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Galactic Radio Emission below 16·5 MHz and the Galactic Emission Measure

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Abstract

New maps of the distribution of the galactic background radio emission are given for wave frequencies of 2·1, 3·7, 4·7, 5·5, 8·3, 13 and 16·5 MHz. The angular resolutions of the observations were 7·5°, 6·8°, 3°×10°, 4·5°, 3·0°, 1·9° and 1·5° respectively. A map of the quantity $\int_0^L (N_e^2/T_e^{3/2})\,dr$ in galactic coordinates is obtained from an analysis of the changes in the radio brightness distributions with frequency. For an assumed electron kinetic temperature of 10^4 K, the emission measure is found to vary from 3·9 cm^{-6} pc near the south galactic pole to 140 cm^{-6} pc near the equator.

Introduction

Between 1962 and 1972, three large radio telescopes designed for observations of the galactic radio emission at low frequencies were built in Tasmania to take advantage of the unusually favourable ionospheric conditions known to occur there (Reber and Ellis 1956; Ellis 1965). During years of minimum solar activity, the ionospheric critical frequency in Tasmania normally falls below 2 MHz for periods of up to 12 h during winter nights, while the lowest frequency at which the galactic radiation has been observed is 0·9 MHz. The observations obtained with these telescopes still remain the only high angular resolution observations of the galactic background radiation so far made at low frequencies, the resolutions ranging from 7·5° at 2·1 MHz to 1·5° at 16·5 MHz. They showed that there are pronounced variations of the brightness distribution on these angular scales, especially for directions away from the galactic polar regions, and that, to be meaningful, any new observations using, for example, space telescopes should aim for at least similar resolution.

New maps of the background galactic radio emission have been produced from the original observations made available by Reber (1968; at 2·1 MHz), by Ellis and Hamilton (1966*a*; 4·7 MHz) and by Cane and Whitham (1979; 3·7, 5·5, 8·3, 13 and 16 MHz). Recent observations of the galactic radio spectrum in the direction of the south galactic pole at low frequencies (Novaco and Brown 1978; Cane 1979) have provided a new absolute intensity calibration for the data. In addition, it has been possible to increase the sky coverage of the maps through the inclusion of data not previously used and to improve the accuracy of the data reduction.

Observations

The 2·1 MHz telescope is a filled aperture array 1·075 km in diameter. It is operated as a transit instrument and has a single beam steered in declination. It was used to make observations of the galactic radiation between 1963 and 1967 (Reber 1968).

The 4·7 MHz antenna was a filled aperture array, 320 m north–south by 1280 m east–west, with a beamwidth $3° \times 10°$ (Ellis and Hamilton 1966*a*), which was also steered only in declination, but which can form six beams simultaneously at different declinations. The multiple beam operation and the higher observing frequency permitted the acquisition of sufficient observations to map the southern sky, in a period of five months in 1963. The signals were recorded on a multichannel chart recorder.

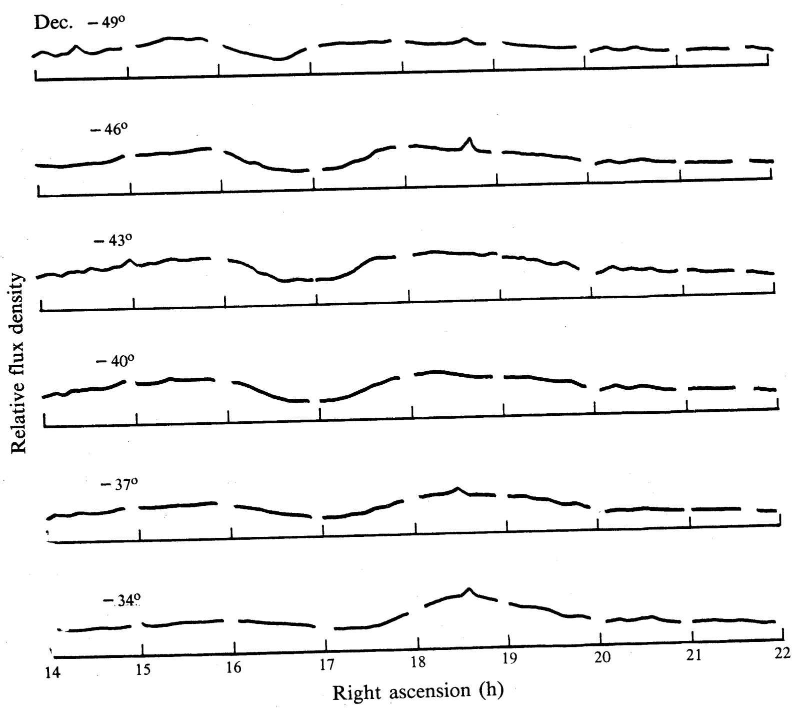
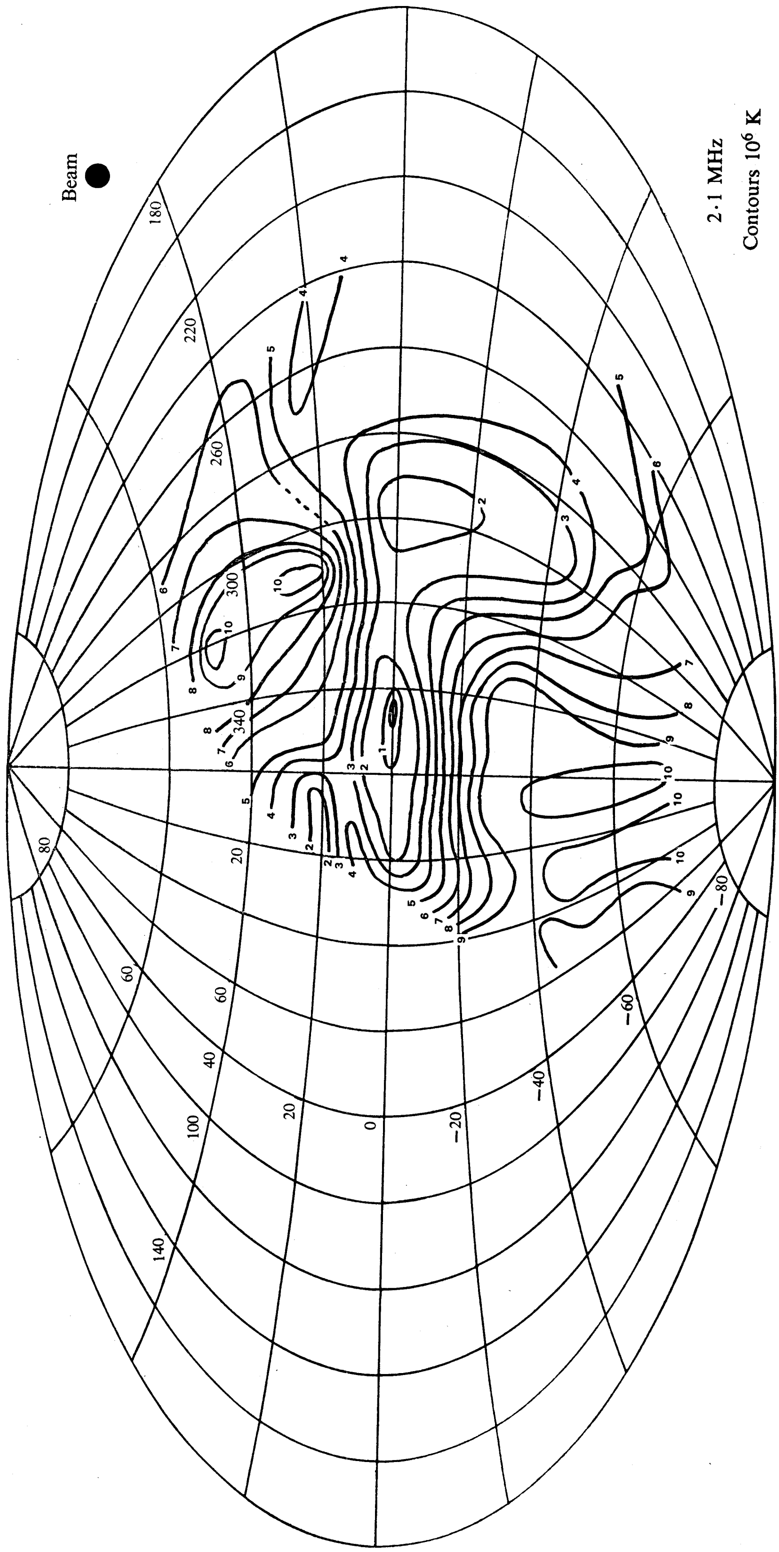


Fig. 1. Records of the galactic background radiation at 8·3 MHz obtained with the 630×630 m Llanherne telescope on 7 July 1975.

The observations at 3·7, 5·5, 8·3, 13 and 16·5 MHz were made with a filled aperture array, 630×630 m (Ellis 1972), which is capable of true broadband operation, that is, the signals over the frequency range 2–18 MHz are available simultaneously at the antenna terminals. The angular resolutions of the observations at the different frequencies were 6·8°, 4·5°, 3·0°, 1·9° and 1·5° respectively. The telescope is steered in declination under computer control, beam-switching taking 10^{-3} s. The beam was normally directed to 10 different declinations over a 5 min period, and the signals from receivers operating at the five specified frequencies were digitized and stored on magnetic tape. The tapes were used subsequently to produce printouts of the variation of signal intensity with right ascension for each declination. The observations were made in 1974 and 1975. Examples of the records from this telescope are shown in Fig. 1.



Figs 2–8 (pp. 93–9). Contours of brightness temperature at 2·1, 3·7, 4·7, 5·5, 8·3, 13 and 16·5 MHz.

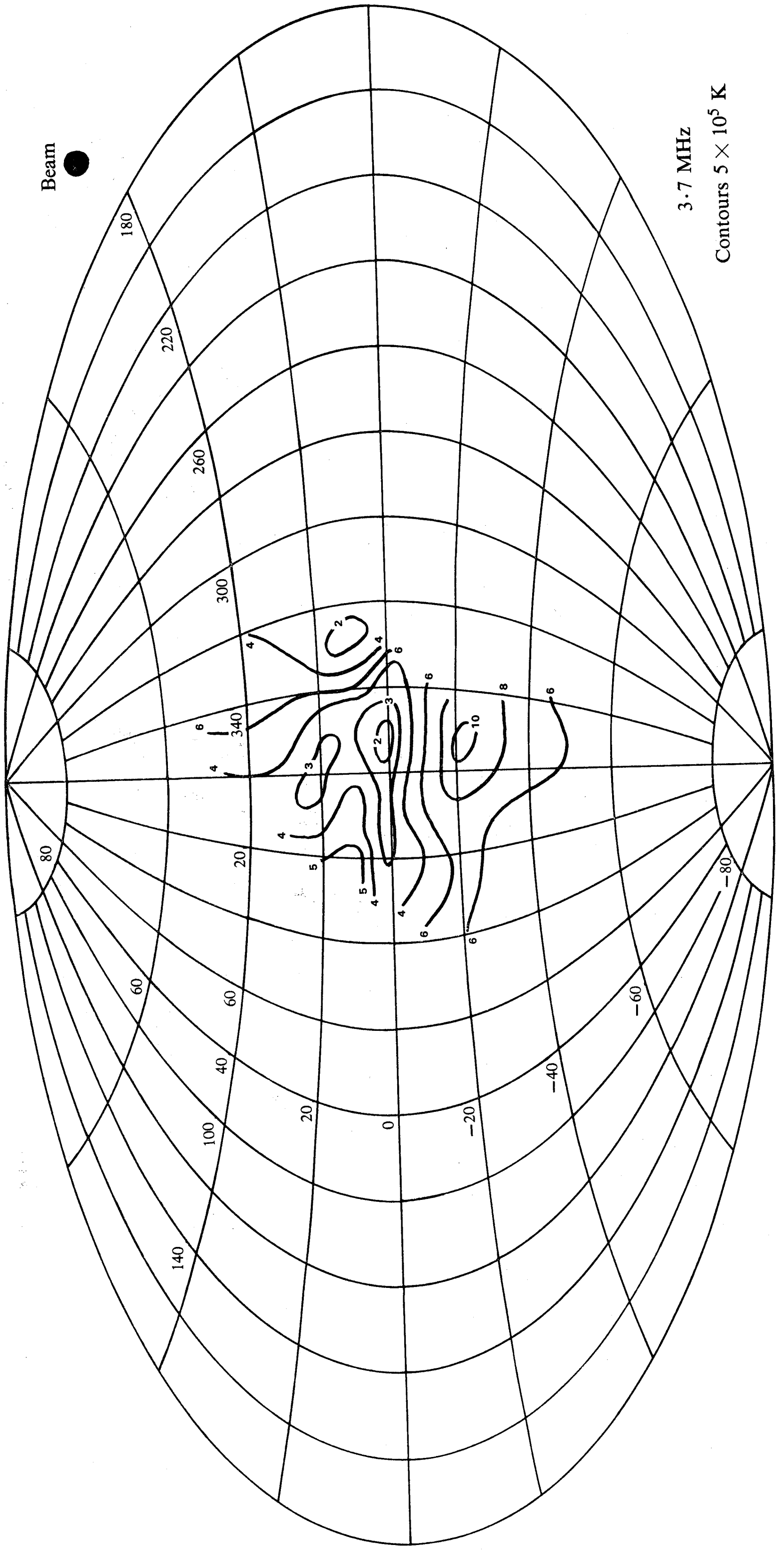

Beam
3·7 MHz
Contours 5×10^5 K
180
220
260
300
340
20
60
100
140
80
60
40
20
0
−20
−40
−60
−80

Fig. 3

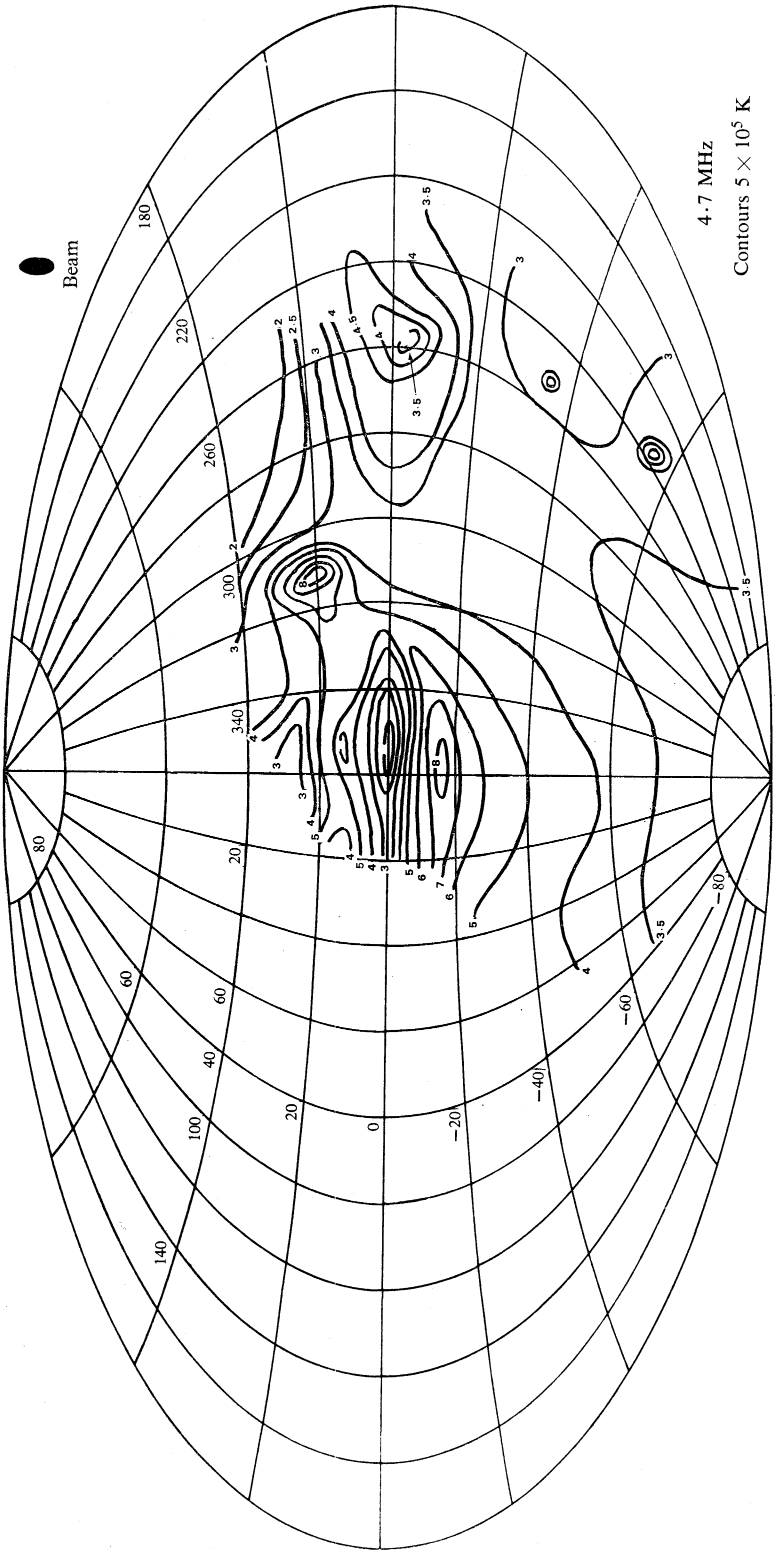


Fig. 4

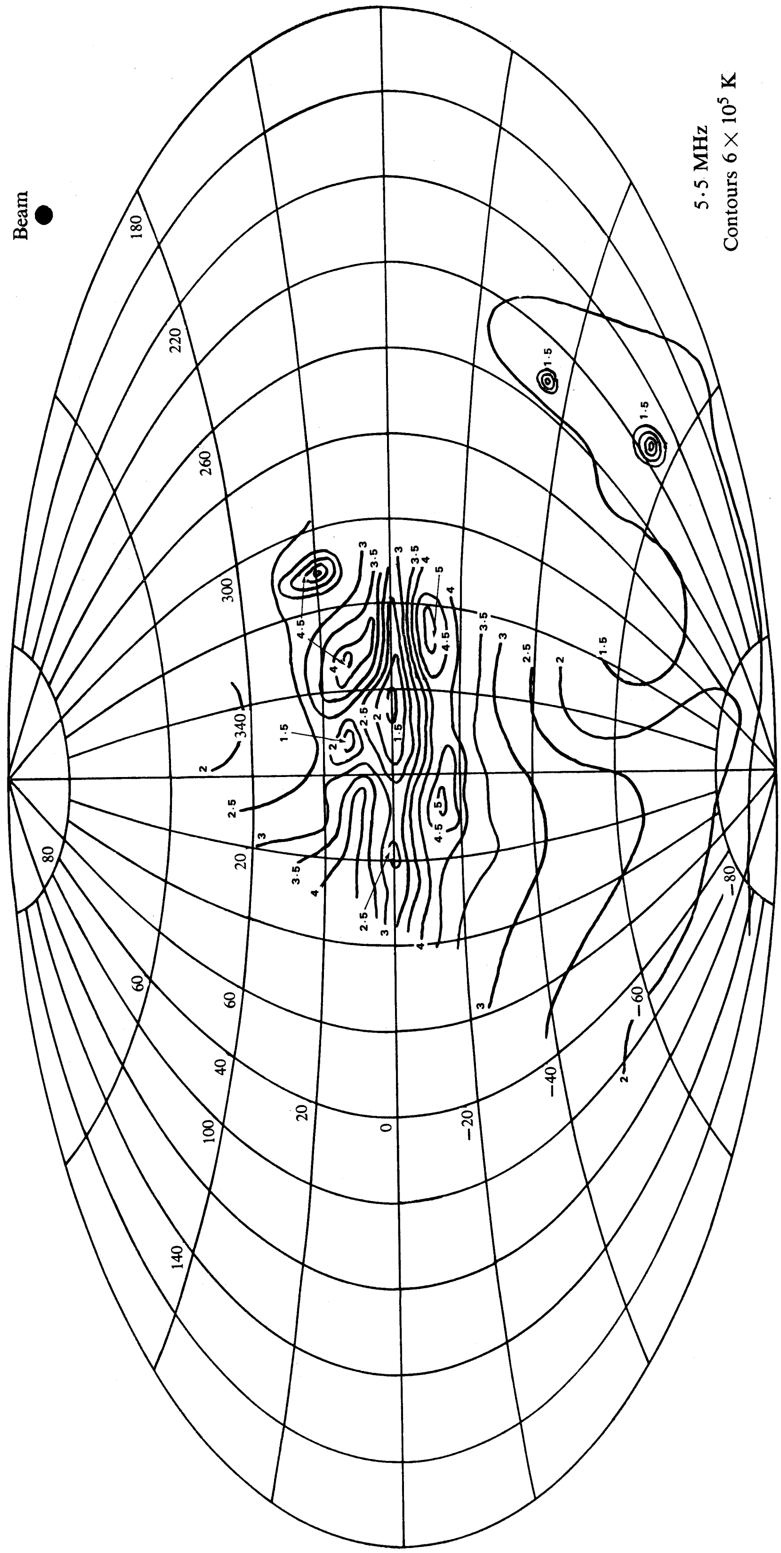


Fig. 5

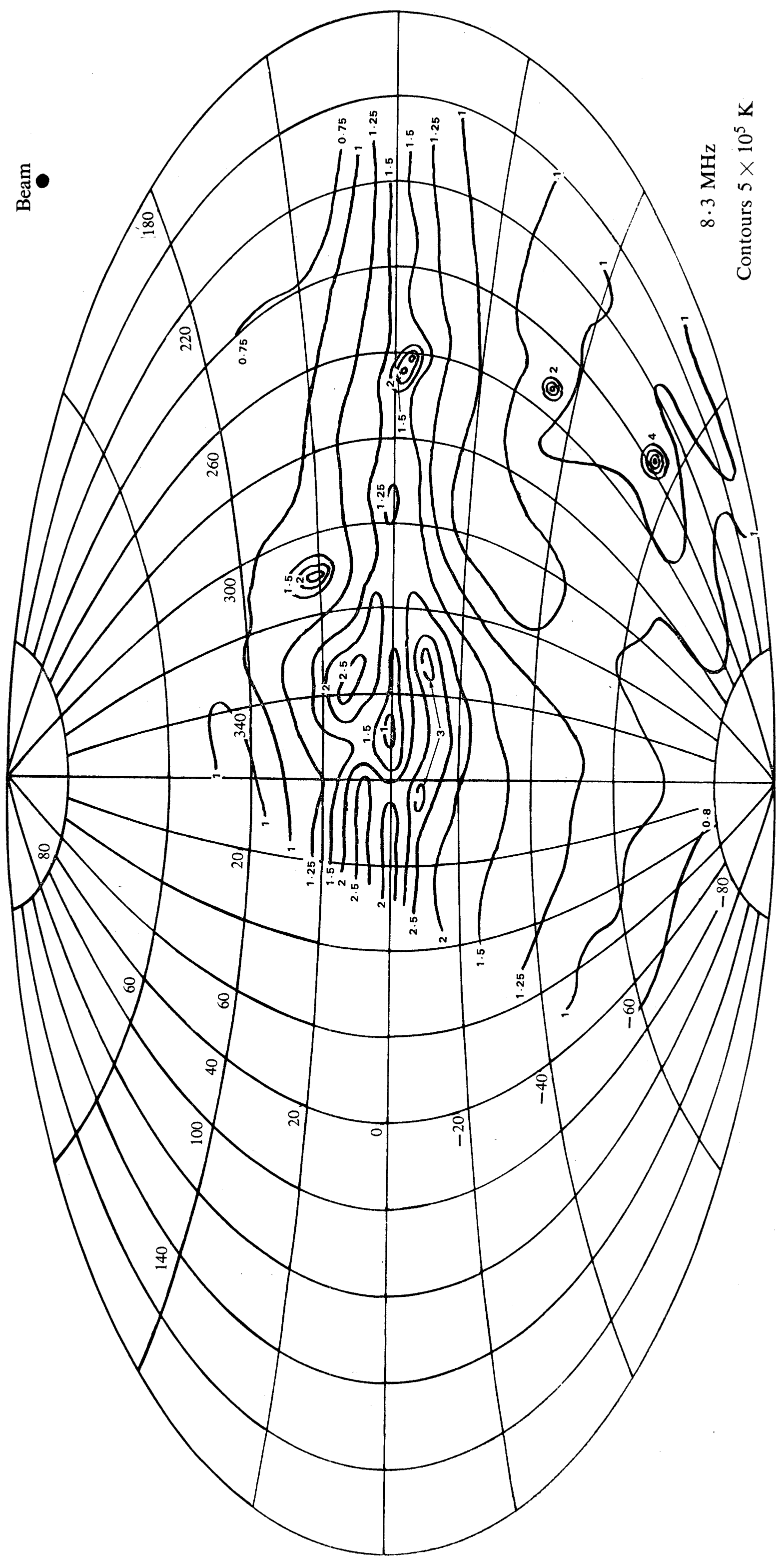

Beam
8·3 MHz
Contours 5 × 10^5 K
180
220
260
300
340
20
60
100
140
80
60
40
20
0
−20
−40
−60
−80

Fig. 6

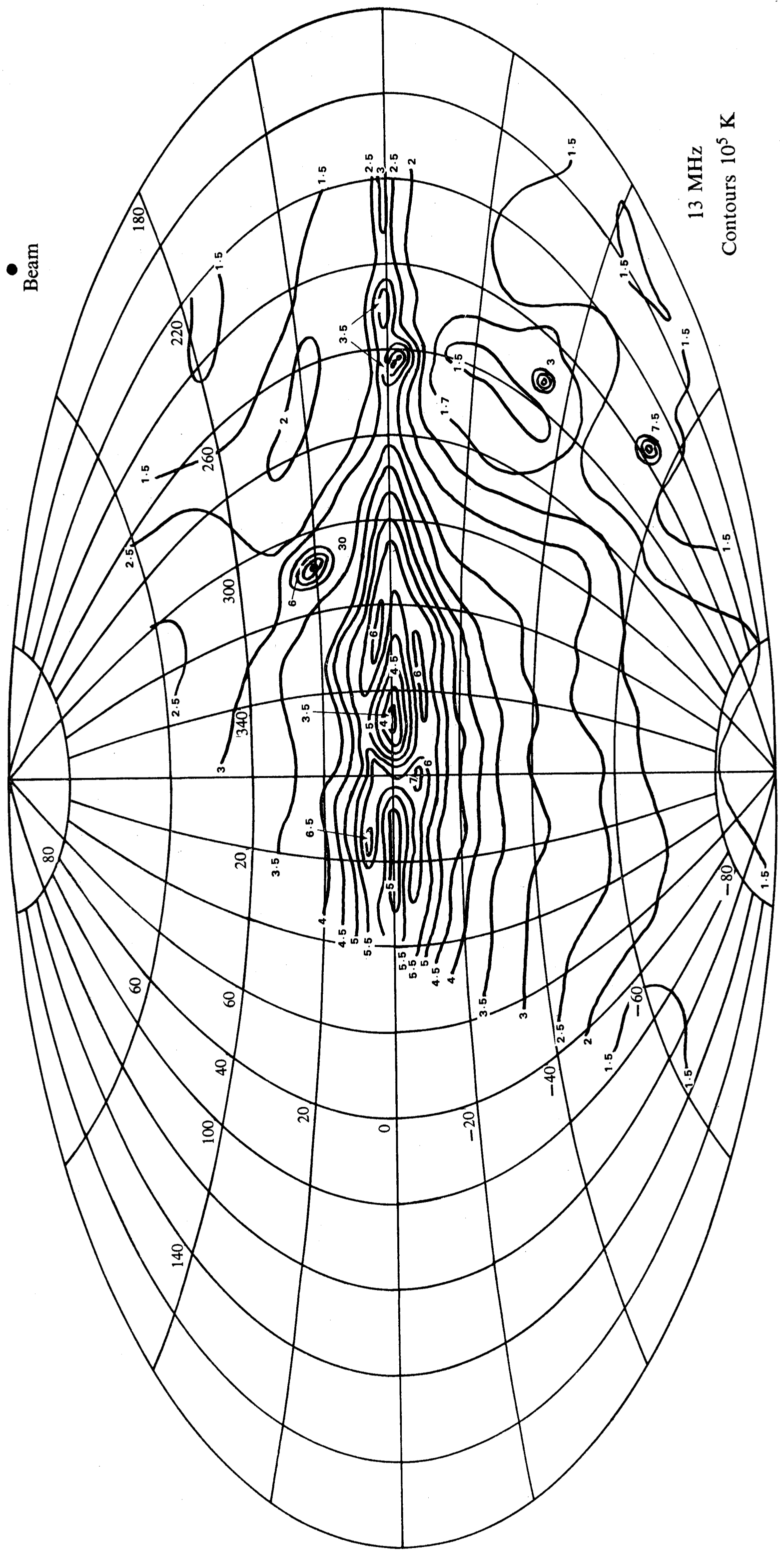


Fig. 7

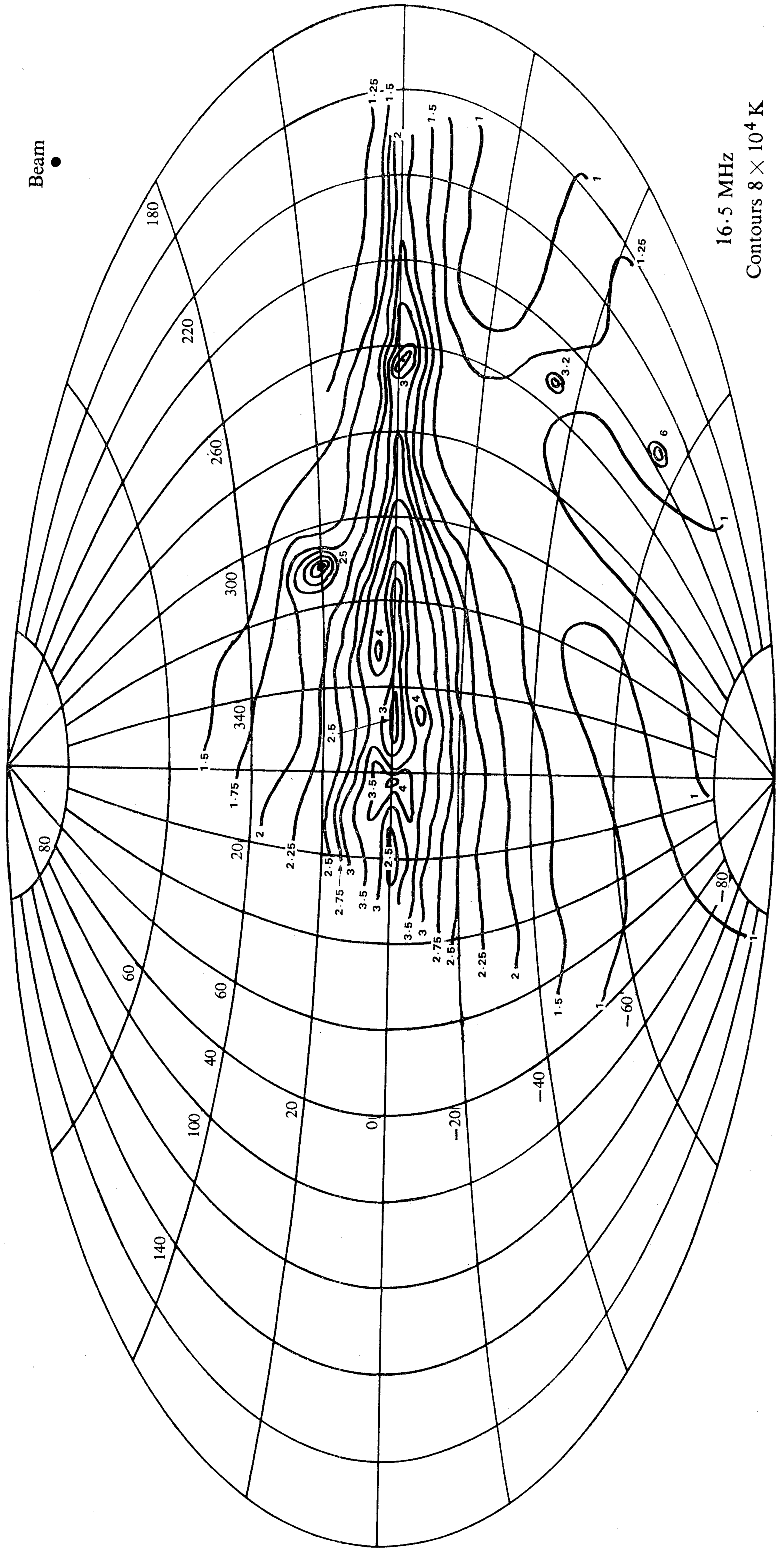

Beam
16·5 MHz
Contours 8 × 10⁴ K
180
220
260
300
340
20
60
100
140
80
60
40
20
0
−20
−40
−60
−80

Fig. 8

The efficiency of a large, low frequency array is affected by variable weather conditions such as moisture on the antenna elements and the transmission lines, and it is not feasible to use only internal noise generators for calibration of the system. The overall efficiency can only be determined by using an external source which in the present analysis was taken to be the galactic background radiation intensity in the vicinity of the south galactic pole. The absolute intensity spectrum in this direction can now be considered to be well established (Novaco and Brown 1978; Cane 1979).

In re-analysing the data, records were chosen which as far as possible included observations for directions near the pole region and hence could be calibrated. For each declination, the best records were selected for smoothness of trace, reproducibility and absence of transmitting station interference, and the average intensity versus right ascension was calculated. No correction for ionospheric absorption was made, since an analysis by Ellis (1965) showed that in the conditions of low ionospheric critical frequency in which the observations were made the total ionospheric attenuation would have been expected to be less than 0·2 dB.

Figs 2–8 show the variation of the background radiation with galactic coordinates for each frequency.

Analysis

The change in the background brightness distribution with wave frequency shown in Figs 2–8 may be used to determine the corresponding distribution of emission measure. The method of analysis is an extension of one used by Ellis and Hamilton (1966*b*) and developed further by Hamilton (1969), where it was assumed that the observed brightness is the sum of the effects of two regions: an extra-disc region remote from the Sun and in which there is emission but negligible absorption, and a disc region in the vicinity of the Sun in which there is both emission and absorption. The terms 'extra-disc' and 'disc' are convenient but do not necessarily imply an assumed shape for either region.

We assume that for the extra-disc region the total intensity at frequency f for a line of sight (l, b) is given by

$$S_{\mathrm{a}}(l,b) = A(l,b)f^{-\alpha} \qquad \mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}},$$

while for the disc region we take the emissivity per unit volume to be

$$E = 4\pi g(l,b)f^{-\beta} \qquad \mathrm{W\,m^{-2}\,Hz^{-1}}.$$

The absorption within the disc region is described by the optical depth τ at frequency f for a line of sight of length $L(l,b)$:

$$\tau = \xi f^{-2}\int_0^L \frac{N_{\mathrm{e}}^2(r,l,b)}{T_{\mathrm{e}}^{3/2}(r,l,b)}\,\mathrm{d}r,$$

where $N_{\mathrm{e}}(r,l,b)$ is the electron density, T_{e} is the electron kinetic temperature and ξ is a constant $\approx 0{\cdot}15$. The total intensity at frequency f for a line of sight in the disc region is then

$$S_{\mathrm{b}} = \frac{1}{4\pi}\int_0^L \left\{4\pi g f^{-\beta}\exp\!\left(-\xi f^{-2}\int_0^l \frac{N_{\mathrm{e}}^2}{T_{\mathrm{e}}^{3/2}}\,\mathrm{d}r\right)\right\}\mathrm{d}l = \frac{gLf^{2-\beta}}{K}\Big(1-\exp(-Kf^{-2})\Big),$$

where

$$K = \xi \int_0^L (N_e^2/T_e^{3/2})\, dr.$$

The total intensity for a direction (l, b) is

$$S(f) = S_a + S_b = Af^{-\alpha}\exp(-Kf^{-2}) + Bf^{2-\beta}\{1-\exp(-Kf^{-2})\}, \qquad (1)$$

where the parameters A, B, α, β and K are all functions of the galactic coordinates l and b. In principle, all these parameters may be determined by fitting a curve of the form of equation (1) to the observational data. Radio spectra are usually plotted on a log–log coordinate system and it is necessary to apply the curve-fitting technique on a similar system also, to avoid giving excessive weight to the low frequency measurements. The method therefore consists of minimizing the function

$$F = \sum_i \{\ln S_i - \ln S(f_i)\}^2, \qquad (2)$$

where the S_i are the observed intensities at frequencies f_i, the $S(f_i)$ are the values of equation (1) at frequencies f_i, and the summation is over all data points. The values of the parameters at the minimum of F constitute the least squares solution of the problem. However, the standard methods of obtaining a least squares solution are not remotely possible because equation (1) remains nonlinear under all transformations of the variables. The process must be, therefore, an iterative one. Methods of locating the minimum of a function by iteration have been given by Fletcher and Powell (1965), and algorithms based on these methods have been developed by Hamilton (1970).

Although observations at six well-spaced frequencies are sufficient to permit a solution for the five parameters, the observations would have to be virtually error-free for the results to be significant. The easiest parameters to eliminate are the spectral indices α and β since of all the parameters these should vary the least from one line of sight to another. Indeed, Hamilton (1969) showed that in the frequency range 30–152 MHz the observed spectral index is almost independent of galactic latitude for $10° < b < 60°$ and $-10° > b > -90°$. The observations were of insufficient angular resolution to determine the spectral index near $b = 0$. The mean spectral index within this frequency range was found to be 0·63, and its invariance with galactic latitude suggests that a single value of spectral index is adequate for use in equation (1). However, the actual value used must be appropriate to the frequency range of the observations (2·1–16·5 MHz), since from an analysis of the energy spectra of the radiating electrons it is expected that the spectral index will decrease with decreasing frequency (Ginzburg and Syrovatskii 1964; Stephens 1971).

A method of determining the emission spectral index from observations in the direction of the galactic pole has been given by Ellis and Hamilton (1966*b*), by using the observed intensity spectrum and correcting for the effect of absorption within the disc region. They showed that the optical depth may be obtained for this direction independently of the method described above, that is, using equation (2), from the way the intensity observed at different frequencies changes with galactic latitude, provided that the disc region is assumed to have the form of an actual disc of constant thickness and density for high galactic latitudes. They found the absorption parameter in the direction of the south galactic pole to be

$$K = 1 \cdot 8 \times 10^{12} \quad \mathrm{cm}^{-5}\,\mathrm{K}^{-3/2}.$$

The intensity spectrum has been measured for the south galactic polar region with low angular resolution telescopes by Novaco and Brown (1978), using a lunar orbital spacecraft, and by Cane (1979), using ground-based antennas (Fig. 9). The extra-disc emission spectrum, obtained using the observed spectrum in the direction of the south galactic pole and the value of K found, is shown in Fig. 9. Between 2 and 16 MHz, the mean value of the emission spectral index is then found to be $\alpha = 0 \cdot 42$. For comparison, the spectral index in this frequency range derived theoretically from analysis of the electron energy spectrum was found to be $\alpha = 0 \cdot 47$ by Ginzburg and Syrovatskii (1964), and $\alpha = 0 \cdot 32$ by Stephens (1971).

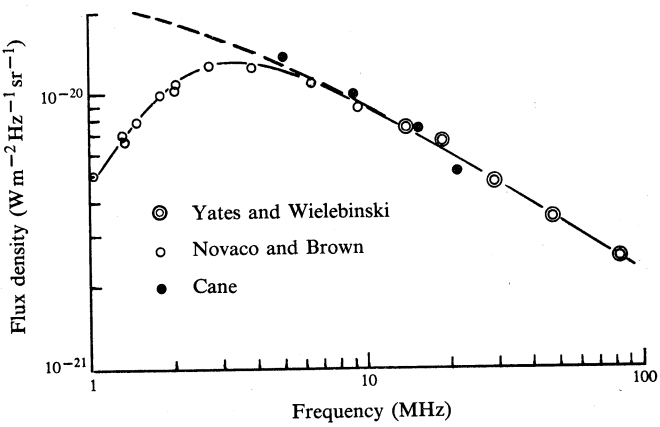


Fig. 9. Measurements of the galactic background spectrum for the south galactic pole made by Yates and Wielebinski (1966), Novaco and Brown (1978) and Cane (1979). The solid line shows the spectrum used in calibrating the observations described here, while the dashed line shows the extra-disc spectrum obtained from this observed spectrum after removing the disc absorption.

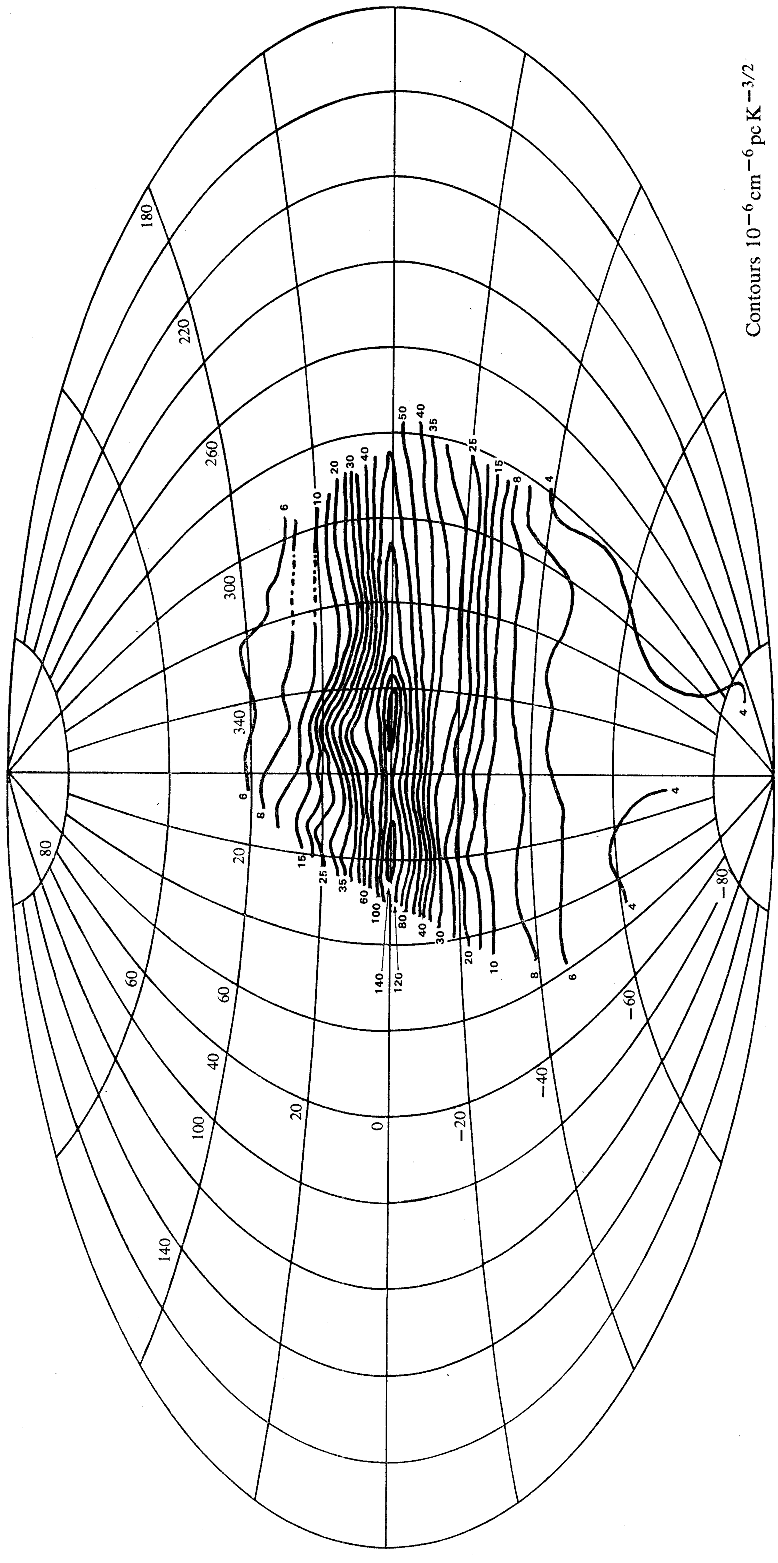
With the observed value of $\alpha = 0 \cdot 42$, equation (1) for the intensity becomes

$$S(f) = Af^{-0 \cdot 42}\exp(-Kf^{-2}) + Bf^{1 \cdot 58}\{1 - \exp(-Kf^{-2})\}, \tag{3}$$

and the absorption parameter K may then be obtained for directions away from the galactic pole by minimizing the function F (equation 2), using equation (3) for the intensity, together with the actual spectrum for each line of sight obtained from the observations (Figs 2–8).

Fig. 10 shows the galactic distribution of

$$\int_0^L (N_e^2/T_e^{3/2})\,\mathrm{d}r = K/0 \cdot 15$$



Contours $10^{-6}\,\mathrm{cm}^{-6}\,\mathrm{pc}\,\mathrm{K}^{-3/2}$

Fig. 10. Contours of the quantity $\int_0^L (N_e^2/T_e^{3/2})\,\mathrm{d}r$ calculated from the brightness contours.

derived in this way. If it is assumed that the electron kinetic temperature is 10^4 K, the emission measure $\int_0^L N_e^2\, dr$ is found to vary from $3\cdot 9\ \mathrm{cm}^{-6}$ pc near the south galactic pole to $140\ \mathrm{cm}^{-6}$ pc near the galactic equator.

Acknowledgment

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