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A RADIO STUDY OF THE NORTH POLAR SPUR

I. THE BRIGHT FEATURE AT $l^{\text{II}} = 30^\circ$

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Summary

The anomalous band of radio emission known as the North Polar Spur poses a problem of theoretical interpretation. To assist theoretical work a 240 Mc/s radio survey has been made of the complex bright region at the base of the Spur, near $l^{\text{II}} = 30^\circ$. The survey was reduced in an electronic digital computer by an extension of techniques previously described. It is found that the Spur possesses a remarkably narrow neck near to the galactic plane and a number of ridge-like structures have been detected. Some scans at 408 Mc/s show that the main ridge is entirely resolved with an $0^\circ.8$ beam. The geometry and polarization of the feature are briefly considered.

1. *Introduction.*—At the present time there is some interest directed towards studies of the radio emission at high galactic latitudes. It is known that the distribution of radiation is not smooth, but displays a complicated structure. In particular it is possible to distinguish a number of extended belts of enhanced radio emission, projecting from the galactic plane and in some cases extending to high latitudes. The North Polar Spur is the strongest of these, and its existence has been known for some years. Recently a similar but weaker belt was discovered in the southern galactic hemisphere (1). The physical circumstances which give rise to these features are unknown but a number of theories have been proposed to account for their origin. Reviews of the theoretical position may be found in (2) and, more recently, in (1). However, the interpretation of the North Polar Spur and the other belts of radiation has so far been hindered by the lack of observational data on these objects. It is the purpose of the present study to help to remedy this situation, at least in respect of the North Polar Spur. Two radio surveys have been carried out at Jodrell Bank using the 250 ft paraboloid at a frequency of 240 Mc/s. The first of these, the results of which are presented in this paper, covers the complex bright region of the Spur, close to the galactic plane at about $l^{\text{II}} = 30^\circ$. This work is of interest as being the first large-scale survey to be reduced entirely by the automatic digital techniques described by Haslam, Davies & Large (3). For this reason a detailed account is given of the reduction process.

The other survey was designed to investigate the large-scale structure of the Spur and in particular the complicated region around $\alpha = 12^{\text{h}}$, $\delta = 0^\circ$. The area covered extends from $\alpha = 8^{\text{h}}$ to $\alpha = 16^{\text{h}}$, and lies between declinations -36° to $+18^\circ$. The results of these observations, including a contour map and

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a list of discrete radio sources, will be described in two later papers, to be known as Papers II and III respectively.

Neither of these surveys covers the northern edge of the Spur between 13^h and 16^h , which exhibits a steep gradient of brightness temperature. However, a treatment of this feature has been given by Davies (4).

2. *Experimental details.*—At 240 Mc/s the half-power beamwidth of the 250 ft telescope was measured to be $85'$ and $60'$ in the E- and H-planes respectively. The E-plane was horizontal. The Dick-type receiver was identical with that described in an earlier paper (1). The sensitivity of the system was better than 1°K when scanning at $2\frac{1}{2}^\circ/\text{min}$. The receiver was calibrated frequently using a noise diode, which was checked daily against the standard radio source 14 N5A. The receiver output was fed to a Honeywell pen recorder, and at one-minute intervals the azimuth and elevation of the telescope were punched in digital form on paper tape, as described in (3).

The main survey was carried out in the period 1961 July–August. The scans were principally along lines of constant galactic longitude but a few scans at constant latitude were made to establish the relative zero levels of the main body of scans. No attempt was made to measure the absolute zero level of the survey. Fig. 1 is a tracing of a typical scan, made at a constant longitude of $l^{\text{II}} = 29^\circ.9$ with the telescope scanning at $2\frac{1}{2}^\circ/\text{min}$.

In 1962 April some further scans were made across the region to check the reliability of the completed map. These later observations were made at two

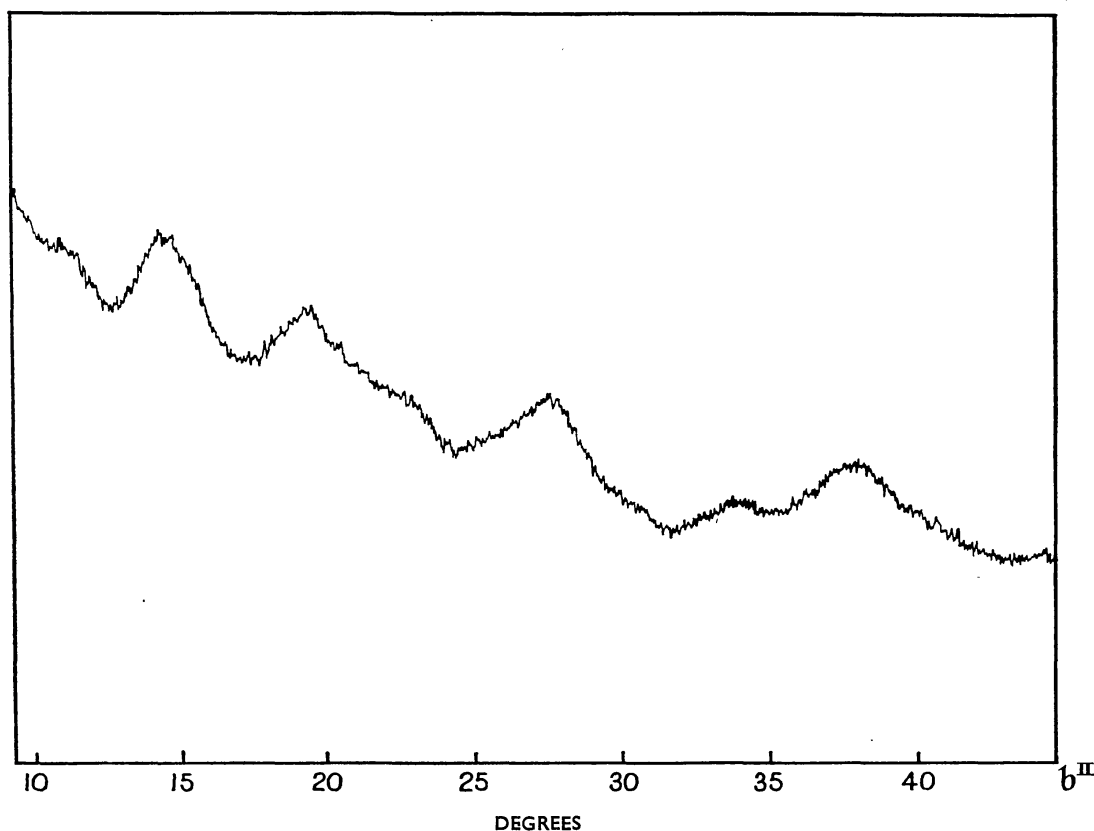


FIG. 1.—Tracing of one of the scans used in constructing the isophote diagram of Fig. 2. It was made at a longitude (l^{II}) of $29^\circ.9$, with the telescope scanning at approximately $2\frac{1}{2}^\circ/\text{minute}$. The latitude marks are in the new galactic system.

frequencies simultaneously, using crossed dipoles at 240 Mc/s and 408 Mc/s. The 240 Mc/s equipment was the same as before. The receiver used at 408 Mc/s consisted of a crystal mixer followed by conventional circuitry. The intermediate frequency was 10 Mc/s and the local oscillator was set at 408 Mc/s. Both sidebands were accepted. The excess noise temperature of the system was 220° K.

3. *Reduction of the data.*—Initially, the signal information was available as a function of time on paper charts. The charts were inspected for interference and a pencil line was drawn through the noisy trace. By means of a manually-operated chart-reading machine, which was guided along the pencil line, the signal information was converted into digital form and punched on 5-hole tape. The signal and position data were now contained in two punched tapes, ready for analysis in the Manchester Mercury computer. The stages in the analysis were essentially as described in (3) but some modifications were made.

These are as follows:—

(i) The relative zero levels of the scans were determined when the data had been converted into *tabular scans* (stage (3) of (3)) by comparing the levels of the main body of scans (in latitude) with those of the crossing scans (in longitude). It was found that the zero level usually remained constant for a day's observations so that the same level could be assigned to a whole batch of scans.

(ii) The region surveyed covered an area of about 900 sq. degrees as against 20 sq. degrees for the example discussed in (3). Because of the large number of data-points involved and because of the limited storage capacity of the Mercury computer the matrix was divided into four equal sub-matrices which were computed separately and combined at a later stage. The sub-matrices were arranged to overlap each other for the purpose of checking.

(iii) The weighting function used to add the signal data into tabular points on the tabular scans and on the matrices was chosen so as to simulate approximately a $(\sin x)/x$ function. The weighting process is really an interpolation which allows for the fact that the data points are samples of a band-limited signal function, the bandwidth of which is determined by the illumination of the telescope aperture. If the width of the $(\sin x)/x$ function is chosen so that its Fourier transform (which has a rectangular shape) cuts off at a higher spatial frequency than is contained in the signal function, then no degradation of the telescope resolution takes place in the weighted addition of data to tabular points.

(iv) Again because of the large size of the region and the limited storage capacity of the Mercury computer it was not practicable to use the contour-plotting programme described in (3), so that contours had to be drawn manually. For this purpose, the numbers in each sub-matrix were printed out at regular intervals on teleprinter paper, thus giving a direct representation of the sub-matrix. The four sub-matrices were inter-compared in the overlap regions and found to agree very well.

At this stage the intensities were known only in arbitrary units. The brightness temperature scale was established, as described in the next section, and contours were drawn on the paper, at 10° K intervals. The resulting map was referred to the x, y coordinate system described in (3). To relate this to conventional coordinates, the Mercury computer was used to calculate the x, y coordinates of selected grid points in the new galactic coordinate system and to punch them out in a form acceptable to the automatic x - y graph plotter

at Jodrell Bank. When this had plotted the grid points on the map, smooth lines were drawn through them to represent lines of constant galactic latitude and longitude (b^{II} , l^{II}). The completed map is shown in Fig. 2.

The information contained in the matrices can be displayed in another way, which for some purposes is more useful than a contour diagram. In Fig. 3 (a), (b), (c) and (d) are reproduced a set of profiles of the Spur at constant latitude. These have been compiled from the matrices by manual operations. The interval between adjacent profiles is 1° of latitude.

The only other survey of this region which allows of easy comparison is that made at 408 Mc/s by Seeger, Stumpers & van Hurck (5). The beamwidth is 2° . To facilitate this comparison, the sub-matrices of the 240 Mc/s map were separately convolved by a two-dimensional gaussian function in the Mercury computer to a resolution of 2° . This process reduces the number of data points in the survey by a factor of 4, and it was found practicable to use the contour-plotting sub-routine described in (3) to compute the x , y coordinates of points

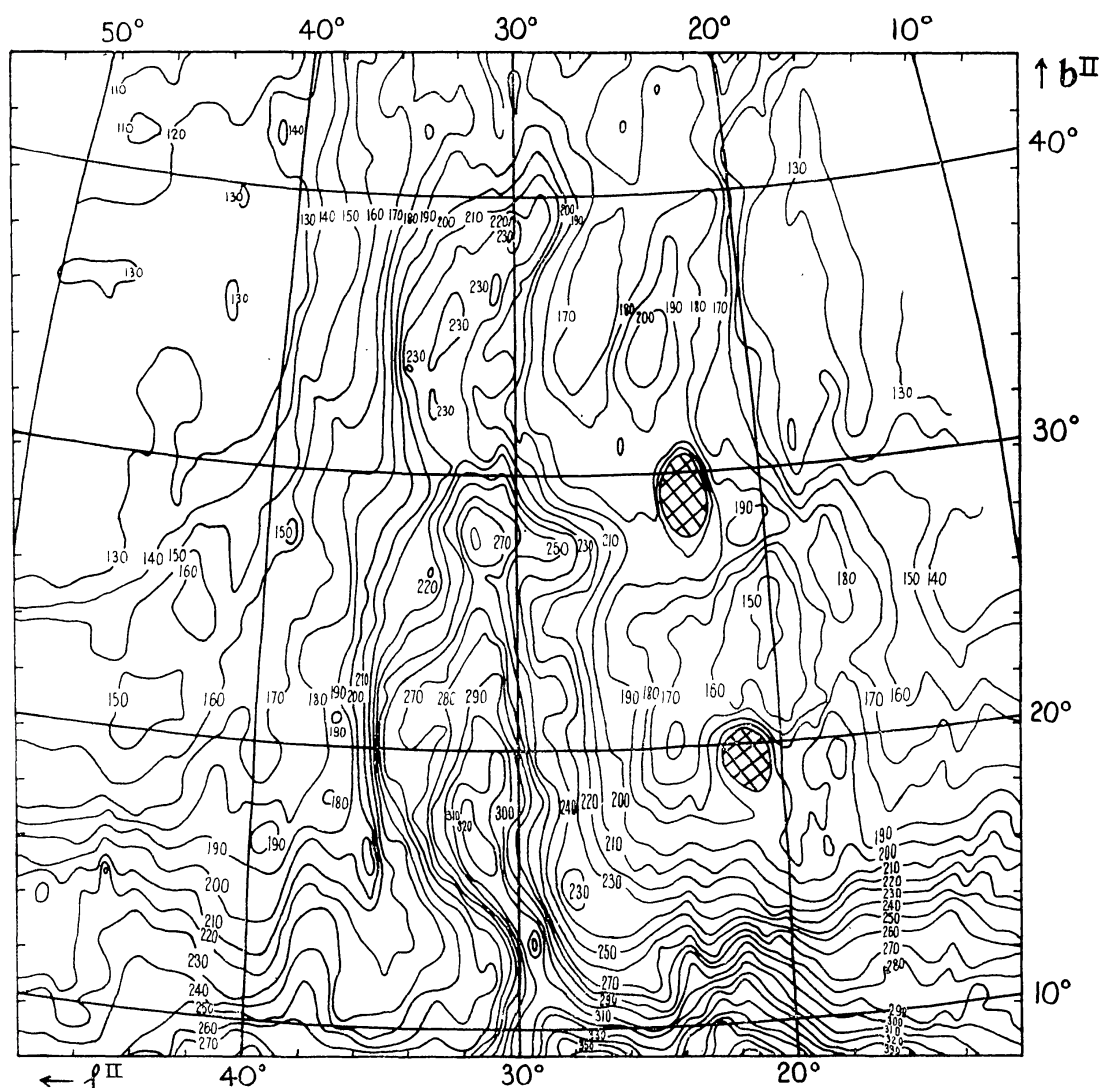
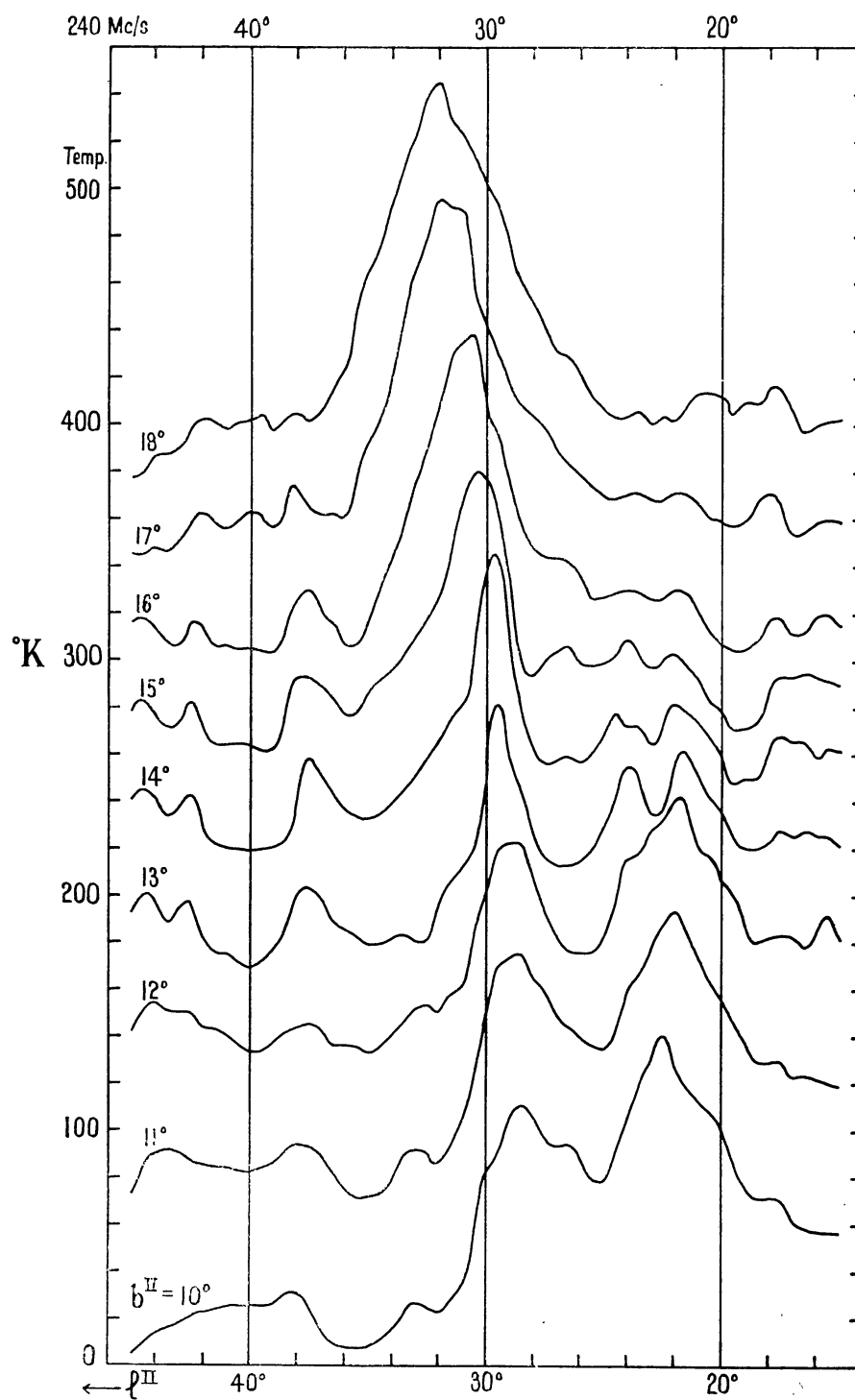


FIG. 2.—240 Mc/s isophotes of the base of the North Polar Spur. The curved grid lines represent the new galactic coordinate system. The isophotes are marked in $^\circ\text{K}$ above a true zero. Two intense point sources which appear on the map have been represented by hatched areas.



(a)

FIG. 3 (a), (b), (c) and (d).—Profiles of the North Polar Spur at constant latitude. The temperature scale is marked but the profiles are drawn above arbitrary zero levels. The coordinate system is new galactic.

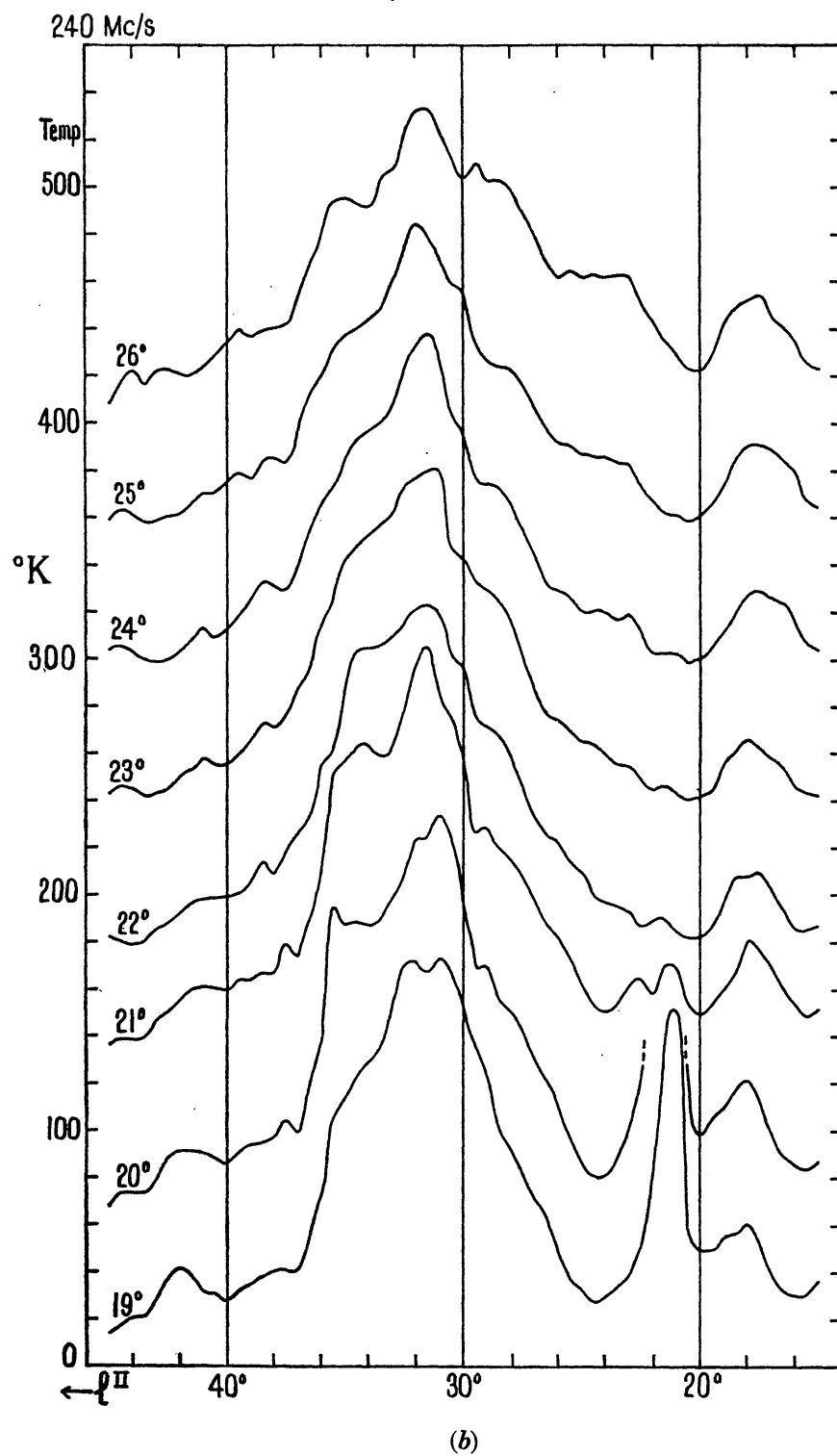


FIG. 3 (continued).

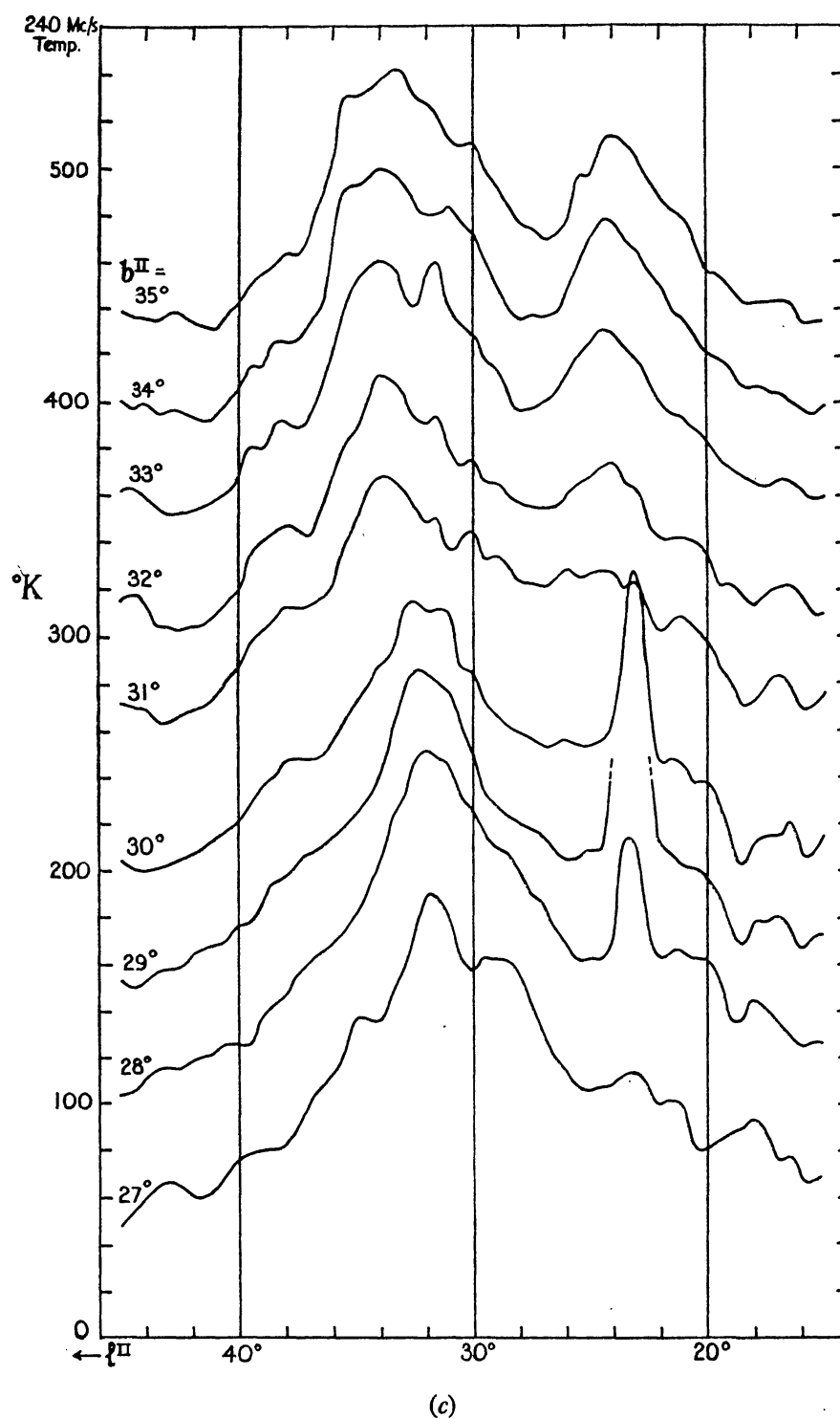


FIG. 3 (continued).

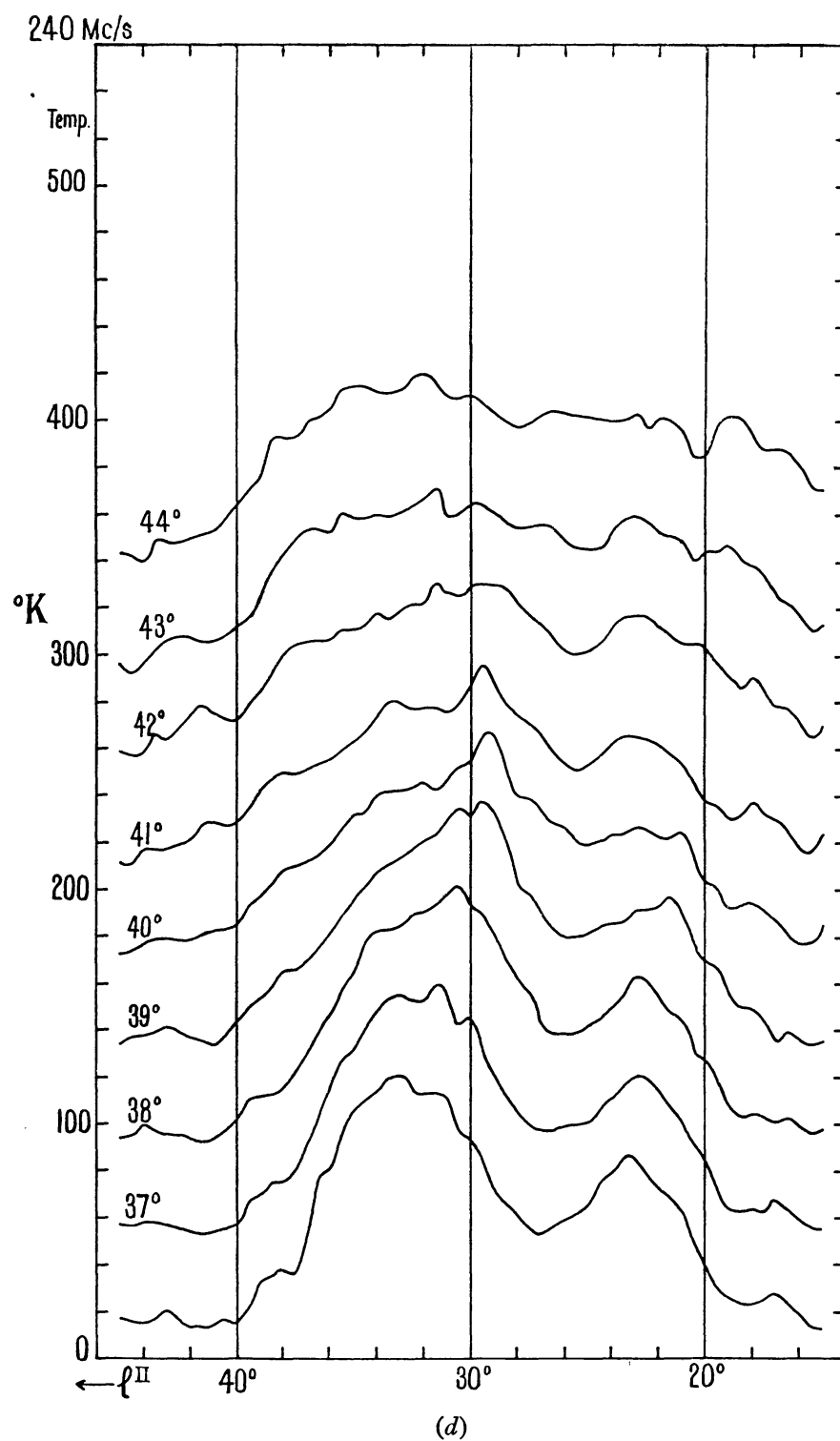


FIG. 3 (continued).

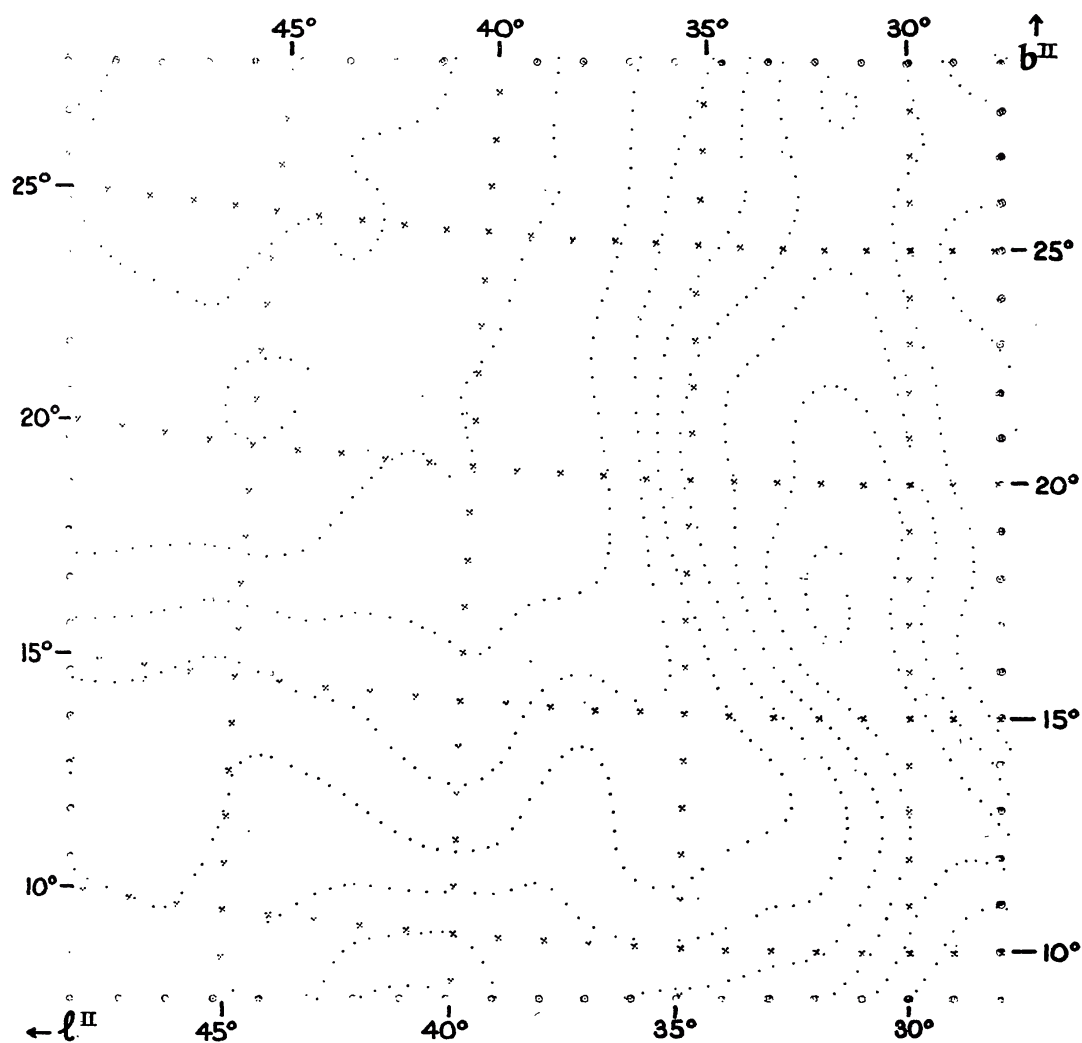


FIG. 4.—A machine-plotted isophote diagram, representing part of the map of Fig. 2 convolved to a resolution of 2° . The curved grid lines indicate the new galactic coordinate system. These too have been machine-plotted.

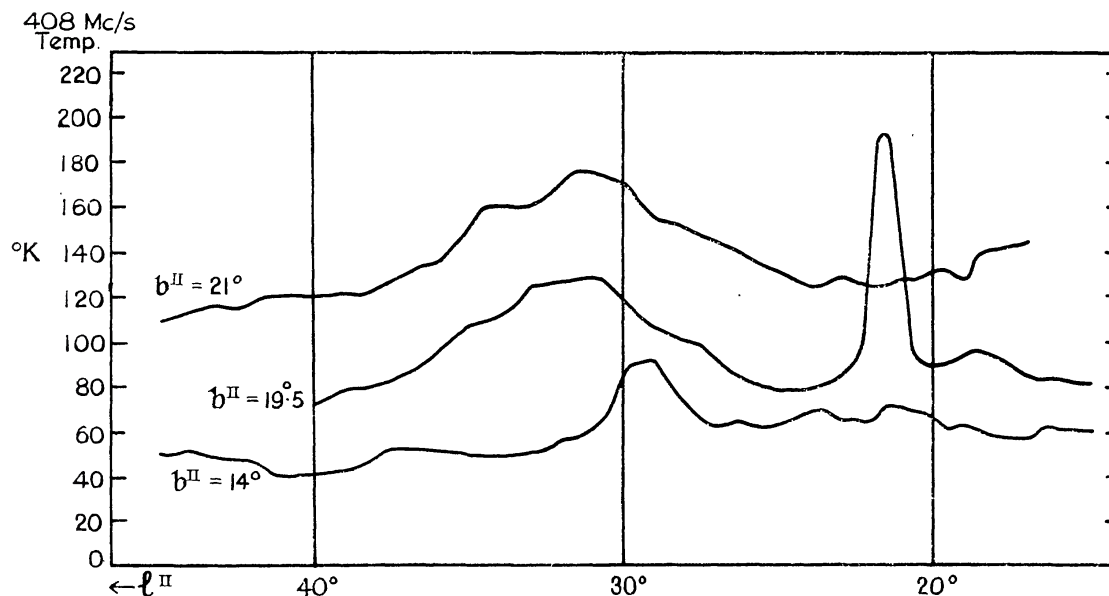


FIG. 5.—Three scans across the Spur at constant latitude. The frequency is 408 Mc/s. The scans are referred to arbitrary zero levels.

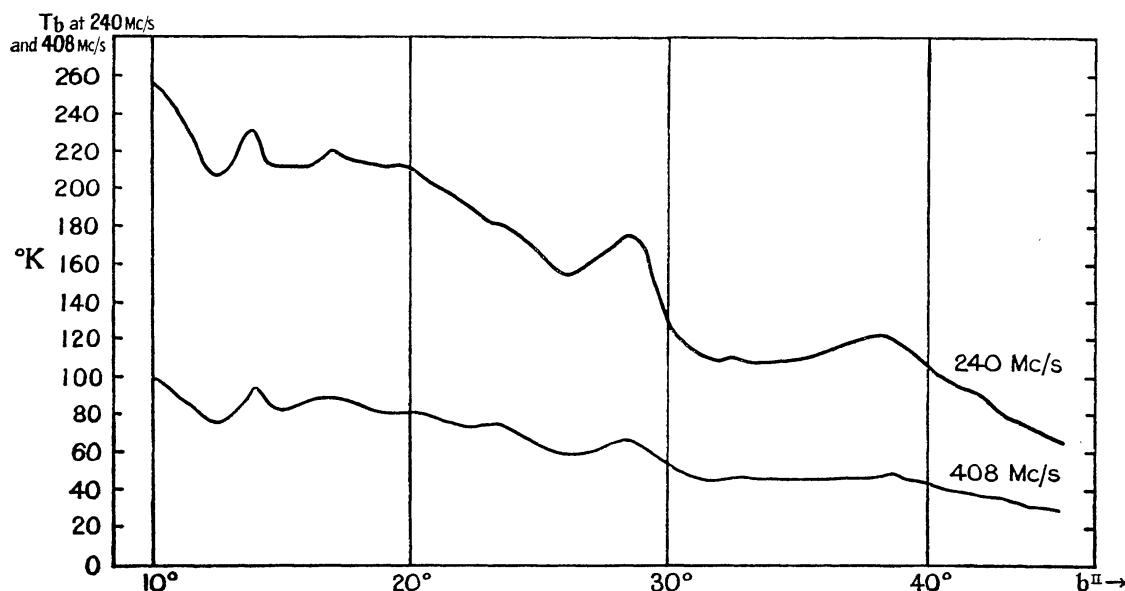


FIG. 6.—Scans showing the variation with latitude of the peak intensity of the Spur. The scans are referred to arbitrary zero levels.

lying along contours of constant intensity. By punching out the coordinates in a suitable form, the x, y graph plotter was used to plot four contour diagrams which jointly constitute a map of the region at 240 Mc/s and 2° resolution. A reproduction of one of these diagrams is shown in Fig. 4.

The scans made in the second observing period were reduced by manual techniques. The nominal positional information given by the telescope computer was used in the reduction. The scans are shown in Figs. 5 and 6.

4. Calibration of the survey.—The brightness temperature scale was established by the method described by Mathewson, Large & Haslam (6). It depends on measuring the effective solid angle of the main beam and nearby side lobes and calibrating on a point source of known flux. The polar diagram out to 5° from the centre was determined by measurements on the source Cassiopeia A, and the effective solid angle was found to be 1.70 sq. degrees. The source $14N5A$ was used for day-to-day calibrations, but its flux has been related to that of Virgo A, which is taken to be $831 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$.^{*} To check the scale of intensity derived by these measurements and to establish the zero level we have compared the present map with other surveys for which the scale and zero level are accurately known. For this purpose, all the surveys used should have the same resolution. It was not possible to realize this ideal but an approximate comparison was made in the following way. The survey of Pauliny-Toth & Shakeshaft (7) at 404 Mc/s and $7^\circ.5$ resolution has been used by Brouw (8) to calibrate the scale and zero level of the map published by Seeger, Stumpers & van Hurck (5) at 408 Mc/s and 2° resolution. The difference in frequency has a trifling effect on the temperatures. The 408 Mc/s map could then be compared directly with the 240 Mc/s map convolved to 2° resolution, as described in the previous section.

^{*} Data kindly supplied by Dr R. G. Conway.

The other survey used was that of Turtle & Baldwin (9) at 178 Mc/s. Although the scale and zero of this map are known accurately the highly elliptical beamshape (about $13' \times 5''$) makes it difficult to compare with the other maps. However, 240 Mc/s temperatures were calculated for various points in the region of interest by interpolation between the 178 Mc/s and 408 Mc/s temperatures, and were then compared with the arbitrary units of the convolved 240 Mc/s matrices. This procedure gave a fairly good estimate of the temperature of the zero level, but because the brighter parts of the map exhibit a complicated structure the comparison of higher temperatures was seriously affected by the difference in resolution between the 178 Mc/s and the other two maps. It was therefore not possible to check directly the intensity scale of the 240 Mc/s map. However the 240 Mc/s observations were contemporary with a survey (11) of a large area of sky in the southern galactic hemisphere, made with the same equipment and also calibrated against point sources of known flux. In this latter region the brightness temperature is for the most part a slowly varying function of angle and it was easier to compare this map with the 178 Mc/s and 408 Mc/s surveys. As a result of making this comparison we believe that the temperature scale, determined by the calibration on a point source, is accurate to within ± 10 per cent. An additional source of error lies in the process of assigning zero levels to the scans when forming the tabular matrices. To estimate the extent of errors arising in this way the constant latitude profiles of Fig. 3 were compared with scans made at the second observing period and driven directly in latitude. By this means it was shown that any spurious features introduced into the map by the use of incorrect zero levels have a peak temperature of less than 5°K .

The scans made during the second observing period were also calibrated by the method described in (6). No attempt has been made to assign an absolute zero level to these scans.

5. *Discussion.*—The improvement in resolution of the present observations over previous surveys is illustrated vividly by the isophotes of Fig. 2. The Spur stands out as a bright ridge emerging from the galactic plane at about longitude 28° and running up the centre of the map. The most striking feature is the extreme narrowness of the ridge between latitudes 11° and 16° but there is a wealth of fine structure visible over the whole area of the survey. Other interesting details include the extremely sharp gradients of brightness temperature at $l^{\text{II}} = 35^\circ$, $b^{\text{II}} = 20^\circ$ and $l^{\text{II}} = 35^\circ$, $b^{\text{II}} = 35^\circ$, and the existence of a number of ridges of emission running roughly parallel to the main ridge of the Spur. These can be distinguished, for example, at $l^{\text{II}} = 38^\circ$, $b^{\text{II}} = 10^\circ$ to 17° , at $l^{\text{II}} = 18^\circ$, $b^{\text{II}} = 15^\circ$ to 28° , and from $l^{\text{II}} = 25^\circ$, $b^{\text{II}} = 30^\circ$ to $l^{\text{II}} = 20^\circ$, $b^{\text{II}} = 43^\circ$. It will be remembered that the original observations were in the form of scans along lines of constant longitude so that it might be thought that these extended features are artificially generated by the assignment of incorrect zero levels to some of the scans. It was partly to investigate this point that the later set of observations was made. As explained in the previous section, no spurious features brighter than 5°K were detected so that these ridges are certainly genuine.

The striking variation in width of the Spur is displayed in the longitude profiles of Fig. 3. At the lowest latitudes it is difficult to distinguish the main

ridge from the complicated background emission, and in particular from the broad ridge at $l^{\text{II}} = 22^\circ - 23^\circ$. At latitudes 13° and 14° the width to half-power points of the Spur is only a little more than that of the telescope beam, but above $b^{\text{II}} = 15^\circ$ it widens rapidly. At $l^{\text{II}} = 35^\circ$, $b^{\text{II}} = 20^\circ$ the steep edge of the feature can be seen clearly.

Fig. 5 shows three scans across the Spur at a frequency of 408 Mc/s and nominally at latitudes 14° , $19^\circ.5$ and 21° . At this higher frequency the resolution is correspondingly finer (about $0^\circ.8$). With the obvious exception of the point source at $l^{\text{II}} = 21^\circ.5$, $b^{\text{II}} = 19^\circ.5$, there does not seem to be any structure which is significantly unresolved. Differences in structure between these scans and the 240 Mc/s profiles are probably mainly due to the departure of the telescope motion from the nominal path. It appears therefore that the background structure in this part of the Spur is entirely resolved with an $0^\circ.8$ beam.

During the second observing period, the ability of the 250 ft telescope to drive in galactic coordinates was exploited by making a scan along the ridge of the Spur. This involved simultaneous motions of the telescope at controlled rates in both latitude and longitude. The positions of points on the scan are listed in Table 1; between a pair of adjacent points the motion of the telescope was linear in l^{II} and b^{II} .

TABLE I

Longitude (l^{II}) degrees	28	31	31	32	28
Latitude (b^{II}) degrees	9	17	27	35	45

Both the 240 Mc/s and 408 Mc/s receivers were operating while the ridge scan was being made. The variation in intensity of the ridge at the two frequencies is shown in Fig. 6. It is noteworthy that an unresolved source appears on the ridge at about $b^{\text{II}} = 14^\circ$ since it is at this latitude that the ridge profile is most narrow (see Fig. 3(a)). It would be interesting to know the true structure of the ridge without the obscuring effect of the source but the resolution of the 240 Mc/s survey is inadequate to perform such a separation.

In an earlier paper (1) it was shown from data published by Seeger, Stumpers & van Hurck (5) and Costain & Smith (10) that the main ridge of the Spur, at higher latitudes, is a good fit to a *small circle* of diameter $111^\circ \pm 5^\circ$ centred on $\alpha = 15^{\text{h}}00^{\text{m}} \pm 10^{\text{m}}$, $\delta = -36^\circ \pm 2^\circ$. The results of the present survey are in agreement with this analysis, down to the lower latitude limit of $+9^\circ$. There is an urgent need for a programme of observations to trace the ridge to even lower latitudes; unfortunately none of the published surveys of the galactic plane at these latitudes is sensitive enough to show whether the Spur can be distinguished against the strong emission near to the plane.

It was pointed out by Hanbury Brown, Davies & Hazard (2) that if the Spur is a shell source of radio emission, such as a supernova remnant, then the average brightness temperature within the main loop of the Spur should be higher than that outside, after making allowance for the variation of galactic background. To investigate this point we have inspected the constant-latitude profiles of Fig. 3. If the shell source model is valid the average temperatures at longitudes lower than that of the main ridge should be higher than the average temperatures at longitudes greater than that of the ridge. However it is not

clear that the profiles extend to sufficiently low values of longitude to be clear of the structure associated with the main ridge of the Spur. On the other hand, if it is necessary to compare temperatures at points removed from each other by more than 30° in longitude, the result will be rendered uncertain by the longitude variation in galactic background. This point will be reconsidered in the light of the results to be described in Paper II. For the present we conclude that the profiles of Fig. 3 do not give an unambiguous answer to the question of whether the Spur is a shell source.

It is generally thought that the background radiation away from the galactic plane is generated by the synchrotron process, a belief which has been confirmed by the recent discovery that the emission is linearly polarized. It is of interest to see whether the isophotes of the Spur show any significant correlation with the direction and magnitude of the polarization. We have received some detailed polarization measurements made at Dwingeloo, with a 2° beam at a frequency of 408 Mc/s (8), and we have inspected them for signs of any such correlation with the isophotes. There seems to be no evidence that this region of the Spur is significantly more polarized than adjoining areas at high latitudes, nor do the polarization vectors (corrected for ionospheric rotation) line up significantly with any of the observed features.

As regards the theoretical interpretation of the Spur, the striking variation in width of the ridge between latitudes 11° and 17° gives an impression that some specific physical process is operative. There are other features, too, such as the steep gradients of brightness temperature and the existence of elongated ridges of emission, which are interesting in this connection. However a discussion of the theoretical interpretation is postponed until the remainder of this observational study has been reported in Papers II and III.

6. *Acknowledgments.*—We thank Professor Sir Bernard Lovell for making available the facilities at Jodrell Bank and for his continuing interest in the work. We also wish to express our thanks to Miss Kay Jones, who undertook much of the work in connection with the data reduction.

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