A PRELIMINARY SURVEY OF THE RADIO STARS IN THE NORTHERN HEMISPHERE

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Summary

Observations with an interferometer of large resolving power have made it possible to locate 50 discrete sources of radio waves or " radio stars " in the Northern Hemisphere ; their positions and intensities (which cover a range of $7\frac{1}{2}$ in apparent magnitude) are given. The positions of the more intense radio stars can be determined with an accuracy of about 5 minutes of arc, but most of them can only be located to within 1°.

The angular distribution of the radio stars, unlike that of the general background radiation, shows no concentration in the galactic plane; this result suggests either that they are at distances small compared with the dimensions of the galaxy, or that they are situated outside the galaxy. Whilst there is evidence that a few of the weakest radio stars represent the total " background " radiation of some of the nearest extra-galactic nebulae, it is concluded that the majority of the radio stars must be situated within the galaxy. Estimates of the relative intensities of the radio stars and of the background radiation have suggested that they are distributed throughout the galaxy with an average population density comparable with that of visual stars.

Attempts to identify the radio stars with various types of visual body have been unsuccessful; it is therefore concluded that the radio star represents a hitherto unobserved type of stellar body, distributed widely throughout the galaxy, and one which is equally numerous in other spiral nebulae.

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1. *Introduction.*—The existence of discrete sources of radio waves in the galaxy was first demonstrated by Hey, Parsons and Phillips (1946), and subsequently confirmed by the observations of Bolton and Stanley (1948) and Ryle and Smith (1948). In these experiments it was found that the angular diameters of the two most intense sources did not exceed 6 minutes of arc, whilst none of the sources appeared to coincide with a bright visual star.

More recent experiments at Cambridge have shown the absence of any measurable annual parallax; it was therefore concluded that the two most intense sources are situated at distances greater than $2 \cdot 10^{16}$ cm. (Ryle, 1950). There is also some evidence (Ryle, 1949; Smith, 1950) that the sources are of stellar dimensions.

Observations of the discrete galactic sources have been maintained at Cambridge since 1948 May, using wave-lengths of 1·4, 3·7 and 6·7 m. The greater part of this programme has been concerned with a survey of the Northern Hemisphere on a wave-length of 3·7 m. In the present communication an account will be given of the results of this survey, including the positions and intensities of 50 sources which have been located.

The results have been analysed in an attempt to deduce the nature of the sources, and although it does not appear possible to relate them to any of the well-known types of stellar body, as observed at visual wave-lengths, there is good reason for believing that they are extremely common bodies distributed throughout the galaxy. For this reason, and because of the greater convenience, the discrete sources of radio waves are here referred to as "radio stars", although there is, as yet, insufficient evidence to prove conclusively that they are of stellar dimensions.

Observations of the disturbing effects of irregularities in the terrestrial ionosphere (analogous to "bad seeing") were also made during this survey; the results obtained have already been described (Smith, 1950; Ryle and Hewish, 1950).

2. *The experimental methods.* (a) *The detection of the radio stars.*—The detection of discrete sources of radio waves presents considerable difficulty, partly because of the small radio-frequency power which is intercepted by the aerial system, but chiefly because of the problem of distinguishing between the radiation from an individual source, and the general background radiation from the galaxy. Even the largest "pencil-beam" radio telescopes which have been

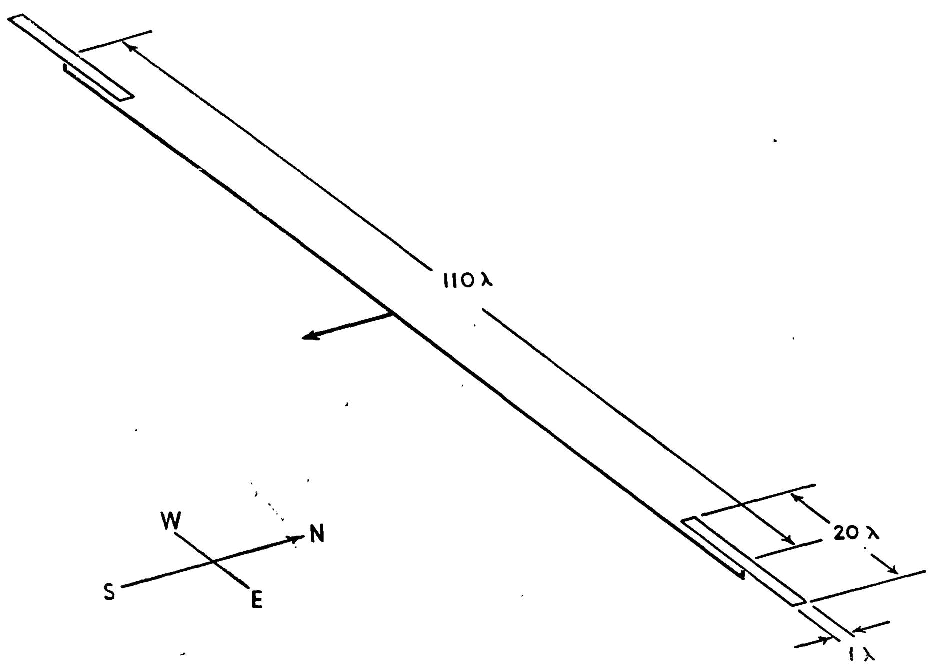

FIG. 1.—*Spaced-aerial interferometer used on a wave-length of 3·7 m.*

built have a resolving power which is very poor compared with a small visual telescope; it is therefore difficult to interpret the variations of received power as the system is directed to different parts of the sky, in terms of discrete sources, since similar variations are also produced by the angular structure of the general background radiation. This problem has been considered in some detail in a recent paper (Ryle, 1950) and it was there shown that the use of an interference system of considerable resolving power had great advantages over a conventional "pencil-beam" aerial system.

In the present series of observations an interferometer having an aperture of 110λ has been used (see Fig. 1). The discrimination against the background radiation with this system corresponds to that of a conventional "pencil-beam" aerial having an aperture of about 1 km. The ability to separate two adjacent radio stars is, of course, a function of the solid angle over which the aerial system is receptive, and is therefore related to the resolving power of the individual aerials of the interference system and not to their spacing.

As can be seen from Fig. 2, the reception pattern of each aerial is restricted to about $\pm 1\frac{1}{2}°$ in an East–West plane but covers about $\pm 45°$ in a North–South plane. The system is mounted horizontally at the latitude of Cambridge (52°) and the reception pattern therefore covers a narrow strip along the meridian, which extends from the pole to about declination $+10°$. The system is therefore analogous to a transit telescope, and each radio star may be observed when it

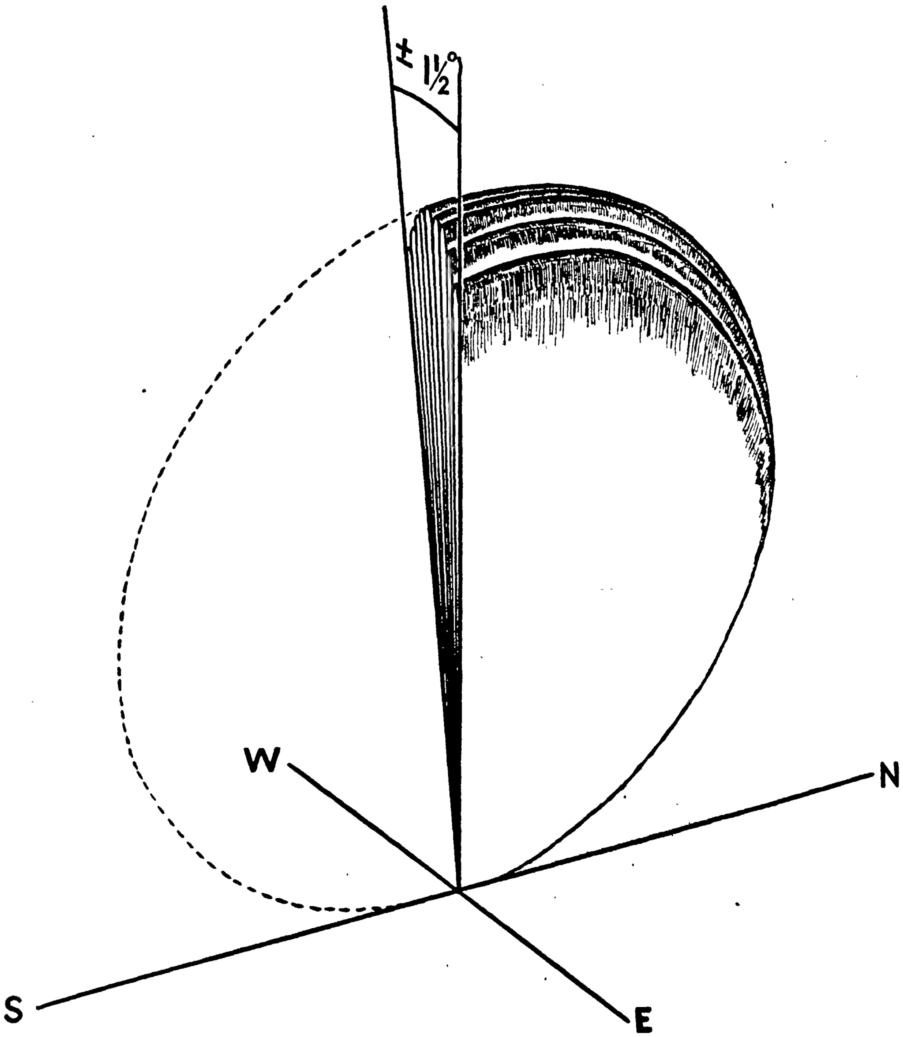

FIG. 2.—*Reception pattern of spaced-aerial interferometer.*

is within $\pm 1\frac{1}{2}°$ of the meridian. (This method of observation has considerable advantages over the "Lloyd's mirror" interferometer used by the Australian workers (Bolton and Stanley, 1948), since each radio star is observed when its zenith distance is a minimum. In the "Lloyd's mirror" method an interference pattern is produced by reflection at the surface of the sea, and observations are restricted to a few degrees above the horizon, where refraction in the troposphere and ionosphere may cause considerable errors.)

As the Earth rotates the interference pattern produced by the two aerials will be swept across the greater part of the Northern Hemisphere. The radiation due to the general background will produce a trace on the record which will exhibit slow variations as the meridian strip includes more or less of the Milky Way; any discrete source of radiation, having an angular diameter small compared with the separation of the interference maxima (30 minutes of arc), will, on the other hand, produce a periodically varying trace whilst it is situated within $\pm 1\frac{1}{2}°$ of the meridian. A typical record showing the transit of the two intense radio stars in the constellations of Cygnus and Cassiopeia and the slow variation of the background radiation is shown in Fig. 3.

Records of the type shown in Fig. 3 are satisfactory if the radio star to be observed produces a power in the aerial comparable with that produced by the background radiation. If, however, the background power is considerably greater, there is difficulty in measuring the small periodic variations produced on the record by the much smaller power from the radio star. It is clearly difficult to detect a radio star which produces a trace less than about $\frac{1}{50}$ of the full-scale deflection of the recorder, and it is therefore not possible with this system to observe radio stars which produce an aerial power much less than about $\frac{1}{50}$ of that due to the background radiation.

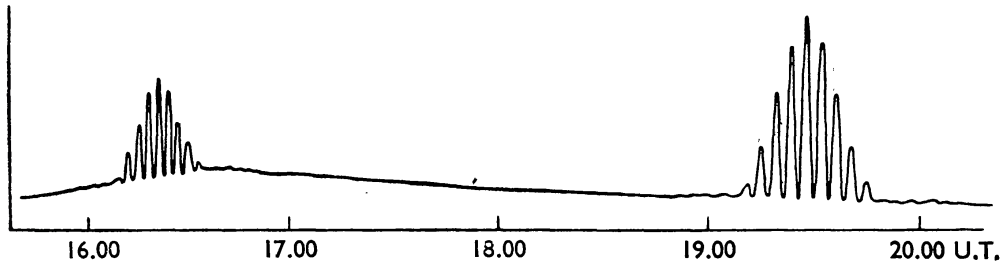

FIG. 3.—*Section of record obtained with spaced-aerial interferometer, showing the intense radio stars in the constellations of Cygnus* (16.20) *and Cassiopeia* (19.30).

In order to be able to make observations of weaker radio stars a new recording system has been developed, in which the power intercepted by the aerial system from an extended source, such as the general background, produces no deflection of the recorder. In this system the two aerials of the interferometer are connected alternately in phase and in anti-phase in such a way as to produce alternately two interference patterns, in which the maxima and minima are interchanged. This aerial system receives the same power from the general background in both positions of the phase-changing switch.

If, now, a radio star is situated near the meridian, it will produce a power in the aerial which depends on its position relative to the interference maxima and minima, and which will, in general, be different in the two switch positions. The output from the aerial will therefore contain a constant component due to the general background radiation and a component due to the radio star which varies periodically at the switching frequency (25 c./s.). The amplitude and phase of this component depend on the position of the radio star relative to the interference maxima and minima; as the Earth rotates the amplitude and phase of this component will change and by arranging that the deflection on the record is proportional to this periodic component it becomes possible to obtain a trace which shows the passage of the radio stars through the interference pattern. No deflection of the trace is produced in the absence of sources of small angular diameter, and a very much greater sensitivity may therefore be used; radio stars whose intensity is a very small fraction of that of the background radiation may then be observed.

A section of a typical record obtained with this system is shown in Fig. 4, in which the transit of a number of weaker sources can be seen. With this system it is found that the detection of very weak radio stars is limited not by the sensitivity of the recording apparatus, nor by the incidence of the background radiation, but by the confusion of the interference patterns produced by adjacent radio stars; under these conditions a further extension of the detection limit is only likely to be achieved by decreasing the solid angle of the envelope of the interference pattern, i.e. by increasing the resolving power of the individual aerials of the interferometer.

(b) *The determination of the position of a radio star.*—The use of an interference system of the type described, in addition to allowing better discrimination than a conventional "pencil-beam" radio telescope, has particular advantages when the positions of discrete sources are to be determined. By observing the precise time of the central maximum of the interference pattern on the record, it is possible to determine the time of transit and hence the Right Ascension of the source, with an accuracy which corresponds to the resolving power of a conventional "pencil-beam" system having an aperture of about 1 km.

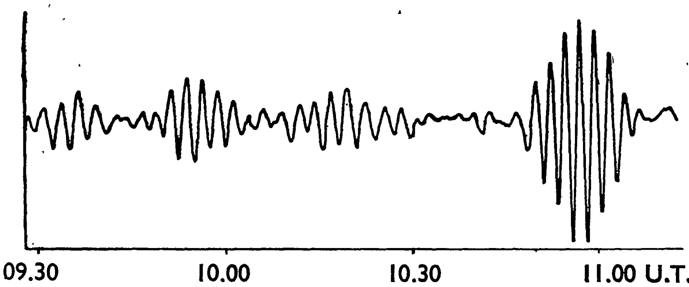

FIG. 4.—*Section of record obtained with "phase switching" system, showing a number of weak radio stars between R.A.* 04.00 *and* 06.00. *The recorder sensitivity is about* 100 *times greater than that of Fig.* 3.

The declination of a radio star may be obtained in the following way from another property of the spaced-aerial interferometer by observing the period of the interference pattern on the record. A radio star in the plane of the equator will give rise to a record whose periodicity (t_0) is given by the time taken for the Earth to rotate through the angle separating successive maxima of the interference pattern (for the present system $t_0 \simeq 2$ minutes). It can be shown that a radio star having a declination δ will produce a record whose periodicity is $t_0 \sec \delta$, so that a measurement of the periodicity enables $\sec \delta$ to be deduced. It is therefore possible to find both coordinates of the source from the same record.

A full account of the methods of determining the coordinates to take account of height and azimuth errors in the aerial alignment will be given elsewhere, together with calculations of the errors introduced by refraction in the terrestrial ionosphere.

The accuracy with which the coordinates of a radio star may be determined depends, of course, on the intensity of the source; for the two intense radio stars in the constellations of Cygnus and Cassiopeia, the time of transit may be determined from the record with an accuracy of 0·25 second, under conditions of "good seeing", but the Right Ascension cannot be determined with this accuracy owing to uncertainty in determining the electrical centres of the two aerial systems. An accuracy of about 5 seconds in time (corresponding to an angular accuracy of $\frac{1}{2}$–1 minute of arc) is possible in Right Ascension, with an accuracy of 5 minutes of arc in declination. For the weaker sources the accuracy is usually limited by difficulties arising from overlapping of the interference patterns of adjacent sources; in the limiting case of the weakest sources the trace on the record may be modified by the presence of nearby sources which are themselves too weak to be detected. Under such conditions the apparent position of a very weak source may be in error by an amount greater than that deduced from the accuracy with which the record may be read; the observed position may then approximate to the "centre of gravity" of two or more very close sources.

It is clear from the relation connecting the declination and the periodicity of the record that the accuracy with which the declination may be determined becomes poor for radio stars at low declinations, whilst for those near the pole the accuracy may be better than that of the Right Ascension.

3. *The results of observations of the Northern Hemisphere.*—Observations on a wave-length of 3·7 m. with the system described in the previous paragraph have enabled a preliminary catalogue of 50 radio stars in the Northern Hemisphere to be compiled. These sources are listed below, in Table I, with their positions. Since the determination of Right Ascension is usually more precise than that of declination, the sources have been numbered in each hour of Right Ascension, the last two figures representing the serial number of each radio star in order of its discovery. (In this initial list the radio stars have been arranged in order of intensity.)

The measured intensity of the radiation from each radio star is tabulated in column 4, and an apparent magnitude is given in column 5. Since the two most intense sources are about three magnitudes "brighter" than the "brightest" of the remaining sources (which are regularly distributed in apparent magnitude*) the zero of the magnitude scale has been arbitrarily chosen as corresponding to an intensity of 10^{-23} watts m.$^{-2}$ (c./s.)$^{-1}$. This flux is approximately that of the fourth most intense radio star (12·01) in the region surveyed.

The limits of accuracy of the positions of the radio stars which are quoted in the table include not only the probable error in reading the records and in determining the aerial alignment but an additional factor which depends on the confusing effect of neighbouring radio stars. As has already been explained in Section 2 (b) it is difficult to determine this factor for the radio stars of very small intensity, since the record may be modified by the presence of other sources which are themselves too weak to be detected. It is therefore possible that the positions of some of the very weak sources may be in error by an amount greater than that deduced; the observed position may then correspond to the "centre of gravity" of the main source and other weaker sources nearby.

Attempts have been made to measure the angular diameter of several of the more intense radio stars, but in no case has it been found to exceed the resolving power of the apparatus; the upper limit determined for the angular diameter of the two most intense sources (19·01 and 23·01) was about 3 minutes of arc.

4. *The distribution of the radio stars.*—Before attempting to make any deductions about the nature of the radio stars it is important to make some estimate of their distribution in space. Previous experiments made to measure the annual parallax of the two most intense radio stars have shown that they are situated at distances greater than $2 \cdot 10^{16}$ cm. (Ryle, 1950).

* The distribution of the radio stars in apparent magnitude has been discussed in an earlier paper (Ryle, 1950).

TABLE I

(Positions refer to Epoch 1950)

Number	R.A.	Declination	Intensity (watts $m.^{-2}$ $(c./s.)^{-1}$ $\times 10^{25}$)	Apparent Magnitude
	h m s m s	° ′ ° ′		
00·01	00 42 ± 6	38 ±5	4	3·5
01·01	01 25 ± 5	30 ±3	8	2·8
01·02	01 09 ± 3	43 15±1	4·5	3·3
02·01	02 16 ± 3	44 15±2	6	3·0
02·02	02 25 ± 3	35 30±2	5	3·2
02·03	02 45 ± 3	45 15±0 45	4	3·5
03·01	03 50 ±20	75 ±1	14	2·1
03·02	03 12 ± 3	43 45±0 30	9·5	2·5
03·03	03 58 ± 1 3	41 ±1 30	4·5	3·3
04·01	04 28 ± 1	25 ±2	33	1·2
04·02	04 56 ± 2	33 ±1 30	12·5	2·3
04·03	04 10 ± 2	35 45±0 30	10·5	2·4
05·01*	05 31 37± 0 10	22 10±0 20	125	−0·2
05·02	05 02 ± 3	37 ±2	10	2·5
06·01	06 17 ± 2	33 ±2	8·5	2·7
06·02	06 57 ± 3	47 30±1 30	3	3·8
07·01	07 19 ± 3	51 51±1	4	3·5
07·02	07 35 ± 4	42 ±2 30	3	3·8
08·01	08 08 ± 0 15	48 15±0 30	10	2·5
08·02	08 48 ± 2	18 ±5	7·5	2·8
08·03	08 22 ± 3	36 ±1 30	4	3·5
08·04	08 51 ± 2	53 ±1	2·5	3·9
09·01	09 16 ± 4	47 ±1	5	3·2
09·02	09 32 ± 6	39 ±2	3·5	3·6
09·03	09 57 ± 2	56 30±1 30	3·3	3·8
10·01	10 00 30± 0 30	43 15±1	7·5	2·8
10·02	10 50 ± 3	44 15±2	3·5	3·6
10·03	10 33 ± 4	56 ±1	3·3	3·8
11·01	11 03 ± 3	39 45±1	6	3·0
11·02	11 48 ± 4	64 ±3	5	3·2
11·03	11 43 ± 3	44 ±2	3	3·8
12·01*	12 28 25± 1 10	12 ±0 20	105	−0·1
13·01	13 26 ± 4	48 ±3	3·5	3·6
13·02	13 40 ± 2 30	38 ±1 30	3	3·8
14·01	14 01 ± 2	51 ±2	7·5	2·8
14·02	14 59 ± 3	58 ±1 30	4	3·5
15·01	15 00 ± 2	70 ±1	9	2·6
15·02	15 29 ± 5	55 ±1 30	4·5	3·3
15·03	15 01 ± 2	36 ±3	4	3·5
16·01	16 49 ± 4	7 ±9	30	1·3
16·02	16 01 ± 4	66 30±1	7	2·9
16·03	16 24 ± 1	38 ±1 30	7	2·9
16·04	16 08 ± 2	40 ±4	3·5	3·6
17·01	17 03 ± 6	63 30±1 30	5	3·2
18·01	18 40 ±10	80 ±1	9·5	2·5
18·02	18 00 ± 0 30	47 30±0 30	8·5	2·7
18·03	18 27 ± 3 30	47 45±1	7·5	2·8
19·01	19 57 46± 0 5	40 30± 7	1350	−2·9
19·02	19 01 ± 4	57 30±1	3·8	3·5
23·01	23 21 12± 10	58 32± 4	2200	−3·4

* See opposite page.

Further information on the distances of the radio stars may be obtained in two different ways from an analysis of a number of them. The first of these analyses concerns the way in which the radio stars are distributed in galactic latitude; in the second, the distribution in intensity, or apparent magnitude, is investigated.

(a) *The distribution in galactic latitude.*—The earlier parallax observations had shown that the two most intense radio stars were situated outside the solar system. If radio stars are comparatively rare bodies situated within the galaxy, it would be expected that those already observed would be appreciably concentrated towards the galactic plane. If, on the other hand, radio stars are comparatively common objects, those which have so far been observed (the most intense) are likely to be situated at distances small compared with the dimensions of the galaxy, and an isotropic distribution would be expected. An isotropic distribution would also occur if the radio stars were situated outside the galaxy, since at a wave-length of 3·7 m. the obscuration even towards the galactic centre is likely to be negligible.

In carrying out the analysis of the experimental results, it is necessary to make allowances for the variation of the overall limit of detection in different regions of the sky. This variation is due to: (*a*) the variation of the receptivity of the aerial system in different directions along the meridian, and (*b*) the confusion in the neighbourhood of the most intense sources, caused by subsidiary maxima in the East–West reception pattern of the aerial system.

The second difficulty (*b*) was overcome by omitting from the analysis areas of the sky in the neighbourhood of the two intense radio stars. The difficulty which arose because the detection sensitivity varied with declination was overcome by restricting the analysis to the area between declinations $+32^\circ$ and $+72^\circ$ (over which the correction factor is small) and including only those sources whose corrected intensity exceeds a given figure. This figure was chosen so that any source producing this flux and situated anywhere within the chosen area would give a measurable trace on the record; the present survey includes all radio stars within the area "brighter" than magnitude 3·6.

An effectively uniform detection sensitivity having been obtained in this way, the average number of sources per unit solid angle was computed for each of a series of strips, 10° wide in galactic latitude, situated between latitudes -30° and $+90^\circ$. The result of this analysis is shown in Fig. 5. Although the number of sources which are available for this analysis is small, it is apparent that there is no marked concentration in the galactic plane, and that within the statistical fluctuations to be expected the distribution is isotropic.

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* Since the axis of the interferometer does not lie precisely along a horizontal East–West line, the observation of the time of transit locates a source on a line which makes a small angle to an hour-circle. For sources of small declination, where the accuracy of the declination measurement is worse than that of the Right Ascension, it is therefore possible to specify the position of a source more precisely than is indicated in the table.

The Right Ascension of the source 05·01 may thus be represented:—

$$05^{h}\,31^{m}\,37^{s}\pm 6^{s}+0{\cdot}4\Delta^{s},$$

where the declination is $22^\circ\,10'+\Delta'$.

The Right Ascension of the source 12·01 may be represented:—

$$12^{h}\,28^{m}\,25^{s}\pm 7^{s}+0{\cdot}3\Delta^{s},$$

where the declination is $12^\circ\,55'+\Delta'$.

It may therefore be concluded either that radio stars are outside the galaxy or that they are comparatively common bodies situated within the galaxy; the distances of the sources which have so far been detected must in the latter case be small compared with the dimensions of the galaxy. The possibility that the sources are outside the galaxy will be discussed in greater detail in Section 5. Additional evidence that radio stars are comparatively common bodies situated within the galaxy is provided by an analysis of their intensities in relation to the general background radiation of the galaxy, and this evidence will now be examined.

(b) *Radio stars in relation to the general background radiation.*—Early theories put forward to account for the observation of radio waves from the galaxy assumed emission from the interstellar gas (e. g. Henyey and Keenan, 1940). The subsequent observation of discrete sources of small angular diameter not only demonstrated the existence of another mechanism for the emission of intense radio waves but also suggested that this mechanism might in fact be responsible for the general background radiation; the existence of a large number of discrete sources distributed throughout the galaxy might produce an apparently diffuse background radiation when observed with aerial systems of comparatively small resolving power. The two alternative theories have been discussed in some detail in two recent survey papers (Unsöld, 1949; Ryle, 1950).

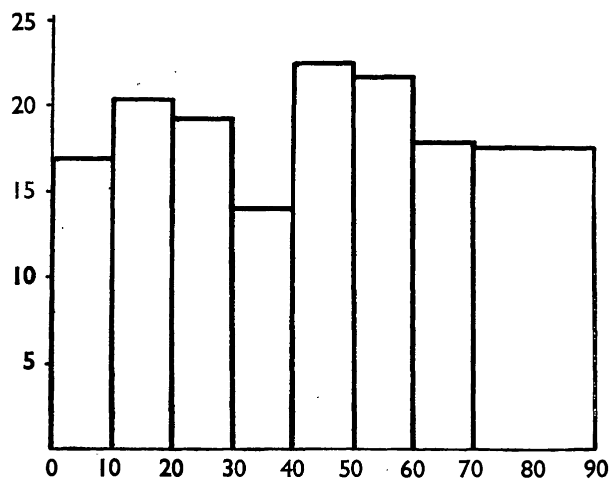

FIG. 5.—*Density of radio stars " brighter " than magnitude 3·6 plotted as a function of galactic latitude. (For latitudes 0° to 30° the average of the northern and southern strips is plotted.)*

Ordinates : Number of radio stars per steradian.

Abscissae : Galactic latitude in degrees.

Whilst the early theories of emission from the interstellar gas might have provided a satisfactory explanation for the observations of galactic radiation on wave-lengths of less than about 3 m., very great difficulties were raised by later observations on longer wave-lengths. Thus observations on 10 m. indicated a well-defined concentration near the galactic plane, and showed that even at this wave-length the galaxy must be "optically thin". The intensity of radio waves emitted by the interstellar gas would therefore be appreciably less than that emitted by a black-body radiator at the temperature of the gas. Furthermore the intensity emitted at any shorter wave-length would be a still smaller fraction of that from a black body, owing to the decrease in the "optical depth" of the interstellar gas with wave-length. Calculations based on the observed intensity at a wave-length of 10 m. and on the observation that even at this wave-length the galaxy is "optically thin" showed that the observed intensity of the background radiation *at any wave-length* could only be accounted for by assuming a temperature of the interstellar gas of at least 10^5 deg. K. At the same time it is difficult to account theoretically for the maintenance of an interstellar temperature much greater than 10^3 deg. K., except in the neighbourhood of early-type stars (Woolley, 1947).

It must therefore be concluded that unless a considerably greater temperature is permissible for the interstellar matter, it is impossible to account for more than about 1 per cent of the observed background radiation at any wave-length, by theories based on the emission from the interstellar gas.

It is therefore important to examine, in greater detail, the possibility that the background radiation is the integrated radiation from a large number of radio stars distributed throughout the galaxy; it is suggestive that the ratio of the intensities of the most intense radio stars to that of the background radiation is of the same order of magnitude as the ratio of the visual intensities of the brightest stars to that of the total integrated starlight.

In order to investigate this possibility further an analysis has been made of the relative intensities of the 25 most intense radio stars, in relation to the integrated radiation from the Northern Hemisphere (Ryle, 1950). The results of this analysis have indicated that all the existing measurements of galactic radiation could be accounted for if there were a large number of radio stars distributed throughout the galaxy, and having an average population density of the same order of magnitude as that of the visual stars.

5. *The nature of the radio stars.*—The analysis of the previous section has suggested two possibilities which must now be examined. They are:

(*a*) The radio stars are situated outside the galaxy, and the general background radiation is due to the interstellar gas; in this case it is necessary to account for the maintenance of a very much greater temperature of the interstellar gas than is predicted by present theoretical work.

(*b*) The radio stars are situated within our galaxy with a population density which is comparable with that of visible stars.

The two alternatives will now be examined in greater detail.

(a) *Sources outside the galaxy.*—The observation of the general background radiation from the galaxy suggests that similar radiation is likely to be emitted by other spiral nebulae; this conclusion is independent of the mechanism responsible for the background radiation. Although there is some evidence (Ryle, 1949; Smith, 1950) that the intense discrete sources are of stellar dimensions, the only direct measurements of angular diameter have indicated a figure less than a few minutes of arc. It is therefore possible that certain extra-galactic nebulae might be of sufficiently small angular diameter, and of sufficient intensity to account for the present observations of "discrete" sources.

The background radiation from directions near the galactic centre produces a flux (at a wave-length of 3·7 m.) of about 10^{-20} watts m.$^{-2}$ (c./s.)$^{-1}$ (steradian)$^{-1}$. If account is taken of the angular variation of intensity as observed from the solar system, it can be shown that it is possible to deduce an effective diameter of the galaxy for radio emission. If now it is assumed that the Andromeda nebula is similar to our galaxy, the emission at a wave-length of 3·7 m. should produce a flux at the Earth of about 10^{-24} watts m.$^{-2}$ (c./s.)$^{-1}$; the effective angular diameter of the source would be 20–30 minutes of arc. This intensity is greater than the detection limit of the present apparatus, and it might therefore be expected that on any theories of galactic radiation "discrete" sources of small angular diameter should be detected in the positions of the nearest extra-galactic nebulae.

An analysis has therefore been made in Section 6 (a) to relate the positions of the radio stars with those of the major extra-galactic nebulae. It has been found that of the five largest nebulae, two coincide with the positions of weak radio stars, while two more are sufficiently near other radio stars to suggest a relationship. Furthermore it has been found that the observed intensities of these sources are in good agreement with the values expected on the assumption that the "background radiation" emitted by other spiral nebulae is comparable with that from our own galaxy. It is therefore likely that whatever mechanism is responsible for the emission of radio waves from our own galaxy is also operative in other galaxies.

It is now important to examine the possibility that all the radio stars might be accounted for by the emission from extra-galactic nebulae. It must first be noted that the intensities of the four sources whose positions are near those of the major extra-galactic nebulae are relatively very small. (For instance, the detection of the source which coincides with the Andromeda nebula is made extremely difficult by the proximity of the intense source in Cassiopeia (23·01) which produces a flux approximately 750 times as great.)

It is therefore necessary to decide whether certain extra-galactic nebulae, which produce a very small visual emission, could produce an intensity of radio waves at the Earth some 750 times that produced by the Andromeda nebula. Although local dust obscuration might be responsible for the absence of any intense visual emission, it seems most improbable that such a condition could apply to all the major radio stars, particularly since many of them are situated in regions where the general obscuration is small. At the same time the emission of radio waves of this intensity by an extra-galactic nebula appears to present very great theoretical difficulties; the observations carried out on the two most intense radio stars have indicated that their intensities, at a wave-length of 3·7 m., are of the order of $2 \cdot 10^{-22}$ watts m.$^{-2}$ (c./s.)$^{-1}$, whilst their angular diameters are less than 3 minutes of arc. If the radiation were due to the emission from the interstellar gas of the nebula it would be necessary to postulate an average temperature of at least 10^8 deg. K.; the maintenance of this temperature appears to present insuperable difficulties, even without the cooling mechanism described by Menzel and Aller (1941).

It would therefore only be possible to account for the majority of the radio stars in terms of the emission from sources outside the galaxy, on the assumption of some new type of body which produces little visible radiation but very intense radio waves. The mechanisms required for such a body seem to present far greater difficulties than those involved in assuming a special body situated at a relatively much smaller distance, within our own galaxy. As has already been shown, the presence of such bodies within our galaxy would not only provide a simpler explanation for the radio stars but would at the same time account for the general background radiation from the galaxy. The presence of similar bodies in the other major extra-galactic nebulae would in the same way account for their observed radio emission.

(b) *Sources within the galaxy*.—The second possibility, that the sources are inside our galaxy, will now be examined.

Several different theories have been proposed concerning the nature of the radio stars. Ryle (1949) suggested that they were a new type of stellar body in which the radio emission was very much greater than that of the Sun, whilst the visual emission was small. This condition could arise if the envelope of a star were maintained at a very great temperature, and he suggested that certain stars, whose surface temperature was small but which had a large magnetic field and rotational velocity, could account for the observed intensity of radio emission.

Bolton, Stanley and Slee (1949), on the other hand, have noted that one of the radio stars is near the position of the Crab nebula, which is thought to be the shell of a past supernova, while two others are near unresolved nebulae. Unsöld (1949) has suggested that the basic mechanism may be analogous to that of the emission from sunspots, and suggests a possible relation to late-type stars.

Now that a considerably greater number of radio stars have been located, it is possible to make a more detailed analysis of these and other possibilities, and the new experimental evidence will now be examined from this point of view.

6. *Identification of the radio stars with visual bodies.*—In the following sections attempts will be made to relate the radio stars to various types of visual body; this will be done by comparing the positions of the radio stars with those of the outstanding examples of each type of visual body.

In carrying out an analysis of this type, it is important to remember that the accuracy with which the positions of most of the radio stars may be found is poor; it is therefore likely that the positions of visual bodies will occasionally fall within the limits of the position of a radio star even if there is no genuine relationship. It is therefore important to calculate the probability of random coincidences in each analysis, in order to determine whether any observed correlation can be regarded as significant.

The survey has been restricted to the region between declinations $+12°$ and $+82°$, an area which covers a solid angle of 4·9 steradians. The total solid angle occupied by the limits of accuracy of all the radio stars which have so far been observed in this area is 0·05 steradians; there is therefore a probability of 1 in 100 that a randomly chosen position will coincide with one of the radio stars. If a total of n visual bodies is examined in any particular analysis, it is therefore likely that about $n/100$ coincidences will be observed even if there is no relation between the visual bodies and the radio stars. In each analysis the number of observed coincidences must therefore be related to the figure for random coincidences in order to determine whether there is a genuine relationship.

(i) *Extra-galactic nebulae.*—The positions of 309 extra-galactic nebulae within the selected area were compared with those of the radio stars, and nine coincidences were found. This number does not greatly exceed the expected figure for random coincidences, but when the analysis was restricted to the five major extra-galactic nebulae a more significant result was obtained; two of the radio sources were found to coincide, while two others each have one coordinate in good agreement, with an error in the other coordinate which is only slightly greater than the error deduced from the record. All four sources are of extremely small radio intensity and, as has already been shown, it is difficult to make accurate allowance for the presence of other undetectable sources when deducing the errors of observation of weak sources. The result of this analysis is therefore regarded as very suggestive.

The five major extra-galactic nebulae in the selected area are listed in Table II, together with the radio sources which appear to be associated with them.

Further confirmation of this association has been provided by an estimate of the expected intensities from the above nebulae. On the assumption that their characteristics are identical with those of our own galaxy, it is possible to estimate the intensity which each would produce at the Earth from the visual observations of their angular diameters. In order to determine the intensity which would be recorded by the present apparatus, it is also necessary to take account of the fact that such a source can no longer be regarded as small compared with the angular separation of the maxima of the interference pattern. The expected intensities, derived in this way, are found to be of the same order of magnitude as those observed experimentally. (A direct measurement of the angular diameters of these particular radio sources would, of course, provide powerful independent evidence for their association with extra-galactic nebulae; unfortunately it has not yet been possible to make measurements of angular diameter on sources as weak as these four.)

TABLE II

Nebula	Position		Radio Source	Position		Magnitude
	h m	° ′		h m m	° °	
M31 (Andromeda)	00 40	41 0	00·01	00 42±6	38±5	3·5
M33	01 31	30 24	01·01	01 25±5	30±3	2·8
M101	14 01	54 36	14·01	14 01±2	51±2	2·8
M81	09 52	69 19	None observed			
M51	13 28	47 28	13·01	13 26±4	48±3	3·6

There is no significant statistical evidence relating more distant nebulae with other radio stars and indeed it has already been shown that there are strong theoretical reasons for supposing that all the radio stars so far observed, except those listed in Table II, are situated within the galaxy.

(ii) The remaining analysis has therefore been based on the assumption that the majority of radio stars are situated within the galaxy. Although there is some evidence (Ryle, 1949; Smith, 1950) that the sources are of stellar dimensions, the analysis has not been restricted to correlations with different types of star but has been extended to include various galactic nebulae and diffuse bodies.

(a) *Identification with stars.*—The positions of the radio stars were first compared with those of visual stars brighter than magnitude 4·0 and lying within the selected area (Schlesinger, 1930). It was found that not one of the 146 visual stars included in this category fell within the limits of accuracy of the position of a radio star. The visual stars examined included the brightest examples of most of the main spectral types (9 O-type, 45 B, 20 A, 19 F, 39 G, 8 K and 6 M).

Attempts to identify individual radio stars with unusual but fainter visual stars were equally unsuccessful; the areas enclosed by the limits of error of the two most intense radio stars (23·01 and 19·01) contain no visual star brighter than 11th magnitude. The positions of other radio stars are not known with comparable accuracy, but it was found that the probability of finding a visual star of given magnitude within the area of a radio source was not significantly different from that of finding one in an equal area chosen at random in a neighbouring region of the sky.

Since the present observations suggest that the radio stars may be relatively abundant, it is likely that those which have been observed at the present time are situated near to the solar system. If the radio sources are stars in which the ratio of radio emission to visual emission is very much greater than that of the Sun (due, perhaps, to the maintenance of a large temperature in the envelope with a comparatively small photospheric temperature), it is possible that the most intense radio stars might be identified with some of the nearest visual stars, without regard to their apparent visual magnitude. An analysis was therefore made of the positions of the radio stars and those of the 90 nearest stars falling within the selected area (Kuiper, 1942). One of these stars (Wolf 424 a) falls within the limits of error of the position of a radio star, but the relation is not significant.

A similar analysis was also made for stars having a large proper motion (Luyten and Ebbighausen, 1936, and elsewhere). It was found that there was no correlation down to 10th magnitude for stars having $\mu > 0''{\cdot}1$ per annum. For the two most intense radio sources, stars having $\mu > 0''{\cdot}05$ per annum were examined, and no correlation was found down to 14th magnitude.

(b) *Novae and supernovae.*—The positions of 21 novae in the selected area were examined (Norton's star atlas); no correlation with radio stars was found.

The proximity of the radio source in Taurus (05·01) to the Crab nebula, which is thought to be the shell of the supernova of 1054, has been noted by Bolton, Stanley and Slee (1949). Although the analysis of Section 4 has already shown that an origin in such a rare body as a supernova is unlikely, the positions of the two other outstanding supernovae in the selected area (areas 1572 and 1604) were also examined; no radio star was found near either position. It therefore seems unlikely that radio stars are related to novae or supernovae.

(c) *Galactic nebulae and clusters.*—The positions of 38 planetary nebulae and 29 diffuse nebulosities in the selected area (*Publications of the Lick Observatory* (1918), Vol. 13) were compared with those of the radio stars, but in neither case were any coincidences found. Thirty-one star clusters were also examined, and again no correlation was found.

7. *Conclusions.*—An interferometer of large resolving power has been used to find the positions of 50 radio stars (covering a range of 7·3 magnitudes) in the Northern Hemisphere. The positions of the weaker radio stars cannot be determined with very great precision, but the two most intense ones can be located with an accuracy of about 3 minutes of arc.

The observation of a considerable number of these bodies has made it possible to carry out various analytical investigations in an attempt to deduce their nature; these investigations were not possible with the small number of sources which were known previously.

It has been found that the radio stars, unlike the general background radiation, show no detectable concentration in the galactic plane. It is therefore concluded either that they are situated at distances small compared with the dimensions of the galaxy, or that they are outside the galaxy.

On the supposition that other spiral nebulae produce a total "background" radiation comparable with that of our own galaxy, it was possible that the radio stars might represent nothing more than the background radiation of extra-galactic nebulae, since all except the nearest are of sufficiently small angular diameter to be unresolved by the present apparatus. An analysis has shown that several of the weakest radio sources coincide with the positions of major extra-galactic nebulae, and that their intensities are in good agreement with those predicted on the hypothesis mentioned above. It may therefore be concluded that whatever mechanism is responsible for the background radiation in our own galaxy, also occurs in other spiral nebulae.

It does not, however, seem possible to suppose that the majority of the observed radio stars are outside our galaxy, both because of the theoretical difficulties encountered in attempting to explain the very great intensities of the more intense radio stars and because of the absence of correlation with other extra-galactic nebulae.

It is therefore concluded that most of the radio stars are situated within the galaxy.

It has already been shown (Ryle, 1950) that the presence of a large number of such bodies distributed throughout our own galaxy would not only provide a satisfactory explanation for the remainder of the observations of radio stars but would at the same time account for the general background radiation from the galaxy; the poor resolving power of the present apparatus would only make it possible to resolve those sources which were nearest, and which would therefore be distributed isotropically, whereas the distribution of the unresolved background radiation would, as is found experimentally, conform closely to the shape of the galaxy. The great difficulties involved in accounting for more than about 1 per cent of the background radiation on theories based on the emission from the interstellar gas are in themselves a powerful argument in favour of the existence of numerous isolated radio sources distributed throughout the galaxy.

In order to obtain further evidence concerning the nature of the radio stars, attempts have been made to identify them with various types of stellar body. No correlation was found with either the brightest or the nearest visual stars or with novae.

Although there is some evidence that the sources are of stellar dimensions, attempts were also made to identify them with various types of diffuse body within the galaxy, and with planetary nebulae and star clusters, but no significant correlation was found with any such type of body.

In the absence of further evidence it is therefore concluded that the radio stars represent a hitherto unobserved type of stellar body, in which a very intense radio emission is associated with a very small visual intensity. One possible mechanism for the emission from such a body has been suggested in a previous communication (Ryle, 1949).

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