PART 1

THE INTERSTELLAR MEDIUM

"It seems to me these structures are not understood."

C. Heiles, in the discussion following his paper

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THE OBSERVATIONAL EVIDENCE FOR AN INTERCLOUD MEDIUM

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Abstract. The 21-cm evidence for an intercloud medium is reviewed. The observations include the sky distribution and velocity structure of 21-cm emission profiles, self-absorption features in emission profiles, and absorption profiles in the directions of discrete sources. It is concluded that the intercloud medium in the solar neighbourhood has a temperature between 10^3 and 10^4 K, a column density of $\sim 1.4 \times 10^{20}$ cosec $|b|$ atoms cm^{-2}, and a brightness temperature of ~ 4.4 cosec $|b|$ K wherever the line of sight does not intersect optically thick cold concentrations.

The notion that interstellar matter occurs in clouds or concentrations had its beginnings in the patchy appearance of both bright and dark nebulae, and in the grouping of lines noted by Adams (1949) in optical interstellar absorption spectra. In over two decades since the detection of the 21-cm line, more and more evidence has accumulated to indicate that dust, molecules and the heavier atoms occur in concentrations wherein the density is vastly greater than in the in-between spaces separating these concentrations.

Well, what of interstellar neutral hydrogen, the most abundant constituent and one which is clearly detectable in emission in whatever direction of the sky one looks and whatever the angular resolution of the instrument used? Does it also occur only in discrete concentrations or is there a substantial amount of intercloud neutral hydrogen as well? It is the observational evidence relating to this question which I shall attempt to review briefly here.

The column density of hydrogen along any line of sight is usually calculated from the integral of the emission profile. Unfortunately, this calculation is valid only in the situation where the hydrogen is optically thin to a first approximation. Because of the flattened distribution of hydrogen and the enormous column lengths available at low galactic latitudes, measurements in these directions tend to refer to high optical depths. Such low latitude measurements therefore, while telling us almost all we know about the kinematics of hydrogen on a galactic scale, have made very little sense in terms of its temperature and density structure on a smaller scale.

Observations at intermediate and higher latitudes, on the other hand, have invariably demonstrated variations which had less to do with galactic rotation and more with the gas distribution. The many such studies made away from the galactic plane refer perforce to the solar neighbourhood only; however, they have all contributed towards providing a picture that is probably valid for most parts of the Galaxy.

Because 21-cm emission measurements can be made in any direction in the sky, whereas absorption measurements can only be made in the directions of sufficiently intense continuum sources, the number of available measurements of the emission exceeds by a few orders of magnitude the number of absorption measurements. In

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spite of this, the small number of absorption measurements have contributed much to our understanding of the structure of neutral hydrogen because they enable us to get spin temperatures, true column densities and a measure of the turbulence when combined with emission measurements in the same directions.

Interferometers are particularly suited for 21-cm absorption measurements and the early work done at Caltech culminated in Clark (1965) proposing a 'raisin-pudding' model for the neutral hydrogen distribution of cold clouds ($T_s < 100$ K) embedded in a hot medium with $T_s > 1000$ K.

Among the many reasons which led to this suggestion were:

(1) the consistent difference in appearance between absorption and emission profiles, the absorption components invariably appearing narrower;

(2) the presence of self-absorption effects seen occasionally in emission profiles showing that there were significant differences in the spin temperatures characterising different regions in the neutral hydrogen distribution; and

(3) the difficulty of holding the clouds together; the calculated masses in several cases where one could measure or estimate both size and density indicated that these clouds were gravitationally unbound and should disperse in a very short time in the absence of pressure balance from a hot medium or other such restraining influence.

The important point to note about Clark's proposal is that it invoked the existence of large temperature differences in the hydrogen distribution. Most previous models assumed an effectively uniform temperature of around 125 K and relied on density variations alone to explain the various observed phenomena.

Although this important step resulted from absorption studies, it is not as if emission measurements had provided no clues as to the existence of intercloud gas. One of the earliest studies not confined to the plane was that of McGee and Murray (1961). From a sky survey of neutral hydrogen emission they were led to the conclusion that the local distribution was substantially horizontally stratified and that embedded in it were concentrations of gas. Carl Heiles (1967) published an account of high-resolution observations of a small region at a galactic latitude of 15° undertaken with a view to studying the small-scale spatial structure. He found that his observations did not correspond at all with the predictions of the 'standard cloud model' and in particular that about $\frac{3}{4}$ of the integrated 21-cm emission from the observed region originated in a diffuse smooth background.

In both the above studies it was the spatial distribution of the integrated column density that led these authors to their conclusions. Information is also available in the frequency or velocity structure of the profiles and can be extracted by analysing the profile shapes. Grahl *et al.* (1968) and later Mebold (1972) have analysed some 1300 emission profiles obtained at a galactic latitude of 30° and with longitude values between 0° and 360°. It was found that at this latitude profiles had the typical shape illustrated in Figure 1 of Mebold's paper (1972), and that they could be very well approximated by a narrow Gaussian component with a dispersion ≈ 3 km s^{-1} superposed on a wide shallow component with dispersion ≈ 10 km s^{-1}.

Figure 2 in the same paper is a normalized histogram of component areas versus velocity dispersion and the double peaked structure of this histogram clearly demonstrates that there are two types of components contributing to the emission profiles. The narrow components are interpreted as arising in conventional 'clouds' and the wide components as caused by widely dispersed gas. The latter are not necessarily Gaussian and their form has a dependence on the galactic longitude as would be expected from an extended medium acted upon by differential galactic rotation. For this extended gas distribution Mebold (1972) derives a density,

$$n(z) \approx 0.2 \exp(-|z|/210) \text{ cm}^{-3}$$

and a dispersion ≈ 9 km s^{-1} after removing the effects of galactic rotation. The Doppler temperature corresponding to this dispersion is 9400 K, suggesting that for any reasonable amount of turbulence the kinetic temperature must be at least in the hundreds of degrees.

An earlier survey of emission over a range of intermediate latitudes was that of Takakubo and van Woerden (1966). Enormous effort was put into resolving their profiles into Gaussian components and the procedures adopted are discussed in great detail. As in other studies of the emission only, it was not possible to extract any information on the spin temperature from the observations, and in fact one has to put in an assumed spin temperature to convert brightness temperatures to optical depths before any resolution into Gaussian components can be attempted. Components of all the different values of dispersion were assumed to have arisen in clouds, but it was noted (Takakubo, 1968) that for the wider components with dispersion >7 km s^{-1} the velocities were correlated over much larger angles, suggesting that if they were due to clouds then these clouds would have to be large ones.

Mebold (1972) has made a histogram (Figure 6 of his paper) of the Gaussian components obtained by Takakubo and van Woerden (1966) similar to the one using his own data mentioned earlier. Here again the double-peaked nature is evident as also the increased line-broadening effect of differential galactic rotation at the lower latitudes of their observations. As these observations span a range of latitudes, they provide the possibility of demonstrating that the wide shallow components arise in a stratified medium rather than in large individual clouds. In Figure 1, I have plotted the mean column density at each latitude of the widest Gaussian component observed at each of the 191 positions listed by Takakubo and van Woerden. The good fit to the cosecant curve shown in Figure 1 clearly demonstrates that the widest Gaussian component in each profile originates not in individual clouds but in a fairly smoothly stratified distribution of hydrogen in the solar neighbourhood. Very recent work by Schwarz and van Woerden reported at this symposium has also led to the conclusion that the wide components arise in a stratified approximately plane parallel medium affected by differential galactic rotation.

Turning now to absorption studies, Hughes *et al.* (1971) have observed over 90 extragalactic sources for 21-cm absorption with the Caltech interferometer and found measurable amounts in 64 cases. Although they did not make any emission measurements themselves, they have included emission profiles taken from other observers at points close by, and the brightness temperature values taken from these emission profiles have been used in a statistical analysis of the absorption data obtained by them. Their analysis takes into account only the total optical depth of each prominent absorption feature as no Gaussian analysis was performed on the absorption profiles. In their analysis it was assumed that a two-temperature structure ex-

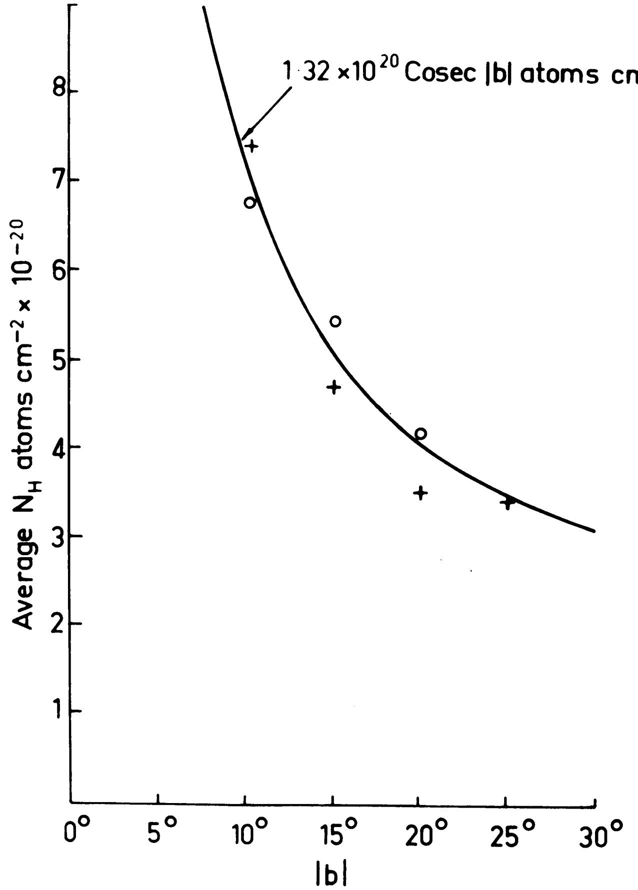

Fig. 1. The mean column density of the widest Gaussian component at each latitude observed by Takakubo and van Woerden (1966) is shown plotted as a function of the absolute value of the latitude. The crosses and circles refer to observations at north and south latitudes. The cosecant dependence on the latitude illustrates the stratified nature of the hydrogen distribution giving rise to the wide components in the profiles.

isted for the interstellar gas and the data were used to calculate the parameters for the two components with different temperatures. The figures arrived at by them for the mean temperature of the cool absorbing gas was 71 ± 9 K and the highest lower limit for the temperature of the hotter gas was approximately 600 K. They also concluded that the fraction of the neutral atomic hydrogen in the cool state was in the range between 40% and 75%.

Concurrently with the investigations referred to above, an extensive survey of 21-cm absorption in discrete source spectra was carried out at the Parkes Observatory. One section (Paper II) of this survey (Radhakrishnan *et al.*, 1972) was specifically designed to throw light on the question of intercloud gas. A detailed comparison was made of emission and absorption spectra obtained in the direction of extragalactic sources situated at intermediate or higher latitudes. As the sources were extragalactic, all the hydrogen seen in emission in their directions is in the path of the continuum radiation from the sources, and would have been expected to produce an absorption profile similar to the corresponding emission profile. However, as shown in Figure 2 there is a consistent dissimilarity in the two types of profiles in

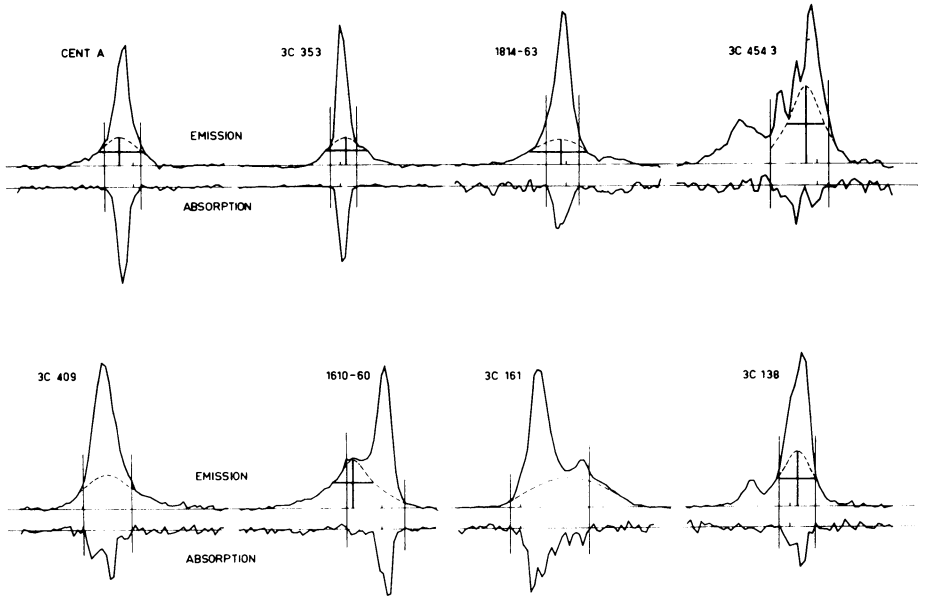

Fig. 2. Comparison of eight emission and absorption spectra obtained at intermediate latitudes and selected on the basis of high signal-to-noise ratio. The velocity limits of the absorption spectra are demarcated, showing clearly the presence of an optically thin component in every emission spectrum. These low, wide components are shown by dashed lines, and in some cases (crosses) their parameters can be determined by a computer analysis into Gaussians.

that there is always a low wide component in the emission spectrum which is absent in the absorption spectrum to the limits of instrumental sensitivity. As seen in Paper II of the Parkes survey, there are continuum sources in the spectra of which 21-cm absorption could not be detected. In the corresponding emission spectra, the narrow components were missing but the wide shallow component was always present. That this optically thin component belongs in a separate category from those with measurable optical depths is seen in Figure 3 where the number of both types of components is plotted as a function of their full widths. In Figure 4, the integrated column density in the wide optically thin component is shown plotted against the absolute

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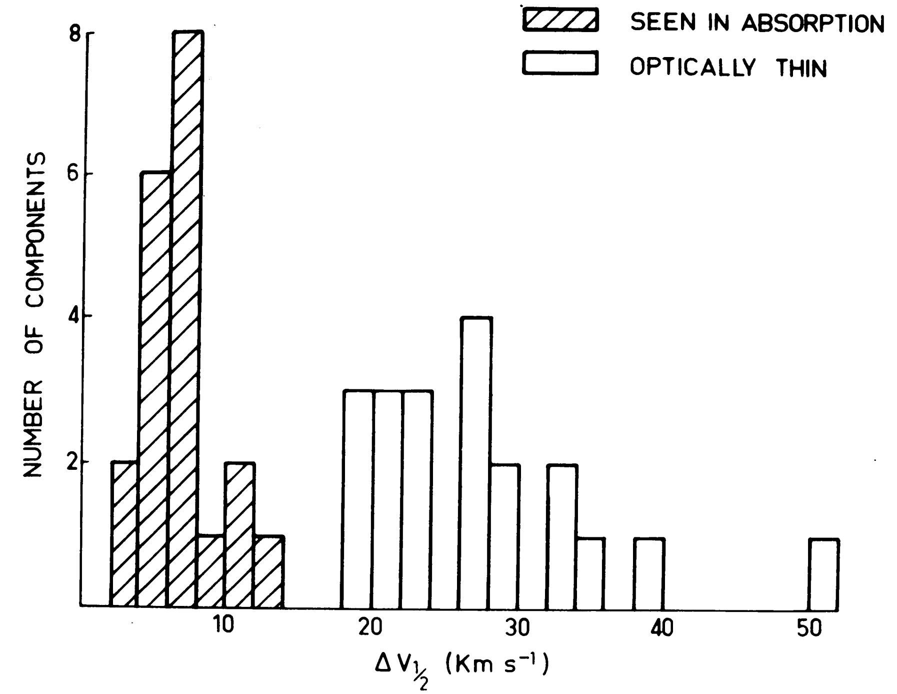

Fig. 3. A histogram of the number of Gaussian components as a function of their full widths observed in the direction of extragalactic sources at intermediate and high latitudes. A clear separation is evident between the narrow components with measurable optical depths and the wide optically thin components. The former originate in low-temperature concentrations and the latter in a high-temperature, widely dispersed medium.

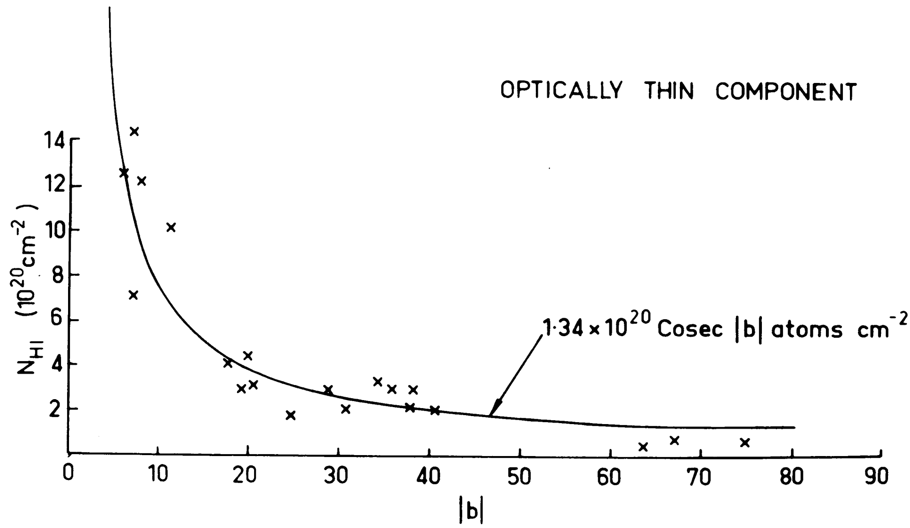

Fig. 4. The integrated column density in the wide optically thin component is shown plotted against the absolute value of the galactic latitude. The stratified nature of the hydrogen distribution giving rise to this component of the emission is shown by the fit to the cosecant curve.

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value of the galactic latitude. The reasonable fit to a cosecant curve indicates again the stratified nature of the hydrogen distribution giving rise to this component of the emission.

If the narrow Gaussian components seen in both emission and absorption profiles arise in clouds, the spin temperatures characterising these clouds can be calculated and these are shown plotted in Figure 5. It is seen that there is a concentration around

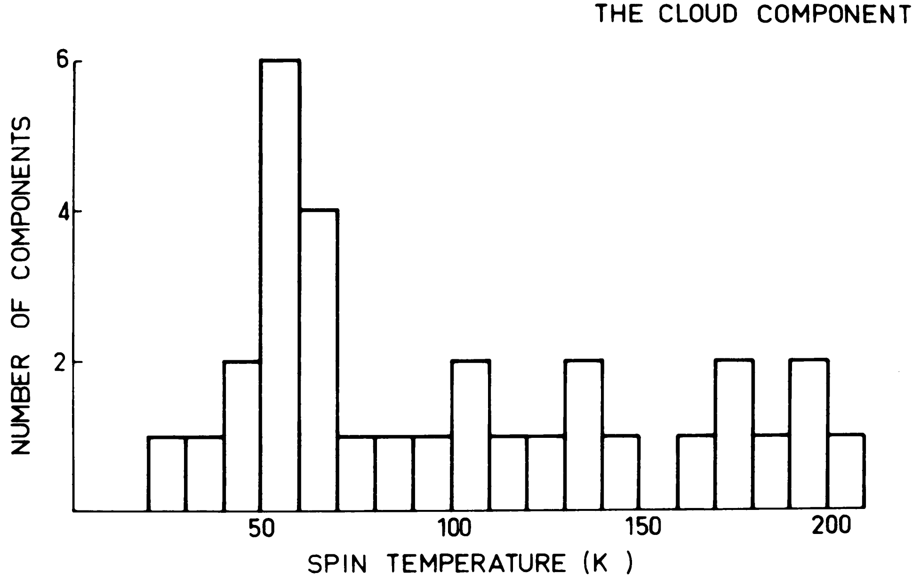

Fig. 5. A histogram of the calculated spin temperatures for the narrow Gaussian components observed in both emission and absorption. The mean for the distribution is around 80 K.

60 K with a shallow distribution extending up to 200 K or so. The corresponding Doppler temperatures for these clouds obtained from their line widths is invariably several times the kinetic temperature showing that there is considerable turbulence within most clouds.

For the optically thin gas, lower limits only can be obtained for the spin temperature, and the highest such lower limit presently available is only of the order of 1000 K. When measurements of adequate sensitivity provide us with values for the spin temperature of the optically thin gas, it is almost certain that a histogram of column density versus temperature for hydrogen of all optical depths will show a clear double-peaked structure like some of the other histograms discussed above. The Doppler temperatures corresponding to the observed line widths of this widely dispersed hot gas is of the order of 10^4 K, but it has not yet been possible to separate the turbulent and thermal contributions making up this apparent temperature.

All of the observations in the Parkes survey put together lead us to the following picture of the neutral hydrogen distribution in the solar neighbourhood. Concentrations with a mean column density of 3×10^{20} atoms cm^{-2}, a mean spin temperature

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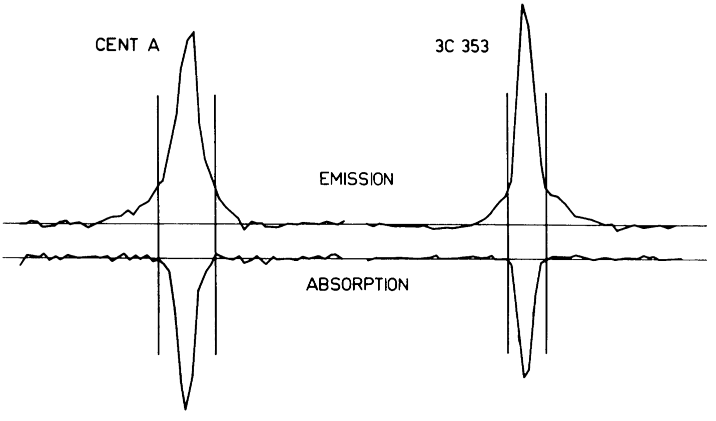
of 80 K and a typical line of sight separation of one full scale thickness of the galactic disk are immersed in a hot medium containing an equal mass of gas at a temperature of somewhere between 10^3 and 10^4 K. The column density of this hot gas is $\approx 1.4 \times 10^{20}$ cosec $|b|$ atoms cm^{-2} and its brightness temperature is ≈ 4.4 cosec $|b|$ kelvins whenever the line of sight through it does not intersect optically thick cold concentrations. When the line of sight does intersect one or more cold concentrations, the profile appearance gets modified in a way depending, among other factors, on the latitude. Extreme examples are shown in Figure 6 where the narrow component is seen as



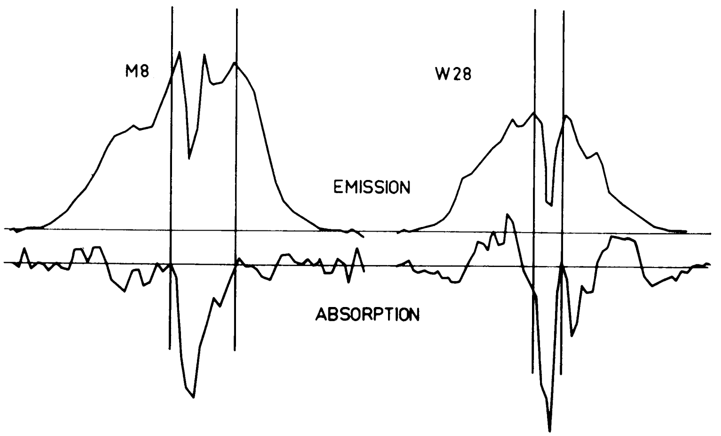


Fig. 6. (Upper) 21-cm emission and absorption spectra obtained in the directions of two intermediate-latitude sources ($b \approx 20°$). The absorption in both cases corresponds to the peaks in the emission profiles caused by low-temperature, high-opacity concentrations of hydrogen. The wings of the emission profiles are from the optically thin high-temperature medium and are not seen in absorption.

(Lower) The absorption spectra of two sources in the plane (M8 and W28) showing correspondence not to peaks but to dips in the associated emission spectra. The cold absorbing concentrations in the foreground are seen in the emission profiles in self-absorption against the integrated contributions of the background diffuse medium.

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a peak at intermediate (or higher) latitudes and as a self-absorption dip at latitudes very close to the galactic plane.

In conclusion, I would like to draw attention to the major areas of ignorance concerning the intercloud neutral hydrogen. We have no actual values for its spin temperature and consequently no knowledge of possible temperature variations from region to region. We do not know how much turbulence there is in the medium, and we are not likely to find out until very sensitive measurements are made of the optical depths in various directions leading to determinations of the spin temperatures and thence to a separation of the thermal and turbulent motions. The degree of ionization of the intercloud medium is another unknown of importance to both theorists and those concerned with the relationship of pulsar distances to their dispersion measures. And lastly, it would be of great interest to know how the medium is disturbed by the formation of a condensation bearing in mind that the mean column density of observed concentrations is equal to that through one full-scale thickness of the intercloud medium.

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DISCUSSION

Zuckerman: What are the lower limits to the spin temperature of the broad component?

Radhakrishnan: They range in the hundreds of kelvins, 400 or 600 to about 1000. The highest lower limit – I think it was done in the direction of M87 by Hughes, Thompson and Colvin – reached 750 or 1000 K. Actually, you can get very low values too, because it simply depends on the sensitivity of your measurement. There are no measurements yet that actually give you the temperature for any one of these. This is one of the most important things which will have to be done, by pushing the sensitivity up.

Habing: Could you give us an idea of the scale size over which the intercloud medium is homogenous?

Radhakrishnan: From the observations available so far, it would seem that within a few hundred parsecs of the Sun there is no evidence for density variations of over a factor of two from the mean density.

Van Woerden: Schwarz and I find, in a detailed study of a region in Camelopardalis (see paper later in this session), for the intercloud medium a column density $N_{\mathrm{H}} = 1.5 \times 10^{20}$ cosec b cm^{-2}, in excellent agreement with Radhakrishnan's figure. The run of this quantity with latitude shows fluctuations of $\pm 10\%$; part of this must be due to error.

Burton: You remarked at the beginning of your talk that hydrogen profiles observed at low latitudes are saturated. I think that this is not the case except near certain directions ($l \approx 0°$, 75°, 180°) where the radial velocity varies slowly with distance. This opinion is suggested by the intensity cut-off observed

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near zero velocity in profiles observed in the galactic plane at, say, $20° < l < 60°$. Intensities at positive velocities are typically twice those at negative velocities. This cut-off is probably due to the double-value of the velocity-distance relation at positive velocities, whereby two regions contribute to each positive velocity; on the other hand, only one region contributes to negative velocities. Both positive velocity regions would contribute to the profile, producing the observed intensity cut-off at zero velocity, only if the nearer region is transparent. This comment applies only to the gross appearance of the profiles; the small-scale self-absorption features apparent in the low-latitude profiles are undoubtedly optically thick.

Radhakrishnan: Absorption measurements on sources lying in the longitude range in question reveal considerable optical depth in almost every case. Since some of these sources lie within the solar circle, the true optical depth along the full line of sight must be even greater. Any satisfactory explanation for the observed cut-off in the emission profiles cannot therefore be based on the assumption that the nearer region is transparent.

Davies: At Jodrell Bank we have used the Mark IA radio telescope (beamwidth 12′) to study the H I absorption spectra of the strong sources Cas A, Cyg A and Vir A. By using the adjacent emission spectra a direct measurement is made of the spin temperature of the hot component of the neutral hydrogen seen in these directions. Vir A, an extragalactic source, lies near the NGP and has only 'hot' H I in its line of sight. The spin temperature of the 0 km s^{-1} component is ~ 950 K and that of the -50 km s^{-1} component ~ 1500 K. No 'normal' cool clouds with $T_s \sim 100$ K are seen. In the case of Cas A and Cyg A, which both lie near the galactic plane, there are regions of the velocity profile which show gas with $T_s = 1000$–2000 K. This gas is most readily identified at velocities which correspond to interarm regions. It is clear from this work that the velocity spread found in these 'hot' clouds is much larger than can be explained by thermal broadening of the profiles.

Baldwin: If there are essentially empty holes in the intercloud medium, what fraction of space could they occupy and yet have escaped detection?

Radhakrishnan: A large number of empty holes distributed homogeneously would appear the same as a lower intercloud density of hydrogen with no holes.