PAPER 39

THE SPATIAL DISTRIBUTION OF RADIO STARS

M. RYLE
Cavendish Laboratory, Cambridge, England

1. THE OBSERVATIONS

The Cambridge survey of radio stars [1], which has been described by Shakeshaft, revealed some 1900 sources of small angular diameter, which appeared to be distributed nearly isotropically. An examination of the number–magnitude distribution shows, however, that they cannot be accounted for in terms of a uniform spatial distribution of sources [2].

The results are summarized in Fig. 1 which shows for seven areas of sky a plot of log N against log I, where N represents the number of sources per unit solid angle having an intensity greater than I. A uniform distribution of point sources would lead to a slope of $-1\cdot5$; it can be seen that for all the areas the slope is substantially greater than this, and that for the five areas away from the plane where the observations are unaffected by the presence of rare galactic sources, the slope is approximately $-3\cdot0$.

Before considering the significance of this result it is necessary to examine all possible instrumental defects or errors in the interpretation of the records which might lead to an apparent increase in the number of faint sources.

(i) *Subsidiary maxima in the primary reception pattern*

The reception pattern has been measured by a technique which allows the determination of subsidiary maxima with great precision. It was found that except near the two principal planes the sensitivity was less than 10^{-5} of that in the forward direction. It is therefore very simple to eliminate errors due to this cause.

(ii) *Accuracy of reading the records*

The signal–noise ratio is more than 5 : 1 even on the weakest sources, and resultant errors in determining the relative intensities of the sources are unimportant.

https://doi.org/10.1017/S0074180900049147 Published online by Cambridge University Press

(iii) *Difficulty of interpreting the records in presence of confusion*

It is clear that the confusing effects of adjacent sources will limit the detection of faint sources; the flattening of the log N–log I curve for small I

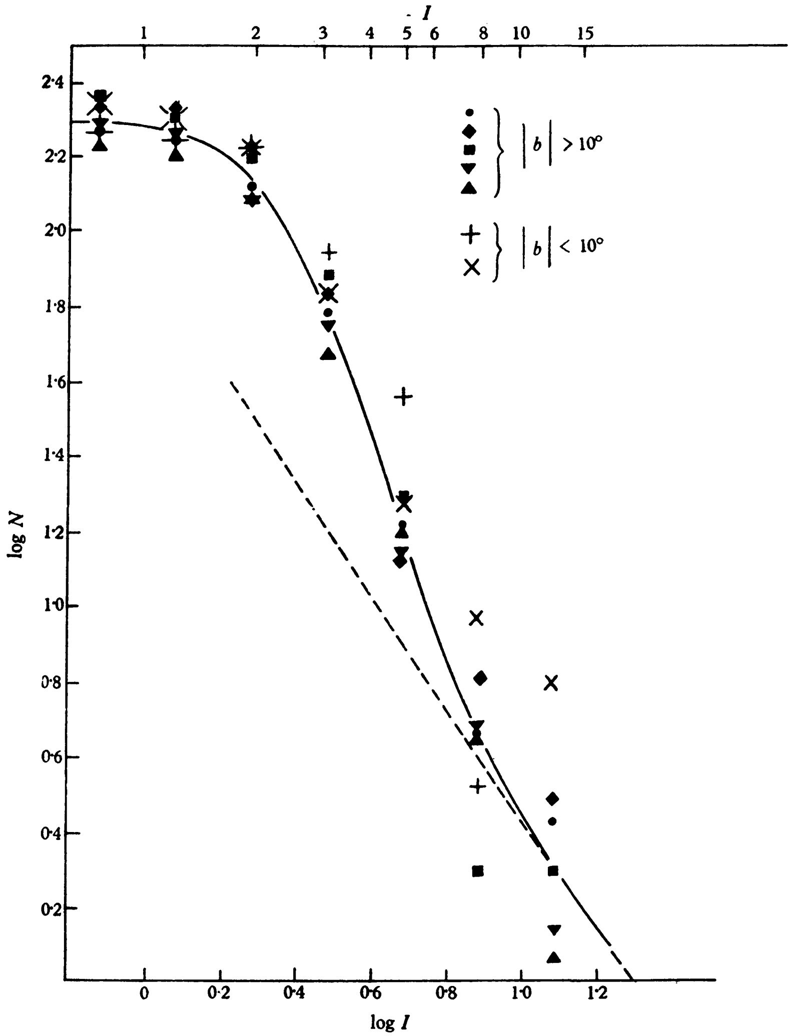

Fig. 1. Curve of log N against log I where N represents the number of 'point' sources per unit solid angle having an intensity greater than I.

is predominantly due to this cause. By making an analysis of the effect it is possible to show that when there are less than 0·25 sources per beam-width, the errors in the deduced number of sources is very small; this result indicates that in the curve of Fig. 1 there should be negligible error for $I > 3{\cdot}5 \cdot 10^{-25}$ M.K.S. units.

Fortunately, however, the possibility of the large apparent slope being due to the effects of confusion can be eliminated entirely by using an independent, statistical method of analysing the records. In this method no account is taken of individual sources, but the probability distribution of the interference pattern amplitude, D (see Fig. 2), is determined.

In the absence of intense sources which could be resolved individually, the record would be composed of the random addition of the components

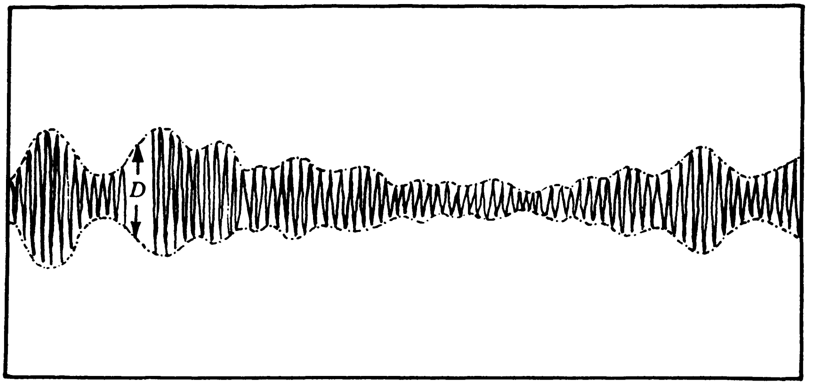

Fig. 2. Section of record showing how the probability distribution $P(D)$ is derived from measurements of the amplitude (D) of the envelope of the interference pattern.

due to a large number of weak sources; under these circumstances the probability distribution $P(D)$ would have a Rayleigh distribution. The presence of intense sources would lead (for the case of a uniform spatial distribution) to a curve which tended to $D^{-\frac{5}{2}}$ for large D. The complete probability curve which would be produced by any particular assumed spatial distribution of the sources can be computed, and that for a uniform distribution is shown in Fig. 3. The observed probability curve obtained for areas away from the galactic plane is also given, and this shows important differences from the computed curve; the observations again indicate an excess of faint sources or a lack of intense ones.

(iv) *The presence of a large number of extended sources*

The main survey of radio stars was designed to ignore sources having angular diameters greater than 20 minutes of arc. If an appreciable fraction of the radio sources had angular dimensions of this order, then the nearest, most intense ones would be missed, or recorded as of smaller intensity, whilst similar sources at greater distances would not be so

https://doi.org/10.1017/S0074180900049147 Published online by Cambridge University Press

affected; in this way, an apparent lack of intense sources might arise. Such an interpretation is, however, incompatible with the result of the second survey described by Shakeshaft in which a different arrangement of the aerials was employed, to allow the detection of sources having angular diameters of up to 3°. The sensitivity of this survey was not as good as in the main survey, but over most of the sky it is believed to include the majority of sources having a flux greater than $4 \cdot 10^{-25}$ M.K.S. units.

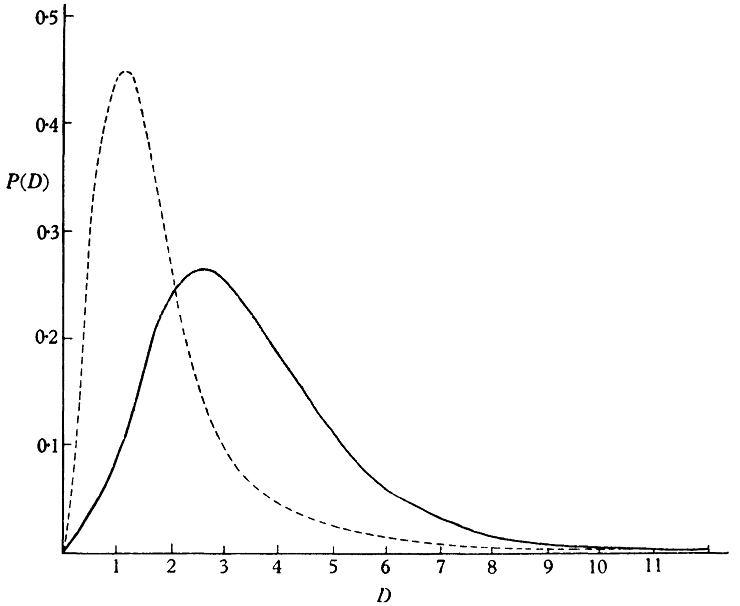

Fig. 3. The probability distribution $P(D)$ of the amplitude of the record D. The full curve represents the observations whilst the theoretical curve for a uniform spatial distribution of sources is shown dotted.

If the apparent lack of intense sources is to be explained in terms of their partial resolution by the main survey it is possible to predict the number of extended sources which should exist in any range of intensities. By comparing this number with that observed it is easy to show that the number of extended sources is quite inadequate for this explanation; for example, for sources having a flux density greater than $12{\cdot}5 \times 10^{-25}$ M.K.S. units, where the second survey must be regarded as effectively complete, a total of six extended sources were found in the area investigated. The number expected on this interpretation would be forty-six.

Similar but more complicated arguments may be used to show that the effect cannot be due to clustering of the sources.

(v) *Dispersion in the absolute luminosity*

It can also be shown that any reasonable dispersion in the absolute luminosity of the sources cannot explain the steep slope of the log *N*–log *I* curve; at least one class of object must have a spatial density which increases with distance.

From the above considerations it is concluded that the effect is real, and that either the spatial density or the luminosity of the sources shows a progressive increase with distance. Such an increase cannot extend indefinitely because both the amplitude of the recorded interference pattern and the

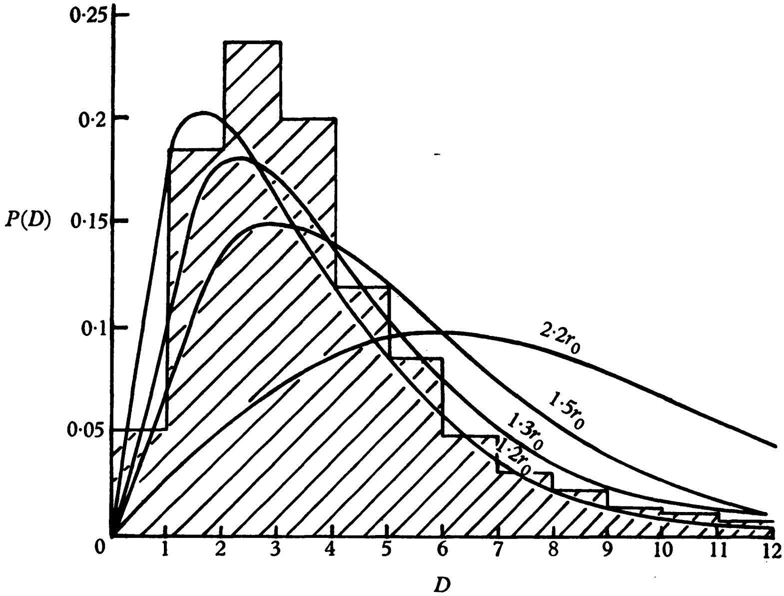

Fig. 4. The probability distribution $P(D)$ computed for a region in which the spatial density of sources increases as r^3 to a distance r_2 (expressed in terms of r_0, the distance of the farthest resolvable source). The observations are shown by the shaded area.

integrated radiation would diverge. A study of the former by the statistical method of analysis already discussed leads to the most sensitive method of deriving the extent of the divergent region in terms of the distance r_0 of the weakest sources which can be resolved individually.

Fig. 4 shows a number of theoretical curves of $P(D)$ derived for a region in which the spatial density of sources is assumed to increase as r^3 out to a distance r_2; four values of r_2 are shown, each expressed in terms of r_0. The shaded area represents the observations. From these results it appears that the region of increasing spatial density or luminosity does not extend much beyond the limit of the present survey.

2. THE INTERPRETATION OF THE RESULTS

(i) *In terms of galactic sources*

If it were supposed that the majority of the radio sources were within the Galaxy, it would be necessary to conclude that the solar system were situated in a region of abnormally low density, in which the density increased with distance equally in all directions. By considering the integrated radiation which would be produced by such a distribution of sources it can also be shown that the region would have to show effectively spherical symmetry out to radial distances from the sun of at least 2 kiloparsecs.

If on the other hand the radio sources were supposed to occur mainly in a spherical shell surrounding the Galaxy, the radius would have to be of the order of 80–100 kiloparsecs or departures from symmetry in directions towards the centre and anti-centre would be detectable.

Both of these models present considerable difficulties.

(ii) *Extragalactic sources*

If it is supposed that the majority of radio stars are extragalactic, it is not possible to account for the isotropic increase of apparent density in terms of random clustering. By applying similar arguments relating to the integrated extragalactic radiation, it can be shown that the radius of the region of increasing density must be at least 10^8 parsecs.

The very large scale which must be adopted in this case suggests that the explanation may be found in effects associated with large red-shifts. Owing to the relatively flat spectrum of the radio stars the spectral term is relatively unimportant even for red-shifts considerably beyond the limit of optical observation, where other effects might become appreciable. The observation that the intense source in Cygnus lies at a distance of 66.10^6 parsecs indicates that other sources of similar luminosity would indeed produce a detectable flux at distances considerably beyond the optical limit.

If this interpretation is correct, the observations give clear evidence that the distant regions differ from those in the neighbourhood of the Galaxy; such a result is incompatible with the predictions of the steady-state theories of cosmology proposed by Bondi and Gold [3] and Hoyle [4] but might be interpreted in terms of evolutionary theories. If indeed the majority of radio stars are of the Cygnus type, resulting from collisions between spiral galaxies, then a progressive decrease in the spatial density of radio sources with time might be expected, especially if collisions

https://doi.org/10.1017/S0074180900049147 Published online by Cambridge University Press

between such galaxies remove the interstellar matter, as has been suggested by Spitzer and Baade [5].

Some independent support for the suggestion that the majority of radio stars are similar to that in Cygnus has been provided by recent observations. Minkowski has reported that the intense source in the constellation of Hercules has been identified as another faint extra-galactic object showing a recession velocity of 26,000 km./sec. This observation indicates that its radio emission must be about 20 % of that of the Cygnus source.

The recent observations made by Palmer and Thompson [6] have shown that three of the four unidentified intense sources they have studied have angular diameters less than 50 sec. of arc; unless these sources are some invisible stellar object within the Galaxy, it seems probable that they are of galactic dimensions. The observed intensity and angular diameter then allow a lower limit to be set to their radio luminosity; their luminosity must be at least 10 % of that of the Cygnus source.

These results are therefore compatible with the suggestion that the majority of the radio stars are of comparable luminosity to that of Cygnus, and that their local spatial density at the present time is of the order of $2 . 10^{-26}$ parsecs^{-3}. In this way it seems possible to explain the observed log N–log I curve in terms of evolutionary theories of cosmology, whilst the difficulty of observing related optical objects as discussed by Mr Shakeshaft has a natural explanation; only some tens of the main class of radio star would be within reach of the 200-inch telescope.

REFERENCES

[1] Shakeshaft, J. R., Ryle, M., Baldwin, J. E., Elsmore, B. and Thomson, J. H. *Mem. R.A.S.* **67**, 106, 1955.
[2] Ryle, M. and Scheuer, P. A. G. *Proc. Roy. Soc.* A, **230**, 448, 1955.
[3] Bondi, H. and Gold, T. *M.N.R.A.S.* **108**, 252, 1948.
[4] Hoyle, F. *M.N.R.A.S.* **108**, 372, 1948.
[5] Spitzer, L. and Baade, W. *Ap. J.* **113**, 413, 1951.
[6] Palmer, H. P. and Thompson, A. R. This publication, paper 28, p. 162.