GALACTIC ABSORPTION OF 19·7 Mc/s RADIATION

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Summary

Observations have been made of galactic radiation at a frequency of 19·7 Mc/s using an aerial having a beamwidth 1°·4. The effect of an absorbing band of H II regions around the galactic equator is clearly seen. Isolated H II regions, some very faint, have been detected in absorption. A detailed study of the sky near the galactic centre shows that the source Sagittarius-A is observed in absorption at 19·7 Mc/s.

It is deduced, as a consequence of the small angular width of the equatorial absorbing band, that even at frequencies as high as 600 Mc/s thermal radiation contributes only a small fraction of the observed emission.

I. Introduction

Following the discovery of cosmic radio radiation by Jansky, it was suggested by Reber (1940) that the origin of the radiation lay wholly in thermal emission from interstellar ionized hydrogen (the " H II regions " of the Galaxy). Although this hypothesis was found to be untenable, because the very high brightness temperatures observed at low frequencies required the existence of a further, non-thermal, source distributed throughout the Galaxy, it was recognized that the interstellar gas must have a profound effect on the distribution of radio brightness. At high frequencies, where the non-thermal component is relatively weak, the gas should appear bright against the low temperature background ; at low frequencies, where the non-thermal component is strong, it should appear in absorption. Until a few years ago, owing to the poor resolving power of the aerial beams used in galactic surveys, there was no direct evidence of the effect of the ionized gas. Interferometer observations by Scheuer and Ryle (1953) showed a narrow bright region along the galactic equator which they attributed to thermal radiation from H II regions, but at the frequency used this bright band is now known to be largely due to non-thermal emission (see below ; also Mills 1955).

The application of high resolution aerials at very high frequencies to the study of cosmic noise led to the definite identification of a number of bright discrete sources with isolated bright H II regions (see, for example, Haddock, Mayer, and Sloanaker (1954) and others who used the 50-ft paraboloid at wavelengths from 3 to 21 cm). At the intermediate frequency of 85·5 Mc/s, Mills, Little, and Sheridan (1956) observed a number of H II regions, including one, NGC 6357, in absorption. Evidence that H II region absorption was affecting the distribution of brightness at 18·3 Mc/s was given by Shain (1953) from a

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comparison of low-resolution surveys at 18·3 and 100 Mc/s, but direct observation in absorption of the belt of H II regions around the galactic equator requires an aerial having a beamwidth less than the few degrees of angular extent of this belt. No such observations have yet been reported.

The present paper gives the first results of observations with the Sydney 19·7 Mc/s "Mills Cross", a high-resolution aerial with a beamwidth of 1°·4. These show clearly the expected absorbing band around the galactic plane and in addition isolated H II regions can be detected in absorption. Of particular interest is a strongly absorbing region in the direction of the galactic centre which is identified with the source Sagittarius-A observed at high frequencies.

II. Observations

It is hoped to give a full description of the aerial and associated equipment in another paper, so only a brief sketch will be given here. The principle of operation of the Mills Cross has been outlined by Mills and Little (1953) and will be given in detail in a paper being prepared for publication by Mills, Little, Sheridan, and Slee.

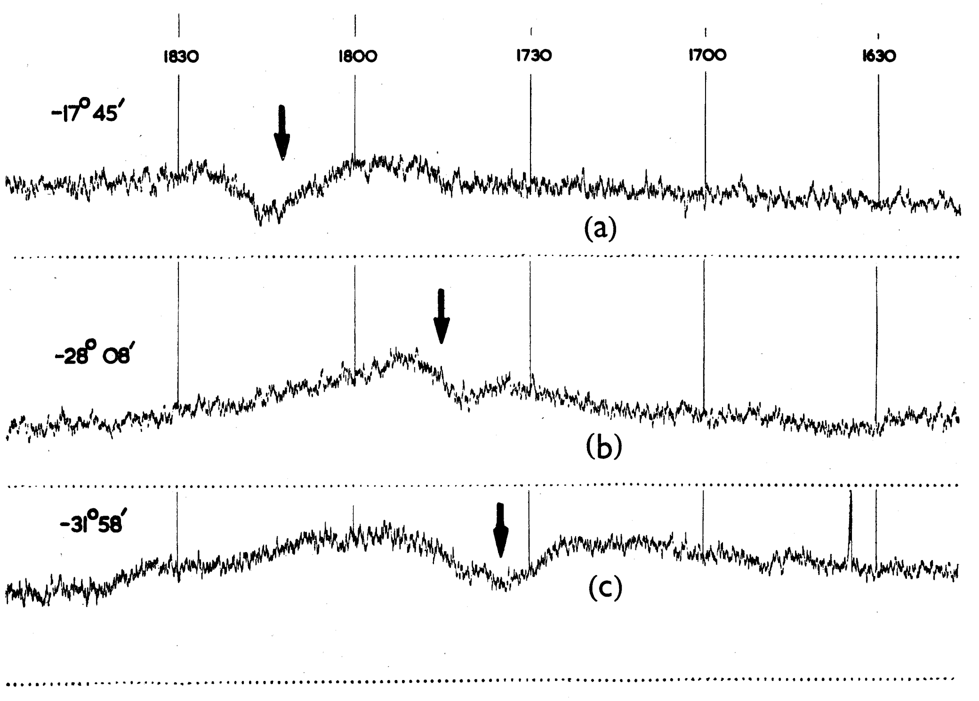

Fig. 1.—Typical records at three declinations as indicated. Sidereal time is marked and the arrows show the time at which galactic latitude —1°·3 passed the aerial beam on each occasion.

The aerial consists of two arrays of horizontal half-wave dipoles arranged in the form of a cross. The north-south array is an array of dipoles one dipole wide spaced at half-wavelength (25 ft) intervals over a length of 3625 ft and suspended one quarter-wavelength above the ground. Each dipole is lightly coupled to a transmission line in such a way that by turning a switch the phase of its current relative to that in any other dipole may be varied in steps of 33 degrees with negligible change in amplitude. Suitable settings of all the switches enable the beam to be directed to any declination. The east-west array is a collinear array extending 3400 ft, with no provision for beam swinging. In each array the amplitude of the current in the nth dipole from the centre is proportional to exp $(-kn^2)$ where k is a constant chosen so that the current in

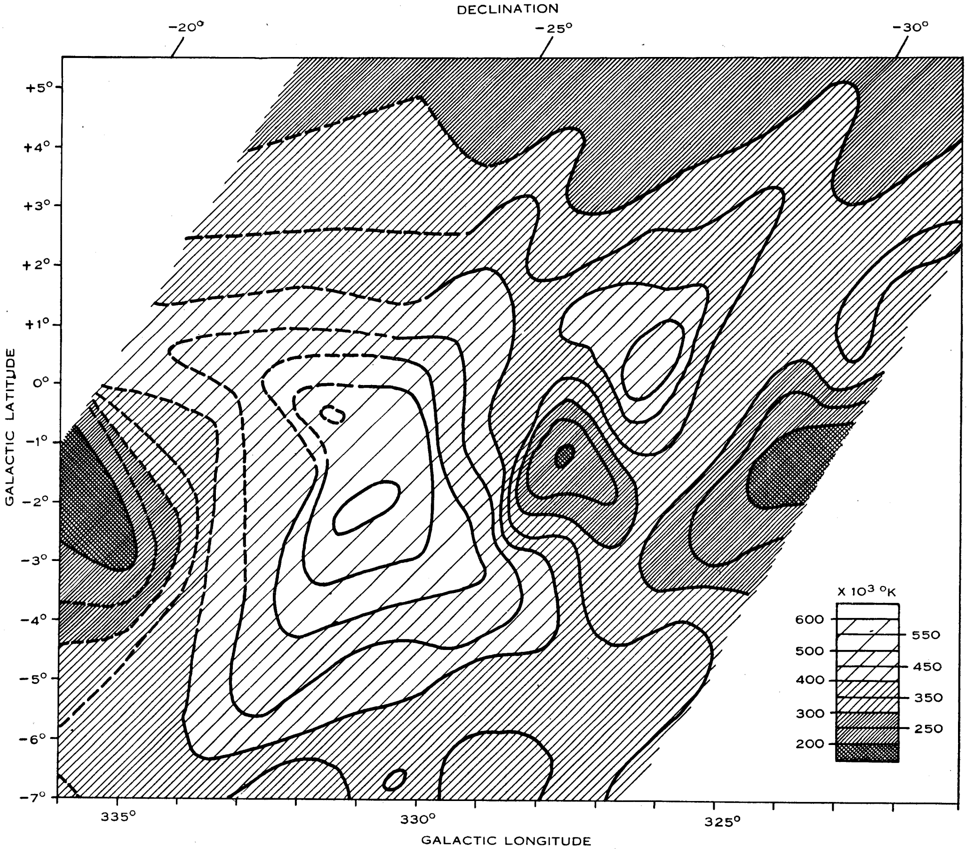

Fig. 2.—Isophotes of 19·7 Mc/s observed brightness temperatures near the galactic centre. The temperature scale is indicated by shading according to the key in the lower right-hand corner. The dark region near the centre is the source Sagittarius-A observed in absorption. The contours are dashed near the left-hand side where there were insufficient observations to give the full detail. A scale of declination is given at the top of the figure.

an end dipole is one-tenth of that in the centre dipole. This current distribution, although broadening the aerial beam, results in very small side lobes. The aerial beamwidth is about 1°·4.

The receiving equipment is similar in principle to that used by Mills, Little and Sheridan (1956) at 85·5 Mc/s. As a compromise between sensitivity and discrimination against interfering signals, most of the observations on which the present paper is based were made with receiver bandwidths of 5 or 8 kc/s, but a few records have also been obtained with 100 kc/s bandwidth. In most cases there was aural monitoring as a check on interference. All the records were made at night between 22^{h} and 06^{h} (local time) so that ionospheric absorption and systematic refraction should be negligible, but some trouble was experienced from scintillations.

Typical records with the narrow bandwidth are shown in Figure 1. The pronounced dip as the aerial beam crosses the galactic plane can be clearly seen.

Absolute calibration of the system is difficult and is not yet complete. In the interim an approximate calibration of the temperature scale has been made by comparison of the present results with previous observations at 18·3 Mc/s (Shain and Higgins 1953). As is usual in radio astronomy observations, although there may well be errors of 20 per cent. or more in the absolute calibration, relative values are known more accurately and in the discussion which follows it is the relative values that are mainly concerned.

A detailed survey of a strip of the sky between declinations —32° 36′ and —25° 34′ has been made in steps of 38 min of arc, and from this survey, with two other records, Figure 2 has been drawn showing isophotes of 19·7 Mc/s radiation in the region surrounding the galactic centre. The contours are drawn in broken lines on the left-hand side of the figure where the spacing of the records in declination was too great to give a complete survey, and some details may have been missed. In addition to those used in constructing Figure 2, other records have been taken at several declinations between —11° 40′ and —42° 49′.

III. Discussion

(a) *Absorption in H II Regions*

The most striking feature of the records is a very deep minimum in observed brightness temperatures as the galactic plane crosses the aerial beam. This has been observed on practically all records between declinations —12° and —42°; the only exceptions are close to declination —27° where the brightness temperatures are very high (near $l=331°$, $b=-2°$ in Figure 2). The appearance of this " trough ", a few degrees wide, is clear evidence that absorption of 19·7 Mc/s radiation is occurring in the band of H II regions near the galactic plane. The relatively bright area at $l=331°$, $b=-2°$ is presumably due to the existence of a " window ".

Figure 3 shows the approximate positions and extent of H II regions observed in this portion of the sky by Gum (1955). Although the incomplete coverage of the 19·7 Mc/s survey prevents the study of detail towards the left-hand side of the figure, it is seen that in the vicinity of the H II regions the contours are distorted in the sense that lower brightness temperatures are observed and there is no doubt that many of the radio dark areas are due to the presence of H II regions.

The absorption coefficient $\varkappa$ at 19·7 Mc/s in an H II region having electron temperature T_e °K and electron density n_e cm^{-3} is given by

$$\varkappa=1\cdot 27\times 10^{3}\times T_e^{-3/2}\times n_e^{2}$$

(Piddington 1951). The optical depth τ assuming T_e is constant is

$$\tau=\int \varkappa \mathrm{d}s=1\cdot 27\times 10^3 \times T_e^{-3/2}\int n_e^2 \mathrm{d}s.$$

The quantity $\int n_e^2 \mathrm{d}s$, the " emission measure ", also governs the emission of $H\alpha$ light and may be deduced from optical data. Taking $T_e \simeq 10^4$ °K, $\tau=1\cdot 27\times 10^{-3}\times$(emission measure), so that an optical depth of unity at 19·7 Mc/s is reached with an emission measure of about 800. An H II region having an emission measure of only 800 would be classed as very faint when observed optically.

If the H II region is sufficiently large to fill the aerial beam the full effect of the absorption will be observed. Smaller regions will show absorption effects in the ratio of the solid angle subtended by the H II region to that of the aerial

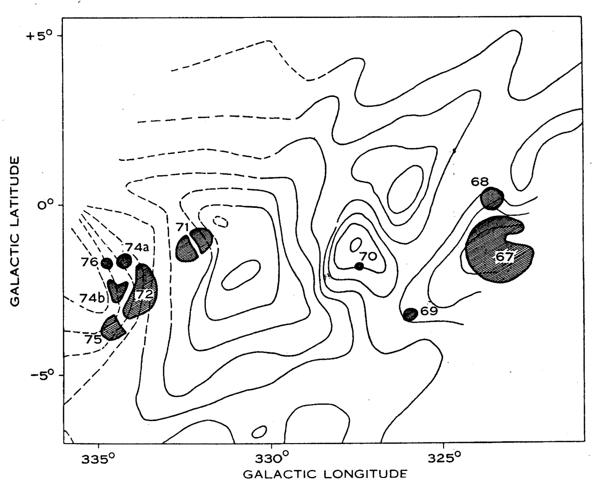

Fig. 3.—The shaded areas show the positions and approximate extent of H II regions observed by Gum (1955); the numbers give Gum's catalogue number.

beam. The effects of most of the H II regions shown in Figure 3 will be reduced in this way. However, it is probable that low frequency radio absorption observations will give more sensitive indications of faint extended H II regions than any other method, radio or optical.

The extended H II region around τ Scorpii (Morgan, Stromgren, and Johnson 1955) is an interesting example. It is observed in absorption on the record of Figure 1 (*b*) from about $16^{\mathrm{h}}\,30^{\mathrm{m}}$ to about $16^{\mathrm{h}}\,50^{\mathrm{m}}$. This record and others show that the absorbing region produces a maximum absorption of about 25 per cent. and has an angular diameter of about 5°. The maximum absorption occurs close to τ Sco and the absorption falls off most rapidly towards the northern side. These observations agree very well with the description given by Morgan, Stromgren, and Johnson. Assuming an electron temperature of

10^4 °K, the radio observations give an emission measure of 230, a value consistent with the application of Stromgren's (1948) theory to the optical data. Even fainter extended H II regions should produce significant absorption of 19·7 Mc/s radiation so that these observations should be of value in studying nearby H II regions (which subtend large angles).

Brighter H II regions may completely absorb 19·7 Mc/s radiation. For example, Stromlo 67 (Gum 1955) is an H II region, classed "faint" by Gum, about 2° in diameter and centred on $l=323°·4$, $b=-1°·3$. It appears near the right-hand edge of Figure 3. A preliminary photometric study by Gum (personal communication) gives an emission measure of about 3500. The 19·7 Mc/s absorption is then so great that an insignificant fraction, less than 0·3 per cent., of any incident radiation is transmitted. The excess of radiation from the direction of such an H II region, assuming proper allowance to have been made for the finite angular size, over that due to the 10,000 °K thermal emission from the H II region itself must then originate in the space between it and the observer.

(*b*) *The Relative Importance of Thermal Emission as a Source of High Frequency Galactic Radiation*

Since the first observations of cosmic noise there has been considerable discussion of the question whether or not thermal radiation from H II regions can account for all, or at any rate most, of the radiation observed in the bright band following the galactic plane (the "discoidal" component). Recently, Mills (1955), using early observations with the 85·5 Mc/s Cross, deduced that less than one-quarter of the emission in this band was due to thermal radiation, but Piddington and Trent (1956) criticized this result and concluded that their 600 Mc/s observations were quite consistent with the hypothesis of a thermal origin for most of this emission. The present observations show clearly that the latter hypothesis is untenable.

If the discoidal component were wholly thermal in origin, 19·7 Mc/s records should show only a trough near the galactic plane. Actually, the records, as in Figure 1, show a considerable rise on either side of the trough and this is conclusive evidence that there must be both thermal and non-thermal contributions to this component of the galactic radiation.

Discussion of the relative importance of the two contributions requires quantitative consideration. The observations show that for latitudes not less than 8° there is a rise towards the galactic equator which is broadly similar on 600, 85·5, and 19·7 Mc/s. At lower latitudes, the 19·7 Mc/s radiation becomes relatively less bright than at the other two frequencies, and within about ±4° of the galactic plane the 19·7 Mc/s records show the trough, whereas the others show a ridge. The simple interpretation is that, outside latitudes ±8°, absorption is not important but it becomes increasingly important at lower latitudes. Further, if the optical depth at 19·7 Mc/s is $\tau_{19·7}$ and at 600 Mc/s τ_{600}, it may be shown (Piddington 1951) that $\tau_{19·7}=1200\ \tau_{600}$. Now, if at latitude 8° the 600 Mc/s radiation were mainly thermal, the observed temperature of 50° requires, for a gas temperature of 10,000 °K, a value of τ_{600} of 0·005 and hence of $\tau_{19·7}$ of $1200\times0·005=6$. The corresponding absorption, greater than 99·99 per cent., appears quite inconsistent with the observed similarity of the 19·7, 85·5, and 600 Mc/s profiles up to this latitude. The assumption of a preponderance of thermal radiation at this latitude is therefore inadmissible. Even at latitudes of 4° it appears that the absorption of 19·7 Mc/s radiation is less than 0·5, from which the optical depth at 600 Mc/s may be deduced as less than 6×10^{-4} and the proportion of 600 Mc/s thermal emission less than 8 per cent.

It is possible that the relative proportions of thermal and non-thermal emission at 600 Mc/s changes as the galactic equator is approached, but the general similarity of the 85·5 and 600 Mc/s contours suggests that the non-thermal component remains the major component.

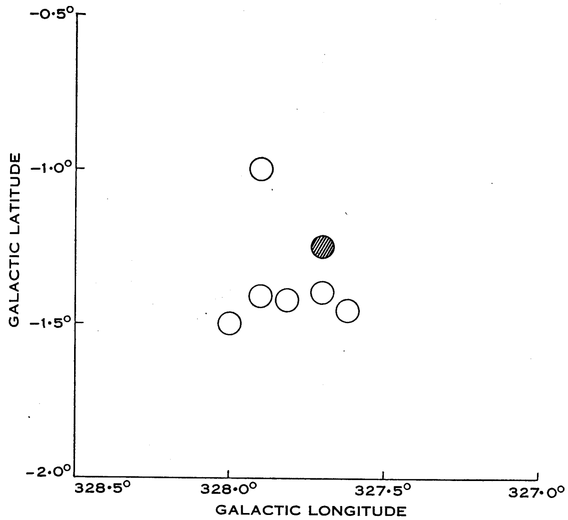

Fig. 4.—The observed position of the source Sagittarius-A. The open circles are the positions observed at high frequencies and collected by Kraus and Ko (1955). The shaded circle is the position of the deep minimum observed at 19·7 Mc/s.

(c) *The Source Sagittarius-A*

An outstanding feature of Figure 2 is the very pronounced local minimum at $l=327°\cdot8$, $b=-1°\cdot2$ which appears as a " hole " of angular width 2°·4 (at half-depth). Its position agrees, within the experimental uncertainty of a few tenths of a degree, with the position of the strong source Sagittarius-A (IAU number 17S2A) observed at high frequencies. The observed positions of this source have been collected by Kraus and Ko (1955) and Priester (1955) and are shown in Figure 4, together with the 19·7 Mc/s minimum. At centimetre wavelengths the very bright small source has been observed superimposed on a moderately bright extended source. Mills (1956) has shown that at 85·5 Mc/s, at which frequency the source is seen in absorption, the observations are readily explained in terms of an H II region in front, or partly in front, of a more extended non-thermal source. At 19·7 Mc/s the absorption is roughly $(85\cdot5/19\cdot7)^2$, that is about 20 times as great and the absorption must be practically complete.

The angular size of the thermal source apparently varies with frequency, as shown in Table 1. As suggested by Mills (1956) the thermal source is probably extended, with a concentration towards the centre. The 19·7 Mc/s (15·2 m wavelength) observations, being very sensitive to absorption in H II regions, take in the full extent of the source.

From the close agreement in position, and the consideration of angular size, there is no doubt that the deep minimum observed near the galactic centre at 19·7 Mc/s is due to the source Sagittarius-A observed in absorption.

TABLE 1

THE ANGULAR SIZE OF THE SOURCE SAGITTARIUS-A

Authors	Wavelength	Angular Size	Remarks
Haddock and McCullough (1955)	3 cm	$\frac{1}{4}°$	Also a more extended source
Hagen and McClain (1954)	21 cm	$\frac{1}{2}°$	Also a more extended source
Kraus and Ko (1955) ..	1·2 m	$>1\frac{1}{2}°$	Possibly includes the extended source
Mills (1956)	3·5 m	$>\frac{1}{2}°$	Observed in absorption
Present observations ..	15·2 m	$2\frac{1}{2}°$	Observed in absorption

IV. FUTURE POSSIBILITIES

The peculiar value of the 19·7 Mc/s observations arises from the fact that the intensity of the radiation at such a low frequency is very much affected by absorption in low density ionized interstellar hydrogen. An obvious application is the detection of very faint H II regions in intermediate and high latitudes.

Probably more important, however, is the study of the intensity of radiation from the direction of large (i.e. extending over several degrees) and dense H II regions in which the absorption is very great. For, if it can be shown that the absorption is essentially complete, it follows that all radiation observed from this direction must have been generated between the Sun and the absorbing region (apart from the comparatively small thermal emission from the region itself). Since, generally, the distances of H II regions can be estimated from optical data, such observations should yield a value for the amount of non-thermal radiation emitted per parsec, a quantity of importance in the study of the origin of the radiation. As a corollary, once this quantity is known for a number of representative situations, it should be possible to use it in the estimation of distances to other absorbing features of the Galaxy.

The present observations are not sufficient to give a definitive value of the emission per parsec and further observations are in progress. However, the data available at present indicate that the absorbing gas is strongly concentrated in spiral arms, and that throughout most of these the absorption is very high, although there are translucent patches.

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