The z-dependence of the Spin Temperature of HI

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I. INTRODUCTION

In 1981 we conducted an extensive, low-latitutde, HI 21-cm absorption survey from the VLA. The goal of the survey was to answer the following questions:

(a) What is the vertical distribution of the cold HI clouds?
(b) Do HI clouds get systematically warmer at high $|z|$?
(c) Does the fraction of warm intercloud medium HI increase with high $|z|$?
(d) How much HI has been missed in previous HI emission surveys because of optical depth effects?
(e) What is the galactic distribution of cool HI clouds?

In order to answer these questions a low-latitude survey is needed because studies of local HI (i.e. distance < 1 kpc) are severely hampered by our lack of knowledge of distances to the HI clouds and hence their $|z|$ values. This problem is circumvented in low-latitude studies wherein a rotation curve can be used to determine distances to the HI absorption features. The HI emission/absorption data has already been reported (Dickey et al. 1983). Here, we present preliminary results which shed some light on the first four questions (§III).

II. INTEGRATED MEASURES

a) Spin Temperature of HI

The 21-cm emission spectrum is described by

$$T_B(v) = T_s[1 - e^{-\tau(v)}] \qquad (1)$$

where

$$\tau(v) = N_H(v)\ C^{-1}\ T_s{}^{-1} \qquad (2)$$

Here $C = 1.823 \times 10^{18}$ cm^{-2} K^{-1} (km s^{-1})$^{-1}$, $N_H(v)$ is the column-density of HI with velocity v, and T_s is the spin temperature of the gas. Thus if $\tau(v) << 1$ then

$$T_B(v) = N_H(v)\ C^{-1}. \qquad (3)$$

The 21-cm absorption spectrum is simply $\tau(v)$. From (2) and (3) it should be clear that absorption is biased towards cold clouds whereas emission is unbiased. T_s', the deduced spin temperature, is given by

$$T_s' = T_B(v)[1 - e^{-\tau(v)}]^{-1}. \qquad (4)$$

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T_s' is equal to T_k, the kinetic temperature only when the HI along the entire line-of-sight is isothermal. In general, as can be seen from (2), (3) and (4), T_s' is the column-density weighted harmonic-mean temperature of HI. It is important to appreciate this point when interpreting the results given below.

b) Definition of Integrated Measures

The integrated emission brightness, V_B is defined by $V_B = \int T_B(v)dv$ and the integrated optical depth, V_τ, is similarly given by $V_\tau = \int \tau(v)dv$. Here the integration is over the observed velocity range. Due to optical depth effects, V_B does not increase with N_H, the total line-of-sight column density of HI. However V_τ samples all HI along the line of sight and is not beset with any problems arising out of the relative location of the clouds with respect to each other. Another interesting parameter is F':
$F' \equiv F_{local}/(V_B/V_\tau)$ where $F_{local} = V_B(\text{Poles})/V_\tau(\text{Poles})$ and is the mean ratio of the integrated emission brightness to the integrated optical depth towards the North and the South Galactic poles. The column density of HI towards the poles is small enough that V_B(Poles) is not affected by optical depth effects. F_{local} has been measured to be 200 ± 20 K (Kulkarni 1983).

The use of integrated measures may appear to throw away a lot of velocity information in the data. However because of the small number of assumptions made, the analysis of integrated measures leads to model independent results. In particular, two broad class of problems are avoided by the use of integrated measures:
(1) Since there is no attempt to finely bin the data by z or R, all the problems connected with the determination of distance are avoided. The distance ambiguity problem in the inner galaxy is also avoided.
(2) Since there is no attempt to do a detailed comparision of the emission and the absorption spectrum, the problems arising from small-scale angular-structure in the HI features are avoided. Structures in HI on an angular-scale smaller than the emission beamwidth lead to systematic biases in analysis involving velocity information. In contrast, integrated measures are not statistically biased.

III. RESULTS

We have divided the galaxy into three regions:
(a) inner galaxy ($R < R_o$ and $|l| < 90°$; R_o has been assumed to be 10 kpc)
(b) outer galaxy in the second and third quadrants ($R > R_o$; $90° < l < 270°$)
(c) outer galaxy in the first and fourth quadrants ($R > R_o$; $|l| < 90°$).
Now consider a line-of-sight with $90° < l < 270°$. This line-of-sight has a minimum $|z|$, z_{min} of 0 pc at the position of the sun and a maximum $|z|$, z_{max} when the line-of-sight crosses a circle with R = 20 kpc; this radius corresponds to the assumed edge of the HI disk (Kulkarni, Blitz and Heiles 1982). For lines-of-sight with $|l| < 90°$, there is an additional complication due to the fact that the line-of-sight will traverse both the inner and the outer galaxy regions (i.e. regions (a) and (c)). For such lines-of-sight we compute F' separately for region (a) and (c). For region (a), z_{min} is clearly 0 pc and z_{max} is the $|z|$ of the line-of-sight when it crosses the circle $R = R_o$. For region (c), z_{min} and z_{max} are simply the $|z|$ value of the

line-of-sight when it crosses a circle of radius R_o and 20 kpc respectively.

In Figs. (1) and (3) we show F' as a function of the z-extent of the line-of-sight for regions (a), (b) and (c) respectively. The z-extent is shown by means of the vertical "error-bar"; thus the tips of this "error-bar" correspond to z_{min} and z_{max} of the line-of-sight. The square in the center of the "error-bar" is simply the arithmetic mean of z_{max} and z_{min} i.e. $\langle z \rangle = 1/2(z_{min}+z_{max})$. In Fig. (2) we show F' as a function of $\langle z \rangle$ to avoid a clutter of lines.

In all the three regions of the galaxy we find that the points with the smallest z-extent have $F' > 1$. This is understandable since at low $|b|$, V_B saturates due to large optical depths whereas V_τ is unaffected. Another striking correlation is the increase of F' with $\langle z \rangle$, or in other words, F' values which average over higher-$|z|$ HI seem to be systematically smaller than F' values which represent smaller-$|z|$ HI. This is most clearly seen and is statistically extremely significant in region (c) (Fig. 3) and somewhat evident in region (b) (Fig. 2) and not seen at all in region (a) (Fig. 1). We attribute this correlation to an increase of Not-Strongly-Absorbing HI with $|z|$.

Stray radiation can produce the correlation seen in Figs. (2) and (3). We believe that this is not an important effect quantitatively since a) stray radiation is important at high latitudes where the signal is weak and the sidelobes lie in the galactic plane and b) all the points shown in Figs. (2) and (3) have V_B in excess of 10^3 K km s^{-1} and V_τ, in all but two lines-of-sight, is not dominated by measurement noise. Thus neither measurement errors nor stray radiation vitiate our conclusion.

IV. DISCUSSION

Concentrating on Fig. 3, where the variation of F' with the z-extent is best seen, we note that at high $|z|$, F' decreases to at least a sixth of the local value of unity. Now a decrease in F' could be either due to (i) an increase in the temperature of HI clouds or (ii) an increase in the fraction of the warm intercloud medium HI or both. In an attempt to determine the variation of the spin temperature of clouds with $|z|$ we estimated the spin temperatures corresponding to the absorption features through the use of eqn. (4). Binning T_s' in $|z|$ shows a weak correlation of increasing T_s' with $|z|$ - T_s' at most increases by a factor of 2 from low-$|z|$ to high-$|z|$. If this is true then the intercloud medium HI increases by a factor of 3 from low-$|z|$ to high-$|z|$. There is a problem with such a naive determination of T_s' because at low-$|z|$, the plethora of absorption components makes determination of emission brightness of each absorption component uncertain. Correspondingly, at high-$|z|$ the increased background of the intercloud medium HI increases T_s'.

We would like to point out that studies of local HI show that the velocity-dispersion of clouds with $\tau < 0.1$ is twice as much as that of clouds with $\tau > 0.1$ (Dickey 1977). Statistically low-τ clouds have larger T_s (this

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is the so called $T_s-\tau$ relation; e.g. Liszt 1983). Thus there is an indication of a z-dependence of of the temperature of HI clouds. For this reason we are in the process of doing a detailed gaussian-component analysis to quantitatively assess the importance of (i) above.

We have also derived average correction factors to account for the underestimation of the density of HI at z = 0 pc as derived from HI emission studies. The underestimation arises because the 21-cm line is optically thick. We find that the HI mid-plane densities have to be revised upwards by ~2 (inner galaxy) and ~1.6 (outer galaxy). The details of the procedure adopted in obtaining these results can be found in Kulkarni (1983).

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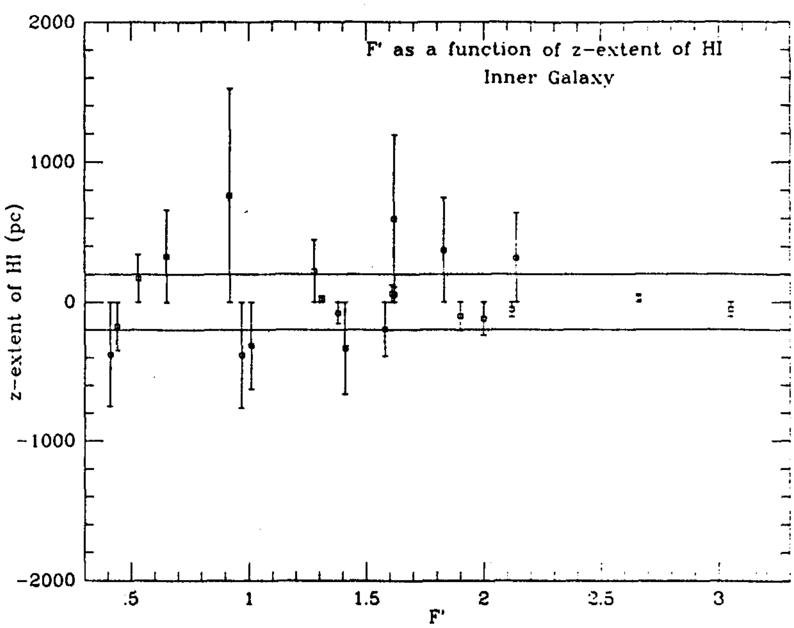

FIG. 1

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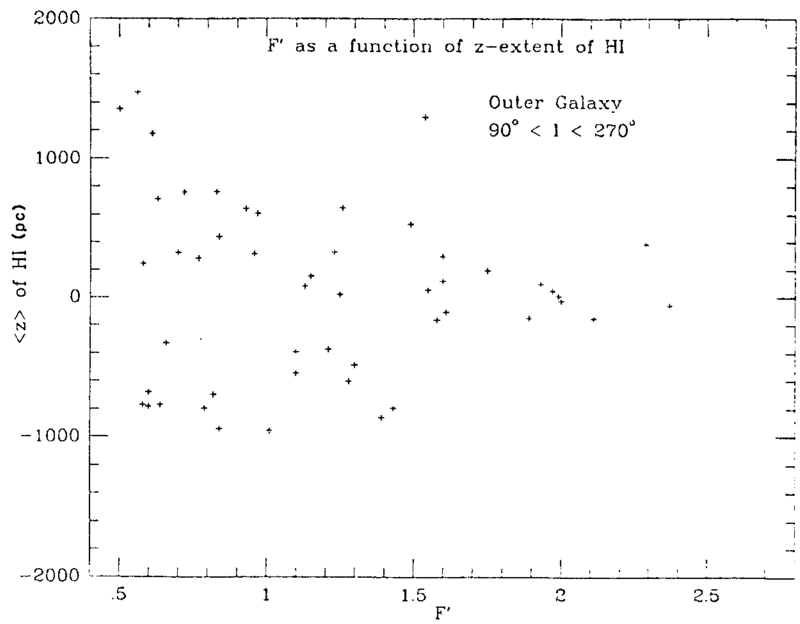

FIG. 2

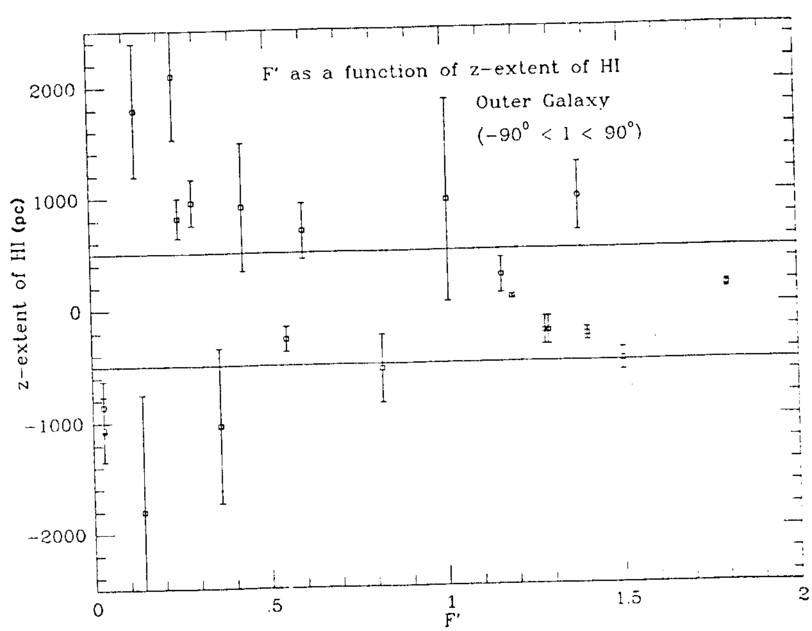

FIG. 3

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