28. RADIO STUDIES OF HII REGIONS AND GALACTIC STRUCTURE

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I. Introduction

Radio studies of galactic HII regions are best carried out at the two ends of the radio spectrum. At high frequencies, of hundreds or thousands of megacycles per second, HII regions are seen by virtue of their thermal emission against a weak nonthermal background. Since radio waves are unaffected by the obscuration along the plane, it is possible in principle to see right through the Galaxy, and the high resolution which can be achieved in the thousands of megacycles range enables us to study at least the nearer regions in considerable detail. At low frequencies, below about 20 Mc/s, ionized hydrogen is seen in absorption against a bright nonthermal background. Since quite tenuous regions may be almost opaque at the lower frequencies, the technique provides quite a sensitive method of detecting them. The absorption increases with decreasing frequency so that studies at different frequencies enable us to see to varying depths along the line of sight and could permit the derivation of rough distance estimates.

II. Low-Frequency Studies

(*a*) *20 Mc/s.*—One of the first to recognize the potentialities of low-frequency studies was the late C. A. Shain. After some early low-resolution work (Shain 1954) he constructed a Mills Cross with a beamwidth of about $1\frac{1}{2}°$ at $19 \cdot 7$ Mc/s. With this he surveyed a strip of the Milky Way extending over 150° of longitude and found a number of radio dark areas along the galactic equator, whose outlines correlated well with optically observed HII regions. In addition, in many directions in which there was little or no optically detectable ionized hydrogen, he found a regular minimum in the radio contours extending along the galactic equator (Shain, Komesaroff, and Higgins 1961). The natural interpretation was that this represented the absorption due to many HII regions too distant to be seen through the optical obscuration. This interpretation was supported by a comparison of the $19 \cdot 7$ Mc/s results with observations at higher frequencies. This comparison also indicated that the nonthermal flux had a spectral index of about $0 \cdot 6$ (Komesaroff 1961).

For areas within about $\pm 30°$ of longitude from the galactic centre, and free of visible HII regions, the optical depth at $19 \cdot 7$ Mc/s was typically between 5 and 10, corresponding to emission measures right through the Galaxy of 5,000–10,000 cm^{-6} pc. If an average HII region has a diameter of about 10 pc and an electron density of 10 cm^{-3} then lines of sight close to the galactic plane intersect on the average between 5 and 10 such regions.

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From observations at a single low frequency, it is also possible in principle to derive rough distance estimates. Even in the direction of quite dense HII regions, the radio brightness at 19·7 Mc/s is as high as 10^5 °K whereas the hydrogen electron temperature is only about 10^4 °K. Therefore most of the observed brightness must be due to nonthermal emission between the HII region and the Sun. If we could measure the brightness in the direction of an HII region whose distance was reliably known, we could estimate the galactic nonthermal emission per unit distance, and this figure could then be used to determine the distances to other HII regions. Shain (1959) attempted this type of measurement but was limited by the limited resolution of his aerial system. At the moment several aerial systems in the 20 Mc/s range are projected or are under construction. These aerials will have resolutions of the order of 10 min of arc, and they could possibly be used for this type of galactic distance measurement.

(*b*) *Below 10 Mc/s.*—At very low frequencies a considerable amount of work is being carried out in Tasmania, which has the advantage of favourable ionospheric conditions. One result which is of particular interest and which has been mentioned by Mills (this volume, paper 25) concerns the radiation spectrum below 10 Mc/s. This was found to have a maximum at a frequency which depended on galactic latitude (Ellis, Waterworth, and Bessell 1962). Hoyle and Ellis (1963) interpret this as due to thermal absorption in a layer of ionized hydrogen 300 pc wide along the galactic plane, containing 0·1 electron per cm^3 with an assumed electron temperature of 10^4 °K. The existence of such a layer would explain the recent Faraday rotation measurements of Cooper and Price (1962) on the source Centaurus A if it is further assumed that the average line-of-sight magnetic flux component in the galactic disk between the Sun and Centaurus A is about 10^{-6} gauss.

However, these results were derived on the assumption that the gas was homogeneously distributed. As shown below, clumpiness of the distribution will decrease the average density considerably.

III. Centimetre-Wave Studies

(*a*) *Distribution of HII Regions.*—The present high-resolution survey being undertaken at Parkes provides further information about the distribution of galactic ionized hydrogen. Some aspects of this survey have been described by Hill (this volume, paper 26). The points to be dealt with here concern the distribution of discrete sources with galactic latitude and the existence of a background of radiation which is continuous even at very high resolution.

Previous galactic surveys around 1400 Mc/s by Westerhout (1958*a*) in the northern hemisphere and Mathewson, Healey, and Rome (1962) in the southern hemisphere have indicated that the majority of discrete sources seen at this frequency have thermal spectra. Thus the latitude distribution of the sources should tell us something about the distribution of HII regions perpendicular to the galactic plane. For a section of the present survey between $l^{II} = 318$ and 348° sources have been counted as a function of galactic latitude. The results are shown in Figure 1. The sources have been arbitrarily divided into those producing an increment of aerial

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temperature between 1°K and 2·5°K and those greater than 2·5°K. A point source of 2·5°K has a flux density of about 3·75 flux units (where one flux unit is 10^{-26} $W/m^2.(c/s)$).

The intense sources are seen to be much more strongly concentrated towards the plane than the weaker ones. Two reasons for the wider dispersion of the weaker sources are, firstly, that they include a number of extragalactic objects and secondly, that a selection effect is operating—it is more difficult to see a weak source close to the galactic plane. Hence the strong sources provide a truer picture of the actual galactic distribution.

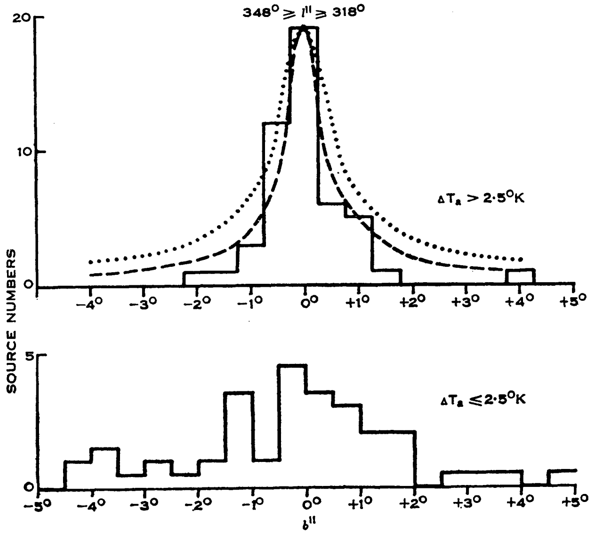

Fig. 1.—Distribution of the sources in latitude.

The two curves on the upper histogram are expected distributions according to very simple models of the Galaxy. It is assumed that the spatial source density is a function only of distance from the plane, that the distribution is a gaussian one, and that the Galaxy is a disk 16 kpc in diameter. For the wider curve the halfwidth of the gaussian was taken as 170 pc in accordance with Kerr's estimate of the halfwidth of the neutral hydrogen layer and for the narrower curve the halfwidth is 100 pc. It seems that the narrower curve fits the observations slightly better than the wider one.

However, this takes no account of the sensitivity limit of our survey. The number of flux units at 1410 Mc/s produced by a sphere of ionized hydrogen of radius R pc and electron density N cm^{-3}, at a distance D pc and having an electron temperature of 10^4 °K, is given by

$$S = 4\cdot0\times10^2\,\frac{N^2R^3}{D^2}.$$

Now for a Strömgren sphere produced by a single star the quantity $N^{2/3}\,R$ is a constant which depends only on the spectral type of the star. On using Pottasch's (1956) estimates of $N^{2/3}\,R$, it appears that an HII region excited by an O5 star, at a distance

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of 16 kpc, would produce only 1·5 flux units, and that a similar figure is obtained for an O8 star at 7 kpc. Thus the range of our survey for moderately intense HII regions is probably about half a galactic diameter. Thus the figures previously quoted for halfwidths in the z direction should be divided by a factor of about 2 giving a halfwidth of 40–60 pc corresponding to $|\bar{z}| \simeq 50$ pc. This agrees with values found for early-type stars within about 1 kpc and to that extent might have been expected. The radio results now indicate that the same dispersion applies at distances of several kiloparsecs and that the distribution remains accurately centred on the galactic plane to these distances.

(*b*) *The Thermal Background.*—Along the galactic plane, the discrete sources are seen on top of a smooth background. Westerhout (1958*a*), Mills (1959), Large, Mathewson, and Haslam (1961), and Mathewson, Healey and Rome (1962) have shown that this background consists of a thermal and a nonthermal component. By comparing the background intensities—after subtraction of the discrete sources—at frequencies of 1400, 400, and 85 Mc/s, it was possible to estimate the intensity distribution of the thermal component. One of the most interesting features in this distribution is a very sudden rise of intensity towards the galactic centre around $\pm 30°$ longitude. Between longitudes $+25$ and $-25°$ the intensity is more or less constant, although around $l'' = +25°$ a maximum occurs. The distribution is excitingly symmetrical with respect to the direction to the galactic centre, so much so that it seems fairly safe to derive a first approximation to a space distribution of emissivity on the basis of axial symmetry. This space distribution shows a sharp maximum around $R = 3 \cdot 5$ kpc, and a considerable decrease of emissivity within $R = 2 \cdot 5$ kpc.

It is curious that the maximum comes at a distance just beyond the assumed distance of the "3-kpc expanding arm", and one wonders whether any connection exists. Is star formation and thus ionization favoured there because the expanding neutral gas is stopped by some force? Or because it has expanded long enough? The maximum density of neutral hydrogen occurs much farther out.

A question which is almost as important is that of the density distribution. The radio observations give the distribution of the emission measure $N_e^2\, ds$, and the actual density distribution depends critically on the "clumpiness" of the gas. If all the gas were concentrated in emission nebulae with densities of a few tens or hundreds of atoms per cm^3, the observed intensities could be explained by an extremely low average space density; but there would be many more bright emission nebulae than we see radiowise. The maximum around $R = 3$ kpc could be explained by an increase in space density, but also by an increase in degree of clumpiness and a constant space density.

One cannot decide anyway what governs the tendency to form dense emission nebulae in some parts of spiral arms. The Sagittarius arm near the Sun, at $r = 2$ kpc, for example, is very rich in dense emission nebulae. If such nebulae were present in other arms, they would be easily observable with high-resolution equipment, such as the Australian 210-foot antenna at 11 cm wavelength.

In order to make a preliminary test, a number of scans across the plane, at constant right ascension, were made at a frequency of 2650 Mc/s. The right ascensions were chosen so that the scans went through a number of longitudes where the 1410 Mc/s observations showed no evidence of discrete sources, only a smooth peak centred on the galactic plane with a halfwidth of a few degrees. Scans made through longitudes 302, 307, 315, and 323° all showed a rise of about 0·7°K centred on the plane, with a halfwidth between 1 and 2°, and were completely smooth in character. Thus, even with a resolution of 7·5 min arc, at 11 cm, there appears to be a background component which shows no discrete source structure.

Comparison with Mills' 85 Mc/s survey shows that at 11 cm the brightness temperature of the thermal component at longitudes 302 and 307° is about 0·5°K. Comparison is easy at these longitudes since the 85 Mc/s contours are very smooth. At longitudes 315 and 323° the interpretation is less definite, since nonthermal sources in Mills' contours make it difficult to find the proper 85 Mc/s background temperature to be used. However, here also the thermal component is not much higher than 0·5°K. A scan made at longitude 329° shows that the level is much higher than at the other longitudes examined, and the comparison with Mills' contours indicates a thermal component of about 1°K. This sudden increase corresponds with the rise in thermal emission mentioned before. But aerial resolution effects need to be taken more fully into account in the comparison between surveys with such widely different beamwidths (7′.5 and 50′), and a more careful analysis is required.

The thermal brightness temperature of 0·5°K found between $l^{\rm II} = 302$ and 307° corresponds to an emission measure of about 1000 cm^{-6} pc if the electron temperature is 10^{11} °K. If the background were indeed due to a completely homogeneous medium of ionized hydrogen throughout the entire Galaxy, this would lead to an electron density of about 0·3 cm^{-3}, or three times larger than the value found by Hoyle and Ellis.

However, it seems highly unlikely that the medium is smooth. A more realistic model is probably one where white dwarfs, or later-type stars, ionize the neutral hydrogen around them. The Strömgren spheres created by these stars would be far too small to be individually resolved, even with a 7′.5 beam. An argument in favour of this hypothesis is that from the work of Westerhout (1958*a*) and Altenhoff *et al.* (1960) it follows that the halfwidth of the smooth thermal component in latitude is considerably wider than the halfwidth of the thermal source component. It corresponds more nearly to the value of 170 pc estimated by Kerr for the halfwidth of the layer of neutral hydrogen.

It is virtually impossible at present to give any value for the actual space density of the ionized hydrogen if we do not know the degree of clumpiness. If all the hydrogen were concentrated in clouds with a density of 5 electrons per cm^3, the average space density corresponding to the above mentioned emission measure of 1000 cm^{-6} pc would be of the order of 0·02 cm^{-3}. Westerhout's (1958*b*) discussion of the total mass of ionized hydrogen in the Galaxy seems to be still the only reasonable guess. He found a value of the order of 4×10^7 solar masses and indicated that this might be uncertain by a factor of at least two in either direction.

Measurements of the Faraday rotation of the polarized radiation from nonthermal sources in the galactic disk might help in solving some of the uncertainties (Gardner, this volume, paper 35). The Faraday rotation is proportional to the product

$NH \cos \phi$ where N is the density, H the magnetic field strength, and ϕ the angle between the direction of the field and the normal to the line of sight. Thus, in principle, these measurements would give the distribution of N if enough nonthermal sources at known distances throughout the Galaxy were available. But one should not exclude the possibility that the strength of the magnetic field is connected with the electron density, thus perhaps making the Faraday rotation proportional to N^2. Nor should one exclude the possibilities that the field occurs in limited regions of space, for example, supernova remnants, and that a typical HII region might have no field connected with it.

Summing up, we conclude that:

(i) Ionized hydrogen has a fairly strong concentration around $R = 3{\cdot}5$ kpc;

(ii) part of it is concentrated in bright emission regions surrounding stars close to the galactic plane;

(iii) the rest is concentrated in very small or very weak emission regions, or in a continuous medium, and not resolved into individual sources even with a 7′.5 beam; the width of this smooth component corresponds with that of the layer of neutral hydrogen;

(iv) it is virtually impossible at present to give a reasonable estimate of the average space density of ionized hydrogen.

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Discussion

Ambartsumian: Are the small fluctuations real on the pictures of distribution of the radio brightness you have shown?

Komesaroff: No, these scans were performed at rather a rapid drive rate for the time constant used.

Large: The 408 Mc/s survey of the galactic plane made at Jodrell Bank gives evidence from the northern hemisphere in support of Mr. Komesaroff's conclusions that the HII regions lie at an average distance of 50 pc from the plane, and that there is a continuous distribution of thermal radiation from $l^{II} = -30$ to $+30°$. The "step" in the thermal emission at $l^{II} = +30°$ is

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complicated by the presence of a number of thermal sources at this longitude. Furthermore, the north polar spur intersects the galactic plane at this point, so that one has to be very cautious in interpreting the results as a 3-kpc ring of thermal material.

Westerhout: With regard to Dr. Large's remark that the "spur" might influence the bump in the galactic radiation near $l'' = 30°$, it must be said that this spur clearly has a nonthermal spectrum. Also, one cannot really connect it with the main body of the Milky Way. I have the feeling that it is a completely separate phenomenon.

Mathewson: Up till now, radiative excitation has been thought responsible for the ionization of the hydrogen in this strong central thermal component. Collisional excitation should also be considered, the energy for which may be supplied by the gas which H-line observers find to be flowing rapidly outwards from the galactic centre. Electron temperatures in excess of 10^4 °K could then be obtained.

Kerr: It has been suggested by two speakers that the ring of ionized hydrogen at 3·5 kpc lies just outside the so-called 3-kpc arm of neutral hydrogen. The latter arm can in fact be followed to longitude 334°. If we are seeing the arm tangentially at this longitude, the corresponding distance from the galactic centre is 3·5 kpc.

Bolton: There is no real evidence that the so-called 3·5-kpc ring is a complete ring. It certainly extends from the tangential points at ±30° longitude from the centre and on the nearby side of the centre. Very high resolution radio observations may confirm its completeness on the other side of the centre but the evidence at present only supports an arc of 120 to 180°.

Westerhout: Our assumption of a ring is only based on the observation that the steps at both sides of the centre occur at exactly the same distance from the centre. Indeed, one can assume that we are dealing with a part of a ring, or even with an accidental occurrence of density maxima. But I feel the symmetry argument rather strongly favours a ring or large arc structure.

29. SUPERASSOCIATIONS IN DISTANT GALAXIES

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It is well known that the Large Magellanic Cloud contains in addition to a considerable number of ordinary O-associations a certain number of large objects which, however, are similar in nature to the associations. These objects were named "constellations" by Shapley. But the large complex 30 Doradus surpasses notably all of these objects both in diameter and in absolute brightness. The latter is of the order of $-15^{\mathrm{m}}.0$ while its diameter is of the order of 600 pc. If we take the average absolute brightness of associations in our Galaxy as equal to $-10^{\mathrm{m}}.0$ then it turns out that 30 Doradus is 100 times more luminous than the ordinary associations. The photographic images of more distant galaxies reveal that sometimes complexes occur in them of the same order of luminosity and dimensions as 30 Doradus. Therefore it seems to us useful to regard these complexes as a special class of objects and call them *superassociations*.

The frequency of occurrence of superassociations within the galaxies is being investigated at the Byurakan Observatory. On plates taken by means of the 21-inch Schmidt reflector the superassociations are almost star-like if the distance of the corresponding galaxy is over 15 million pc. When exposures are of shorter duration (a few seconds) the general background of the corresponding galaxy does not hinder photometric evaluations, and the images of superassociations can be compared with

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