A HIGH RESOLUTION GALACTIC SURVEY AT 19·7 Mc/s

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Summary

An extensive strip of the Southern Milky Way has been surveyed at 19·7 Mc/s, using a Mills Cross with a pencil beam 1·4° wide. The radio contours show a number of dark areas whose positions agree with those of optically-observed H II regions which at this frequency are seen in absorption. In addition, an intensity minimum along the galactic equator appears to represent the effect of absorption due to many H II regions extending to great distances in the galactic plane.

I. Introduction

Observations of the galactic radio emission around 20 Mc/s provide a striking confirmation of conclusions which have been drawn from work at much higher frequencies. A number of high resolution surveys have been made at frequencies well above 20 Mc/s and these show a broad band of emission concentrated towards the galactic plane, on which is superimposed a narrow and intense band only a few degrees wide, following the plane quite closely.

In order to explain this narrow band at least two processes must be considered. One component of the radiation is due to thermal emission from ionized interstellar hydrogen regions (H II regions) which are known to be concentrated towards the galactic plane. Optical observations provide estimates of the electron densities and temperatures in these regions, and from these the expected radio emission can be roughly estimated. At frequencies above 1000 Mc/s the predicted and observed intensities agree in general magnitude.

However, the observed intensity increases with decreasing frequency at a rate far too rapid to be compatible with a purely thermal origin. Some non-thermal component must also be present, and it is generally thought that this is due to " synchrotron " emission from electrons of relativistic energies gyrating in very weak magnetic fields in interstellar space.

* The work described in this paper was initiated by the late C. A. Shain, who had taken it to the stage at which the contour maps were nearly complete before his untimely death in February 1960. His two colleagues, the remaining authors, who had worked with him for some time prior to his death, completed the observation of certain areas, carried out the remainder of the reductions, and wrote this paper. Because of these circumstances, some of the discussion is less complete than might be desired. In particular this applies to the description of calibration techniques. This is based largely on Shain's notes, but it has not been possible to elucidate all the details.

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Shain's observations at low frequencies have vividly confirmed the twofold origin of the galactic emission. Below 20 Mc/s the non-thermal component of brightness temperature often exceeds 100 000 °K. Since the electron temperatures of H II regions are commonly about 10 000 °K and since their optical depths are considerable at these frequencies, they appear in absorption against a very bright background. The first experimental evidence of absorption was found by Shain (1951, 1954) and Shain and Higgins (1954), who carried out galactic surveys at 18·3 Mc/s, using very broad-beam aerial systems. It was found that the ratio of brightness temperature at 18·3 Mc/s to that at 100 Mc/s (as measured by Bolton and Westfold 1950) was lower towards the galactic centre than in other directions.

In order to progress further, better angular resolution was required, and Shain therefore adapted the Mills Cross principle to low frequency observations. The instrument he designed had a pencil beam 1·4° wide and operated at 19·7 Mc/s. With this it was possible to explore the region near the galactic equator in considerable detail.

In contrast with high frequency results, he found an intensity minimum along the equator where ionized hydrogen is known to be concentrated, and, in addition, he found a number of discrete radio " dark " areas corresponding in position with optically-visible H II regions. He was also able to confirm Mills's (1955) conclusion that the bright band observed near the equator at 85 Mc/s is mainly of non-thermal origin. Preliminary accounts of this work over restricted areas have been given previously (Shain 1957, 1959).

It was Shain's aim to survey a large section of the Southern Milky Way, but difficulties associated with the low observing frequency made the program a very lengthy one. The 18·3 Mc/s work had shown that ionospheric absorption can be quite severe, and, accordingly, the 19·7 Mc/s observations were taken in the pre-dawn period when absorption is low. Ionospheric refraction was still considerable, however, and a separate investigation of this effect had to be undertaken. It was found possible to calculate refraction corrections provided data were available from two or more appropriately located ionospheric sounding stations for the time of observation. The most serious experimental difficulty was the severe loss of observation time due to short-wave interference.

Despite these difficulties, Shain had completed most of the work before his untimely death in early 1960. The observations required to fill the remaining gaps in the contours were attempted after his death, but as they were all in high southerly declinations where conditions are most unfavourable, not much was added to his survey.

The main aim of the present paper is to present Shain's results in the substantially complete form in which he left them. The survey covers an area extending between $l^{\mathrm{I}}=224°$ to 16° and over 10° of latitude. A chart of optically-observed H II regions is presented with the radio map and from this the good correlation between H II and radio " dark " areas can be seen.

In areas where the radio contours are unaffected by " nearby " H II regions or strong non-thermal sources, a comparison of the present results with high frequency observations yields information about the non-thermal radio spectrum and the large-scale relative distribution of thermal and non-thermal emission. This question is discussed in a companion paper (Komesaroff 1961).

II. Observations

(a) *Procedures and Difficulties*

The observational program was carried out between 1956 and mid 1960. The instrument is of the Mills Cross type and has a beamwidth of 1·4°. The general principles of operation have been described by Mills, Little, and Sheridan (1956), and Shain (1958) has outlined the features peculiar to the low frequency instrument; in particular these include a set of narrow-band tunable i.f. amplifiers which permit utilization of the maximum frequency band while avoiding interference from short-wave transmitters.

Calibration of an instrument of this type presents considerable difficulties. Little (1958) has described a method by which the gains of larger antenna systems can be compared with the known gain of a half-wave dipole, but this technique was found unworkable at 19·7 Mc/s, due to the effect of ionospheric scintillations. The method finally adopted involved determining two sets of parameters.

(i) The directivity diagrams of the individual arrays, which were derived from their known complex current distributions and from the diagram of a single half-wave dipole.

(ii) Efficiency factors, computed by comparing observed aerial temperatures with those to be expected from the earlier 18·3 Mc/s observations of Shain and Higgins (1954).

By combining the results of (i) and (ii), it was possible to derive a calibration procedure along the lines described by Mills *et al.* (1958). The absolute calibration was estimated to have a possible error of about 20%, but the relative accuracy was thought to be considerably better.

The "scanning" system of observation was used almost exclusively throughout. This gives quasi-simultaneous records on each of five declinations spaced at intervals of about $\frac{1}{2}$–$\frac{3}{4}$°, depending on zenith distance. In the subsequent analysis mean values of "beam temperature" were taken at intervals of 4 min (sidereal time). Since the aerial beamwidth is 1·4°, this led to no significant degradation of the original information.

The low observing frequency of 19·7 Mc/s entailed a number of difficulties which were enhanced by the fact that observations were taken during a period of exceptionally great sunspot activity.

Firstly, the spectral density of short-wave signals, mostly from long distances, was very high. In order to avoid them it was necessary to use the system of tunable i.f. amplifiers mentioned earlier and described in greater detail by Shain (1958). Interference at a high level was easily recognized, but at a low level it could be quite insidious, requiring a beat-frequency oscillator for its detection, and necessitating continuous aural monitoring throughout the observing period.

Secondly, ionospheric refraction was often severe, sometimes exceeding 1°. To correct for the "steady" component of refraction, formulae derived by

Komesaroff (1960) were used, expressing the refraction in terms of measurable ionospheric parameters. Scintillation effects could not be estimated, but were mitigated by the time-averaging procedure mentioned earlier. Duplication of records provided a cross-check on refraction and it is believed that residual errors were only of the order of 10′ of arc.

To minimize the above effects and also that of ionospheric absorption, recording was mainly restricted to the period between 2200 h and 0600 h local time. Even at this time, a percentage of records was rendered useless by short-wave interference and atmospherics. Nevertheless, several " good " records were obtained on each of the declinations covered. It was therefore possible to check their mutual consistency and also to improve the signal-to-noise ratio by averaging.

(*b*) *Analysis of Results*

In their paper describing the original 85 Mc/s Mills Cross, Mills *et al.* (1958) showed that, in order to determine the brightness temperature in the direction of the main beam, two quantities must be measured. These are the mean product of the voltages from the individual arrays (the pencil-beam temperature) and the power from the north-south array. The required brightness temperature is the sum of these two terms multiplied by appropriate weighting factors.

In the 19·7 Mc/s equipment, the two quantities are recorded independently. The record of pencil-beam temperature consists of a sawtooth pattern, the height of each " tooth " being proportional to the beam temperature integrated over 12 s (sidereal time). Adjacent " teeth " represent adjacent declinations in the five-position cycle. The output of the north-south array appears on a separate recorder.

In the first step of the analysis, the five declinations of the pencil-beam record were separated, and for each of these constant-declination profiles, the average temperature was computed at 4-min intervals ; this last step was to reduce the effect of scintillations. The north-south component was then added, giving five constant declination profiles of brightness temperature.

The measured declinations and Right Ascensions were then corrected for refraction effects. In an earlier paper (Komesaroff 1960) it was shown that refraction corrections can be calculated using hourly values of critical frequency measured at a number of ionospheric sounding stations. When sufficient ionospheric data could be obtained, refraction corrections were first applied and then all the available records on each (corrected) declination were averaged, in order to achieve the best signal-to-noise ratio. In a number of instances, however, the hourly ionospheric data were incomplete or unavailable. In these cases the records were fitted together empirically and averaged, and corrections were computed from the predicted monthly mean values of critical frequency.

The next step was to transfer the mean values of brightness temperature from the corrected records to a rectangular grid of Lund galactic coordinates, on which lines of constant declination and Right Ascension were drawn for guidance. When this had been done a further correction had to be applied to allow for the effect of the aerial side lobes. This question has been discussed in some detail by Mills *et al.* (1958) and the system of correction used for the 19·7 Mc/s results was essentially similar to the one they describe. The final step was to draw smooth contour lines through points of equal brightness temperature.

III. Results

The results of the survey are shown in Plate 1. Contour lines of equal brightness temperature at intervals of 50 000 °K are drawn on a grid of Lund galactic coordinates. A considerably coarser grid of equatorial coordinates (epoch 1958) is also included. The galactic equator according to the new I.A.U. system (1958 revision) is indicated by a dashed line.

The map covers a strip of the Milky Way about 10° wide extending over a considerable range of longitudes (l^{I}=224–16°) on either side of the galactic centre. The gaps in the contours between l^{I}=234° and 282° arise from the great observational difficulties in this region. This is the most extreme southerly declination of the survey and had to be observed near midsummer. Consequently ionospheric effects and interference—both atmospheric and man-made—were at their most severe. For several of the declinations it was found that the degree of correlation between successive records was too poor to warrant their inclusion, and it was decided to publish the map in its incomplete form. It should be noted that the region between about l^{I}=290° and 318° was also observed under difficulties and may be somewhat less reliable than the region beyond the galactic centre.* Finally, the break in the contours near l^{I}=288° indicates what appears to be a discontinuity, presumably of instrumental origin. The discrepancy is about 20% of the mean level.

IV. Comparison with Optical Observations

The transparent overlay accompanying Plate 1 shows the distribution of optically-observed ionized hydrogen along the Milky Way, according to the work of Rodgers *et al.* (1960). Areas containing Hα-emission are enclosed by a dashed line and, within these, more intense emission is outlined with a full line. Smaller regions, believed to be separate, but seen against the broader areas, are indicated in black.

On comparing Plate 1 with the transparent overlay, a very good correlation is noted between optically-observed H II regions and localized radio "dark" areas. Conversely, between longitudes 328·5 and 332°, where the optical data show a break in the H II distribution, there is a maximum of radio brightness. Thus the observations provide a striking illustration of the absorption of low radio frequencies in ionized hydrogen. Two radio features which are apparently unrelated to the optical data are the dark areas near longitudes 287° and 5°. In the next paper (Komesaroff 1961) it is shown that these are not produced by absorption but by a deficiency of emission.

It might not have been expected that the two sets of data would show such good agreement considering the vast dust clouds—opaque to optical wavelengths

* Most of the records were taken in one month at a time when ionospheric conditions were adverse and when ionospheric sounding data were incomplete.

but transparent to radio waves—which lie along the galactic plane. Despite the obscuration, however, the optical observations appear to delineate the distribution of "nearby" ionized hydrogen fairly completely. It must be emphasized that this can only be said of regions whose angular dimensions exceed about $\frac{3}{4}°$; owing to the finite resolution of our aerial smaller regions would scarcely be detectable.

The electron temperature of an H II region is only about 10 000 °K (Mills, Little, and Sheridan 1956), and Shain (1957) has shown that even H II regions which are faint by optical standards are nearly opaque at 19·7 Mc/s. In all cases, however, the 19·7 Mc/s brightness temperatures in the direction of H II regions greatly exceed 10 000 °K. Part of this temperature excess arises because generally an individual region does not fill the aerial beam, but another part represents "foreground" radiation generated between the obscuring region and the observer. Shain (1959) has correlated values of "foreground temperature" with optically-derived distance estimates and draws the tentative conclusion that an upper limiting value of 50 000 °K is reached at a distance of about 600 parsecs. This suggests that the emission is fairly strongly concentrated in spiral arms. It is hoped to investigate this problem further, using more extensive data; however, it will not be discussed further in the present paper.

Away from the galactic centre and where the radio contours are unaffected by nearby absorbing regions, they show an extended minimum following the equator quite closely out to longitudes of about $\pm 35°$ from the centre. This would appear to be the integrated effect of many H II regions extending to such vast distances that they are not individually distinguishable. Radio-spectral studies of this region can provide information about its structure in depth. This question is discussed in detail in the next paper (Komesaroff 1961).

V. Acknowledgments

The present results represent the combined efforts of a number of workers. In particular, Mr. C. F. Attwood and Mr. L. F. Clague took many of the observations and also contributed to the development and maintenance of equipment. Mrs. J. Raengel carried out much of the laborious record analysis, a task which was taken over in its later stages by Miss W. Wolfe.

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EXPLANATION OF PLATE 1

Contours of brightness temperatures at 19·7 Mc/s. The main grid is in Lund galactic co-ordinates. The galactic equator according to the new I.A.U. system (1958 revision) is indicated by a dotted line. The coarser grid gives equatorial coordinates (epoch 1958). Between $l^{\mathrm{I}}=290°$ and 318°, the contours may be less reliable than elsewhere; and the break near $l^{\mathrm{I}}=290°$ indicates what appears to be a discontinuity of instrumental origin in the contours. The transparent overlay gives the distribution of ionized hydrogen, according to Rodgers *et al.* (1960).