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An investigation of galactic radiation in the radio spectrum

BY J. S. HEY, S. J. PARSONS AND J. W. PHILLIPS

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[PLATE 8]

An investigation of the distribution of the sources of galactic radiation at 64 Mcyc./sec. is described. Methods are discussed by which the characteristics of the receiving antenna were measured and by which the magnitude of the received galactic power was estimated by comparison with a reference signal of similar amplitude characteristics. The method of analysis of results is described in detail, with emphasis on the need for allowing for the finite width of the main cone of reception of signal power and for the sensitivity of the antenna to signal sources outside the main cone. The necessary corrections are effected by a method of successive approximations, and contours of the distribution of the signal source between declinations $+50^\circ$ and -30° are derived. The results are expressed in terms of power flux and also of effective aerial temperature. Possible sources of error are discussed and an accuracy better than 1·2 db. (30 %) is expected for the regions of highest radiation intensity. Reference is made to the fluctuations observed in the radiations coming from Cygnus.

The correlation of the derived distribution of galactic radiations with other astronomical data is discussed with special reference to the galactic structure. It is shown that correlation with the near galactic structure, as indicated by the general distribution of visible sources of light, is not very good, but that a more satisfactory correlation is obtained with data which are believed to be characteristic of the structure of the galaxy as a whole. The bias to the south of the galactic circle shown by radiation sources in the vicinity of the galactic centre is especially significant. Various relevant astronomical data are collected together in the accompanying diagrams.

The bearing of these correlations on the question of the nature of the source of radiation is examined. It is shown that they do not clearly favour any one theory, and that neither a simple theory in terms of a distributed source in interstellar gas nor one in terms of discrete centres of radiation analogous to sunspots appears adequate to account for the observed phenomena. It is suggested that sources of both types contribute to the observed radiation and that, in general, they must be very distant and associated with the main body of the galaxy.

1. INTRODUCTION

The discovery in 1932 of cosmic electromagnetic radiations at radio-frequencies was due to Jansky (1932, 1933, 1935 and 1937) who, in a series of measurements at about 20 Mcyc./sec., was able to establish the close connexion between the direction of greatest intensity and the centre of the galaxy. Measurements have also been made by Reber (1940*a*, *b*, 1942, 1944) at about 160 Mcyc./sec., and, although the intensity of radiation was much less, the higher frequency enabled him to use a narrower radio beam; he was thus able to detect a number of subsidiary peaks which demonstrated further the correlation between the distribution of the radiation intensity and galactic structure. The elucidation of the origin of this radio phenomenon and the interpretation of its astronomical significance require a detailed analysis of the spatial distribution of the source. In a brief communication by the authors (Hey, Phillips & Parsons 1946*a*), an analysis was given of results obtained in a preliminary investigation carried out during June and July 1945 at 64 Mcyc./sec. This frequency had the advantage of giving a considerably higher intensity of the cosmic radiations than at 160 Mcyc./sec.; and, although the beam width was greater than that used by Reber, this disadvantage was offset by the method of analysis in which the measured sensitivity pattern of the aerial beam was taken into account. The present report discusses a further investigation at 64 Mcyc./sec. carried out with improved techniques, the most important being the introduction of a narrower beam aerial system and more rigorous methods of calibration. The observations were made at various times during 1946, and interference from the radio emissions associated with sunspots (Appleton & Hey 1946) often proved troublesome. The final analysis was based mainly on results taken during July and August 1946 at times when the Sun was comparatively quiescent. The equipment was situated near London at latitude 51° 25′ N., and longitude 0° 15′ W.

2. THE EQUIPMENT

The equipment, shown in figure 1, plate 8, was similar to that used in the preliminary investigation (Hey *et al.* 1946*a*), except that the aerial system consisted of four Yagi arrays instead of two. The arrays were placed with their elements horizontal and their axes parallel in the same horizontal plane at a height of approximately 1 wave-length (λ) above a horizontal wire-mesh mat of radius about 12λ. Ground reflexion was thus utilized to produce a narrow beam in elevation, and the mat ensured that the reflexion was as uniform and perfect as possible. The horizontal

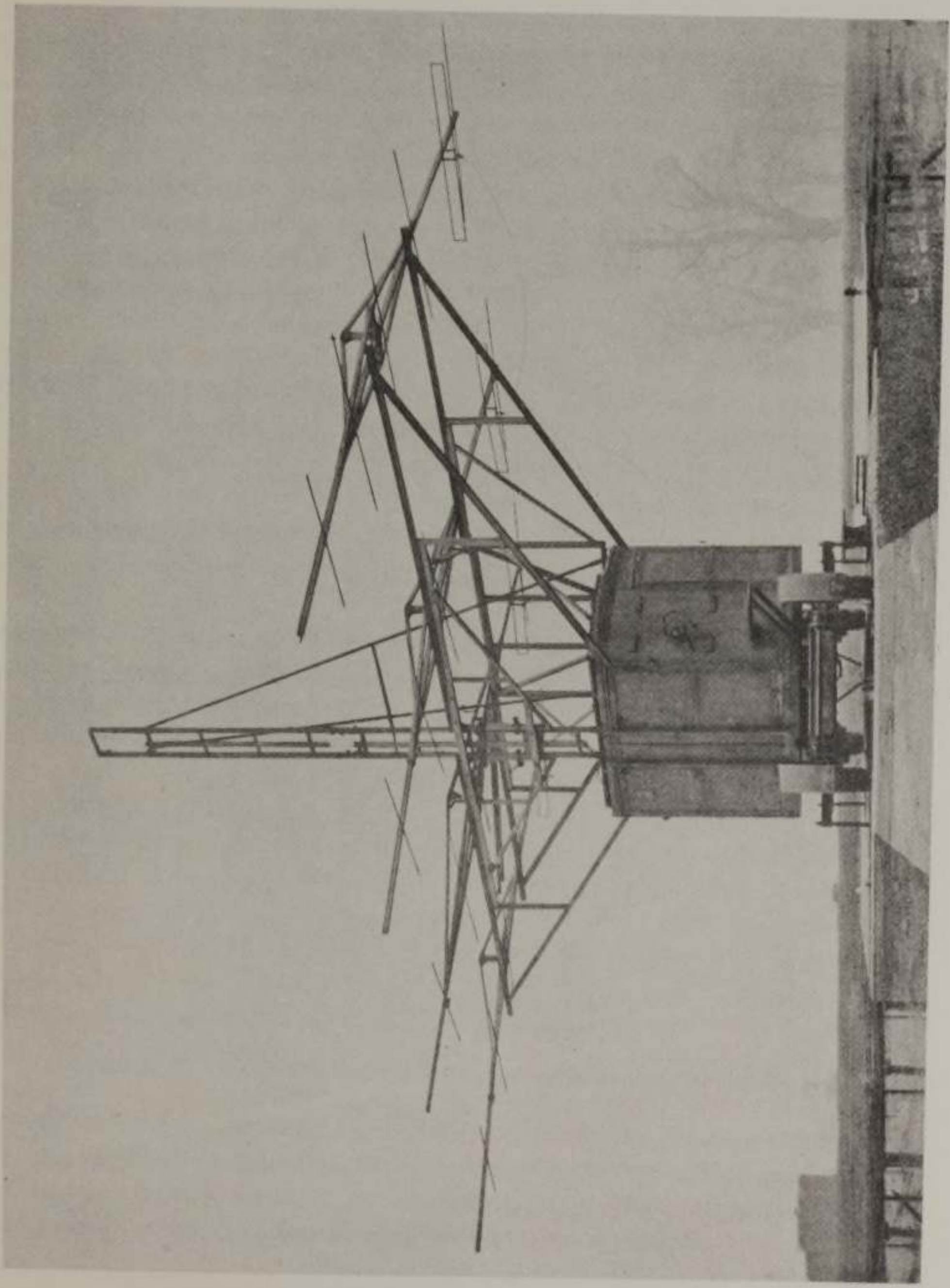


FIGURE 1

separation between adjacent Yagis was $0{\cdot}7\lambda$, a distance which gave a narrow beam width in bearing without introducing large side-lobes. The arrays were connected in series-parallel, an arrangement which was found to give satisfactory matching together with narrow beam width. The feeder and aerial system is illustrated in figure 2. The feeders from the aerials to the junction box were of equal lengths, each being an integral number of half wave-lengths, and the length of the feeder from the junction box to the receiver was adjusted for optimum matching. Balanced feeders of approximately 95 ohms characteristic impedance were used throughout. The whole equipment could be rotated in bearing and gave a well-defined main beam at a fixed angle of elevation. The determination of the aerial sensitivity pattern is described in the next section.

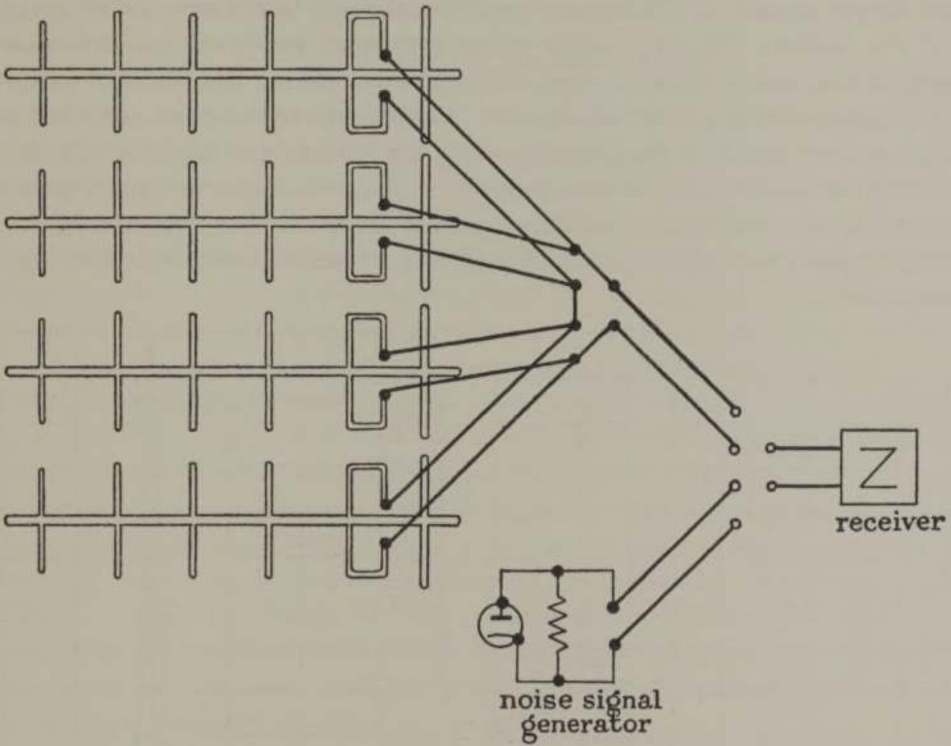


FIGURE 2. Diagrammatic representation of feeder and aerial system.

The received power was measured by the current in the detector diode of the receiver, the method of calibration being described later in § 4. This current could be read directly from a sensitive galvanometer, or graphed automatically on a recording galvanometer. The former method was normally used.

3. DETERMINATION OF AERIAL CHARACTERISTICS

A detailed knowledge of the power gain of the aerial system in all directions is necessary for the satisfactory analysis of results. If θ is the bearing relative to that of the aerial system and ϕ is the elevation, the power gain in any direction can be written as $G_0 f(\theta, \phi)$, where $f(\theta, \phi)$ represents the variation of power gain with direction taking the value at the maximum of the beam as unity, and G_0 is the power gain in the direction of the maximum.

In order to determine the aerial sensitivity pattern $f(\theta, \phi)$, a small oscillator with a dipole was suspended from a balloon, and relative received signal strengths at suitable intervals of elevation and bearing were observed for both horizontally and vertically polarized radiation. Although the receiving equipment aerials were horizontal, an appreciable signal could be received from radiation with the electric vector in the vertical plane; since it could be assumed that the cosmic electromagnetic radiation has the same mean power for both polarizations, it was necessary to measure the power gain for both. An unmodulated oscillator proved most suitable, since a light-weight apparatus of adequate power could easily be constructed for suspension from the balloon. The slant range of the suspended oscillator was determined by triangulation, and the relative signal strengths normalized to a constant range. The results (expressed in power) for the two polarizations were added and the function $f(\theta, \phi)$ derived directly. Diagrams showing the variation of aerial sensitivity with direction for mixed polarization are shown in figure 3. Since the aerial system was mounted above an extensive horizontal wire-mesh mat, it was considered that power losses at reflexion would be negligible and that no account need be taken of ground absorption.

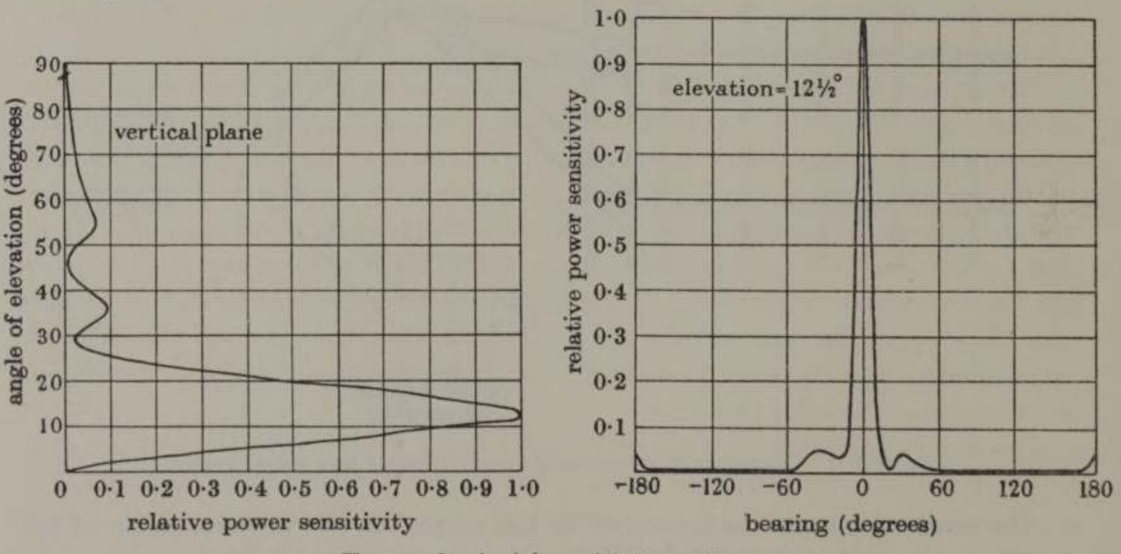


Figure 3. Aerial sensitivity patterns.

To derive G_0, the power gain in the direction of maximum aerial sensitivity, the equivalent power absorption area of the aerial was compared directly with that of a single horizontal half-wave dipole at a height $0{\cdot}4\lambda$ above the wire-mesh reflecting surface. Sensitivity patterns in the vertical plane were derived for both aerial systems, using the method described above. Readings at any one angle of elevation were taken first with one aerial system connected and then with the other, the signal source remaining unchanged. In each case, the feeders from the aerials had been adjusted for optimum matching. For a dipole at a height exceeding $0{\cdot}25\lambda$ above a perfectly reflecting plane, the maximum power gain compared with a dipole in free space is $4r/R$, where R and r are the radiation resistances for the dipole above ground and in free space respectively. The maximum power gain of a dipole at height $0{\cdot}4\lambda$ was hence calculated to be 3·2, and it was thus estimated that the maximum sensitivity of the Yagi aerial system was 52 times that of a half-wave dipole in free space. The axis of the main lobe was at an elevation $12\frac{1}{2}^\circ$, and the beam widths to half maximum power were $\pm 6\frac{1}{2}^\circ$ in elevation and $\pm 7^\circ$ in bearing. Of the total equivalent power absorption area of the beam, 65 % was accounted for by the main lobe.

4. CALIBRATION OF RECEIVED POWER

In order to measure the absolute level of power received from the galactic radiations it is necessary to calibrate the receiver by means of a signal of similar amplitude characteristics. Non-linearities in the relation between receiver output and input may cause the output to vary with the type of signal modulation when the mean input power is constant. Since the galactic radiations have the characteristics of random noise fluctuations, a noise signal generator was used. As will be seen from the formulae derived below, a further advantage in using a generator of this type is that the receiver calibration is independent of the receiver band width.

The method of connexion of the noise signal generator was by direct substitution as illustrated in figure 2. Provided that the output impedances of the noise signal generator and of the aerial system are equal, a condition which was realized approximately in practice, a given e.m.f. existing in either the signal generator or in the aerial produces the same dissipation of power at the receiver input terminals. Thus the e.m.f.'s present in the two sources may be compared without any knowledge of the receiver input impedance and the receiver calibration is independent of this quantity. For convenience of calculation it is assumed that the receiver was matched to its source in both cases, and the power transferred under these conditions is referred to as 'available power'.

The noise signal generator consists, in principle, of a resistive element through which is passed the current of a saturated tungsten filament diode. In such a generator, if I is the direct current flowing through the diode then, by Schottky's equation, the mean square noise current is

$$\overline{i_{nd}^2} = 2qI\Delta\nu, \tag{1}$$

where q is the electronic charge and $\Delta\nu$ is the frequency band width. The mean square noise current due to fluctuations generated within the resistance itself is, by Nyquist's theorem,

$$\overline{i_{nr}^2} = \frac{4}{R}kT_R\Delta\nu, \tag{2}$$

where k is Boltzmann's constant, R is the value of the resistance and T_R is its absolute temperature. Thus the power available to a matched receiver is

$$P\Delta\nu = \tfrac{1}{2}qIR\Delta\nu + kT_R\Delta\nu, \tag{3}$$

where P is the power per unit frequency band width.

5. SYSTEM OF OBSERVATIONS

Any one day's observations consisted of twenty-four series, each series being made at a sidereal hour. During any one series the receiving equipment was rotated through 360° of bearing in steps of 5 or 10°, and the receiver output was noted for each bearing. It was found that in only one region of the sky, in the vicinity of the galactic centre, did the power received vary sufficiently with a small change in direction to make the direction of the main lobe, and hence the timing of observations, very critical. Care was taken to note the readings from this region within a minute of the exact sidereal hour, and other readings were taken within about ± 5 min. Each series was followed immediately by a noise signal generator calibration of the receiver.

6. ANALYSIS OF RESULTS

In the following analysis we derive the distribution of cosmic electromagnetic radiations received at the Earth in terms of the celestial co-ordinates of direction, namely, the right ascension ρ and declination δ. It is often convenient, however, to refer to the aerial characteristics in terms of 'terrestrial co-ordinates', namely, the bearing θ measured relative to the orientation of the axis of the aerial beam, and the elevation ϕ. These terrestrial co-ordinates define a direction in space at a given instant provided the orientation of the aerial and its location are specified. With this condition in mind we shall, in certain of the equations below, use both systems of co-ordinates.

The intensity distribution of the source of cosmic noise can be expressed in terms of a function p such that the intensity of power flow at the aerial from an element of solid angle $\Delta\omega$ in the direction (ρ, δ) is $p(\rho, \delta)\,\Delta\omega$. The maximum equivalent area of absorption of power-flux for a matched half-wave dipole in free space is $0{\cdot}065\lambda^2$, for a field of random polarization. Thus the total power available at the aerial terminals (see § 4 above) at a given sidereal time and for a given terrestrial orientation of the aerials is

$$P\Delta\nu = 0{\cdot}065\lambda^2 G_0 \Delta\nu \int_{4\pi} f(\theta,\phi)\,p(\rho,\delta)\,d\omega, \tag{4}$$

where G_0 and $f(\theta,\phi)$ are as defined above (see § 3), and (θ,ϕ), (ρ,δ) are equivalent co-ordinates under the conditions stated.

If now an attenuation factor α is introduced for the difference in attenuation between the aerial and noise generator feeders, then one derives from equations (3) and (4)

$$\tfrac{1}{2}qI_nR + \alpha kT_R = 0{\cdot}065\alpha\lambda^2 G_0 \int_{4\pi} f(\theta,\phi)\,p(\rho,\delta)\,d\omega, \tag{5}$$

where I_n is the noise generator anode current which gives a receiver output power equal to that obtained with the aerials connected. $\int_{4\pi} f(\theta,\phi)\,p(\rho,\delta)\,d\omega$ can now be determined, since all other factors are known. The derivation of $p(\rho,\delta)$ from this expression involves a special method of treatment such as that now to be described.

For each position of the aerial beam, a quantity $\overline{p}_w(\rho_0,\delta_0)$ was calculated such that

$$\overline{p}_w(\rho_0,\delta_0)\int_{4\pi} f(\theta,\phi)\,d\omega = \int_{4\pi} f(\theta,\phi)\,p(\rho,\delta)\,d\omega. \tag{6}$$

The co-ordinates (ρ_0,δ_0) assigned to $\overline{p}_w$ were the celestial co-ordinates of the axis of the main lobe of the beam. It will be seen from equation (6) that $\overline{p}_w$ is the mean of the incident received power weighted according to the aerial sensitivity. The problem thus became that of finding a function $p(\rho,\delta)$ such that equation (6) was satisfied for all positions of the beam. The method used was one of successive approximations and is described below.

Values of $\overline{p}_w$ calculated from equation (6) were plotted on a plane projection of the celestial sphere such that declination circles became concentric circles of radii proportional to polar distances and great circles of right ascension became radial lines. The values of $\overline{p}_w$ were plotted at the respective positions of the main lobe axis, and the values calculated for different bearings at any one sidereal hour lay on a closed curve. The twenty-four such curves formed a lattice of intersecting curves contained within the circles of declination +51° and −26°. Thus for each region of the sphere, two values of $\overline{p}_w$ were obtained corresponding to the two curves of the lattice intersecting in that region. In general, these values were not equal, since the positions of the minor lobes were different for the two cases, but, owing to the highly directional aerial in use, they did not differ greatly. From this array of values of $\overline{p}_w(\rho,\delta)$ it was necessary to derive values of $p(\rho,\delta)$ to satisfy equation (6) for all positions of the aerial beam. The process was accomplished with the aid of a movable transparent grid, on which values of $f(\theta,\phi)$ were plotted, and through which the array of numbers representing the power distribution could be viewed. The approximation was carried out in two stages as follows:

The first stage of approximation was that of correction for subsidiary lobes. From equation (6),

$$\overline{p}_w(\rho_0,\delta_0)\int_{4\pi} f(\theta,\phi)\,d\omega = \int_m f(\theta,\phi)\,p(\rho,\delta)\,d\omega + \Sigma\int_s f(\theta,\phi)\,p(\rho,\delta)\,d\omega, \tag{7}$$

where $\int_m$ and $\int_s$ denote integration over the solid angles containing the main and subsidiary lobes respectively. Putting, for the main lobe,

$$\int_m f(\theta,\phi)\,p(\rho,\delta)\,d\omega = \overline{p}_m(\rho_0,\delta_0)\int_m f(\theta,\phi)\,d\omega \tag{8}$$

and similar expressions for the subsidiary lobes, it follows that

$$\overline{p}_w(\rho_0,\delta_0)\int_{4\pi} f(\theta,\phi)\,d\omega = \overline{p}_m(\rho_0,\delta_0)\int_m f(\theta,\phi)\,d\omega + \Sigma\overline{p}_s(\rho_s,\delta_s)\int_s f(\theta,\phi)\,d\omega, \tag{9}$$

where (ρ_s, δ_s) are the co-ordinates of the axis of a subsidiary lobe. The aim was now to determine $\overline{p}_m$, which, as indicated by equation (8), is the mean of the power flux over the main lobe weighted according to aerial power sensitivity. As a first approximation the known values of $\overline{p}_w$ appropriate to the various regions of the sky viewed in the subsidiary lobes were substituted for the terms $\overline{p}_s$ and an approximate value of $\overline{p}_m$ was obtained. The operation was repeated for different regions, the values of the $\overline{p}_m$ terms being used, where available, as improved approximations for $\overline{p}_s$. This was justified, since the angular dimensions of the subsidiary lobes were of the same order as those of the main lobe. Owing to the high concentration of power sensitivity in the main lobe the approximations converged rapidly. It will be noted that an increase of the calculated value of $\overline{p}_m$ in one part of the sky led to a decrease in calculated values in other parts so that the expression

$$\Sigma \overline{p}_s(\rho_s \delta_s) \int_s f(\theta, \phi)\, d\omega$$

changed very little from its original estimated value. One cycle of approximation was sufficient for the evaluation of $\overline{p}_m$ in most regions, and never more than three were needed. This completed the first stage of approximation.

The values of $\overline{p}_m$ thus obtained were used as a basis for correcting for the shape of the main lobe in order to make the final derivation of p. Equation (8) may be written

$$\overline{p}_m(\rho_0, \delta_0) \int_m f(\theta, \phi)\, d\omega = \sum_{(n=0,1,2,\text{ etc.})} \int_n f(\theta, \phi)\, p(\rho, \delta)\, d\omega, \tag{10}$$

where $\int_n$ denotes integration over a section of the main lobe contained within a small solid angle and $\int_0$ refers to the axial section. If one puts

$$\int_n f(\theta, \phi)\, p(\rho, \delta)\, d\omega = \overline{p}_n(\rho_n, \delta_n) \int_n f(\theta, \phi)\, d\omega, \tag{11}$$

where (ρ_n, δ_n) are the co-ordinates of a mean direction contained within the section number n, and if further, for convenience, the sections are chosen so that $\int_n f(\theta, \phi)\, d\omega$ has the same value for all sections, equation (10) becomes

$$\overline{p}_m(\rho_0, \delta_0) \int_m f(\theta, \phi)\, d\omega = \int_n f(\theta, \phi)\, d\omega \sum_{(n=0,1,\text{ etc.})} \overline{p}_n(\rho_n, \delta_n). \tag{12}$$

In equation (12), $\overline{p}_m$ was known and the integrals could be computed and thus the problem became that of devising values of $\overline{p}_n$ to satisfy the equation for all positions of the main lobe. Trial values of $\overline{p}_n$ were substituted in the equation and the calculated values of $\overline{p}_m$ compared with those already obtained. Since the beam was narrow, the region of the sky involved in any one equation was small and the trial values converged rapidly.

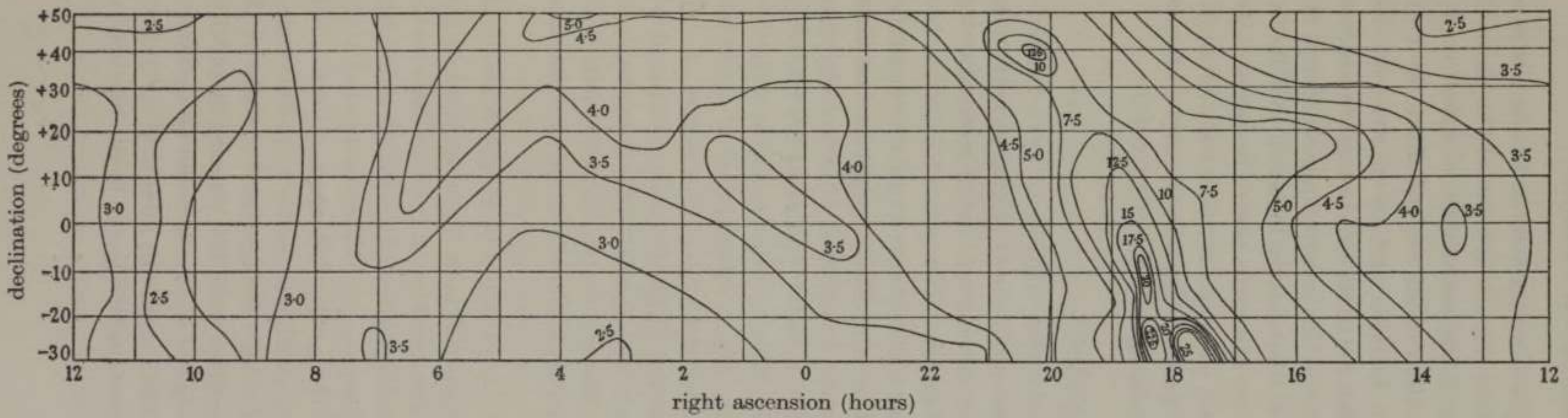


FIGURE 4*a*. Equatorial co-ordinates. Cylindrical projection with standard parallels +30° and −30° declination.

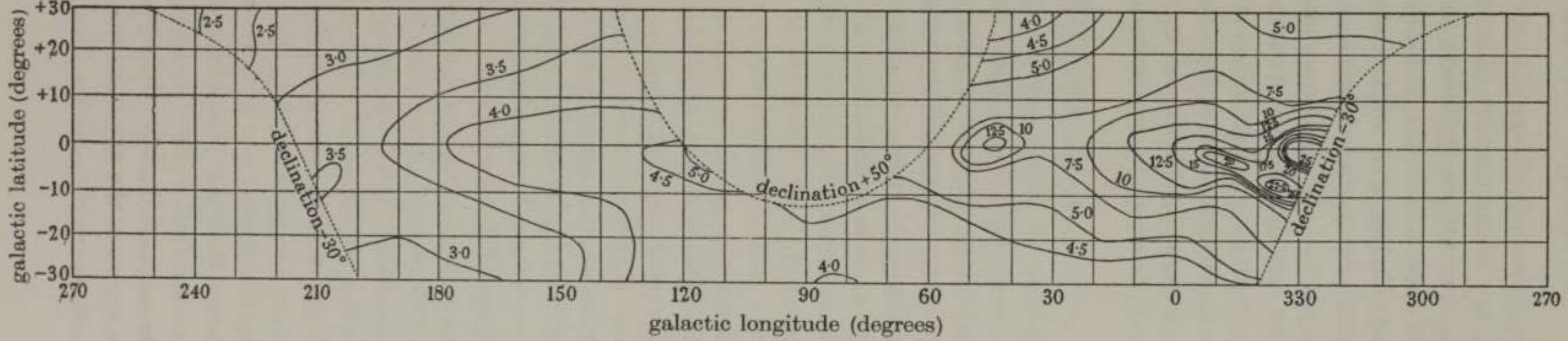


FIGURE 4*b*. Galactic co-ordinates (I.A.U. 1932). Cylindrical projection with standard parallels +30° and −30° latitude.

FIGURES 4 *a*, *b*. Distribution of cosmic electro-magnetic radiation at 64 Mcyc./sec. Unit of power flux = $10^{-21}\Delta\nu\,\Delta\omega$ W/sq.m. $\Delta\nu$ = band width (cyc./sec.). $\Delta\omega$ = element of solid angle (steradians).

To minimize the work of computation it is plainly desirable to divide the main lobe into the minimum number of sections, provided further subdivision of the sections does not introduce significant variations in the summation of equation (10). The section of least solid angle, namely, the axial section corresponding to $n = 0$, then represents the limit of angular resolution for this method of analysis. The size of the axial section was chosen to be 0·0044 steradian (or 14 square degrees). The values of p_0 obtained, although mean values of the function $p(\rho, \delta)$ within this axial section for various positions of the main lobe, were used as values of the function $p(\rho, \delta)$ to map contours of distribution of the noise source as shown in figure 4. The agreement between observed noise powers and those calculated back from the computed distribution is illustrated in figures 6*a* to *d*. The distribution of noise source along a cone swept by the beam is shown in figure 7 for comparison.

7. DISCUSSION OF RESULTS

The distribution of radio noise power over the sky appears to have remained substantially unchanged since 1945, when the preliminary investigations commenced. Except for a region in Cygnus, which is discussed in detail later, any day-to-day changes observed are in the general level and are of the order of ± 10 %, which is probably within the limits of experimental error. The results have been examined for evidence of diurnal variations of radiation intensity which might be associated with ionospheric influences, but no positive results have been obtained. As mentioned previously (§ 1), the observations used in the above analysis were limited to times when the solar emissions were negligible. Among other possible influences which may limit the consistency of results are radio interference of terrestrial origin, and distortions of the aerial sensitivity pattern at very low angles of sight due to variations in ground contours on different bearings and to ionospheric conditions (e.g. E layer scattering). Interference was normally distinguishable by the characteristics of the signal, while site and ionospheric effects were likely to be appreciable only at angles of elevation less than 5° and, therefore, only in directions in which the aerial sensitivity was very low.

Any one region of the sky for which $-26° < \delta < +50°$ could be viewed in the main lobe twice during the course of a sidereal day, once as it ascended through the beam and again as it descended. A comparison of the observations in the two cases served as a test of consistency. It was necessary first to take account of the fact that different regions of the sky were exposed to the minor lobes, and with due allowance for this effect the inconsistencies were generally small. In a very few cases, in low-power regions, they were as great as 15 %. This may be attributed partly to the influences discussed above and also to a lack of any survey of the regions of the sky in the neighbourhood of the Pole. Minor errors in the estimates of the magnitudes of side-lobes, or of the intensities of the power sources viewed by them, could be significant if the main beam was directed towards a region of low-power intensity. In most of the low-power regions, the consistency was better than 10 %, and in the high-power regions the consistency was better than 5 %.

By the method of analysis described above it has been found possible to derive the distribution in detail between declinations $-30°$ and $+50°$. Contour maps of the distribution are shown in equatorial co-ordinates in figure 4*a* and in galactic co-ordinates (I.A.U. 1932) in figure 4*b*. The main source of cosmic noise radiation appears to be in the region of R.A. 17 hr. 45 min., Dec. $-26°$ (galactic longitude 330°, galactic latitude $-1°$) and to extend southward beyond the limit of the survey along the line of the galactic equator. There are lesser peaks at R.A. 18 hr. 20 min., Dec. $-25°$ (336°, $-7°$) and R.A. 18 hr. 22 min., Dec. $-12\frac{1}{2}°$ (348°, $-2°$), a minor peak in Cygnus, R.A. 20 hr. 15 min., Dec. $+39°$ (44°, $+1°$), and a general concentration along the line of the galactic equator. It may be noted that the distribution is a revision of that derived in the preliminary investigation (Hey *et al.* 1946*a*), the accuracy and detail having been improved by the use of the narrower radio beam and a more thorough analysis of results.

The maximum and minimum intensities at 64 Mcyc./sec. deduced by us are $25{\cdot}0 \times 10^{-21}$ and $2{\cdot}2 \times 10^{-21}$ W/sq.m. steradian.cyc./sec. band width with a mean value of $4{\cdot}0 \times 10^{-21}$ W/sq.m. steradian.cyc./sec. band width. Burgess (1941) has shown that an aerial, considered as a noise generator, may be replaced by a resistance equal to the radiation resistance of the aerial at a temperature equal to the effective temperature of surrounding space. Using this concept, and supposing the sky uniformly illuminated at the maximum, the minimum, and the mean intensities stated above, the corresponding effective aerial temperatures would be 18,000, 1600, and 2900° K respectively.

The accuracy of location of the more marked features of the cosmic noise distribution is of the order of $\pm 1°$ in declination and $\pm 1° \times$ secant (declination) in right ascension. The angular subtensions shown for these features are, in general, the greatest consistent with observed results. They may exceed the true dimensions by an amount not greater than 2°, and the estimated power density would then need to be raised to give the same total radiated power. The estimate of general power level is believed to be accurate to 1 db. (25 %) with additional local inaccuracies in a few low-power regions of the order of 0·6 db. (15 %) and in the main concentrations of 0·2 db. (5 %).

The radiation from the region of Cygnus is notable for a short-period fluctuation in power which has been maintained in variable degree since the phenomenon was first noted by the authors (Hey *et al.* 1946*b*) in February 1946. There is some indication of a long-period (several months) fluctuation, but the evidence of a short-period fluctuation is more conclusive. During the time that the region has been favourably placed for observation with the main lobe of the aerial beam, recordings of the received power have been made. The disturbance has been found to be of very variable character, and may change within a few minutes from an almost steady level to large fluctuations of only a few seconds' duration. These appeared to be random in character and have been observed at all times of the solar day. It is difficult to obtain an accurate location of a variable source with the use of a comparatively wide beam, since the normal direction-finding technique is not possible.

Fluctuations observed with the beam directed to various parts of the sky in the neighbourhood of Cygnus were noted for several days and average fluctuation figures obtained for these points. The first analysis (Hey *et al.* 1946*b*) of observations taken during the early part of 1946 was consistent with a well-defined centre of disturbance of angular subtension not exceeding 2°, located at R.A. 20 hr., 00 min., Dec. + 43°, with possible areas of occasional disturbance in the immediate neighbourhood (within 8°). Recent observations during October and November of 1946 indicate a more diffuse source in the region of R.A. 20 hr., 30 min., Dec. + 38°. This latter location is very indefinite, but it appears to correspond closely with the secondary peak in Cygnus. Various types of fluctuation observed are illustrated in figures 8*a* to *f*.

8. CORRELATION OF OBSERVED DISTRIBUTION WITH OTHER ASTRONOMICAL PHENOMENA

The correspondence between the distribution of the cosmic radio-frequency radiations and the known evidence of galactic structure is now considered. The contours of power flux are mapped in galactic co-ordinates in figure 4*b*; these co-ordinates refer to the estimated galactic equator which is itself based on the distribution of the fainter stars in the sky. Faint stars are used rather than bright stars since the latter are few in number, and, in most cases, appear bright merely because they are close to the earth; their distribution is not typical of the configuration of the whole galaxy. From similar considerations the position of the galactic centre has been estimated by various observers to be within the interval of galactic longitude 325 to 330°. This interval is marked as the shaded area in figure 5*b*. The source of radio-frequency radiations shows a significant bias to the south of the galactic plane in the neighbourhood of the galactic centre.

The apparent rough outline of the Milky Way is shown in figure 5*a*, and the approximate distribution of light based on observations by Hopmann (1924, 1933) with a photoelectric cell is shown in figure 5*b*; in neither case is the correlation with the radio-frequency distribution particularly close. We have examined our observa-

Legends to Figure 5.

Figure 5*a*. Comparison with distribution of reddened stars and novae. $\underline{3{\cdot}5}$ lines of constant intensity of radio power. —— outline of Milky Way. • reddened stars, ∘ novae.

Figure 5*b*. Comparison with distribution of visible light, O-type stars and regions of Hα emission. $\underline{3{\cdot}5}$, lines of constant intensity of radio power. $\underline{2}$ approximate light distribution (scaled in power). ∘ regions of Hα emission. • star types O_5 and O_6. · star types O_7, O_8 and O_9. ▨ estimates of galactic centre.

Figure 5*c*. Comparison with distribution of O and B type stars. $\underline{3{\cdot}5}$ lines of constant intensity of radio power.

Figures 5 *a* to *c*. Comparison of cosmic electro-magnetic radiation at 64 Mcyc./sec. with astronomical data. Unit of radio power flux = $10^{-21}\Delta\nu\,\Delta\omega$ W/sq.m.

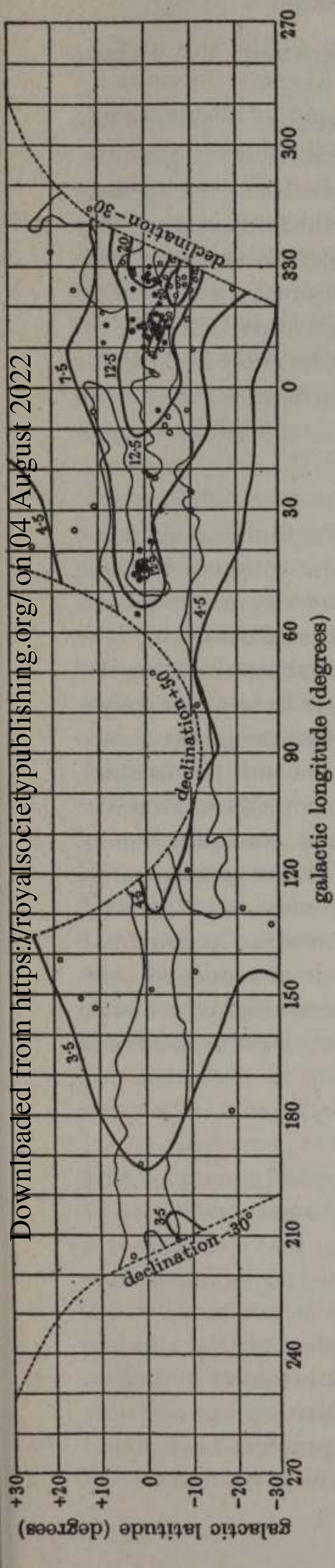


FIGURE 5*a*

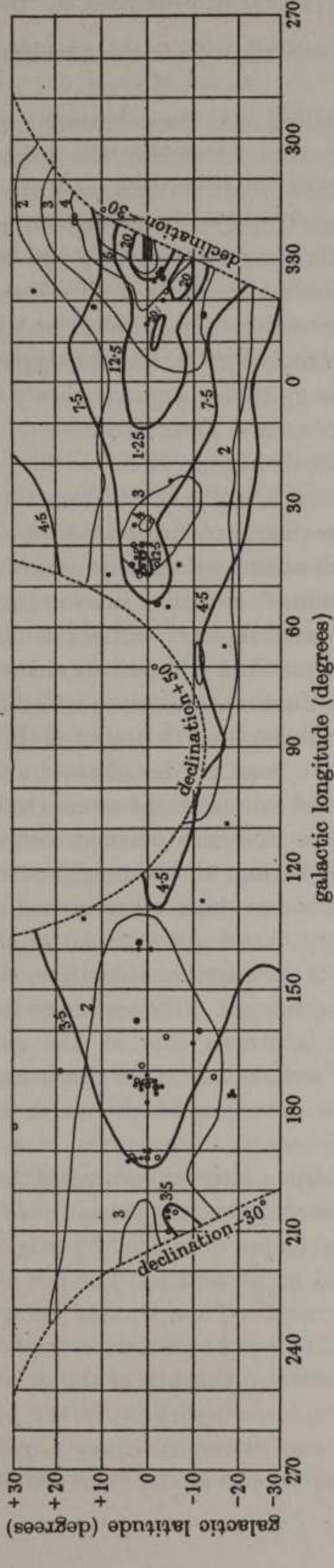


FIGURE 5*b*

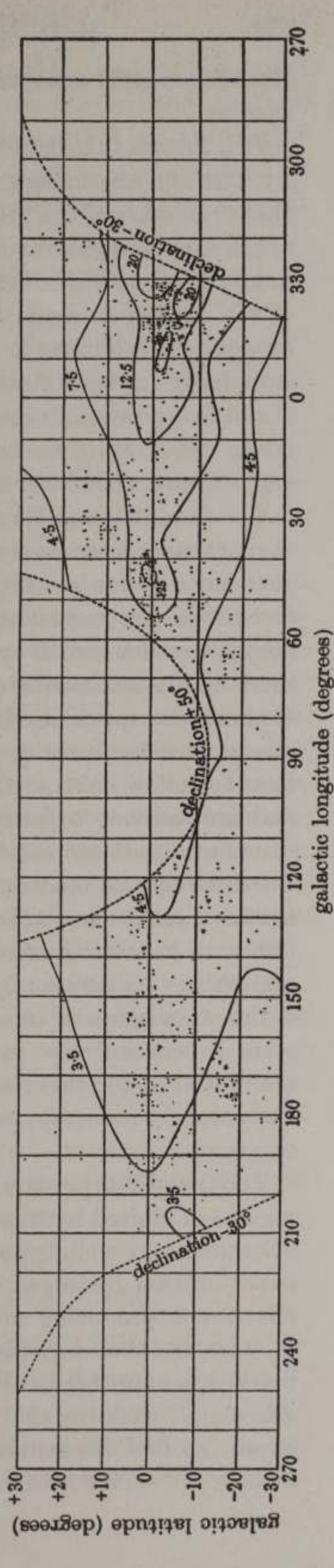


FIGURE 5*c*

tions for specific evidence of radiation from the near and bright stars, but without success.

It is known that light travelling near the galactic plane is subject to attenuation by dust and obscuring matter concentrated in the neighbourhood of the plane, so that even stars of the brightest absolute magnitudes are not visible at the distance of the supposed galactic centre. Thus the distribution of even the faintest stars may not be a true picture of the galaxy as a whole. To probe the more distant parts stars of the highest intrinsic luminosity must be used; these are novae (which are of exceptional brilliance in their early stages) and O and B type stars. The faintest stars have not been classified according to spectral type, but we show in figure 5*c* O and B type stars down to magnitude 8 approximately and in figure 5*a* the known novae. The data have been obtained from Stebbins, Huffer and Whitford (1939) and Payne-Gaposchkin & Gaposchkin (1938).

The distant O and B type stars are of special interest in other ways. An examination of their spectra reveals the degree of obscuration of their light by dust along the path since such obscuration is accompanied by a selective attenuation of the blue end of the spectrum. The resultant reddening has been measured by Stebbins *et al.* (1939) for all O and B type stars brighter than about the 9th magnitude, and the more highly reddened stars more than 400 parsecs distant are shown in figure 5*a*. It should be appreciated that the total reduction in light power from a star due to obscuration by dust varies as about the 7th power of the relative reduction of blue light to yellow light, so that the most reddened stars are, in general, the faintest, and are unlikely to be included amongst the stars studied up to now. Thus the distribution of reddened stars in figure 5*a* may be taken as an indication of the directions of moderate reddening. In the neighbourhood of the galactic circle between longitudes 325–0–60°, any lack of reddened stars may be attributed either to lack of O and B type stars (probably the case between longitudes 0 and 30°) or to excess of obscuring matter; elsewhere, the lack of reddened stars is due to absence of obscuring matter. The tendency for known highly reddened stars to concentrate on the southern side of the galactic circle is generally attributed to the presence of a dark nebula or obscuring cloud to the north, and the more frequent appearance of novae to the south is attributed to the same cause.

The O and B type stars are also of interest because of the expected connexion with regions of ionized hydrogen. Strömgren (1939) has shown that such stars would be surrounded by well-defined envelopes of ionized hydrogen, and that elsewhere it is expected that hydrogen would be un-ionized. The hot stars would be much more effective in producing such ionization, one O_7 star being as effective as 5,000,000 A_0 stars, and thus the regions of extensive ionization would be relatively few and well marked, amounting in all to about one-tenth of the galactic stratum of hydrogen. Associated with the partially ionized hydrogen in the boundary regions one may expect to find $H\alpha$ emission, and Struve & Elvey (1938, 1939*a*, *b*, *c*) have found evidence of such emission from regions of the expected dimensions (subtensions of the order of one degree). Their survey is by no means completed but we show in figure 5*b* the emission regions so far discovered.

The correlations between the contours of noise radiation and the plotted data appear to be confined to those in the region of Cygnus, where phenomena of all kinds are observed, and those in the Scorpio-Sagittarius region. In the latter case the two minor peaks of the triple peak of radio-frequency radiation correspond to marked concentrations of reddened stars and novae respectively, and the general bias to the south of the galactic circle appears in all the phenomena.

We feel that these apparent correlations cannot be accepted without caution, especially as the concentrations of reddened stars and novae appear to relate to two very different conditions, one being a region of considerable obscuration and the other a region where obscuration is notably absent. In connexion with the bias to the south of the galactic circle we would point out that radiations at 64 Mcyc./sec. are much less subject to attenuation by dust than those at visual frequencies, so that one might expect to 'see' by these means into remote regions of the galaxy. It would appear therefore that the bias to the south of the galactic equator is a true feature of the general galactic structure rather than merely a consequence of optical absorption to the north. On the other hand, as pointed out in the next section, the radio-frequency distribution is likely to be at least markedly influenced by interstellar ionized hydrogen. It would be of considerable value in this connexion to be able to compare detailed distribution of radio-frequency power at different radio frequencies.

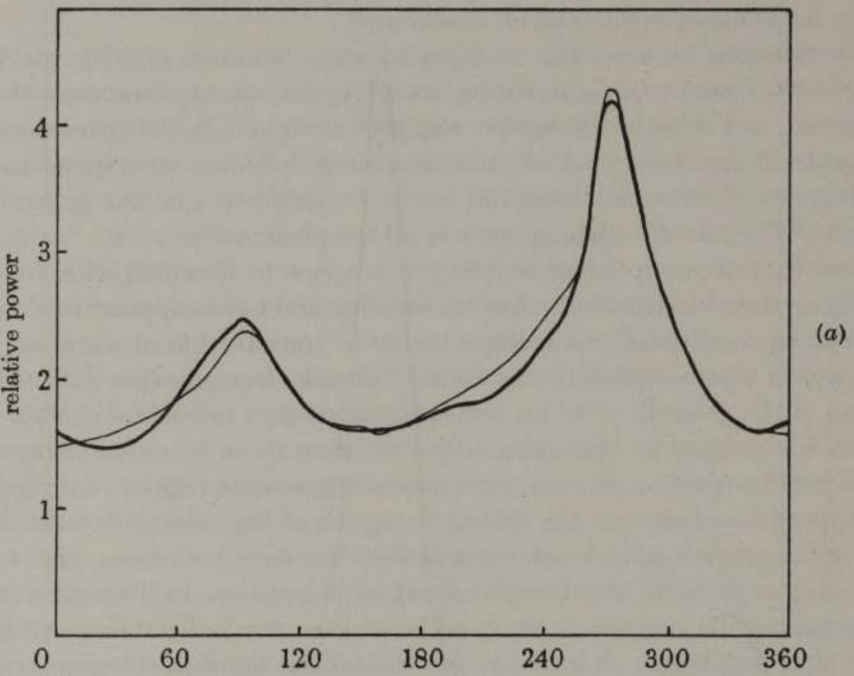
We do not find any features corresponding to certain other 'windows' believed to be present in the curtain of dust, nor do we find any obvious association of the minor peaks and troughs of radio power flux with visual phenomena. During early investigations in 1945, using aerials inclined at 35 and 25° to the horizon, we found some evidence of peaks at galactic longitudes 85 and 110° near marked concentrations of reddened stars in Cassiopeia and Perseus respectively. It is intended to make a fuller investigation of this region with an appropriate beam elevation.

Thus, the most that we can say of the correlation between radio power flux and other astronomical phenomena is that the concentrations of known distant stars in the directions of the galactic centre and Cygnus correspond to concentrations of power flux and that, in the former region, both radio power and star concentration show a significant bias to the south of the galactic circle.

9. Evidence of the nature of the source of radiation

There appear to be several possible theories of the cause of cosmic radiation at radio-frequencies. One, which was suggested by Reber (1940*a*), is that the radiation arises from free transitions of electrons in the field of protons in interstellar space. The theoretical treatment of radiation arising in this way was originally given by Kramers (1923) to account for the continuous radiation in X-ray spectra.

29-2


relative power
4
3
2
1
0
60
120
180
240
300
360
(a)

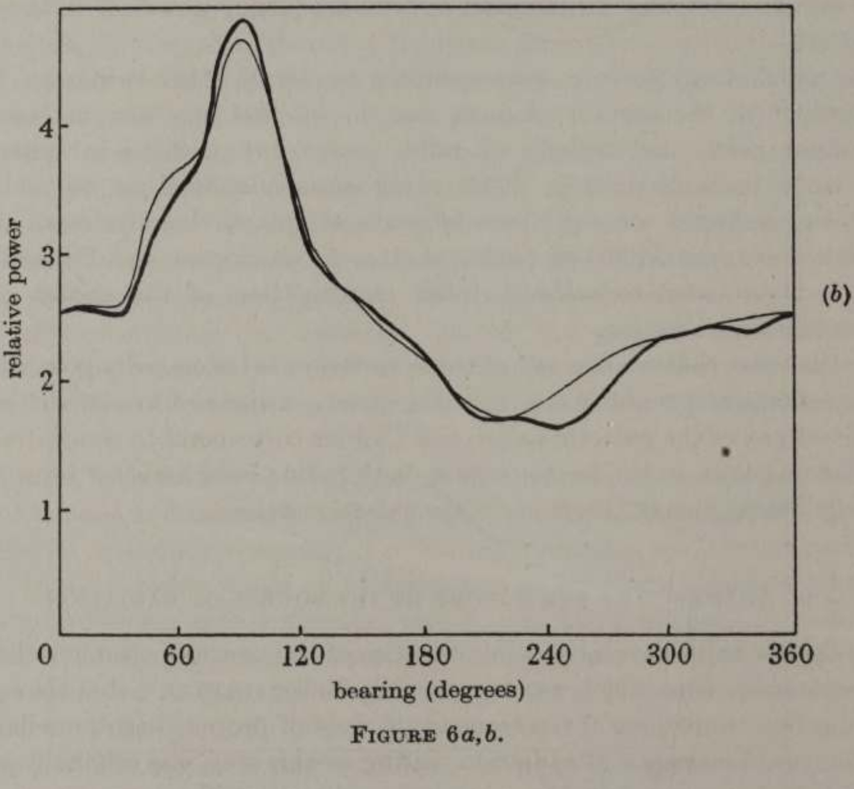

relative power
4
3
2
1
0
60
120
180
240
300
360
bearing (degrees)
(b)

FIGURE 6*a*, *b*.

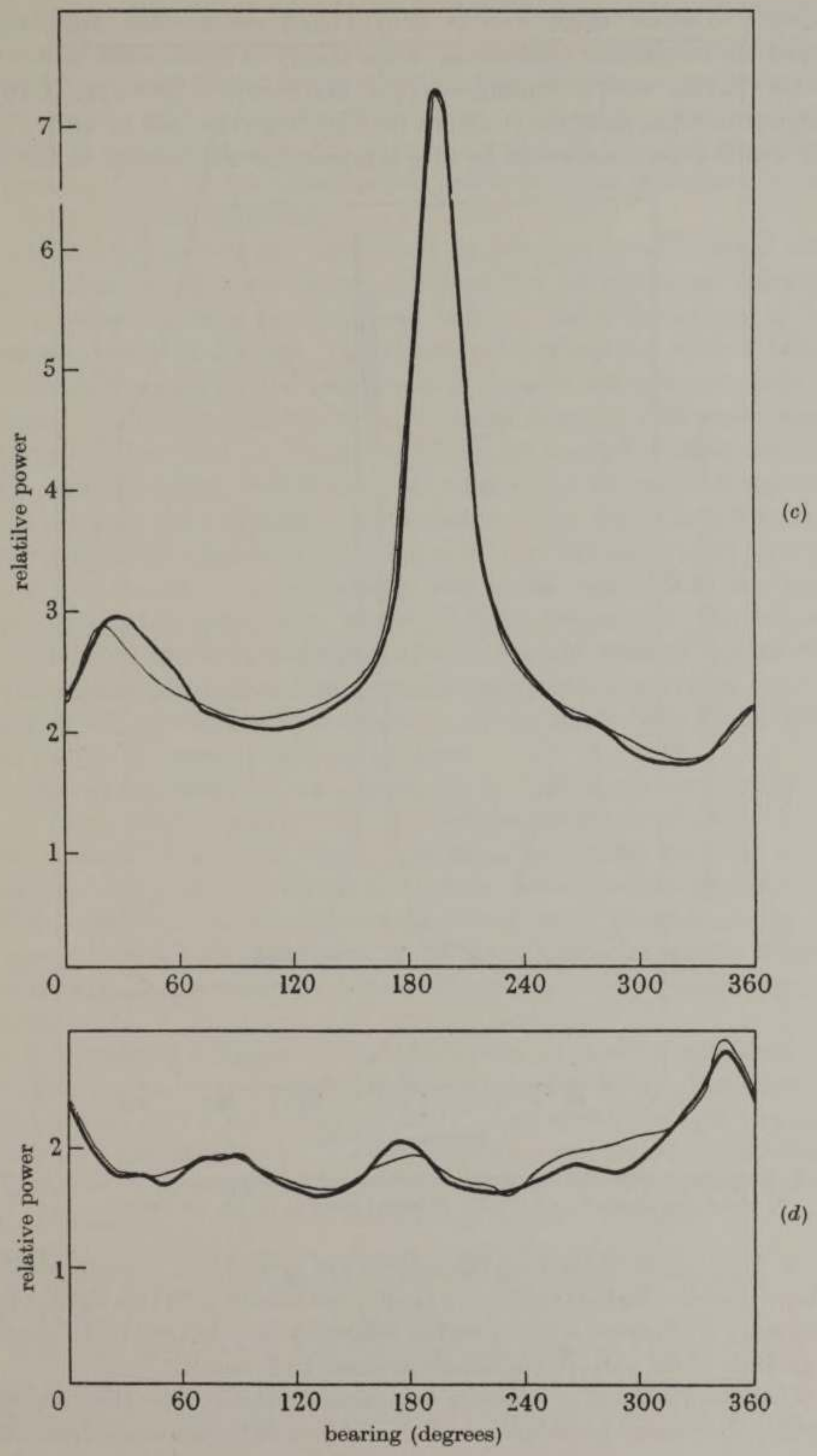


FIGURE 6 *a* to *d*. Comparison of observed power at the receiver with that calculated from the distribution shown in figure 4. Sidereal times (*a*) = 01 hr., (*b*) = 13 hr., (*c*) = 19 hr. and (*d*) = 07 hr. ━━ observed power, —— calculated power.

Henyey & Keenan (1940), Van de Hulst (1945) and Townes (1946, 1947) have developed the interstellar application of the theory in more detail, and it is in this connexion that the work of Strömgren (1939) and Struve & Elvey (1938, 1939*a*, *b*, *c*) is of interest (see § 8), since the electrons from hydrogen ionized by ultra-violet light from O and B type stars would be at a temperature appropriate to the observed radiation. The various writers on the subject are agreed that experimental results at 64 Mcyc./sec. and higher frequencies are in good accord with this theory, but that it is necessary to suppose a much higher temperature (150,000° K) to account for the magnitude of the galactic radiations at lower frequencies.

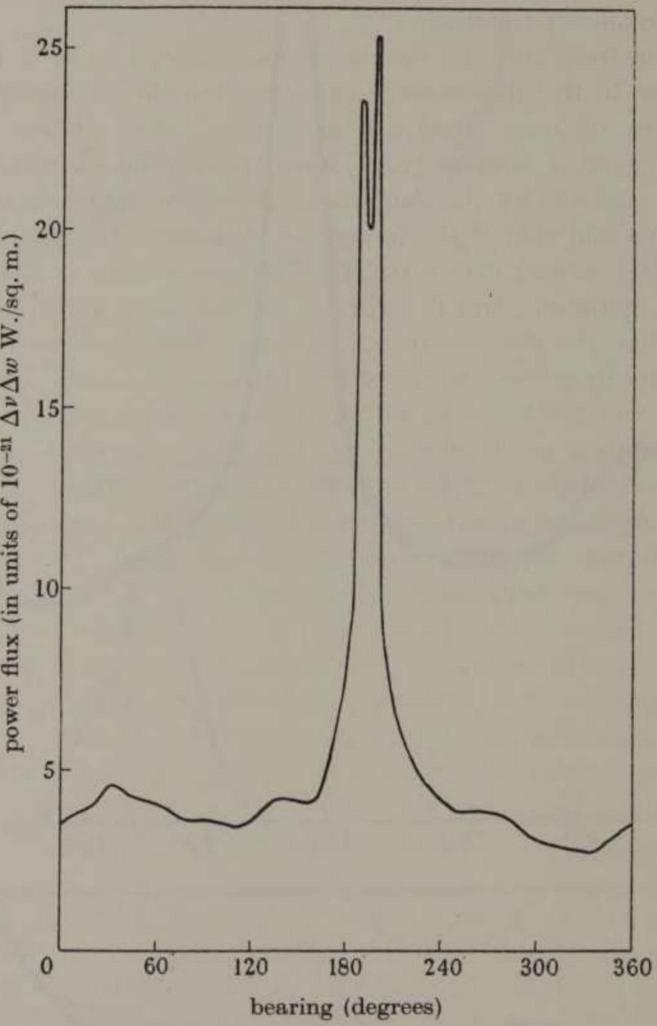


FIGURE 7. Example of distribution of radiation source for comparison with figure 6c. Latitude of observing station = 51° 27′. Sidereal time = 19 hr., elevation = $12\frac{1}{2}$°.

The other theories have one feature in common, namely, that they are based on the recently discovered phenomenon of the intense radio emissions from sunspots

(Appleton 1945; Hey 1946; Appleton & Hey 1946); it appears probable that there would be similar radiations from stars. The nature of the origin of the solar radiations is at present largely a matter for speculation, and the various suggestions made by different workers will not be elaborated here. A useful account has been given recently by Reber & Greenstein (1947) in a survey of all the available information, up to January 1947, on the experimental and theoretical researches on solar and cosmic radio-frequency emissions.

The radiation from any one star would be expected to show large variations, similar to those in the intense solar radiation, but the integrated radiation from a great number of stars could appear steady. Both Reber (1944) and also Greenstein, Henyey & Keenan (1946) have pointed out the serious difficulty in attempting to account for the magnitude of galactic radiation in terms of solar phenomena. We find that if the power radiated from the Sun at a frequency of 64 Mcyc./sec. is averaged over a period of several months in 1946 and compared with the light radiation, and if a similar comparison is made for regions of the Milky Way, then the radio-frequency radiation from the Milky Way is proportionately greater by a factor of the order of 10^7 (i.e. 18 magnitudes). It is possible, of course, that the Sun is not an average star in this respect, and that some stars emit proportionately much more energy at radio frequencies. Further, we have shown that much of the radio-frequency radiation may traverse regions where the attenuation of light is so great that normal stars are no longer visible, but where the attenuation of radio-frequency radiation may be small. This factor alone may account for the discrepancy referred to above.

The marked variations we have observed in Cygnus are very similar to those observed in sunspot radiation, of which examples are given in figure 8 *g* to *i*. It is felt that a theory in terms of widely distributed interstellar gas does not readily account for such localized disturbances. It seems that such radiations could originate only from a few discrete sources of comparatively small dimensions. On the other hand, the radiation from most parts of the sky is characteristically steady, much more so than one would expect if conditions in the direction of Cygnus were generally applicable.

The experimental evidence of the distribution of galactic radiations does not enable us to reach any firm decision in favour of either theory. The general lack of correlation with visible light, and the fairly good correlation with known distant stars, whether partially obscured or not, makes it seem probable that most of the radio-frequency radiations come from the main body of the galaxy and are subject to little attenuation. Attempts to find a closer correlation either with certain types of stars or with regions of ionized gas are equally unsuccessful.

Radiation from most parts of the sky is notably steady and consistent with the theory of a distributed source, but that from Cygnus is a marked exception. In our view, it is most likely that the observed galactic radiation originates from a combination of both types of source and that there are in the Cygnus region stars with particularly active 'star spots', or disturbed stars much nearer to us than is usual.

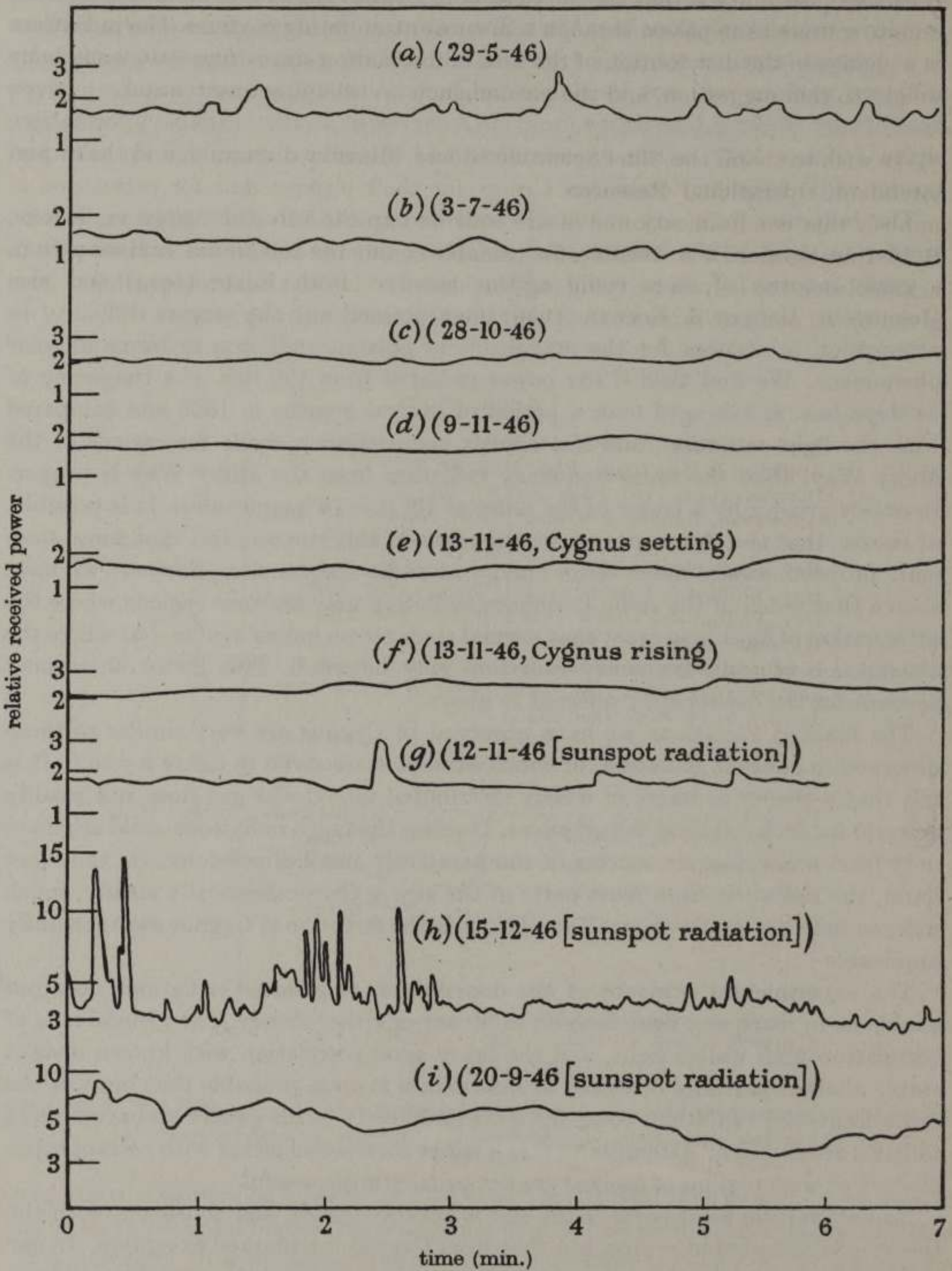


FIGURE 8. Fluctuations in galactic and sunspot radiations. (*a*) to (*f*) = galactic radiations (Cygnus region). (*g*) to (*i*) = sunspot radiation.

A further possibility is that the fluctuation in Cygnus is imposed on radiation from remote sources as it passes through some near attenuating medium. The indication of a change in the distribution of the area of fluctuation since June 1946 lends some weight to this suggestion, and the phenomenon is still under observation.

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