US/GRBK/ G.L.V.

Verschuur

INTERSTELLAR NEUTRAL HYDROGEN AND ITS SMALL SCALE STRUCTURE

PART 1 - GENERAL THEORETICAL CONSIDERATIONS

A. The 21 cm Emission Line of Neutral Hydrogen

Approximately 5 to 10 per cent of the mass of the Milky Way is in the form of interstellar atomic hydrogen. The study of the physical properties of this matter is only possible because the ground state ($1^2 S_{1/2}$) can undergo a hyperfine transition giving rise to radio emission (or absorption) at a wavelength of 21.2 cm. The transition occurs when the electron reverses its spin relative to that of the proton, the higher energy state being the one in which the two spins are parallel (the magnetic moments are parallel) and the lower state the one when they are anti-parallel. The prediction that this should be an observable transition was made in 1944 well before radio telescopes and receivers existed to make the measurements and in 1951 three groups, nearly simultaneously, reported the detection of emission from interstellar neutral hydrogen (HI).

The frequency of the transition has been accurately determined in the laboratory during the 1960's, using hydrogen masers. It is 1420.405752 MHz.

1. The Emission Spectrum

The equation of transfer can be written in the usual form

$$\frac{dI\nu}{ds} = j_\nu - \kappa_\nu I_\nu \qquad (1)$$

where I_ν is the specific intensity at frequency ν at a distance r from the observer. The volume coefficients of emission and absorption are j_ν and κ_ν following the notation used by Kerr (1968). A similar discussion to the one that follows is given in Shklovsky (1960) page 208.

The general solution to this equation is

$$I_\nu = \int_0^\infty j_\nu \exp\left(-\int_0^r \kappa \, dr^1\right) dr \qquad (2)$$

and we may express the observed intensity as a brightness temperature, T_B, which is customary in radio astronomy.

$$T_B = \frac{I_\nu c^2}{2k\nu^2} \qquad (3)$$

by the Rayleigh-Jeans law and similarly the emission coefficient can be expressed in temperature units by writing

$$j_\nu = \frac{j_\nu c^2}{2k\nu^2} . \qquad (4)$$

Finally, Kirchoff's law, relating the emission and absorption coefficients with a temperature can be used, i.e.,

$$J_\nu = K_\nu T_s . \qquad (5)$$

T_s is called the spin temperature.

Combining (4), (3) and (2) we can get

$$\begin{aligned} T_B(\nu) &= \int_0^\infty T_S K_\nu \exp\left(-\int_0^r \kappa_\nu \, dr^1\right) dr \\ &= \int_0^{\tau_\nu^1} T_S e^{-\tau_\nu} d\tau_\nu \end{aligned} \qquad (6)$$

where $\tau_\nu = \int_0^r K_\nu \, dr^1$ is the optical depth to a distance r at frequency ν.

If T_S is constant along the line of sight we derive the most basic equation for hydrogen line work, i.e.,

$$T_B(\nu) = T_S[1-e^{-\tau(\nu)}] \qquad (8)$$

where $\tau(\nu)$ is the total optical depth at frequency ν, through the entire line of sight.

2. The Spin Temperature, T_S

If a cloud is in theromodynamic equilibrium at temperature T_S, the number of atoms in the upper and lower states (n_1 and n_o) is given by the Boltzmann distribution law, viz.

$$\frac{n_1}{n_o} = \frac{g_1}{g_o} e^{-\frac{h_{\nu 10}}{kT_s}} \qquad (9)$$

where g_1 and g_o are the statistical weights of the upper and lower levels respectively. We find that since $g = 2F + 1$, where F is the sum of the electronic and nuclear spins, which takes on the values 1 or 0, that $g_1 = 3$ and $g_o = 1$.

$$\therefore n_1 = 3n_o\ e^{-\frac{h_{\nu 10}}{kT_s}} \qquad (10)$$

The important point to note is that even if the cloud is not in thermodynamic equilibrium we can define a convenient temperature which would account for the distribution of atoms between the two states and it is this temperature which is called the spin or excitation temperature, T_S.

It is generally assumed that the population of the states is determined primarily by collisions between atoms, since Field (1950) has shown that other factors, such as Lyman α, light or microwave radiation cannot compare with collisions in importance. Normally the probability of a spontaneous transition occurring is given by the Einstein coefficient,

$$A_{10} = 2.85 \times 10^{-15} \text{ sec}^{-1},$$

which implies one event per atom per 11 million years. Collisions however, increase this to one transition per 400 years, which makes the 21 cm emission observable.

3. Line Widths

The natural line width of the transition is given by $\frac{A_{10}}{\pi}$ which is insignificantly small, but the Doppler broadening produced by thermal motions in the clouds gives the line a finite width.

Within each cloud the atoms have a Maxwellian velocity distribution which means that the numbers at any velocity are proportional to a term like $\exp\left(\frac{-mv^2}{2kT}\right)$. This has the shape of a quassian function, i.e., $\exp\left(\frac{-v^2}{2\sigma^2}\right)$, where σ is the dispersion. We can use the observed dispersion to derive an estimate for the temperature in the gas. This is done by equating exponents in the two expressions above, namely

$$\sigma^2 = \frac{kT}{m}$$

The kinetic temperature, T_K, is then given by

$$T_K = \frac{m}{\kappa}\sigma^2$$

$$= 121\ \sigma^2 \text{ if } \sigma \text{ is measured in Km s}^{-1} \qquad (11)$$

$$\text{or} \quad = 5.4\ \sigma^2 \text{ if } \sigma \text{ is measured in KHz} \qquad (12)$$

Since the spin temperature T_S is determined primarily by collisions, it is usual to equate T_S and T_K.

We should briefly prove that the emission line is Gaussian, but first we will derive an expression which will allow us to calculate the number of hydrogen atoms responsible for an observed spectral line.

4. Line of Sight Hydrogen Content

Again, following Kerr, we note that the atomic absorption coefficient, a_ν, is related to the volume coefficient of absorption by

$$K_\nu = a_\nu \left(n_o - n_1 \frac{g_o}{g_1}\right) \tag{13}$$

from Milne (1930).

In radio astronomical work $h\nu << T_S$ and therefore using (9) and (13) we get

$$K_\nu = a_\nu \, n_o \, \frac{h\nu}{kT_s} \tag{14}$$

Now a_ν is related to the Einstein coefficient A_{01} (absorption) by;

$$a_\nu = A_{01} \, \frac{c^2}{8\pi\nu^2} - \frac{g_1}{g_o} \, f(\nu) \tag{15}$$

where $f(\nu)\, d\nu$ is the probability that a transition occurs between ν and $\nu + d\nu$.

From (10) we note that, for $h\nu << T_S$, the total number of atoms in the cloud (n) is given by $n \simeq 4\, n_o$.

Combining equation (14), (15), and (7) and considering only a unit frequency interval of 1 kHz, the total number of hydrogen atoms in a cylinder of unit cross-section (1 cm^2) along the whole line of sight is given by

$$N_H = 3.88 \times 10^{17} \int T_S \, \tau(\nu) d\nu \qquad (16)$$

(or if a 1 Km s^{-1} interval is used, $N_H = 1.823 \times 10^{18} \int T_S \, \tau(\nu) d\nu$).

A more readily usable version of (16) is obtained by noting that equation (8) reduces to

$$T_B(\nu) = \tau(\nu) \, T_S$$

for low optical depth. Provided we can assume low optical depth, and this is often done in hydrogen line work since any other assumption makes the job more difficult, we can rewrite (16) as

$$N_H = 3.88 \times 10^{17} \int T_B(\nu) d\nu. \qquad (17)$$

which is a quantity which can be derived from the spectrum since the integral is the area under the observed spectral line.

5. <u>The Line Shapes</u>

From the fact that the number of atoms at a given velocity is a function of velocity (or frequency) we can write that the number at frequency ν, in terms of the number at some central frequency ν_o, is

$$N_\nu = N_{\nu_o} \, e^{-\frac{(\nu-\nu_o)^2}{2\sigma^2}} \qquad (18)$$

But from (16) we see that

$$\tau_\nu = \text{constant X } \frac{N_H}{T_S} \quad ,$$

therefore we can write

$$\tau_\nu = \tau_{\nu_o} e^{-\frac{(\nu-\nu_o)^2}{2\sigma^2}} \quad . \qquad (19)$$

This means that the hydrogen emission (or absorption) line is gaussian on a linear optical depth scale and is only gaussian in brightness temperature if $\tau << 1$, since then $T_B = \tau T_S$.

Gaussian shapes (in optical depth) are found for the narrowest absorption lines, but the narrowest emission lines observed to date do not show a gaussian shape when plotted as T_B versus ν. This forces us to conclude that, in these cases at least, $\tau \gtrsim 1$.

B. Absorption Spectra and Emission Spectra Contrasted.

1. Measuring Absorption Spectra

Absorption and emission line observations reveal very different aspects of the interstellar HI. The first most obvious difference is that single dish observations of emission or absorption spectra have very different angular resolutions. All the emission in the beam of the telescope contributes to the emission spectrum whereas only the matter directly in front of the radio source, whose angular size may be orders of magnitude less than the telescope beamwidth, contributes to the absorption spectrum.

The second important difference is shown by a discussion of the detailed equations relating to the absorption measurements.

If a radio telescope is pointed at a radio source producing a brightness temperature, T_{BS}, which is assumed constant over the frequency range in which we are interested, then a cloud of optical depth τ will absorb this radiation to give a spectrum like

$$T_B^{1}(\nu) = T_{BS}\, e^{-\tau(\nu)} \tag{20}$$

However, the emission in the beam of the telescope will add to this absorption spectrum and give an observed spectrum given by

$$T_B(\nu) = T_{BS}\, e^{-\tau(\nu)} + T_S\, [1-e^{-\tau(\nu)}] \tag{21}$$

In practice the emission spectrum [2nd term in (21)] has to be determined separately and subtracted from $T_B(\nu)$ in order to derive the true absorption spectrum $T_B^{1}(\nu)$. This can be done by assuming that the hydrogen structure varies slowly around the source. This assumption is invariably wrong however, and is only valid of $T_{BS} >> T_B(\nu)$, for then the errors introduced by such an assumption are considerably reduced.

A practical observation of an absorption spectrum neccesitates making a measurement off the frequency of the spectral line so that receivers are used which switch between a measurement of T_{BS} (unabsorbed) and T_{BS} (absorbed). In other words the data are usually better expressed by

$$\begin{aligned} T_B(\nu) &= T_{BS}\, e^{-\tau(\nu)} + T_S\, [1-e^{-\tau(\nu)}] - T_{BS} \\ &= (T_S - T_{BS})\, [1-e^{-\tau(\nu)}] \end{aligned} \tag{22}$$

Now note that for large τ

$$T_B(\nu) = T_S - T_{BS} \tag{23}$$

which is constant over that part of the spectrum where large τ holds. We then say that the line is saturated. Clearly a very cold cloud will give the largest negative going signal (T_S small), whereas a hot cloud will give a smaller signal.

For low τ, $T_B(\nu) = \tau(\nu)\ (T_S - T_{BS})$ and it is still true that the colder cloud gives a larger signal than the hot cloud.

This may be contrasted with the expression (8) for the emission spectrum alone. For high optical depth.

$$T_B(\nu) = T_S \tag{24}$$

so the hotter the cloud the larger the signal. For low τ, $T_B(\nu) + \tau(\nu)\ T_S$, so we still observe the larger signal for the hotter cloud.

Hot clouds are more readily observed in emission spectra work, but cold clouds are selected out in absorption work. Comparison of the results of emission surveys or absorption line surveys is therefore not valid since they appear, to a first approximation, to deal with different clouds and also with different resolutions. However, the picture is not quite so simple since in many cases very cold clouds can clearly be seen in emission. In fact, the coldest clouds observed to date are seen in emission.

2. Obtaining An Accurate Absorption Line

We note briefly that in order to derive the two unknowns, T_S and $\tau(\nu)$, in equation (21) one had to interpolate between surrounding emission spectra in order to estimate the second term, which would allow one to solve for the two unknowns. A more accurate method exists however. Ideally one would like to observe the spectrum in the presence, and then in the absence, of the radio source. This is possible for pulsars, since they switch themselves on and off and is also possible when observing variable radio sources which do not actually switch themselves completely off. One then has two equations like (21) with T_{BS}^{1} and T_{BS}^{2}, which are measurable and one can solve for T_S and τ unambiguously. Alternatively, a linearly polarized radio source can be observed parallel and normal to the plane of polarization, but this means that the polarization characteristics have to be very well understood before reliance can be placed in the difference spectrum that emerges.

Lastly, an interferometer can be used to get rid of the unwanted emission in the primary beam. If the lobe size is comparable to the radio source size then the surrounding emission will hopefully cancel out in the other lobes of the interferometer and a true absorption spectrum can be obtained.

3. Superposition of Clouds

Notice that if several clouds are lined up at the same velocity in front of a radio source, the absorption they produce is given by

$$T_{BS}\, e^{-\tau} = T_{BS}\, e^{-\tau} \cdot e^{-\tau_2} \cdot e^{-\tau_3}$$

$$\therefore \tau = \tau_1 + \tau_2 + \tau_3 + \ldots \qquad (25)$$

so that optical depths add in absorption lines. For an emission line produced by several clouds alligned in the line of sight we must write

$$T_B(\nu)_1 = T'_{S_1}\ (1-e^{-\tau_1}) + T_2\ (1-e^{-\tau_2})\ e^{-\tau_1} + \ldots \qquad (26)$$

and provided $T_{S_1} = T_{S_2} = T_S$ we find that,

$$T_B(\nu) = T_S\ [1-e^{-(\tau_1 + \tau_2 + \ldots)}] \qquad (27)$$

Therefore optical depths only add if the spin temperatures are constant. For large τ in emission, the second and subsequent terms in (26) are zero so that only the nearest cloud is seen.

Kahn (   ) has suggested that the maximum brightness temperature observed in any direction will be the harmonic mean of the spin temperatures in the line of sight, i.e.,

$$T_B(\max) = \left(\overline{\frac{1}{T_S}}\right)^{-1}$$

Since the maximum temperature observed anywhere in 21 cm emission work is 135°K [Burton (1971)], many workers have assumed that T_S = 135°K everywhere, which is a very poor assumption as will be discussed later. The assumption is that the maximum T_B is seen where the optical depth is greatest and therefore the cloud responsible has T_S = 135°K. For example, this temperature may equally well be produced when the hot intercloud medium of 1000°K has a maximum optical depth of 0.135.

PART II - DISCUSSION OF THE OBSERVATIONS OF THE SMALL SCALE STRUCTURE IN THE INTERSTELLAR HI

A. Clouds or No Clouds?

First we need to make one point clear and that concerns the use of the word cloud in referring to the interstellar HI. Many radio astronomers have objected to the use of the cloud concept because it may not be applicable to the HI. The clouds we are familiar with on earth are discrete physical entities with well defined boundaries containing matter clearly distinguishable from the immediate surroundings. Interstellar space contains widespread HI and from this HI stars ultimately form in some way. Obviously, when the stars have formed it is possible to clearly distinguish between them and their surroundings. Furthermore, there are discrete physical entities which are called dust clouds and which have well defined boundaries, visible on photographs of the Milky Way. So at least we know that there are clouds in interstellar space and at some time a proto-star must also separate itself from the more general distribution of matter. The question now is, at what stage can the distribution of the more common interstellar HI best be described by invoking a cloud concept or will this really misrepresent the true situation? Alternative words, such as a concentration or a complex have been used, but these do not really make any (but a semantic) difference.

Let us suggest the following definition for a "cloud" in interstellar space. It is an entity which has clearly defined borders, either indicated by a transition between the presence and absence of the material under consideration or by a distinct transition in some other property of the medium. The border may be an "apparent" one if the transition from "cloud" to "intercloud" space involves only a change in temperature. It is conceivable that a radio astronomical observation only sensitive to cold matter would reveal such a cloud in "temperature space", e.g., if there were a cold region suspended in a hot medium. The density might remain constant, but with our definition we would still be entitled to talk about a discrete entity, or "cloud".

Another situation which could be envisaged is that the velocity of material in a particular region of space might suffer a sudden discontinuity. An observation of the way the intensity of emission at a given velocity varies with position might indicate the disappearance of emission at that velocity at some point in space with the appearance of emission at some different velocity at an adjacent point. Clearly it would be difficult, from such a limited amount of information to be sure whether one had observed two "clouds" at physically different distances or one coherent entity with sudden velocity changes within it.

These considerations suggest a definition of a cloud as an object within which the various observable properties, such as density, temperature or velocity remain coherent. Sudden discontinuities of any of these, which cannot be accounted for by a simple physical model of a single object, would necessitate invoking more than one "cloud" to account for the data. The cloud concept is therefore used in this chapter although there may well be many marginal cases where the boundaries between the cloud and intercloud medium appear so vague that the use of the word cloud may not be justified. If such cases occur they will be pointed out.

The two-component model now being constantly referred to in discussions of interstellar HI, that is, a model in which two distinct phases of the interstellar HI exists, a cold, cloud phase and a hot, intercloud phase, gives us some justification for continuing to use the concept of clouds, because distinct phases are predicted theoretically. Naturally we should expect that they may well have a range of temperatures and densities. Many examples of "real" clouds will be discussed below.

B. 21 cm Emission Surveys

1. Interstellar HI In Clusters, Associations and H II Regions

At present stars are known to form in regions where the density of interstellar matter is high. We might still expect to see an excess of matter in these regions unless there has been very highly efficient star formation which has used up all the gas.

Several observers have investigated the HI distribution in those directions where star formation has recently occurred or in which it might still be occurring. These are the young population I objects such as H II regions, stellar associations and galactic clusters.

The results can be summed up as follows; there is strong evidence of excess HI in the immediate vicinity of several very compact H II regions, but observations in the direction of at least 28 clusters show no excess HI emission which can be unambiguously associated with those objects. For the case of some other clusters and associations, HI is found in their directions, but no obvious connection between the stellar groups and the HI "clouds" is apparent.

The search for HI associated with H II regions was motivated by the hope of finding expanding shells of neutral matter around the ionized region. Riegel (1966) examined 27 galactic HI regions and claims that in the direction of 4 of them neutral hydrogen components are found which are clearly related to the H II regions, although there is no evidence for expansive motions around any of them. The data he shows do reveal, rather strongly, that IC 5146 is indeed associated with an HI cloud of about 700 $M_{\odot}$. The mass of HI associated with NGC 281 is at least 1.6×10^4 $M_{\odot}$ however, which compares with a more recent announcement by Kesteven and Bridle (1970) that a large HI cloud of 10^5 $M_{\odot}$ is associated with the extended thermal radio source NRAO 621, of which two compact H II regions, K3-50 and NGC 6857 form a part. They suggest that this region may be in an early stage of formation of a star cluster.

2. The Orion Region

The Orion nebula is a well-known H II region associated with the Trapezium stars and is located in a larger area showing strong emission and reflection and containing dust clouds. The latitude of the nebula, -20°, makes it a favorable one for detailed study since there is not too much foreground, or background, matter at such a high latitude. C. P. Gordon (1970) has reported on a comprehensive H-line survey of this general region and finds evidence for a large HI complex showing rotational motions and centered on the nebula. Again, no evidence for expansion was found. A maximum in the HI was found to be associated with the optical object, but no excess hydrogen emission could be associated with Barnard's ring, the giant loop of bright material in the neighborhood of the Orion nebula. The mass of gas associated with the nebula is found to be about 7×10^4 $M_\odot$ and Gordon found that a distinct cloud at -10 Km s^{-1} with respect to the local standard at rest covered about 30% of the Orion region.

Menon (1970) has discussed evidence for the existence of excess emission associated with the dense conical absorption band seen in projection against the nebula. This is confirmed by the data shown in Fig. . These are several spectra, both on the position of the nebula and 15 minutes and 30 minutes of arc away from the source to the N, S, E, and W. The only way to explain the variation of the brightness at +13 Km s^{-1} is to place a cloud, at this velocity, on the position of the dense dust cloud. Such a good correlation between the position of a dust cloud and an HI feature is, however, not common in 21 cm observations published to date.

The conclusions we may draw from these discussions of the hydrogen distribution in and around these various population I objects is that sometimes we see excess HI emission and sometimes we don't. This statement holds true for any direction observed in space of course, so the results are inconclusive. Perhaps we can only state that the very young objects are located in regions generally containing lots of HI, e.g., spiral arms, which is not surprising. Since most of the objects studied are in the plane we cannot attach much significance to the apparent lack of excess emission at the position and velocity of these objects since there is so much HI around that it effectively "obscures" a good look at the object in question.

3. The Cold Cloud In The Direction Of The Galactic Center

One striking HI cloud, not obviously associated with anything else, such as a dust cloud or any population I objects, is an extensive object covering at least 100 square degrees between longitude about 350 and 11°. It is seen in absorption against all the radio sources in the plane in this part of the sky and is also visible in the surrounding emission spectra as a deep absorption line. This means that it must be very close to the sun for it to be absorbing the more distant hydrogen emission. Riegel and Jennings (1969) have estimated that this cloud has a probable temperature of about 20°K and is located within 1 Kpc of the sun. The cloud is interesting because it is not obviously associated with anything else in this part of the sky and its velocity (+7 Km s^{-1}) is constant over much of its extent.

4. Explosive Events in The Galactic Plane

Supernovae shells must at some point in their evolution have expanded so far that they merge with the normal interstellar medium. It has been suggested that they push HI along with them in their slow expansion phases before they disappear entirely.

At least two papers have presented evidence for expanding motions at low galactic latitudes. Katgert (1969) discusses a shell centered at $\ell = 6\overset{\circ}{.}5$, $b = 0\overset{\circ}{.}3$ with the mass of hydrogen involved being 5×10^5 $M_\odot$ assuming a reasonable distance of 5 Kpc for the object. He admits that there is only a "...rather weak resemblance with a ring" in the HI he maps, which is moving 7 Km s^{-1} faster than the maximum velocity allowed for this longitude, according to the galactic rotation law. In the next chapter (Burton) it is noted that random, or non-circular motions, of 10 Km s^{-1} are often found in our galaxy.

A much larger explosive phenomenon has been invoked by Rickard (1968) in order to explain his observations of the HI in the Persecs arm (ℓ = 100 to 140°). It has always been well-known that optical absorption lines in this part of the sky show a double-peaked structure and the hydrogen emission and absorption lines also show this very strongly. Rickard explains this in terms of an expanding ring or shell in the galactic plane which contains about 10^7 $M_\odot$ and is expanding at about 20 to 30 Km s^{-1}. It is centered on ℓ = 120° and obviously no single supernova is involved here, but he suggests that several may have been required. The ring of hydrogen is not unlike those seen in the Magellanic clouds. We might note in passing that pulsars are supposed to be the last remains of stars which exploded to give rise to supernova and there are 3 located within 5° of the center of Katgerts HI ring and nearest observed in the direciton of Rickards event is about 8° from his suggested center. Later we will discuss HI shells and explosions at high galactic latitudes.

5. Dust and HI

Probably the most confusing aspect of the HI distribution problem is whether or not the gas is correlated with interstellar dust. Before we discuss the present situation we should state strongly that there is a very large amount of HI in the Milky Way and since we always have many clouds in the line of sight at latitudes less than about 10°, picking one out of the mess and associating it with some other feature such as a dust cloud, is going to be nearly impossible in most cases.

Many introductory texts on H-line work state that we are fortunate to have the 21 cm line because it enables us to see right through the obscuring dust which hampers the optical study of distant parts of the galaxy. However, although large numbers of nearly transparent HI clouds lined up one behind the other might not actually obscure the view, untangling the data becomes so confusing that the possibilities for a detailed study of interstellar matter in the plane are considerably hampered.

The study of the correlation between dust and HI has produced almost any result one can imagine. The most recent paper on the topic is aptly entitled "Correlation Between Gas and Dust?" by Wesselius and Sancisi (1971). They compared the distribution of dust, as derived from galaxy counts, with the integrated hydrogen density averaged over the same areas used for the galaxy counts and find no "general" correlation between gas and dust. However, some parts of the sky, when examined more closely do show a positive correlation, in particular two parts of the Gould's belt system.

In searching for more detailed correlation between HI and dust clouds one generally needs to investigate whether there is an excess of emission at any velocity over the area covered by a dust cloud. One such association has been pointed out before, in the discussion of the Orion region.

A preliminary examination by this author of maps showing the intensity of the HI emission at various velocities as a function of position in a region of sky at about +15° latitude, reveal that at <u>some</u> velocities <u>some</u> peaks coincide with <u>some</u> dust clouds and at other velocities some minima coincide with dust clouds and some dust clouds coincide with neither peaks no minima at any velocity. This result would probably be true for any areas chosen randomly on the maps. Such a project needs to be followed through rigourously to test the significance of any correlations found.

Various workers, notably Heiles (1967) have noticed the apparent anti-correlation between dust and excess HI emission. His data have suggested that distinct minima, perhaps absorption features, are associated with some dust clouds. A notable example is the HI spectrum in the direction of the Taurus dust cloud where the dip in the hydrogen spectrum is very deep and is only present on the position of the dust cloud (Fig.). In general such a depression or minima in the spectrum could be produced by three situations:

a) A true lack of hydrogen gas,

b) An apparent lack of hydrogen, produced because it is all in the molecular form or

c) Because the HI which is present is very cold and produces an absorption line.

In the latter case the associated HI needn't even be denser than the surroundings, for, if its temperature is low enough and its optical depth high enough, it will absorb the background HI emission.

Heiles, in the case of the Taurus dust cloud, and Garzoli and Varsavsky (1969) for the same general region, claim that the apparent anti-correlation between dust and HI brightness is explained by the presence of much molecular hydrogen in the dust clouds concerned. Sancisi and Wesselius (1971) have argued strongly that the more plausible explanation is simply that the neutral hydrogen is cooler in these regions and in particular in the dust cloud #2 of Heiles. Spin temperatures of 30 to 50°K combined with optical depths of ≥ 0.5 would produce the observed effects.

However, it is very nearly impossible to favor either interpretation unless strong additional arguments are made for one or the other case. Until then neither should be preferred over the other. One cogent argument concerns the stability of the clouds. Since they are very discrete, in so far as the apparent dust distribution is concerned, they might be expected to be gravitationally stable and enough is known about them so that one can argue that this can only be achieved if large quantities of invisible molecular hydrogen exist within them. On the other hand, a mere lack of HI seems unlikely to produce such narrow "absorption" lines.

In an extensive survey of dust clouds in order to find excess HI emission from them, Heiles (1967) found none and concluded that the clouds were deficient in HI. However, the results could just as well be interpreted as being due to the great variability that normally exists in the HI line of sight densities from point to point in the sky so that observing a considerable excess in one direction and deficiencies in 2 others (as he did) and finding nothing very interesting in 45 other cases may in fact, means very little. It certainly does not support the conclusion that there are deficiencies caused by the hydrogen all being in the molecular state. Perhaps all the neutral matter, in these clouds too, is very cold and just isn't visible as excess emission and is not cold or dense enough to produce absorption.

Lastly, reference might be made to two papers discussing the dust - HI relationship in a region in Ophiuchus. Meźaros (1968) finds no marked excess of HI at the position of some of Khavtassi's well mapped dust clouds and suggests that there is some evidence for a decrease in N_H for sufficiently high dust density from which the presence of molecular hydrogen is again inferred. Sancisi and von Woerden (1970) examine the same region and note only the presence of a distinct elongated (although not completely mapped) feature not associated with the obscured regions. They note that their elongated feature shows "no connection with any optical features". Some people have observed that this "non-connection" is so striking as to be an anti-correlation!

The conclusion I wish to suggest after this brief discussion of dust - HI relationships is that it is still a case of "anything goes". It depends what you want to prove!

7. Summary of Section III B

Clearly one may now ask whether anything useful can be learned about the HI distribution at low latitude which may be relevant to the study of the gas dynamics of clouds in interstellar space. The answer is probably, no! On the other hand, we will show below that when one gets above about |10°| latitude the hydrogen is much less "confused" owing to the absence of matter beyond a few hundred parsecs in the line of sight so that the picture becomes much clearer.

Of course, low latitude surveys are still essential for the study of the large scale, gross distribution of matter in the Milky Way and this will be dealt with in the next chapter.

C. 21 cm Absorption Experiments

1. W49

The earliest published works on 21 cm absorption spectra dealt only with the strongest radio sources and the spectra looked much the same no matter which telescope was used. The interpretation of the data were basically similar too. But recently, as these measurements have been carried forward to include weaker radio sources, the situation gets more and more confused, especially when it comes to an examination of the conclusions reached by various authors. Let me stress that these remarks apply mainly to single dish measurements. Interferometer measurements are hopefully less subject to errors produced by the presence of small HI clouds in their beam.

We will consider the present situation by first examining the rather unusual case of W49. Six papers totaling 24 pages of print, all concerning the absorption spectrum of W49, have appeared in the journals. Three of them are based on the same data as the Maryland-Green Bank Galactic 21 cm Line Survey! There are some startling differences between the conclusions drawn. Hughes and Routledge (1970) find a spin temperature of between 60 and 70°K for a cloud at +17 Km s^{-1} whereas Gosachinskii and Bystrova (1968) analyzed the same data differently to get 22°K. The relevent cloud covers the two components of W49 unequally and Hughes and Routledge find optical depths of 2.5 and 1.8 in front of W49 and B whereas Sato et al. (1967), used a 210' dish with a beamwidth not very different from that of the 300' to get optical depths of 1.3 and 0.6 for the same features.

The original use to which the study of the absorption spectrum of W49 was put was to derive the distance to the H II region since it was so highly obscured optically as to be invisible. 21cm absorption line data are useful for this because if absorption features are found out to a given velocity then one can estimate, from the galactic rotation law (next chapter), what the lower limit at the distance to the radio source is. Sato et al. and Sato (1968) believe that the two components of W49, one an H II region, the other a supernova remnant, are at least 1 kpc apart in the line of sight.

Our Fig. shows the absorption spectrum of W49 taken with the 140' telescope with a beamwidth of 20' arc which includes both W49A and B. Also shown are four spectra taken 30' of arc away from the source to N., E., W., and S. The so-called "true" absorption spectrum is also shown. This spectrum illustrates perfectly the problems that are faced in interpreting single dish 21 cm absorption data. It is customary to compare the average of the four spectra taken around the source with the on-source spectra to get the true absorption line.

There are 9 "absorption" minima in Fig. and two (possibly 4) excess-emission maxima. These positive going peaks suggest that around the position of the source there is certainly excess emission at several wavelengths. Now which are "true" absorption lines? Clearly the feature at +17 Km s^{-1} is one because it is most strongly visible. If the highly asymmetric feature around +40 Km s^{-1} and the clear double line near +63 Km s^{-1} are real absorption lines then are we not also entitled to attach significance to the two positive going features at -30 and -12 Km s^{-1}? Do they indicate hydrogen which must be associated with W49, or are these merely statistical fluctuations in the HI distribution. On the other hand, if we do not attach any weight to the presence of large positive-going signals of 10°K, what significance can we attach to negative going signals of this size? If 10°K antenna temperature indicates the random spatial fluctuations to be expected in this part of the sky then we might only "believe" the +17 Km s^{-1} line since it is the only one clearly visible at the position of the source.

In the absence of any other information we would suggest that the 140' data (bandwidth 6.5 KHz, beamwidth 20') are too confusing to allow a rigorous analysis to be undertaken. This is probably also true of the other papers, which are no less subject to the confusing effects of the spatial structure of the HI in the plane.

One might suggest that unless the absorption lines are deeper than about twice the peak-to-peak variation of the surrounding emission spectra one should not place too much weight on single dish data.

2. Virgo A

Another good example of difficulties encountered is illustrated by the case of Virgo A. Using an 85' telescope (36' of arc beamwidth) Williams (1965) found evidence for an absorption line of optical depth 0.17, using the "classical" method of observation, i.e., comparing the on-source spectra with the average of several off-source spectra. Radhakrishnan and Murray (1969) disagree with this result and set an upper limit of 0.005 to the optical depth. They used a 210' dish although Radhakrishnan (1971) has since repeated the experiment and found a line at -7.3 Km s^{-1} with τ = 0.008. Measurements made with the 140' telescope (20' of arc beam) show a line with τ = 0.020 at -6 Km s^{-1}! The optical depth here appears to depend inversely on the size of the telescope used!

Clearly there is only one reliable way to check the result and that is to observe the source with an interferometer. This has been done and Colvin et al. (1970) report the presence of an absorption line at -8.5 Km s^{-1} with a τ = 0.019. This result is based on observations at three baselines, 200, 400 and 800 feet, indicating that the measured optical depth has ceased to be a function of telescope size!

Virgo A is at a very high latitute (+75°) so that one would hope that the confusion due to small scale HI structures around the source direction would be small, but clearly this isn't the case, even there. Obviously one must not take the interpretation of single dish data too far unless the results are confirmed by observations with a very different resolution or if the absorption lines are so intense as to be considerably in excess of the fluctuation in the emission around the source. This condition is satisfied for Cas A, Tau A, Cygnus A and to a lesser extent for only about 4 or 5 other sources in the Northern Hemisphere.

3. Interpretation of Other Absorption Line Data

Shuter and Verschuur (1964) decomposed their single dish observations of absorption lines into individual gaussian components and estimated that the median of the temperatures of the cool clouds is 67°K. Clark (1965), using the Cal Tech interferometer was able to observe several more sources and obtained brightness distributions for several absorbing clouds. Clark suggested that the data could be well approximated by involving a two-component model, one a cold cloud medium at ~100°K, the other a hot inter-cloud medium at about 1000°K.

Hughes, Thompson and Colvin (1971) find a mean temperature of 72 ± 9°K for the clouds seen in absorption against 64 sources in the Northern Hemisphere. Optical depths greater than 0.5 are found only within 20° of the galactic plane except in the region of the Cetus arc where they found $\tau \sim 1.4$ at a position near $b = -40°$. Hughes et al. used the Cal Tech interferometer to make their measurements and were able to obtain apparently reliable results on many more sources than would have been possible with a single dish.

More recently a series of papers based on 21 cm absorption line data obtained with the Parkes interferometer have appeared. At least 60 sources are listed by Radhakrishnan et al. (1971a) and Goss et al. (1971) and the equipment is described by Radhakrishnan et al. (1971b). Radhakrishnan and Goss (1971) have performed a statistical analysis of the gaussian fits to the absorption spectra and concluded that the hydrogen seen in the galactic disk has a mean value of N_H/T_S of 1.5×10^{19} atoms $cm.^{-2}$ $K.^{-1}$ Kpc^{-1}. The line of sight intersects on average 2.5 clouds per Kpc which compares well with the estimate of Clark (1965) who found 4.1 for this number.

The next few years will see a rapid increase in the number of papers interpreting these data further as well as discussing other data obtained with 21 cm interferometers, especially the synthesis obser- tions now being made at Cal Tech and at the NRAO.