I

The Disk-Halo Interface in our Galaxy

THE NEUTRAL HALO IN THE INNER GALAXY

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ABSTRACT. Neutral gas extends out of the disk to form a modest halo over most of the inner Galaxy except for the area at R $\lesssim$2.5 kpc. The HI halo probably consists of several populations including a relatively quiescent layer and a cloudy component that has peculiar velocities. This latter component often appears between 150 and 400 pc from the plane. Most of the neutral gas at $|z|$ $\gtrsim$500 pc has the same kinematics as the gas below it.

1. INTRODUCTION

> *"... clouds unquestionably exist at heights of the order of 1 kpc."*
> — Munch and Zirin (1961)

> *"... well outside the real disk one still finds neutral hydrogen with an average density of between 5 and 10 per cent of the density in the plane."* — Oort (1962)

Neutral gas that lies far from the galactic plane has been studied for at least thirty years, and has been the subject of debate for every bit of that time. It is fascinating to read the papers and discussion in the *Proceedings of the Third Symposium on Cosmical Gas Dynamics* held in June 1957, where the participants wrestled with issues that have remained puzzling into our time, in large part because the neutral halo is often difficult to detect and doubly difficult to disentangle from the disk. In the last decade, though, there have been major advances in the field including Albert's (1983) study of the halo's distribution and kinematics using optical absorption lines; measurement of halo hydrogen at 21 cm and in the Lyman-α ultraviolet absorption line (Lockman 1984; Kulkarni and Fich 1985; Savage and Massa 1987); and a growing number of studies that combine radio, optical and ultraviolet techniques (Hobbs *et al.* 1982; Lockman, Hobbs and Shull 1986; Albert

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et al. 1989). It is an active field. Recent reviews that discuss the topic of HI in the galactic halo include those by Kulkarni and Heiles (1987) and by Dickey and Lockman (1990; hereafter DL90), as well as contributions in this volume by Burton, Danly, Mirabel, Reynolds, Savage, and Wakker.

For this review of the neutral halo in the inner Galaxy I will first summarize some of the observations, especially the 21 cm studies, and then consider the more specific problems of halo kinematics and support. It is useful to begin with a list of the questions that, in my mind, form the background for this review. Many of these are likely to have interesting answers:

1. How pervasive is high-altitude HI? Is it, for example, entirely in clouds that have a small filling factor?
2. Is the amount of HI far from the galactic plane determined by the support available against gravity, or by ionization of the hydrogen? Does the temperature and ionization state of neutral gas change with z?
3. Are there several populations of neutral gas above the disk; is "halo gas" also found in the galactic plane?
4. How is the gas supported in the galactic potential?
5. Why does the HI halo change so dramatically at R=2.5 kpc but so little at larger radii?
6. What is the kinematics of halo gas; how tightly coupled is it to galactic rotation?
7. Is halo HI related to high-velocity clouds, the Magellanic Stream, or infall of extragalactic gas?

2. AVERAGE HI DENSITY ABOVE THE PLANE.

Figure 1 shows three recent experimental estimates of $n_H(z)$. The Dickey and Lockman (DL90) and the Lockman (L84) curves describe the distribution of 21 cm HI emission averaged over the range 3.4 – 6.8 kpc from the galactic center; the Savage and Massa curve is an exponential fit to Lyman-α column densities for about 60 stars within $\lesssim$10 kpc of the Sun, concentrated towards the inner Galaxy. The DL90 curve differs from L84 because it includes a correction for cool gas at low $|z|$. Quantitative values for these functions are given in DL90.

The DL90 curve is approximately Gaussian within a few hundred parsecs of the plane, where it is very similar to the functions found by previous 21 cm observers (e.g., Schmidt 1957; Baker and Burton 1975). For this review I am defining the "HI halo" as the gas well beyond the Gaussian core, typically at $|z| \gtrsim 400 - 500$ pc, where the observations, both radio and UV, show that there is a significant amount of neutral gas. Current estimates are in general agreement with Oort's (1962) values: at $R \sim R_0 = 8.5$ kpc between 5% and 10% of all HI lies at $|z| \gtrsim 500$ pc (L84; DL90).

It is interesting that optical and UV absorption line studies of the ISM have always derived a larger scale-height than 21 cm studies (cf., e.g., Bohlin, Savage

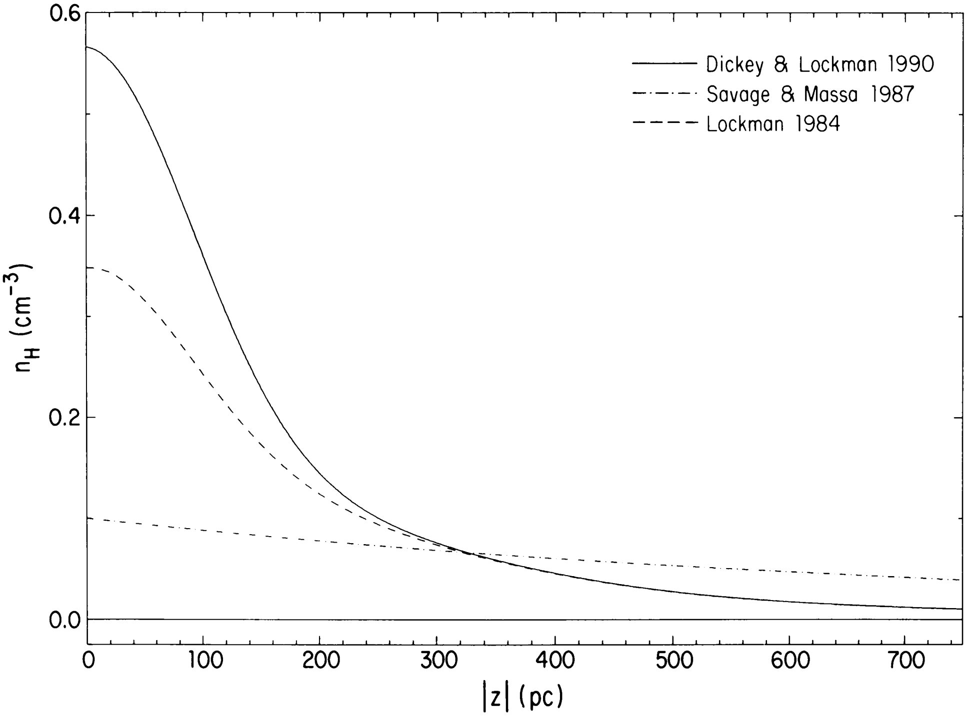

Figure 1. Recent estimates of the neutral hydrogen density above the galactic plane in the inner Galaxy. The Savage and Massa (1987) curve is derived from Lyman-α observations in the ultraviolet; the others come from 21 cm observations.

and Drake 1978; Celnik, Rohlfs and Braunsfurth 1979). Of course there are strong selection effects: the UV data are biased toward low reddening sitelines and positively avoid directions through dense clouds. This tendency artificially enhances the halo at the expense of the disk because the densest clouds are at low |z|. Also, the radio and UV data sample different parts of the Galaxy that might not have the same amount of halo gas. So all in all, within the range of uncertainty, and given the limited data, it is possible that the UV and radio estimates of the halo at $|z| \gtrsim 400$ pc do not actually disagree. But we cannot completely dismiss the possibility that the radio analyses are missing some gas at the higher altitudes, or more likely assigning it to the wrong location, because it has slightly different kinematics than disk gas. This is discussed further in section 5. Many more cooperative radio/optical/UV studies will be needed to establish the reality of the apparent differences.

There is some evidence that there is little neutral hydrogen at $|z| > 1$ kpc, at least in the part of the Galaxy near the Sun that has been probed by Lyman-α and optical absorption studies (Albert 1983; Albert *et al.* 1989). In this region the 21 cm column densities toward high-z stars are identical to the Lyman-α column densities, which give only the HI below the star, for all stars at |z| $\gtrsim$1500 pc (Lockman, Hobbs and Shull 1986; DL90). On the other hand, there are places in the Galaxy where discrete HI structures are found more than 1 kpc from the plane (Smith 1963; L84; also see section 3). Most likely the upper boundary of the neutral halo varies from place to place.

Beyond the question of the accuracy of the derived $n_H(z)$ distributions is the question of how they should be interpreted. Do they supply evidence for a pervasive "intercloud" atmosphere around the galactic disk? Probably not. The 21 cm data are a smooth function of |z| only when averaged over an enormous volume; individual positions sometimes show considerable clumpiness in the high-z gas. Likewise, the Lyman-α observations scatter about the simple exponential function to such an extent that a statistical analysis formally rejects the fit, unless it is assumed that there are line of sight variations of a factor of two in density (Danly *et al.* 1991; see also Lockman, Hobbs and Shull 1986). There are signs of structure in at least one halo cloud on a scale $\gtrsim$60 pc, but the observations are so coarse that they are not very restrictive (Albert *et al.* 1989). In sum, we do not know how much of the gas at, say, z=500 pc, is in discrete structures with a low filling factor, and how much is so widely distributed that it would be useful to describe it as an atmosphere.

3. A NOTE ON SHELLS AND SUPERSHELLS

An all-sky map of integrated HI column densities (e.g. DL90) shows a number of arching filaments rising up out of the galactic plane to moderate and high latitudes. Many of these correspond to radio loops (e.g. the North Polar Spur; radio Loop II), others are parts of shells identified by Heiles (1979, 1984), others do not fit any clear pattern. Relatively dense HI associated with catalogued supershells (Heiles 1979) sometimes extends $>$ 1 kpc from the plane. It can be difficult to detect old shells far from the Sun, but these data suggest that throughout the Galaxy there will be HI in the halo that has come from shells or their fragments, in addition to any diffuse component of halo HI.

4. VARIATION OF THE HI HALO IN THE INNER GALAXY

Figure 2 shows a cross-section of the distribution of HI in the Galaxy interior to the Sun (adapted from L84) with curves that enclose 90%, 75%, and 50% of the HI emission. It illustrates, first, that the halo undergoes an abrupt change around $R = 3$ kpc, and second, that the halo, and the entire HI layer, appears nearly constant between 3.5 and 7 kpc from the center. The absence of an HI halo in the innermost Galaxy is further illustrated in Figure 3, which shows normalized density profiles at locations 2.2 and 3.6 kpc from the galactic center. The vertical structure of the disk at the smaller radius approximates a single Gaussian, whereas at the larger radius it has wings and a second component in addition to the Gaussian core. The change in the halo at $R \sim 3$ kpc is a striking feature of our Galaxy. It

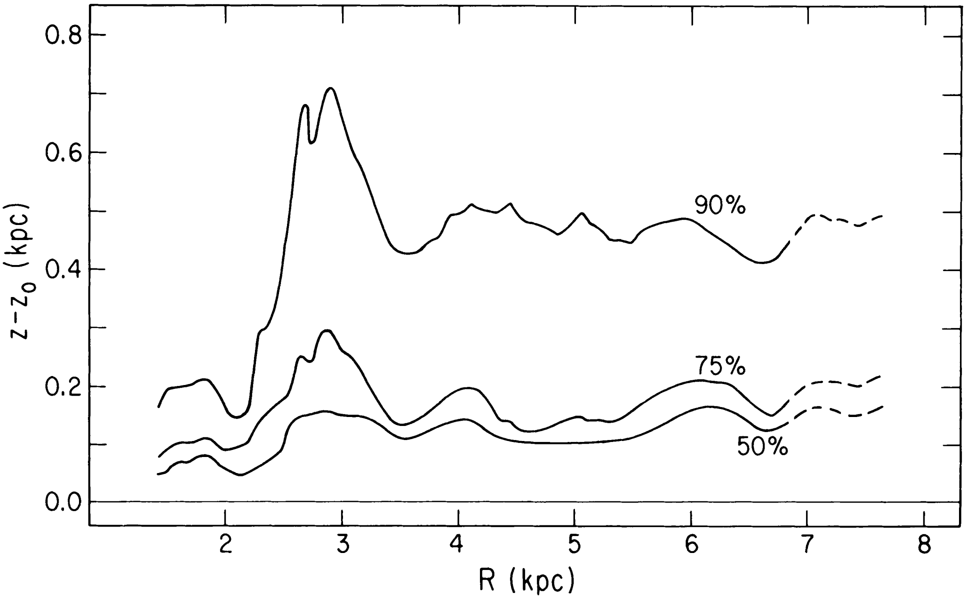

Figure 2. A cross-section of the galactic disk showing the extended HI halo. The contours enclose 50%, 75%, and 90% of the integrated HI column density (i.e., at R = 4 kpc 90% of galactic HI emission lies below 500 pc). Vertical distances are given from the mean location of the plane, which may differ from z= 0 by up to 100 pc. This figure is adapted from Lockman (1984) with the Sun at $R_0 = 8.5$ kpc. Note that there is no HI halo at R $\lesssim$2.5 kpc.

may be caused by a wind from the galactic bulge. Within the bulge the wind will sweep gas from the halo and outer parts of the disk, leaving behind only a narrow layer (Bregman 1980a). The observed break in the halo comes at approximately the radius of the galactic bulge.

The HI layer does not change much, on average, at R$\gtrsim$3 kpc, and this is puzzling because the gravitational force should vary by at least a factor of two over this range (Oort 1962). The HI thickness increases slightly with R beyond 3 kpc, but not nearly as much an one would expect assuming constant support. While the relative constancy of the HI scale-height over the inner Galaxy has recently been challenged by Knapp (1987), I do not believe that that analysis of the data is inconsistent with previous work given that there is a break in the distribution at R $\sim$ 3 kpc.

Beyond the Sun the situation is different. The HI layer thickens monotonically to the edge of the Galaxy even as it bends into the warp (Lozinskaya and Kardashev 1963). This is discussed by Burton elsewhere in this volume.

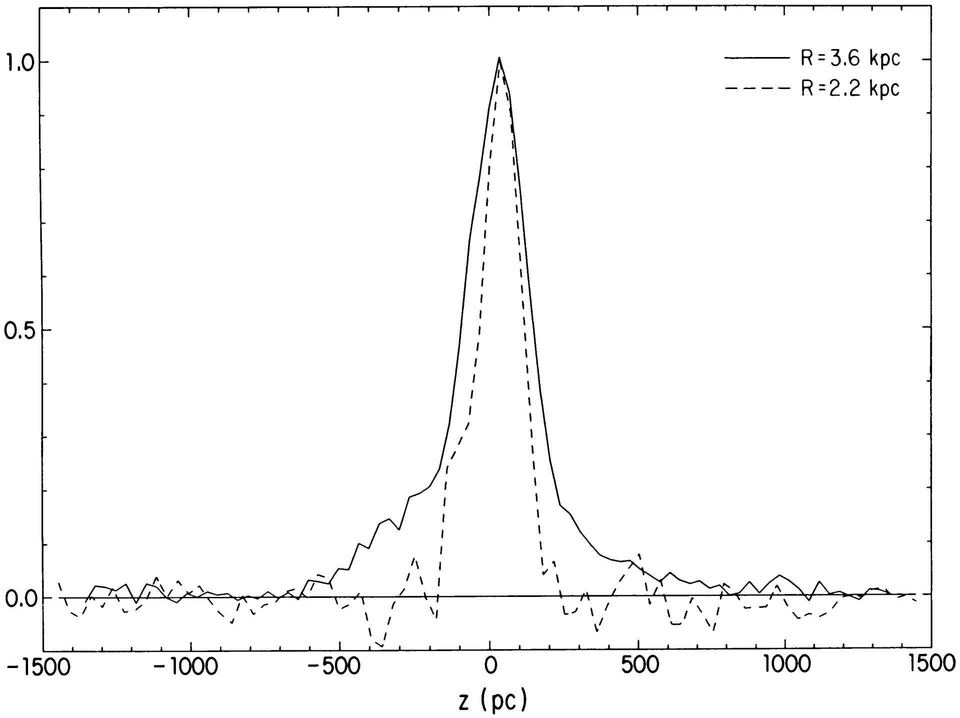

Figure 3. The normalized volume density of HI perpendicular to the galactic plane at two tangent points corresponding to R = 3.6 kpc and R = 2.2 kpc from the galactic center. The data are from the Weaver and Williams (1973) HI survey. This further illustrates the absence of a broad HI halo near 2 kpc and its presence beyond about 3 kpc.

5. KINEMATICS

It is now generally recognized that most galactic HI (at least in the inner Galaxy) is in cylindrical rotation (or "corotation"), i.e., its velocity is overwhelmingly rotational and the rotational velocity does not change with z. The 21 cm results shown in Figures 1, 2 and 3 refer to HI that is strictly corotating (L84). (Note that most of these results were derived from observations at $|b| \leq 10°$ so they are not greatly influenced by typical vertical motions). But in addition, there are interstellar components that are probably not corotating, an example being the classic high-velocity clouds (Giovanelli 1980; Kaelble, de Boer and Grewing 1985; Wakker this volume). There are also neutral clouds that are known to have large vertical velocities (e.g., Wessalius and Fejes 1973).

In a classic paper on the halo, Albert (1983) reported the comparison of optical absorption spectra (in lines of Ca, Na and Ti) toward pairs of high latitude stars that are nearly aligned on the sky but are at significantly different distances. From studying the difference between the spectra of foreground and background stars Albert concluded that the neutral halo has two principle components: a corotating thick disk that extends from the plane to well beyond most OB stars and lies within ±10 km s^{-1} of zero velocity, and a high velocity gas observed only far from the plane. The two components differ in kinematics, distribution and abundances. This arrangement might result from a galactic fountain (Bregman 1980b).

These findings make it tempting to imagine that the ISM is fairly calm close to the plane, then becomes quite turbulent with large peculiar motions somewhat further out. This image, however, is not quite correct, for the low velocity corotating gas must also extend far from the plane. Furthermore, when I look at Albert's data it seems that the velocity extent of absorption below the foreground star is significantly smaller than that below the background star only when the foreground star is at $|z| < 100$ pc. If the foreground star is at $|z| > 200$ pc, its absorption velocities are similar to those seen against the background star. This implies that Albert's "high-velocity" layer starts at $|z| \sim 150$ pc.

5.1 The Halo in Three Interesting Directions

Figure 4 shows spectra toward three stars that are especially revealing about kinematics in the halo. The solid lines show the 21 cm spectra corrected for stray radiation; this is the total galactic HI in each direction. The stars were chosen because they have $N_{21} > N_{L\alpha}$ by a factor of at least two, i.e., there is at least as much HI above each star as below. Thus the neutral halo is especially pronounced in these directions. Finally, there are high velocity-resolution optical or UV interstellar absorption spectra available so that the spectral components below each star can be identified. The dashed lines show the absorption spectra inverted and drawn with an arbitrary vertical scale. Above each spectrum is a horizontal line (ending in an arrow) showing the expected relationship between velocity and distance for galactic rotation in the direction of the star. Tic marks are every kpc.

These stars are the only ones I know of that have $N_{21} \gtrsim 2\ N_{L\alpha}$, good absorption spectra, and lie at an interesting distance from the plane. The point of this display is to answer the question: what is the velocity of the large amounts of HI that lie above these stars?

Toward μ Col and ρ Leo the answer is simple: absorption covers virtually every velocity that has 21 cm emission. Thus the gas beyond these stars (from half to two-thirds of the total) must have the same kinematics as at least some of the gas below the stars. Only in the direction of the star closest to the plane, HD 28497, is there substantial HI emission at a velocity that shows no absorption. In this case the gas at $V \sim 10$ km s^{-1} must be in the halo beyond the star. For circular rotation this velocity corresponds to a distance of about 2 kpc and a $z = -1.2$ kpc. There is nothing astonishing about finding HI at this location. The inescapable conclusion from these data is that halo gas has the same kinematics as some (or all) of the disk gas below it. More precisely: *the large amounts of HI above each of these stars lies either at a velocity permitted by galactic rotation, or is in the range of velocities seen below each star.*

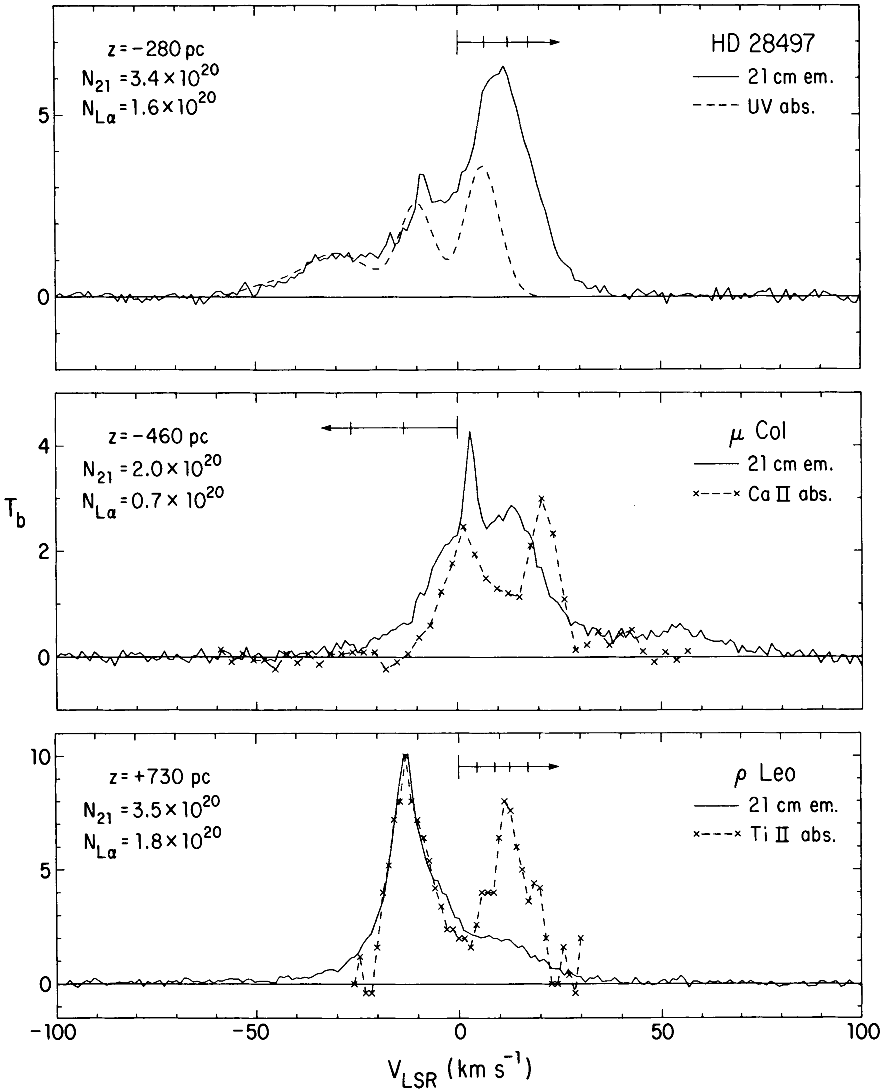

Figure 4. The kinematics of halo gas. In the direction of these stars more HI lies above the star than below ($N_{21} \gtrsim 2\ N_{L\alpha}$). The solid lines show the HI spectra. The other curves are inverted and arbitrarily scaled absorption spectra. The line that ends with an arrow in each panel shows the relationship between distance (tics are every kpc) and velocity for galactic rotation. The 21 cm data are from Lockman, Hobbs and Shull (1986). Absorption spectra are from Giovanelli *et al.* 1978 (an amalgam of low-ion stages observed by Shull and York, 1977, using the Copernicus satellite), the Ca II observations of Hobbs (1984) and the Ti II observations of Stokes (1978).

The region of "high-velocity" halo gas seems to be fully established by $|z| = 280$ pc as judged by the spectrum towards HD 28497. This is entirely consistent with the conclusion from Albert's data that the layer begins at $|z| \sim 150$ pc. But the situation cannot be as simple as this. The HI at +50 km s^{-1} toward μ Col, although only a small fraction of the total, does not appear in the Ca II absorption spectrum and so must lie at $|z| > 460$ pc. And in at least one other direction peculiar velocities do not appear until $|z| > 420$ pc (toward HD 119608; Albert *et al.* 1989). Also, it is a fact that many high- latitude directions show little gas at peculiar velocities. For example, virtually all of the HI is within 20 km s^{-1} of zero velocity toward ζ Lib and 53 Ari (Lockman, Hobbs and Shull 1986). These directions also have $N_{21} \sim N_{L\alpha}$, even though the stars are only 150 and −280 pc, respectively, from the plane.

The high-velocity component of the halo is clearly irregular. But it seems worthwhile italicizing a second conclusion at this point: *A layer of high-velocity halo gas (i.e. gas either not obeying galactic rotation or having a large V_z) is often present* $\sim$ 150 *pc to* $\sim$ 500 *pc from the plane.* In those cases where there is a significant amount of HI above 500 pc, it lies in the velocity range of the gas at lower z. I neglect, of course, the classic high-velocity clouds which occupy their own region of the halo at $|z| > 1$ kpc (see Wakker, this volume).

It is curious, and perhaps significant, that the directions discussed in Figure 4, where a large fraction of the gas is in the halo, also have a large fraction at velocities forbidden by galactic rotation. Most of the HI toward ρ Leo and μ Col has an anomalous velocity, and in the direction of HD 28497 only half of the HI obeys galactic rotation. To add to the mystery, the anomalous velocity gas is at relatively low $|z|$, i.e., it is below, not above, each star. A plausible explanation for these facts is that the neutral halo is most pronounced in regions where the HI layer near the plane has been disturbed. Much more data are needed to evaluate this suggestion, and careful consideration must be given to the role of the "local bubble" on the structure of the high-latitude sky (e.g., Cox and Reynolds 1987).

6. SUPPORT

Kulkarni and Fich (1985) pointed out that many 21 cm emission profiles have extended wings, implying that there is a population of "fast" HI clouds in the Galaxy (as first suggested by Radhakrishnan and Srinivasan, 1980). The energy in this component is sufficient to carry gas many hundreds of parsecs above the galactic plane, and it might produce a halo of sorts. [A similar discussion is in Albert (1983)]. Expanding on this suggestion, Lockman and Gehman (1991) have analyzed entire 21 cm emission profiles toward the galactic poles to see what sort of equilibrium layer might be established in the local gravitational field by the available kinetic energy. They calculated the density profile $n_H(z)$ that would give the observed $N_H(v)$ in the gravitational potential $\psi(z)$ believed to be appropriate for the solar neighborhood (e.g., Kuijken and Gilmore 1989).

Lockman and Gehman find that density functions like the L84 curve in Figure 1 can be maintained by the kinetic energy in observed 21 cm profiles, with no need for extra pressure support from cosmic rays or the magnetic field. Therefore, in the solar neighborhood there is enough energy in turbulent motions (for that is what determines an HI profile's width) to support a layer like the one we observe.

At the heart of the analysis is the assumption that galactic HI is composed of distinct components whose vertical distribution, rms velocity and density are independent. The components must not interact very much (as discussed by Kulkarni and Fich 1985). This requires a rather porous ISM and may imply that random motions of HI clouds are not isotropic. There is much work to be done in this area, but these initial results are quite suggestive.

7. CONCLUSIONS

Several questions were posed in the Introduction that can be answered to some degree:

1. **Pervasiveness**: The filling factor of high altitude HI is still not known. In some directions the halo seems to be populated by large clouds with peculiar kinematics but in others there is no discernable break with the disk. I would guess that much of the neutral mass in the halo comes from fragments of supershells, although the line of sight towards HD 28497 looks as if it intersects a smooth corotating layer in addition to clouds with peculiar velcities.
2. **Ionization**: The electron ("Reynolds") layer seems to have a greater scale-height than the neutral layer shown in Figure 1, but whether this is because the ionization fraction approaches unity as $|z| \rightarrow 1.5$ kpc, or because the electrons reside in a separate component, is not yet known.
3. **Populations**: There are probably several neutral components above the plane, distinguished by their kinematics, distribution and abundance (depletion). In some directions a "high-velocity" layer of gas appears between 150 and 400 pc from the plane.
4. **Support**: Locally, the kinetic energy in turbulence is sufficient to support the HI layer against gravity. Elsewhere in the Galaxy this may not be true.
5. **Large-scale Structure**: The lack of a halo at $R < 2.5$ kpc may signify that there is a wind flowing from the galactic bulge. Other factors that influence the form of the halo at different parts of the Galaxy are not known.
6. **Kinematics**: Most galactic HI corotates. A lot of halo HI also corotates, but some clearly does not. The halo seems to have a mix of kinematics. This may be a sign that a galactic fountain is at work.
7. **Other Halo Constituents**: A task for observers in the coming years is to untangle the relationship between the various populations of gas far above the disk, and also seek their connection with (or independence from) events in the disk itself. This work will be greatly helped by the new Green Bank Telescope, currently under construction, which will be a powerful tool for measuring faint 21 cm emission. The next decade will be an exciting time for studies of the HI halo.

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