galactic irregularities, and these have been excluded from the present analysis.

(iii) Even after due allowance has been made for the systematic difference between the MSH and CKL scales of flux density (paper I, Fig. 1(c)), the groups of sources found in the present work do not always account for the total flux density reported by Mills, Slee, and Hill.

To show how these causes operate, we follow Mills, Slee, and Hill (1958) in examining extended sources between right ascensions 09^h and 15^h, and between 21^h and 05^h, and with total flux density exceeding 30 (on the CKL scale, i.e. 40 on the MSH scale). Mills, Slee, and Hill found 20 such sources, where they expected only 2 by chance. Of these sources, 10 were examined in the investigation of paper I; they appear among the 16 sources in Table 1 of paper I which lie in the same region. Extrapolating flux measurements at higher frequencies down to 85 Mc/s suggests that only 5 of the 10 sources actually have total flux densities exceeding 30 on the CKL scale. Among these five, only one (00—09) contains two component sources each with a flux density greater than 15 (part of Mills and Slee's criterion for computing "blends" with total flux greater than 30), and these are further apart than the 0·83° taken as the limiting separation by Mills and Slee. Thus, in this sample of extended sources, half of the discrepancy can be attributed to cause (iii) and the remainder to (i), while (ii) is unimportant.