A SURVEY OF COSMIC RADIO EMISSION AT 600 Mc/s

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Summary

The results are given of a survey of cosmic radio emission at 600 Mc/s between declinations 90 °S. and 51 °N. using a 3°·3 wide beam. Isophotes are plotted in a system of celestial coordinates (epoch 1955).

The determination of radio spectra from surveys at different frequencies is discussed. A vital factor which tends to be neglected is the allowance made for side and back aerial lobes; a method of making such allowance is suggested.

The possible sources of the emission are discussed. Away from the galactic plane the radiation is non-thermal. On the galactic plane and near the galactic centre the evidence, while not conclusive, suggests a mainly thermal origin.

The radio isophotes are used to determine a galactic pole. In Lund coordinates this is at $l\sim330°$, $b=89°\cdot1$ with the Sun at a distance of about 50 parsecs north of the galactic plane.

I. Introduction

A survey of cosmic radio emission at 600 Mc/s has been made over most of the celestial sphere between declinations 90 °S. and 51 °N. from a field station near Sydney, N.S.W. In a previous communication (Piddington and Trent 1956) the localized sources found during the survey were discussed. In the present paper the general background of radiation is described.

Radio surveys of the whole southern Milky Way are available at 200 Mc/s (Allen and Gum 1950) using a beam of width 25°, and 100 Mc/s (Bolton and Westfold 1950) using a beam of width 17°. Attempts were made to deduce from these surveys the true brightness distribution by making allowance for the blurring effect of the wide aerial beam. It is now known that detail lost because of finite beamwidth cannot be recovered by subsequent graphical or other processes (Bracewell and Roberts 1954) and that the 100 Mc/s and 200 Mc/s plots of brightness distribution in the region of the galactic plane cannot be accepted as even approximately accurate. No full survey has been made with a narrower beam.

The present survey was made with a beam of width 3°·3 between half-power points. No attempt is made to reconstruct the observed brightness distribution plot to correct for the aerial beamwidth. Any structure smaller in size than this width is lost.

The aerial system, radiometer, and calibration equipment have been described in the previous (discrete source) paper and will not be discussed further. The observations were made by setting the aerial at a fixed declination

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and allowing the emitting regions to pass through the stationary beam. The declination was then changed by $1\frac{1}{2}°$ and the process repeated. Several repetitions of some plots were made to eliminate the effects of external interference and random drifts in the equipment. All plots were repeated at least once.

II. Results

The experimental results were reduced in the usual manner to a system of isophotes giving the aerial beam temperature* for any direction. The temperatures† are not absolute but above a minimum value, which persists in the cold parts of the sky, and which is discussed in Section III. The plot is shown in Figure 1 (Fig. 1 (*a*) shows the full plot, Figs. 1 (*b*), 1 (*c*), and 1 (*d*) enlarged sections) in celestial coordinates (epoch 1955). To allow estimates to be made of the different degrees of " blurring " which might be expected in different parts of the plot the aerial response diagram is included. It should be noted that when the beam is swung north or south of the celestial equator the width in minutes of Right Ascension increases as the secant of the declination angle.

Discrete sources which lie within or near a contour line have been retained in the plot. This is desirable since their separation from the background is often a matter of judgement. The strongest sources, such as those in Cygnus near Dec. 40 °N., are enclosed by several contour lines. The weakest sources do not raise the intensity by even one contour interval; these are outlined by dotted lines. Several examples are seen near R.A. 12^{h}, Dec. 60 °S. Isolated sources, lying outside the minimum intensity contour, are not shown but a full list of all sources has been given in an earlier paper (Piddington and Trent 1956).

The general pattern of brightness distribution is similar to those in earlier surveys. It closely follows the Milky Way, the lowest measurable level of brightness extending out to 40° latitude but generally being confined to 25° or less. The outstanding features of different surveys change with frequency and beamwidth and in this survey they comprise the " galactic nucleus " (17S2A), the sources in Cygnus (19N4A and 20N4A), the main Centaurus source (13S4A), and the main Taurus source (05N2A) in that order followed by a string of sources lying nearly on the galactic plane and probably comprising thermally emitting H II regions. The elongation of the sources near Dec. 60 °S. is due to distortion by the linear plot used.

The plot may be compared with that of Reber (1948) on the neighbouring frequency of 480 Mc/s. A common feature of both is the small amount of radiation received from the general direction of the anticentre where, at 600 Mc/s, there are large parts of the galactic plane yielding beam temperatures less than 5 °K above the background. A more detailed comparison reveals a difference between the two plots in this region (about R.A. 06^{h}). Reber's emission region

* The precise meaning of this term and its implications are described in Section III.

† The absolute temperatures may readily be obtained from Figure 1 by applying the corrections given at the end of Section III.

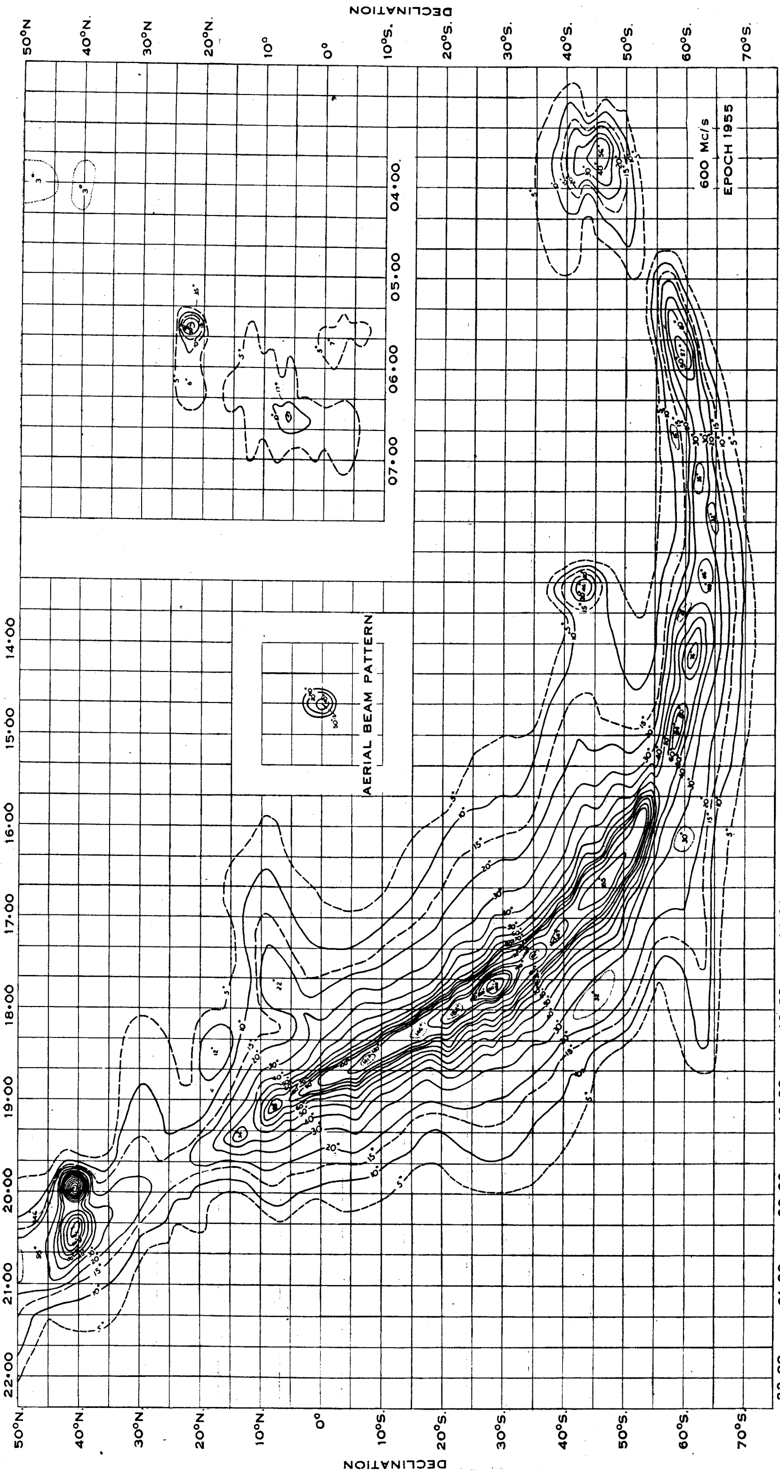

Fig. 1 (*a*).—Isophotes of cosmic radio emission. The quantity plotted is "beam temperature" which is defined as 100/65 times the observed effective aerial temperature. The full plot.

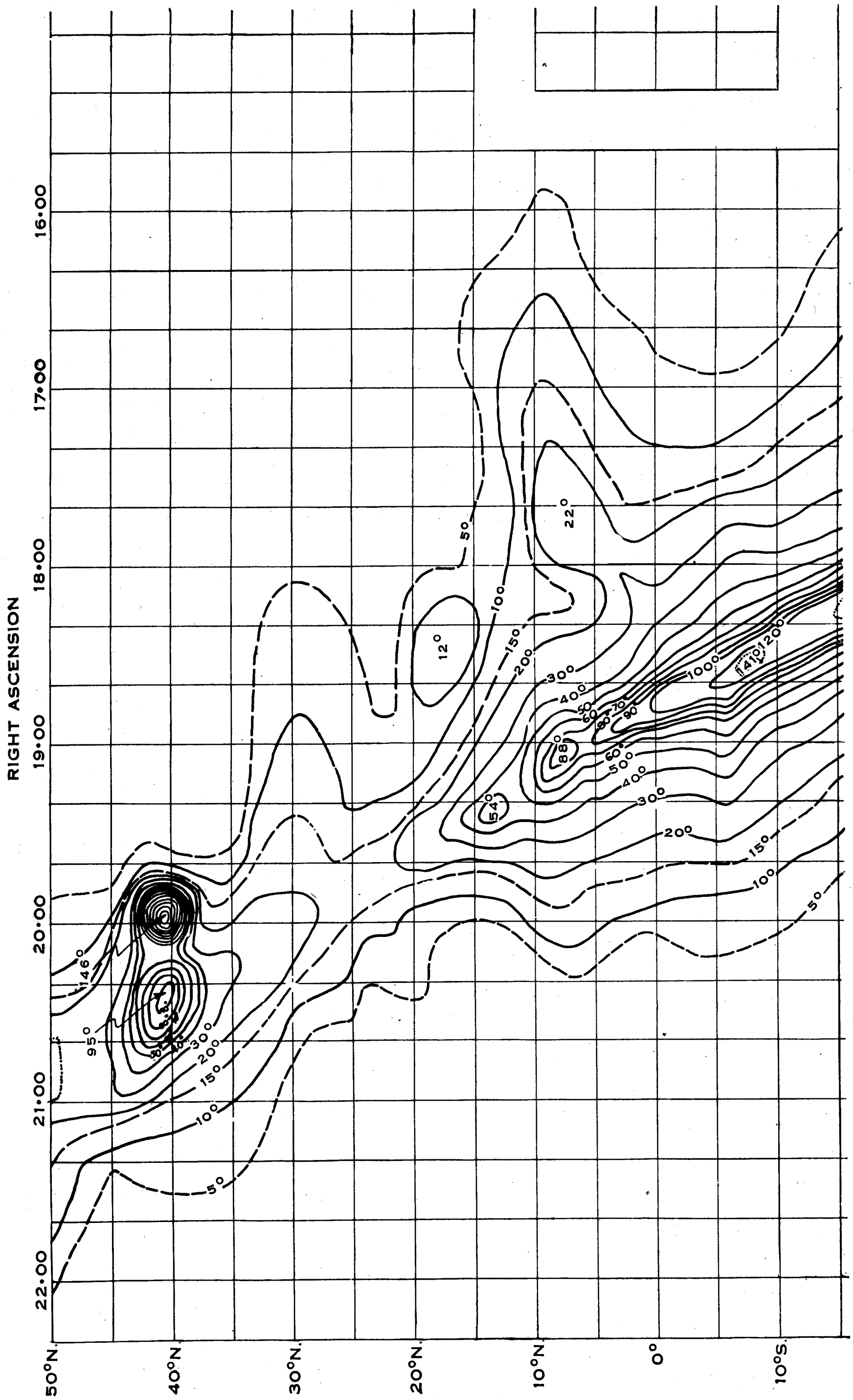

Fig. 1 (*b*).—Isophotes of cosmic radio emission. The plot of the northern sky.

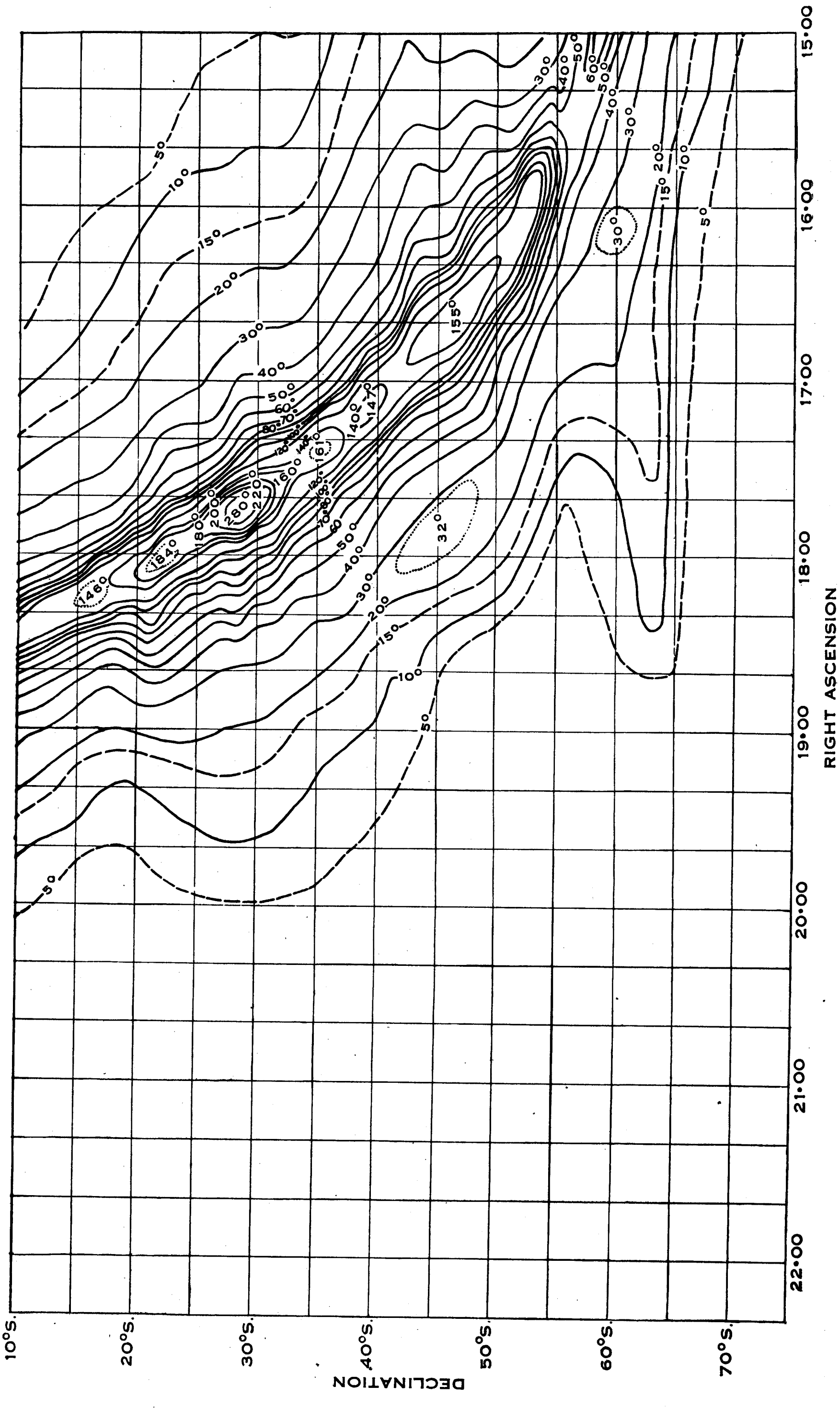

Fig. 1 (c).—Isophotes of cosmic radio emission. The southern plot R.A. 15^h to R.A. 22^h.

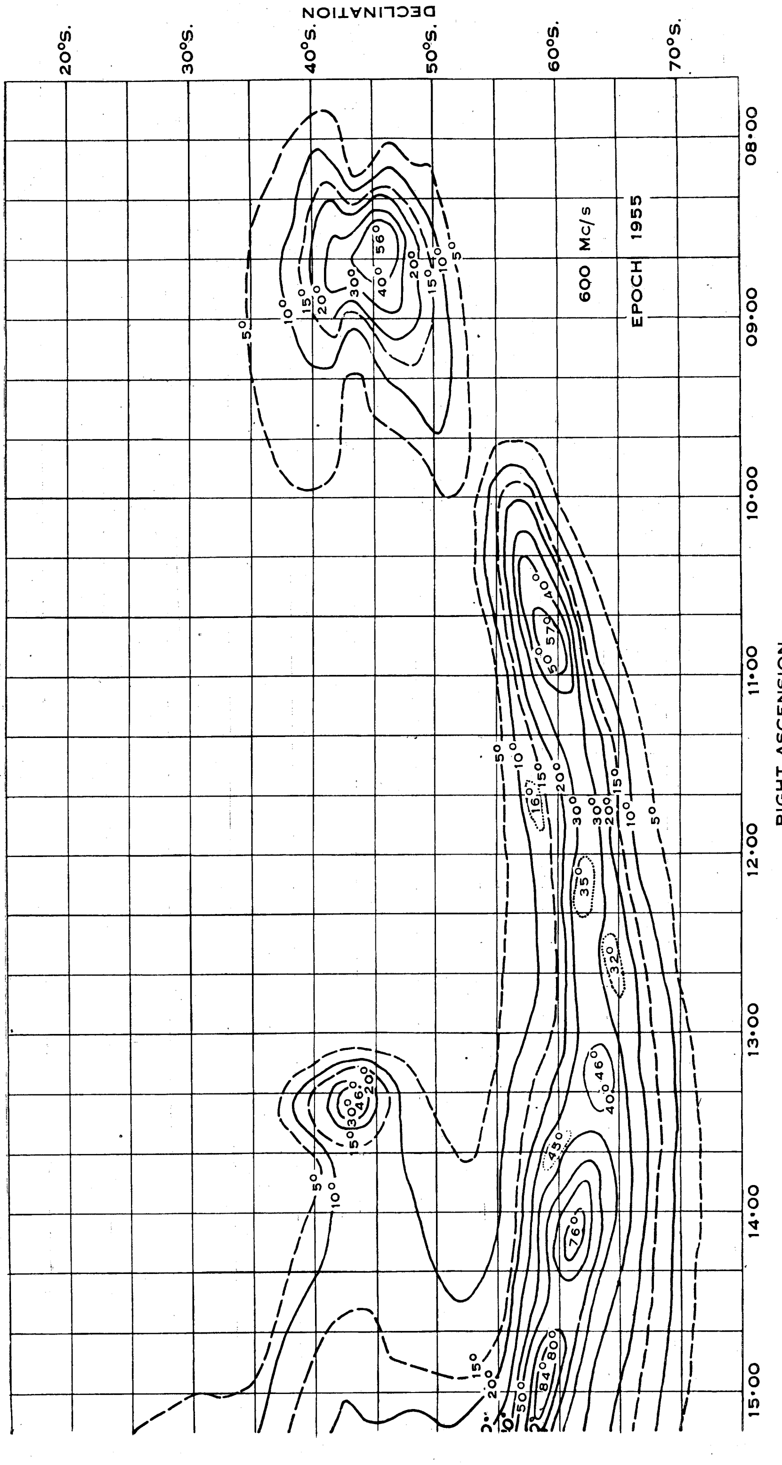

Fig. 1 (*d*).—Isophotes of cosmic radio emission. The southern plot R.A. 08^h to R.A. 15^h.

extends from about Dec. 2 °S. to 28 °N. while the present plots show a main region between Dec. 6 °S. and 17 °N. together with two or three discrete sources clustered at about 22 °N.

III. Accuracy of the Plot

Before discussing sources of error in the plot it is desirable to decide just what should be the quantity plotted. Broadly speaking, a well-designed aerial system of the type used in the present survey when used to transmit, radiates about two-thirds of the total power into the main beam. The remaining one-third is scattered over the whole of the rest of a sphere concentric with the aerial (into the so-called " side lobes "). Similarly, when receiving energy we may consider the equivalent aerial resistance as composed of two parts, the first, of two-thirds the total, being exposed to radiation from the main lobe and the second, of one-third, to radiation from the side lobes. Evidently, when the main lobe is directed at a region of brightness temperature T and the side lobes at regions of zero temperature, the measured aerial temperature is $2T/3$. What we call the " beam temperature " is then 3/2 times the measured aerial temperature, that is T.

This idealized case is never realized during a survey. Radiation from the ground and from some bright parts of the sky enters the side lobes at all times and the sum total of this radiation will vary as the aerial moves or as the Galaxy passes overhead. However, in the present survey, the aerial is never moved during an observation and only aerial temperature differences are measured. This completely cancels out the effects of ground radiation. It would be virtually impossible to integrate the varying contributions entering the side lobes from the Galaxy both directly and via ground reflection. To do so would require a detailed knowledge of the whole three-dimensional aerial pattern together with varying ground reflectivity, the whole to be combined with the as yet unknown plot of sky brightness. However, because of the wide scatter of the side lobes and the small angular extent of the bright parts of the sky, it is a reasonable approximation to assume that the energy entering the side lobes over a period required for the Galaxy to pass through the main beam is constant. The error involved is never likely to reach 10 per cent. for any of the brighter areas of the survey.

In the plot of Figure 1 changes in energy entering the aerial through side lobes are neglected and the measured aerial temperature is multiplied by a factor 100/65 (Piddington and Trent 1956) to give the plotted values of beam temperature.

The alternative method, of plotting equivalent aerial temperatures, has often been followed. In a personal communication Professor J. D. Kraus has kindly informed us that his intensity contours at 242 Mc/s (Kraus and Ko 1955) are neither aerial temperatures nor beam temperatures but approximately the mean value of the two. The plotted values are 1·26 times the aerial temperature, the beam temperature is 1·5 times the aerial temperature. This method might give more accurate values of brightness temperature in regions of low intensity. Summing up, it seems unimportant which method is adopted provided the method is clearly specified ; otherwise errors up to 50 per cent. are likely when making spectrum comparisons.

A second source of inaccuracy in the plot is the unknown base-level of radiation outside the 5 °K contour. In making the plot the zero level for each declination was that below which no decrease could be measured. Such a procedure is not justified at lower frequencies where variations in the minimum level are measurable. These measured variations at lower frequencies may be used to determine corrections at 600 Mc/s. The true zero level was estimated by combining the spectrum of emission from the coldest parts of the sky (near

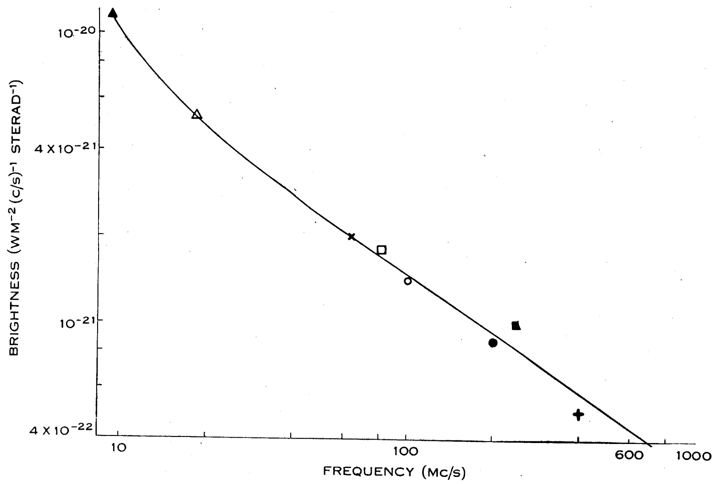

Fig. 2.—The observed cosmic radio spectrum from the coldest parts of the sky (near R.A. $09^h\ 50^m$, Dec. $+22°$ and R.A. $04^h\ 30^m$, Dec. —37°) in units of brightness.

▲ Higgins and Shain (1954). △ Shain (1951). × Hey, Parsons, and Phillips (1948). □ Baldwin (1955). ○ Bolton and Westfold (1950). ● Piddington (1951), a theoretical estimate based on the survey of Allen and Gum (1950). ■ Kraus and Ko (1955). + McGee, Slee, and Stanley (1955).

R.A. $09^h\ 50^m$, Dec. $+22°$ or R.A. $04^h\ 30^m$, Dec. $-40°$) with a general plot of brightness at a lower frequency where brightness in these regions has been measured. The best available data are combined in Figure 2 to provide the required spectrum curve. If this curve is extrapolated to 600 Mc/s the brightness is about $4 \cdot 5 \times 10^{-22}$ W m^{-2} (c/s)$^{-1}$ sterad^{-1}, corresponding to a brightness temperature of 4 °K. This figure gives the base level at declinations where the aerial beam passes over the coldest parts of the Galaxy. At other declinations the base level will be slightly higher and may be estimated by comparing Figure 1 with a plot for a frequency at which absolute levels have been measured and assuming the distribution at the two frequencies broadly similar. The highest frequency at which such measurements are reasonably easy and accurate is about 100 Mc/s and so the isophotes of Bolton and Westfold (1950) are used.* The absolute levels were determined at points where our 5 °K isophotes intersected lines of constant declination of values 30 °N, 0°, 30 °S., and 60 °S. The levels, adjusted to 600 Mc/s by means of Figure 2, ranged from 9 to 13 °K, with an average value of 10·7 °K. Thus the base level ranged from 4 to 8 °K, with an average value of 5·7 °K.

To find absolute values of brightness temperature from Figure 1 a mean value of 5·7 °K may be added to the plotted value or the correction for the particular declination found as above; it should lie between 4 and 8 °K.

IV. The Origin of the Radiation

There are at least two sources of galactic radio emission, one being ionized hydrogen emitting thermally (Piddington 1951). It is now fairly certain that the second source is relativistic electrons emitting by the synchrotron process (Alfvén and Herlofson 1950; Kiepenheuer 1950; Shklovskii 1953; and others). The interpretation of surveys is greatly complicated by the fact that the emitting hydrogen also acts as an absorber of both the thermal and non-thermal radiation, the effect being significant at 100 Mc/s and increasing rapidly with decreasing frequency.

Estimates of the temperature of the hot hydrogen (H II) regions agree at about 10^4 °K. The cold hydrogen (H I) regions may be at 100 °K or less but as they emit and absorb negligible amounts of 600 Mc/s energy their presence may be ignored. The maximum brightness temperatures found in the survey are less than 300 °K so that, if all the emission were from H II regions, the maximum optical depth, averaged over the beam, would be less than 0·03. Thus absorption is negligible except perhaps by H II clouds which subtend angles much less than the beamwidth; these would obscure only small areas on the plot. It is reasonable to conclude that, within the limits of sensitivity of the equipment, all or nearly all galactic radiation is observed.

The proportions of thermal and non-thermal components in the observed radiation is more difficult to determine. From the early analysis (Piddington 1951) it was concluded that, at frequencies above a few hundred Mc/s, most of the radiation from regions near the galactic plane had a thermal origin. Objections to this conclusion were raised by Hanbury Brown (1953) on the grounds that the early observational data were not reliable and that the result is not consistent with visual evidence. He assumed, in developing a galactic model of radio sources, "that the majority of the galactic radiation observed towards the galactic centre at 480 Mc/s does not arise in ionized interstellar gas". This assumption appears to be based on the fact that the observed components of Baade's Population I are rare in the nuclei of spiral nebulae similar to our Galaxy.

There is now no doubt that the earlier plots of galactic emission were in serious error. However, the conclusions regarding the origin of galactic radiation

* Although inaccurate near the galactic plane, these should be satisfactory in the regions of reasonably uniform brightness with which we are concerned.

were based on general spectral trends, much of the data being obtained with aerial beams of more or less similar breadth. This tended to eliminate errors due to individual inaccurate plots so that the conclusions, while far from definite, should carry some weight. On the other hand Hanbury Brown's argument concerning galactic structure is based on optical evidence which is not yet adequate to determine the type of galaxy, so that inferences made from observations of " similar " galaxies are not justified.

More recently Mills (1955) has estimated the maximum proportion of the thermal component near the galactic centre. He divided the total observed radiation into a " spherical subsystem " and a " flattened subsystem " and found that, at 85 Mc/s, only 26 per cent. or less of the latter could be of thermal origin. Since the radiation from the spherical system is certainly non-thermal this would mean a proportion of thermal component in the total radiation of less than 20 per cent. If the non-thermal spectrum is similar to that shown in Figure 2 then the corresponding proportion of thermal radiation at say 200 Mc/s would be less than 32 per cent., in contrast with the earlier conclusion that most of the radiation was thermal. However, Mills's analysis seems open to question. To eliminate the contributions of the " spherical subsystem " and of the discrete source in this direction he divided the observed intensities at 85 Mc/s, 400 Mc/s, and 1210 Mc/s by factors of about 1·3, 2·6, and 1·0 respectively. Such estimated factors are subject to considerable uncertainty which is reflected in the derived ratio of the components. Thus if the observed intensities are compared directly,* then the possible proportion of thermal radiation at 85 Mc/s could be about 50 per cent.

This raises the question of the division of the non-thermal galactic radiation into the two subsystems mentioned above. As evidence Mills (1955) states that the galactic sections of his Figure 6, with the sharp peaks (the " flattened subsystem ") removed, all have maxima at the Right Ascension of the galactic centre. This conclusion depends on the amount of peak which is shaved off. An alternative interpretation which appears to fit the data equally well is that the non-thermal emission constitutes a single spheroidal system of variable emissivity per unit volume, the latter increasing towards the galactic plane where the thermal radiation is also concentrated. This interpretation lies between those of Shklovskii (1953), who perhaps overestimated the part played by the thermal component, and Mills, who may have underestimated it.

At the galactic crossing at $25\frac{1}{2}$ °S. (a region of high intensity yet reasonably free of discrete sources) a comparison was made of the brightness at frequencies of 242 Mc/s (Kraus and Ko 1955), 400 Mc/s (McGee, Slee, and Stanley 1955), and 600 Mc/s (the present survey). To obtain beam temperatures the 242 Mc/s data were multiplied by 1·19 (see Section III) and the 400 Mc/s data by 1·5

* The 1210 Mc/s data with which one of the authors was associated (Piddington and Minnett 1951) are *aerial* temperatures. The conversion factor to beam temperatures was never determined but is likely to be much higher than 1·5 because the feed dipole was located away from the focal point and among several other dipoles. Furthermore, the reflector was subject to sag and distortion. It is undesirable, therefore, to use these data in determining spectra.

(a factor kindly provided by Mr. R. X. McGee, personal communication). The intensities in power units fall within ± 4 per cent., the 242 Mc/s value being the lowest and the 600 Mc/s value the highest. This result provides considerable evidence in favour of a preponderance of thermal radiation. Some measurements at 900 Mc/s (Denisse, Leroux, and Steinberg 1955) do not appear to be consistent with such a conclusion, however, unless the aerial beam used was much wider than at the lower frequencies. The 900 Mc/s intensity falls well below those at the other frequencies.

Optical evidence (the absence of H II clouds) shows that emission from regions well away from the galactic plane must be non-thermal.

V. The Radio Galactic Equator and Position of the Sun

The combination of the narrow beam used and the wide extent of the present survey may make it useful in redetermining the position of the galactic equator and estimating the distance of the Sun above the galactic plane. If the conclusions of the last section are correct then the " galaxy " in question is largely the H II distribution.

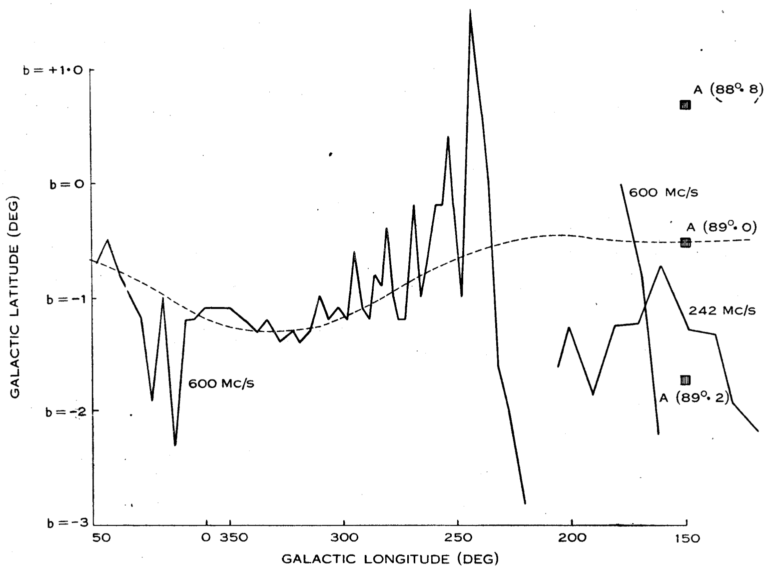

FIG. 3

Fig. 3.—The position of the ridges of maximum brightness at 600 and 242 Mc/s and of a hypothetical galaxy (galactic coordinates, Lund pole).

In Figure 3 the position of the ridge of maximum intensity of radio emission is plotted in galactic coordinates ; the Lund tables were used and correction made for changes in the celestial coordinates since epoch 1900. The plot covers longitudes between 50°, through zero, to 220° and is shown by the full line marked 600 Mc/s. The other lines are discussed below. It is evident that only within about $\pm 40°$ of the galactic centre (near $l \sim 330°$) is the curve smooth.

This is because radiation from this region is the integrated emission from numerous sources lying at all distances up to perhaps 20,000 parsecs. Beyond this sector the plot is increasingly irregular since the radiation originates in fewer and closer sources. The statistical value of the plot in the region $l \sim 330°$ is very much greater than elsewhere. The maximum displacement between the Lund equator and the 600 Mc/s radio equator lies in this sector and so may be determined with considerable accuracy. However, the galactic longitude at which this maximum occurs cannot be accurately determined. The displacement is $1° \cdot 3$ with an error probably not more than $0° \cdot 1$; this maximum occurs near $l=330°$.

The equatorial displacement of $1° \cdot 3$ is due to the combination of two factors: the radio pole is displaced from the Lund pole and the Sun is displaced from the radio equatorial plane. It is desirable to estimate the approximate relative importance of the two factors; this is done on the assumption that the Galaxy is circularly symmetrical and of diameter 19,000 parsecs with the Sun 1600 parsecs from the outer edge.

A configuration corresponding to the radio pole lying at $b=89° \cdot 0$ (and $l \sim 330°$) is shown by the dashed curve of Figure 3. The corresponding position of the Sun is 42 parsecs from the equatorial plane. Corresponding curves with the pole at $88° \cdot 8$ and $89° \cdot 2$ would coincide with the dashed curve near $l=330°$ but diverge to pass through the squares marked A ($88° \cdot 8$) and A ($89° \cdot 2$). The dashed curve appears to give the best fit.

Also shown in Figure 3 is a plot of the radio equator near the galactic anticentre obtained at 242 Mc/s by Ko and Kraus (1955). These data favour a displacement of the galactic pole to about $89° \cdot 1$ with a solar distance of 56 parsecs.

Either of the above polar positions agrees well with that of van Tulder (1942); from a wide array of optical evidence he set the pole at $l=328°$, $b=89° \cdot 0$. His solar displacement was much smaller, however, at $13 \cdot 5$ parsecs.

VI. Acknowledgments

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