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THE MEASUREMENT OF THE DISTANCE OF THE RADIO SOURCES

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1. INTRODUCTION

In radio astronomy it is becoming increasingly important to know the distance of the radio sources. An identification with astronomical objects observed optically is then more readily obtained and this in turn may allow further investigation of the mechanism of radio emission. A measurement of the distance of sources will also resolve the problem of their distribution in space, showing which are galactic and which are extra-galactic. Furthermore the surface area and absolute luminosity can be estimated from a knowledge of the distance and angular size of a source.

Early attempts to measure distances by the method of parallax by Ryle [1] and Mills [2] served to place the major sources outside the solar system at a distance greater than $\frac{1}{2}$ parsec. This paper describes a completely new method, which involves a measurement of the absorption spectrum of the source produced by interstellar neutral hydrogen at a wave-length of 21 cm. Three different methods have been used to obtain a distance from these data. First, the very existence of absorption at the frequency of a spiral arm in the direction of a source places it within or beyond that arm. Secondly, the absorption line width of a source enables its distance to be determined in a way analogous to that used in optical astronomy. Thirdly, if the distribution of hydrogen along the line of sight in the direction of the source is known, the distance can be determined from the known amount of hydrogen between the sun and the source. The last two methods are useful in the galactic centre and anti-centre regions where the Doppler displacement relative to the sun is small.

Absorption measurements have been made on the four intense sources in Cassiopeia, Cygnus, Taurus and Sagittarius. Cygnus A lies beyond the limits of the Galaxy while the other sources are within it. Cassiopeia A appears to have a distance of at least 2·5 kiloparsecs which is five times

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greater than the optical determination. The Sagittarius source which some observers have identified with the galactic nucleus is at a distance of 3 kiloparsecs. An identification is suggested.

2. THE OBSERVATIONS

Preliminary results [3] indicated that the equipment had to be made more sensitive to give higher accuracy on the absorption in the Cassiopeia and Cygnus sources and to permit observations on weaker sources. The improved equipment consists of a radio spectrometer used in conjunction with a focal plane paraboloid 30 ft. in diameter illuminated by a dipole feed and reflector. The beam-width to half-power points is $1^\circ.45$ in the H-plane and $1^\circ.65$ in the E-plane. The aerial mounting is alt-azimuth and in order to be able to follow a source to within a quarter of a beam-width an autofollow mechanism is employed in the altitude and azimuth driving circuits. It is thus possible to obtain a spectrum. The accurate aerial position calibration for all parts of the sky was made through observation of the sources on total power.

The receiver employs the comparison principle in order to obtain the required stability. It is switched at 30 c./s. between the line frequency and a comparison band 1 Mc./s. on one side of the line. A new principle, whereby the line is observed continuously, involves having a second pair of receiving bands, one on the line frequency and a comparison band on the other side of the line. This 'double comparison technique' gives an improvement in sensitivity of 1·5 db. In order to observe the line profile a variable frequency is added to the frequency-controlled first local oscillator. The noise factor of the receiver was measured to be 8·5 db. using an argon noise source. This was checked by comparing the receiver noise temperature with the observed sun temperature. The receiver band-width was 40 kc./s. and the observing time constant was 30 sec. which gave peak-to-peak fluctuations of 7° K.

A total power receiver is required to measure the intensity of the radio sources in the continuum. A rotating capacity switch which has a switching ratio of 20 db. gives the desired stability. The measurements were made using the broad-band (1·1 Mc./s.) section of the receiver. The temperature of the sources was obtained by using narrow-band (40 kc./s.) and comparing Cassiopeia with the hydrogen-line intensity at $l = 50^\circ$ which was taken as 100° K.

In order to determine the absorption of the continuous emission of a source, it is necessary to observe the spectrum not only in the direction of the source but also in adjacent directions. The changing spectrum of the hydrogen near the source can then be taken into account in order to obtain the real emission spectrum in the precise position of the source. Accordingly, spectra were taken on a grid of eight points displaced 3° from the source either side in right ascension, declination, and at the four diagonal points. Spectra were obtained in sets of three across the source and were repeated three times. Two spectra are then obtained for each source, one of which is the average of all the points surrounding the source and

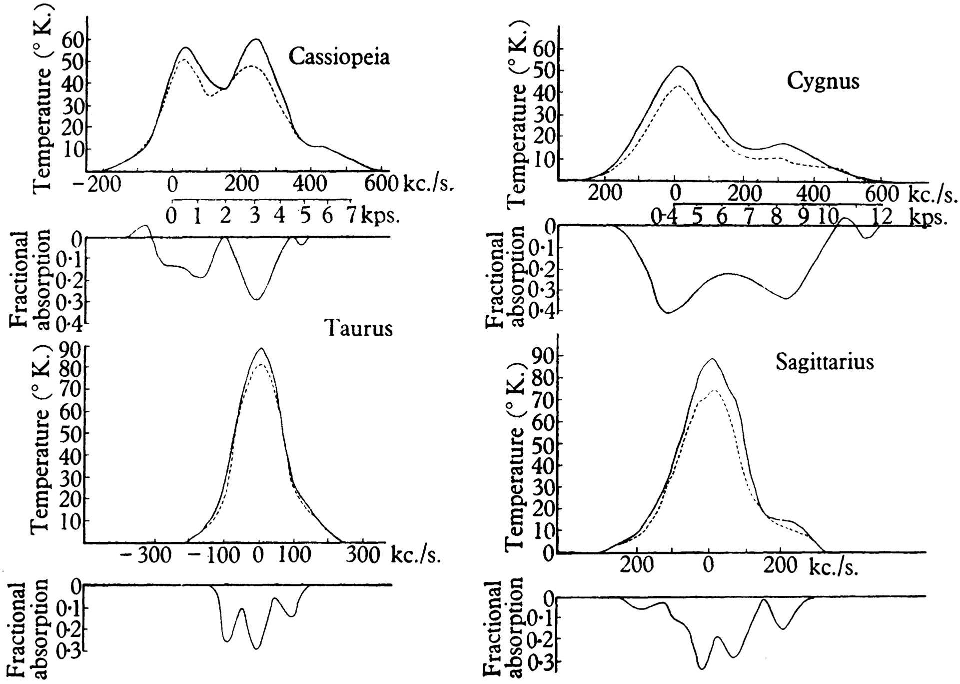

Fig. 1. The averaged spectra obtained on the source and immediately adjacent. The latter is the uppermost curve in each case. The fractional absorption spectra are plotted in the lower set.

represents the emission spectrum of the hydrogen if the source were not present, and the other is the average of the spectra taken on the source. The absorption spectrum for a source is obtained by subtracting these two spectra. Further, the fractional absorption can be derived from a knowledge of the temperature of the source obtained using the receiver on total power. A 10 % correction to the observed source temperature is required to allow for reception at the image frequency. The averaged spectra and the fractional absorption spectra for each of the four sources studied (Cassiopeia A, Cygnus A, Taurus A and Sagittarius A) are given in Fig. 1.

3. THE POSITION OF THE CYGNUS AND CASSIOPEIA SOURCES RELATIVE TO THE SPIRAL ARMS OF THE GALAXY

The concentration of neutral hydrogen into spiral arms within the Galaxy is now well established [4]. The exact position of these spiral arms depends upon an accurate knowledge of the rotational velocity in all regions of the Galaxy. In the present study the circularly symmetrical Oort model is used in conjunction with the hydrogen-line profiles to establish the distance of the arms in the direction of the various sources. In Cygnus the first peak comes from hydrogen near the sun and at 4 kiloparsecs while the second peak is from hydrogen at 8 kiloparsecs. In Cassiopeia the arms are at 0·5 and 3·0 kiloparsecs with a third faint arm at 5·5 kiloparsecs, while in Taurus and Sagittarius there is insufficient Doppler displacement to assign a distance to the hydrogen.

The following simple picture is used to describe the observed absorption results. It is assumed that the source itself blocks out only a negligible amount of neutral hydrogen from behind it. Let there be a source lying between two spiral arms. Fig. 2*a* represents the spectrum observed very close to the source; in fact, it is the spectrum in the direction of the source if it were not there. Fig. 2*b* is the absorption spectrum of the source due to its continuous emission traversing the nearer spiral arm. Then the observed spectrum in the direction of the source will be that in Fig. 2*c*. The absorption spectrum of the source, which contains all the required information, can be obtained by subtracting spectrum Fig. 2*c* from Fig. 2*a*. It can be seen that if a source lies beyond or within a spiral arm it will exhibit absorption at the frequency characteristic of that arm. Thus the Cygnus source which shows absorption within both arms must be extra-galactic while the Cassiopeia source lies between the outer two arms at 3·0 and 5·5 kiloparsecs. This distance for Cygnus is consistent with the optical identification of the source with colliding galaxies at 34 megaparsecs. The Cassiopeia result is at variance with the distance of 500 parsecs derived by Baade and Minkowski [5] for a supernova remnant in this direction. On the above interpretation of the radio results the nearest that this source could be placed is at 2·5 kiloparsecs, on the inner side of the second arm.

Hagen, Lilley and McClain [6] have studied the Cassiopeia source with a band-width of 8 kc./s. and found fine structure within the two absorption peaks, one line within the first peak and two within the second. It is not certain whether these narrow absorption lines are due to individual gas clouds. They may rather be due to groups of clouds because the density of clouds in the line of sight is probably about 10 per kiloparsec within an arm [7]. Whichever interpretation is given, these results do not affect the above conclusions, for these individual clouds or groups of clouds can only belong to the spiral arm within whose velocity limits they lie. The hydrogen line emission profiles may be considered as the probability distribution of cloud velocities within the arms and as the profiles fall almost to zero between the arms it is very unlikely that a cloud with a velocity characteristic of one arm should belong to the other.

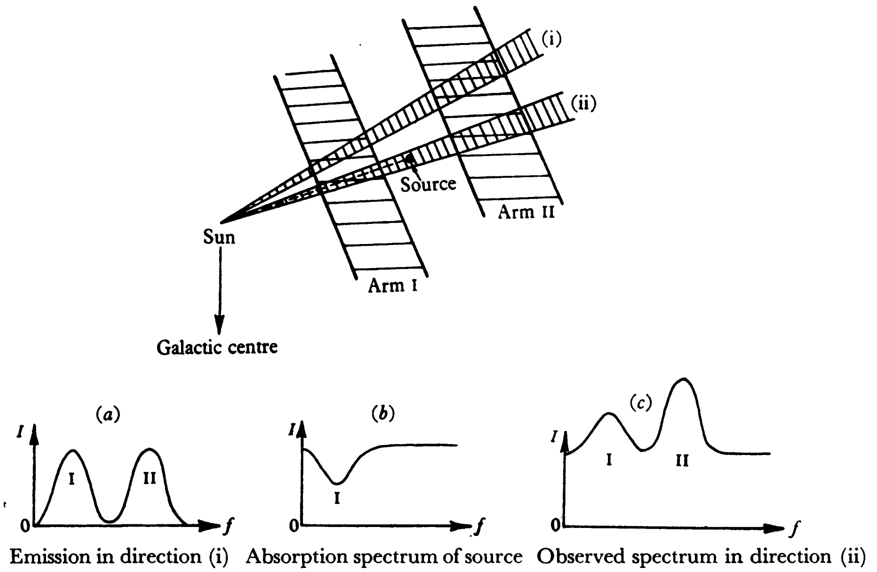

Fig. 2. A schematic diagram of the production of absorption of a source by neutral hydrogen.

4. THE TAURUS SOURCE

The Taurus A measurements enable the total number of hydrogen atoms/cm.^{2} in the line of sight between the sun and the source to be determined by the method described in the above section. The kinetic temperature of the gas was assumed to be 125° K. Since the distance of this source, which is identified with the Crab nebula, is known to be 1·1 kiloparsecs [8] the proportion of hydrogen in front of and behind this distance may be estimated: 30 % of the hydrogen is between the sun and the source and 70 % is beyond it. This information is of some value because in this part of the Galaxy ($l = 153°$, $b = -1{\cdot}5°$) there is too little Doppler diplacement to find the distribution of hydrogen by the conventional method. The published survey of the Galaxy [4] gives the hydrogen distribution only up to $l = 135°$ and beyond $l = 160°$. The published density contours were extrapolated across this region and the percentage of hydrogen up to and beyond a distance of 1·1 kiloparsecs was found to be precisely that obtained in the present work. This suggests that there may be some justification in extrapolating the distribution in (4) across the region $l=135°$ to 160°.

5. THE SAGITTARIUS SOURCE

This source lies very close to the galactic centre, where its distance cannot be measured by the method used for the Cassiopeia and Cygnus sources. Two new methods have been devised to deal with sources in the centre and anti-centre regions in particular, although in principle they may be applied to any source.

(*a*) *The equivalent width of the source absorption line.* In optical astronomy the intensities of interstellar absorption lines are known to give a statistical measure of the distance of stars. In a recent study Beals and Oke [9] compared the measured distance of a large number of stars up to 2·5 kiloparsecs with the equivalent width of their absorption lines and found a linear relationship. The distance of individual stars could be measured to an accuracy of at least 25 % using the derived linear relation. This error was largely due to the non-uniform distribution of absorbing gas in the direction of the stars.

This method can be used to measure the distance of radio stars by calculating the equivalent widths of their 21-cm. absorption lines. The equivalent width, H, is defined by

$$H=\int_{-\infty}^{+\infty}\frac{I_0-I_v}{I_0}\,dv\ \text{km./sec.},$$

where I_0 is the intensity of the unabsorbed continuum from the source and I_v is the intensity of absorbed radiation at a velocity v. It follows from this definition that the equivalent width is independent of the receiver bandwidth. Table 1 gives the distances and derived equivalent widths of the absorption lines for the four sources.

The distance assigned to the Cassiopeia source is the shortest possible consistent with the above interpretation, which brings it closest to the optical determination. The distance given in the case of Cygnus A is the

Table 1

Source	Distance (parsecs)	Equivalent widths (km./sec.)
Cassiopeia	2500	13 ± 2
Cygnus	8000	36 ± 3
Taurus	1100	8 ± 3
Sagittarius	?	14 ± 3

distance to the outer arm of the Galaxy in that direction, which is the path-length to the source lying in neutral hydrogen. The data for the three sources in Cassiopeia, Cygnus and Taurus along with the origin, enable a linear line-width against distance calibration curve to be drawn as in the optical case. The linear relation may be written

$$r = 220H \text{ parsecs.}$$

The optical result for the interstellar calcium K line was

$$r = 34 \cdot 8K \text{ parsecs}$$

which holds at least to a distance of 2·5 kiloparsecs. The hydrogen absorbing line is about six times weaker than the calcium line and the linear relationship for hydrogen may be expected to hold to 15 kiloparsecs before saturation effects come into play. This calibration curve becomes increasingly accurate for more distant sources but is liable to some error for the nearer sources because of the known non-uniform distribution of neutral hydrogen. This method is applicable to all sources but is particularly useful in cases where galactic rotation is small.

At first sight it is unexpected that the equivalent width of a line should increase linearly with distance since Oort [10] has shown theoretically that clouds are likely to have optical depths of the order of unity, and therefore where there are a number of clouds in the line of sight saturation effects are likely to come into play. The fallacy in this argument is in expecting the absorption spectrum of each cloud to be the same, whereas in fact each cloud has, in addition, its own peculiar line-of-sight motion, thus spreading the absorption spectrum and making the total equivalent width nearly equal to the sum of the individual equivalent widths. The above explanation was derived from Wilson and Merrill [11] who clarified a similar anomaly in the optical case.

This method is now applied to find the distance of the source in Sagittarius (17S2A). From the calibration curve its equivalent width of 65 kc./s. corresponds to a distance of 2·9 kiloparsecs.

(*b*) *The distribution of hydrogen in the direction of the source*. The observed absorption spectrum of a source allows an estimate to be made of the number of hydrogen atoms per unit cross-section in the line of sight to the source. Then, if the distribution of the hydrogen in this direction can be determined by some means, the distance of the source is known.

For the Sagittarius source a useful estimate of the distribution can be made by examining the emission spectra of neutral hydrogen from the inner parts of the Galaxy. A rigorous solution is not attempted here but a workable result comes from an analysis of the observed intensity of the low-frequency cut-off end of the spectra taken between galactic longitudes 350° and 35°. This leads to an estimate of the number of hydrogen atoms at points where the line of sight makes a tangent to a circle about the galactic centre. The locus of such points is a circle centred midway between the sun and the galactic centre. The number of hydrogen atoms at a given radius on that locus is then taken to be the number at the same radius on the line of sight to the centre of the Galaxy.

In a preliminary survey, a number of spectra were taken with an 18 kc./s. band-width at galactic latitude $-1^{\circ}.5$. The narrow band-width was necessary to delineate more clearly the arm structure shown in the Dutch profiles [12]. The profiles show a sharp rise to a high temperature when the line of sight is tangent to a spiral arm. In other directions there is a wide tail to the spectrum showing the existence of inter-arm hydrogen which is emitting at the frequency expected on the Oort rotation model. The observed temperature is then read off the spectrum at the frequency expected at the tangent point in the line of sight. In the inter-arm regions the effect of the adjacent spiral arm at a slightly higher frequency is removed before the temperature can be derived. This temperature distribution with distance from the galactic centre shows maxima at $R = 4\cdot 0$, 5·8 and 7·8 kiloparsecs. The temperatures are then converted to optical depths assuming a kinetic temperature of 125° K. for the gas. Since the line of sight is at a tangent to the observed distribution, the depth from which this emission comes is difficult to obtain since it is a function of the beam-width, the band-width of the receiver and the velocity distribution (η) of the clouds. As a first approximation the depth of emission is taken to be the same throughout the distribution and its value is then obtained by equating the observed number of hydrogen atoms derived from spectra in the line of sight to the galactic centre with the number obtained using the above distribution of optical depth with distance.* The number of hydrogen atoms between the source and the sun was computed from the absorption spectrum of the source to be $1\cdot 9 \times 10^{21}$/cm.^{2}, compared with $6\cdot 5 \times 10^{21}$/cm.^{2} in line of sight to the centre of the Galaxy. The result places the source at a distance of 2·7 kiloparsecs from the sun. The errors involved in this estimate are difficult to assess. Although the close agreement with the previous method is probably fortuitous, the results suggest that the source is much nearer than 8 kiloparsecs and is probably of the order of 3 kiloparsecs from the sun.

* Account is taken of the greater values of η observed near the galactic centre (see *B.A.N.* no. 452).

(*c*) *Discussion of the Sagittarius source*. Further information is available to clarify the nature of this source. Its diameter at 21 cm. can be obtained from a comparison between the intensity observed with the present equipment using a beam-width of 1°.6 and the intensity observed by Hagen, Lilley and McClain [6] using a beam-width of 0°.9. From an examination of the Jodrell Bank records it was evident that the size of the source was less than the beam-width because no broadening of the beam pattern was observed. The reduced ratio of intensity of the Sagittarius to the Cassiopeia source on the N.R.L. survey could be attributed to the Sagittarius source having a diameter between 0°.8 and 1°.0. This result is similar to that obtained at the lower frequencies [13], and corresponds to a region about 50 parsecs across at 3 kiloparsecs.

The spectrum already published [14] has now been extended to 3·15 cm. by Haddock and McCullough [15] confirming that it is due to emission from an optically thin body.

The above evidence led Davies and Williams [14] to suggest that the Sagittarius source may be associated with a group of 38 O- and B-type stars and emission nebulae observed by Hiltner [16] and Sharpless [17] to lie in this direction at a distance of 3 kiloparsecs. Such an identification has since been tentatively proposed by Haddock and McCullough.

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