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THE GLOBAL PROPERTIES OF THE GALAXY. I. THE HI DISTRIBUTION OUTSIDE THE SOLAR CIRCLE

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ABSTRACT

We have searched for high-velocity 21-cm emission from a possible extended Galactic neutral hydrogen disk. The HI surface density at ~50 kpc from the Galactic center is less than \(10^{-2} \, M_\odot/\text{pc}^2\). This limit is consistent with the HI surface density in M31, but well below observed densities in M63, M81, or M101 at this radius. The Galactic HI surface density distribution for \(R > R_\odot\) is consistent with an exponential model whose scale length is 0.4 \(R_\odot\). There is no observational evidence for a "cutoff" in the HI distribution. The agreement with observations is best for a value of the solar circular velocity \(\Theta_\odot\) of ~220 km s\(^{-1}\).

I. INTRODUCTION

Recent 21-cm observations (Roberts 1975; Bosma 1978) have shown that many spiral galaxies contain an HI disk which extends to very large galactocentric distances (e.g., \(R > 75\) kpc in M101). A similar disk in our Galaxy would emit detectable 21-cm radiation at high velocities relative to the local standard of rest (\(V = -200\) to \(-300\) km s\(^{-1}\) near \(l = 90^\circ, b = 0^\circ\)). This paper reports a search for the emission from such a disk.

Any search for low-level Galactic emission which is extended in both position and velocity space is usually limited by receiver baseline problems. Nevertheless, an HI disk of large radius is relatively easy to detect. The reasoning is as follows. If the circular velocity at radius \(R\) is \(\Theta(R)\), the observed radial velocity of the gas at radius \(R\) is

\[
V_r = [\Theta(R)R/\Theta_0 - \Theta_0] \sin l. \tag{1}
\]

Here \(R_0\) is the solar distance and \(\Theta_0 = \Theta(R_0)\). Note that as \(R \rightarrow \infty, V_r \rightarrow \text{const}\). Thus all the HI at large distances is crowded into a very small region in velocity space, so it can be detected much more easily. For example, assume that the rotation curve is Keplerian, \(\Theta(R) \propto R^{-1/2}\), and neglect turbulent velocities. Then at \(l = 90^\circ\) all of the HI beyond \(R = 50\) kpc lies within only ~20 km s\(^{-1}\) of \(V_r = -\Theta_0\). (The detection of this gas would thus permit a determination of the solar circular velocity \(\Theta_0\).)

Existing surveys of galactic 21-cm emission are not suitable for this purpose. The survey by Weaver and Williams (1973, 1974a, 1974b; hereafter, WWI--WWIII) is sensitive enough (their lowest contour corresponds to brightness temperature \(T_b = 1\) K) and does not extend to sufficiently high velocities. Dieter's (1972) survey has better sensitivity (\(T_b > 0.25\) K) and better velocity coverage; however, the low-velocity end of her coverage lies within the nearby galactic HI distribution so her baselines may not be very well determined. Accordingly, we have made new high-sensitivity observations mostly near \(l = 90^\circ, b = 0^\circ\) in an attempt to detect extended high-velocity emission. The observations are described in Sec. II; no emission beyond ~160 km s\(^{-1}\) was detected. A simple model for the HI distribution outside \(R_0\) is described in Sec. III and compared with our observational results in Sec. IV.

Baker (1976) and others have argued that observations similar to ours show that there is a cutoff in the galactic HI disk near \(R = 30\) kpc. We discuss the reality of this cutoff in Sec. IV. Section V contains our conclusions.

II. OBSERVATIONS AND REDUCTION

The observations were made in June 1977 with the NRAO 43-m telescope, the cooled parametric amplifier dual-channel front end at prime focus, and the 413-channel Mark II autocorrelation spectral line receiver. Typical system temperatures were ~50 K in both channels (hereafter A and B). The outputs of the two front ends were detected independently, using the autocorrelator in its parallel mode. The bandwidth used for all the observations was 2.5 MHz, which gives a channel spacing of 2.74 km s\(^{-1}\), a velocity resolution of 3.3 km s\(^{-1}\), and a total useful velocity coverage of ~470 km s\(^{-1}\). The observations were carried out in the frequency-switched mode, switching ±2.2 MHz; this particular...
To our disappointment, our baselines were not as linear as those reported by Baker (1976), and the baselines had different shapes in each receiver. However, we were able to produce satisfactory baselines by the following method. Every hour or so we observed an "off" point at high galactic latitude by the same frequency-switching technique. We fitted a fifth-order polynomial baseline to the "off" point profile, using only those points containing no signal, and removed this polynomial from the "on" observations. Finally, we removed a linear baseline which was fitted to the first and last ten usable channels, which lay well outside the expected velocity range of the Galactic H\textsc{i}. The profiles were smoothed to a resolution of $\sim$10 km s$^{-1}$ by averaging in groups of three channels. The H\textsc{i} line intensity was expressed as brightness temperature assuming a main-beam efficiency for the 43-m telescope of 75%. [Observations of the standard region S6 agreed satisfactorily with those of Williams (1973).]

Examples of the "off" profiles and the resulting polynomial baselines are shown in Fig. 1. Note that the baseline shapes are stable over about 4 h, the time interval between the observations of Figs. 1(a) and 1(b). The baseline removal from the intervening "on" profiles can therefore be performed satisfactorily. However, since both receivers suffer from nonlinear baselines, it is generally better to believe in very weak features only if they appear in both receivers.

The most extensive observations (in latitude coverage)...
were those made at $l = 90^\circ$, 100$^\circ$, and 225$^\circ$. These are displayed in Figs. 2–6 and discussed below.

a) $l = 90^\circ$ (Figs. 2 and 3)

These are the most sensitive of our profiles. We observed seven points at intervals of 5$^\circ$ of latitude between $b = \pm 15^\circ$, with integration times of 50 min each. Because of baseline problems in receiver B, only the A receiver was used. In Fig. 2, the profiles are presented on a sensitive temperature scale; in Fig. 3, the profiles at $b = 0^\circ$ and $b = +10^\circ$ are plotted on a reduced scale to show the profile shapes. For all of these profiles, the extreme negative velocity emission plunges directly to the baseline and there is no evidence of any emission beyond $\sim -160$ km s$^{-1}$ above $\sim 0.05$ K. The warping of the galactic plane is quite evident in these observations.

b) $l = 100^\circ$ (Fig. 4)

At this longitude we observed a series of positions from $b = +20^\circ$ to $-15^\circ$ at 1$^\circ$ intervals with integration times of 5 min. For these observations (which were made on a different night from those at $l = 90^\circ$) receiver B was well behaved and the profiles from both receivers were added together. Again there is no emission beyond $\sim -160$ km s$^{-1}$ above 0.1 K.

c) $l = 225^\circ$ (Fig. 5)

These profiles were observed at intervals of 2$^\circ$ over a range of $\pm 20^\circ$ with integration times of 10 min. Both channels were added together, and the extreme velocity is $\sim +120$ km s$^{-1}$. The behavior of the outer contours about $b = 0^\circ$ is much more regular than near $l = 90^\circ$, reflecting the behavior of the higher-intensity contours. (See WWII and III.)

The latitude-averaged profiles at each of these three longitudes are presented in Fig. 6. These profiles are much more sensitive than the individual profiles at each latitude if the emitting region covers a large range in latitude. No faint residual emission was found at any longitude; however, baseline effects dominate in every case. None of the observations made at other longitudes shows any evidence of emission beyond $\sim -160$ km s$^{-1}$, to a level of $\sim 0.02$ K.

Note that the positive-velocity side of the $l = 90^\circ$ and
100° profiles shows apparent emission at a very low level out to about +60 km s$^{-1}$. Baker (1976) has suggested that this might be due to stray radiation, i.e., the detection of emission by the distant sidelobes of the antenna. This effect has been discussed by Kalberla (1978) and Giovannelli et al. (1978), who find effects at the ~0.3-K level. However, it is unlikely that stray radiation has affected our observations at large negative velocities because the gas we are looking for is at the largest negative velocity of any gas above the horizon at that sidereal time.

Our observations show a sharp fall-off in the HI emission at velocities well short of any reasonable rotation velocity. This effect has been pointed out by Baker (1976) and others. In Sec. IV we discuss whether this falloff represents a cutoff in the HI distribution or is a kinematic effect.

Our observations agree well with those of Dieter (1972), Baker (1976), and Davies (1972). Davies finds localized regions of high-velocity emission which appear to be connected (in velocity space) with the main galactic emission, and which he attributes to distant galactic spiral arms (cf. Verschuur 1975). Dieter (1972) also finds high-velocity gas in this and other directions in the 90°-200° region. However, much of the high-velocity gas is distributed very sporadically, and in clouds, unlike the gas near about −160 km s$^{-1}$ (l = 90°), whose distribution is smooth. The nature of the high-velocity clouds is not investigated in this paper.

Finally we attempted to detect high-velocity absorption against Cygnus A (l = 76°, b = 6°). The observed profile (Fig. 7) shows no absorption beyond −110 km s$^{-1}$ at a level ≥0.2 K. This corresponds to a limit in the brightness temperature of any intervening high-velocity HI of ~0.05 K (where the continuum brightness temperature of Cyg A is ~400 K and we assumed that the spin temperature of any gas is 100 K). This result is consistent with the data of WWII; Cygnus A produces no perturbation of the outer negative velocity contours. It is also consistent with the observations of Davies and Cummings (1975), which show no absorption beyond −125 km s$^{-1}$.

In summary, there is no evidence in any available body of data, including our own, of any extensive HI emission beyond projected velocities of ±160 km s$^{-1}$. The sensitivity of our result depends on the latitude width of the emitting region, but the limits on brightness temperature are between 0.1 and 0.02 K.

III. MODEL HI PROFILES FOR GAS AT R > R$_{0}$

a) Description of the Model

In this section, we describe a simple model of the HI distribution at large galactocentric distances and the
expected emission profiles derived therefrom; these are compared with the observations in Sec. IV. We made no attempt to describe the profile in detail at lower velocities where, presumably, noncircular motions due to spiral arm perturbations affect the profile shapes.

If the gas is optically thin, the intensity at any velocity $V_r$ is proportional to the number density of atoms at that velocity and to the velocity scale length $[dV_r/ dr]^{-1}$, the path length per unit velocity interval.

Consider a cloud of gas at distance $R$ from the galactic center ($R > R_0$), and at longitude $l$ (latitude $b = 0^\circ$). The heliocentric distance is $r$ and the rotation velocity $\Theta(R)$. Then, assuming circular motion, the observed radial velocity is given by Eq. (1). The brightness temperature of the gas at velocity $V_r$ is

$$ T_b(V_r) = n(R) \left[ 1.823 \times 10^{18} \frac{dV_r}{dr} \right] K, $$

where $n(R)$ is the HI density at $R$ in cm$^{-3}$. More rigorously, we calculated the optical depth $\tau$ and assumed a spin temperature $T_s = 125$ K everywhere. From simple geometry,

$$ \frac{dV_r}{dr} = \frac{1}{R^2} \left[ \frac{d\phi}{dR} - \frac{\Theta}{R^3} \right] R_0 \cos l (r - R_0 \cos l). $$

Now let us assume that

$$ \Theta = \Theta_0 (R/R_0)^{-\alpha}, $$

where $\alpha$ lies between 0 (flat rotation curve) and 0.5 (Keplerian rotation curve). [$\alpha \sim 0.2$ for the model by Schmidt (1965).]

This form for the rotation curve adequately reproduces all of the observed forms for external galaxies except those in which the rotation curve reaches a maximum outside the solar distance.

From Eqs. (3) and (4), we can see that for large values of $r$, $(dV_r/dr)^{-1}$ becomes very large, almost 1 kpc/km s$^{-1}$. Thus our observations smooth over large-scale irregularities such as spiral arms, and their effect on the shape of the observed HI profile is minimized. We can also see that at longitudes other than $90^\circ$ or $270^\circ$ we are able to detect gas to greater distances than in these directions because of velocity crowding effects.

b) Input Parameters to the Models

i) Surface density

From observations of CO and HI emission in the Galaxy at $R < R_0$, Gordon and Burton (1976) have shown that the surface density of interstellar H (which is essentially all in the form of HI at large galactocentric distances) varies exponentially with radius. This result is consistent with HI observations of external galaxies (e.g., Roberts and Whitehurst 1975; Bosma 1978). Then the surface density may be expressed as

$$ S[R/R_0] = S_0 \exp \left[ (1 - R/R_0)/\lambda \right] \text{atom} \text{cm}^{-2}, $$

where $\lambda R_0$ is the scale length of the galactic HI and $S_0$ its surface density at $R_0$. The observations of Gordon and Burton (1976) yield $S_0 = 6.6 \times 10^{20}$ cm$^{-2}$, $\lambda = 0.43$, for $R < R_0$. This value agrees with scale lengths found from surface photometry of external galaxies (Freeman 1970). In this region, at least 40% of the H is molecular everywhere (Gordon and Burton 1976). However, we have used the total gas distribution because the fraction of H in the form of molecules at large galactocentric distances appears to be small.

Gordon and Burton derive their distribution using a rotation curve determined from tangent-point observations and assuming $\Theta_0 = 250$ km s$^{-1}$. It is important to point out that the derived values of $\lambda$ and $S_0$ are independent of the assumption of $\Theta_0$ as can be seen by the following simple argument. For a gas cloud at galactocentric distance $R (< R_0)$, heliocentric longitude $l$, and galactocentric longitude $\phi$, the observed heliocentric radial velocity is

$$ V_r = \Theta(R) \sin(\phi + l) - \Theta_0 \sin l, $$

while $\Theta(R)$, the circular velocity at $R$, is derived from the tangent-point velocity $V_M$ via

$$ V_M = \Theta(R) - \Theta_0 R/R_0. $$

It is then easy to show that

$$ V_{\text{obs}} = V_M (R_0/R) \sin l, $$

independent of the assumed value for $\Theta_0$.

ii) Scale height and number density

The number density is derived assuming that the HI density distribution is Gaussian in $z$, the distance perpendicular to the galactic plane, as is appropriate for a constituent with a Gaussian velocity distribution and a scale height small compared to that of the overall mass distribution. Then

$$ S \left[ \frac{R}{R_0} \right] = n_0 \left[ \frac{R}{R_0} \right] \int e^{-z^2/2h^2}dz $$

$$ = (2\pi)^{1/2} h n_0 \left( \frac{R}{R_0} \right). $$

where $h$ measures the width in $z$ and $n_0$ the density in the plane.

As is well known, the scale height of the Galactic HI thickens appreciably outside $R_0$ (e.g., Jackson and Kellman 1975). To a good approximation $h$ can be expressed as

$$ h/R_0 = a $$

$$ (R < R_0) $$

$$ = a + b [R/R_0 - 1] $$

$$ (R > R_0), $$

which fit the data satisfactorily. At each of our observed longitudes, we have derived values for $\Delta b$, the latitude
half-intensity thickness, as a function of velocity. Our data agree very well with those of Jackson and Kellman (1975). Δh then translates into h if the distance is known; this may be derived from the observed velocity via Eqs. (1) and (4). For example, for a flat rotation curve (α = 0) and Θ₀ = 250 km s⁻¹, we find a = 0.012 and b = 0.05.

The increase of h with R does not necessarily imply an increase in the turbulent velocity of the gas with R, because we do not know the potential field in the outer parts of the Galaxy. Thus we have used observational values of h, derived from Δh.

Note that all of the lengths (scale length, H₁ layer thickness, etc.) are expressed in terms of R₀. Thus the resulting model calculations for T_b(V_r) are independent of the value of R₀.

### iii) Effect of turbulence

Observed Galactic H₁ profiles have fairly large velocity widths (tens of km s⁻¹), probably due to turbulent motions of the H₁ clouds. We examined H₁ profiles from WWII and III, and found that these motions give typical values of ΔV (the full width at half power) of ≤ 30 km s⁻¹. (See, for example, the profiles at l = 180°, or see Fig. 1.) This value corresponds to a dispersion of 12 km s⁻¹, which will be used in all the following calculations. It is unknown whether such turbulent motions are present in the very distant gas, since the phenomena responsible for turbulence (stellar winds, supernova explosions, etc.) may not be present at great distances. In any case, it is a simple matter to study the effect of this turbulence, supposing it to be present, by smoothing the calculated profiles by an appropriate Gaussian weighting function.

Using the foregoing equations, model profiles were then calculated for a range of the parameters Θ₀, α, and λ, and then compared directly with the observations.

### IV. INTERPRETATION OF H₁ PROFILES OBSERVED AT R > R₀

#### a) Large-Scale Features of the Model Profiles

In Fig. 8 we show our observed profiles at l = 90°, b = 0° [Fig. 8(a)] and l = 225°, b = 0° [Fig. 8(b)] with model profiles calculated assuming Θ₀ = 220 km s⁻¹, α = 0.0, and λ = 0.4 plotted also. These models have been smoothed by the aforementioned Gaussian function. The values of the integrated brightness under the observed and model profiles in units of Kelvin times km s⁻¹ are given also, as is the distance corresponding to the velocity scale in units of R/R₀.

Note that varying the values of Θ₀ and α does not change the total area under the model profile in the absence of large optical depth effects, since the effect of varying these quantities is to redistribute the emission with velocity. Varying the value of λ does change the profile area, however, since it changes the total amount of H₁ at R > R₀. It is impressive that the integrated brightnesses of the model and observed profiles agree so closely in both the l = 90° and 225° directions. The main point is, however, that the curves agree over the last 30 km s⁻¹ (and emission is detectable for another 20 or 30 km s⁻¹, though the scale on Fig. 8 is too course to show it—see rather Figs. 2–5). This velocity range (∼ 110 to −160 km s⁻¹) at l = 90° corresponds to a distance range R/R₀ of 2–3.7 (α = 0, Θ₀ = 220), and thus, as suggested earlier, the enormous velocity scale lengths [(dV_r/dr)⁻¹ ∼ 1 kpc per km s⁻¹ near V_r = −160], effectively smooth out any irregularities in the emission. Thus, in comparing our model profiles with the obser-
vations, we confine our attention to roughly the last 60 km s\(^{-1}\) of the profile.

Of course, the most striking result of Fig. 8 is that the model profiles predict a sharp cutoff in the emission at velocities well short of the rotation velocity (or its projections). In the models, the extent of the disk is infinite, of course, but the exponential decrease in density wins out over the rapid increase in \((dV_r/dr)^{-1}\). It is unnecessary to postulate a cutoff in the HI disk, as has been done, for example, by Baker (1976) and others, or even so much as a change in the behavior of \(n(R)\) at large radii. This conclusion does not depend strongly on the value of \(\Theta_0\) or the shape of the rotation curve.

**b) Velocity Extrema of the Model Profiles—Implications for the Value of \(\Theta_0\) and the Galactic Rotation Curve**

As described above, the velocity extent of the emission in the model profiles is affected by the values of \(\Theta_0\), \(\alpha\), and \(\lambda\). We can thus compare the model and observed profiles to study the implications for the values of these quantities. As examples we use the profiles at \(l = 225^\circ\), \(b = 0^\circ\), and at \(l = 90^\circ\). Profiles in this last direction are strongly affected by the warping of the HI layer, so we have used a "ridge-line" profile beyond \(V_r \sim -80\) km s\(^{-1}\), i.e., constructed a profile whose value of \(T_b\) at each \(V_r\) is the maximum value of \(T_b\) as selected from the observations at various latitudes.

Model profiles were calculated from Eqs. (1), (4), and (10), using values of \(\Theta_0\) of 200, 220, and 250 km s\(^{-1}\), values of \(\alpha = 0.0\) (flat rotation curve) and 0.2 (Schmidt model), and values of \(\lambda\) of 0.4 \(\pm 0.08\) (20%). The results are compared with the observed profiles in Figs. 9–11. In Figs. 9 and 10, we show the extrema of the profiles at \(l = 90^\circ\) and \(l = 225^\circ\) compared with curves calculated for scale length \(\lambda = 0.4R_0\) and a variety of values of \(\Theta_0\) and \(\alpha\). In Fig. 11, the calculated \(l = 225^\circ\) profile is shown again for various scale-length values. In Figs. 9 and 10, both the unsmoothed and smoothed profiles are plotted, the latter as dotted curves; in Fig. 11, only unsmoothed profiles are plotted. In Fig. 10, we have also replotted the observed data points scaled such that the areas under the observed and model HI profiles are equal. Examination of these figures shows that the velocity extent of the emission is increased by (1) smoothing, (2) increasing \(\Theta_0\), (3) increasing \(\alpha\), or (4) increasing \(\lambda\).

In the following discussion we use these observations and models to derive constraints on the values of \(\Theta_0\) and \(\alpha\). It is clear that the large values of \((dV_r/dr)^{-1}\) mean that noncircular motions in the outer parts of the Galaxy do not affect these considerations. That this is true at all longitudes can be seen from Fig. 12, in which the extreme velocity of the HI (that corresponding to \(T_b = 1\)) is plotted as a function of longitude. These points are taken from the surveys of WWII and III, and of Kerr, Harten,
and Ball (1976). Also plotted on Fig. 12 are our predicted model curves for $\lambda = 0.4$, $\alpha = 0$, and $V_0 = 220$ and 250 km s$^{-1}$. It is clear that for our particular observations, the profile shapes at large velocities are not seriously distorted by noncircular motions, such as infall.

Figures 9–12 show that the profiles are well fit by a variety of models, with, for example, $V_0 = 220$ km s$^{-1}$, $\lambda = 0.4$, $\alpha = 0$, or by $V_0 = 250$ km s$^{-1}$, $\lambda = 0.32$, $\alpha = 0$. We adopt the values $V_0 = 220$ km s$^{-1}$, $\lambda = 0.4$, $\alpha = 0$ as our standard model.

First consider the value of $\lambda$. Figure 11 shows that the high-velocity tail can be fit by various values of $\lambda$ as long as $V_0$ is varied appropriately. However, we have already argued that the total area under the profile is independent of $V_0$ and $\alpha$ and depends only on $\lambda$; moreover, Fig. 8 shows that the areas under the observed model profiles agree for $\lambda = 0.4$. This value also consistent with the scale length $\lambda = 0.43$ of the total hydrogen surface density for $R < R_0$ (Gordon and Burton 1976; Burton and Gordon 1978). Thus we conclude that $\lambda = 0.4$.

Figures 9 and 10 are drawn with $\lambda = 0.4$. They show that the high-velocity tail could only be fit with the standard solar circular velocity $V_0 = 250$ km s$^{-1}$ if the rotation curve was rising at $R \geq R_0$ (i.e., $\alpha < 0$). On the other hand, a Keplerian curve ($\alpha = 0.5$) would only agree with the data for $V_0 < 200$ km s$^{-1}$. We feel that our standard model ($\alpha = 0$, $V_0 = 220$ km s$^{-1}$) represents the most conservative rotation curve which agrees with the data.

Is there any way to save the conventional solar circular velocity $V_0 = 250$ km s$^{-1}$? There are at least three possibilities, none of which is very attractive. First, the rotation velocity could be rising at $R = R_0$, but the rotation curves of most external galaxies are already decreasing at $R \approx 10$ kpc (Bosma 1978), and moreover a rising rotation curve requires $|A| < |B|$ ($A$ and $B$ are Oort’s constants), which is inconsistent with measurements of the local velocity ellipsoid. Secondly, there could be a sharp cutoff in the H I distribution at large radii, but then it seems unlikely that our simple exponential model would fit the data. Finally, the observations could be fit by using a larger value of $S_0$, the local surface density; but we have already used a rather large value of $S_0$ by including a local contribution from molecular hydrogen, so if anything $S_0$ ought to be smaller.

Thus, the observations suggest that the velocity extent of the detectable outer boundary of the Galaxy can be described by a simple model in which the H I falls exponentially with radius with the same scale length parameters as its falloff at $R < R_0$. The most conservative interpretation of the velocity field of the Galaxy beyond $R_0$ is that the rotation curve is close to flat as far out as the detectable extent of the H I, while the solar rotation velocity $V_0$ is close to 220 km s$^{-1}$.

**c) Extent of the Galactic H I Disk and Comparison with Other Galaxies**

Our most sensitive observation from the point of view of calculating the H I extent of the Galaxy is that at $f = 225^\circ$. Beyond $\sim 130$ km s$^{-1}$, no emission is detectable above a limit of $\sim 0.1$ K (this is the limit for a single observation, and we assume that the distant H I disk fills the telescope beam to arbitrary distances). Thus, beyond $R = 6.1R_0 = 50$ kpc, if $V_0 = 220$, $\alpha = 0$, $R_0 = 8.5$ kpc, see, e.g., Oort and Plaut (1975), the H I surface density is less than $0.008 \, M_\odot$ pc$^{-2}$. Although we have used the scale height given by Eq. (10), this result is very insensitive to the H I scale height. This is because at large scale heights, the surface density corresponding to a fixed brightness temperature increases, but in this case we can use the latitude-averaged results of Fig. 6 so that our observational sensitivity improves.

For comparison, Roberts (1978) has measured an H I surface density of $\sim 0.5 \, M_\odot$ pc$^{-2}$ at 50 kpc from the center of M101 (Scd I) and $\sim 0.2 \, M_\odot$ pc$^{-2}$ at the same distance in M81 (Sab I–II). Bosma’s (1978) observations are not as sensitive as those of Roberts, but he has measured on H I surface density of $1 \, M_\odot$ pc$^{-2}$ at $R = 40$ kpc in NGC 5055 = M63 (Sbc II). On the other hand, there are galaxies which are as deficient in H I as the Galaxy; the surface density in M31 (Sb I–II) has already dropped to $0.01 \, M_\odot$ pc$^{-2}$ at $R = 30$ kpc (Roberts and Whitehurst 1975). Note that the H I surface density at large radii shows no obvious correlation with Hubble type or luminosity class.

**V. CONCLUSIONS**

The surface density of neutral hydrogen in the Galactic disk at 50 kpc from the Galactic center is $< 10^{-2} \, M_\odot$ pc$^{-2}$. At this distance the Galaxy contains less H I than M81 (Sab) or M101 (Scd); the upper limit is consistent, however, with the H I distribution in M31 (Sb).

At large distances the Galactic H I distribution is consistent with an exponential model with $S(R_0) = 6.6$
\times 10^{20}\, \text{cm}^{-2}$ and scale length $\lambda R_0 = 0.4 R_0$. There is no evidence for a cutoff in the Galactic HI distribution, and no very strong evidence that any spiral galaxy has such a cutoff.

The observations of the outer HI envelope suggest that the distant rotation curve of the Galaxy is close to flat and that $\Omega_0 \approx 220\, \text{km s}^{-1}$.

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