WHERE DOES THE DISK TURN INTO THE HALO?
COOL $\text{HI}$ IN THE OUTER MILKY WAY DISK

John M. Dickey\textsuperscript{1}

Abstract. Using HI absorption spectra taken from the recent surveys of $\lambda$21-cm line and continuum emission in the Galactic plane, the distribution of cool atomic clouds in the outer disk of the Milky Way is revealed. The warp of the midplane is clearly seen in absorption, as it is in emission, and the cool, neutral medium also shows flaring or increase in scale height with radius similar to that of the warm atomic hydrogen. The mixture of phases, as measured by the fraction of HI in the cool clouds relative to the total atomic hydrogen, stays nearly constant from the solar circle out to about 25 kpc radius. Assuming cool phase temperature \(\sim 50\) K this indicates a mixing ratio of 15\% to 20\% cool HI, with the rest warm.

1 Background

The structure of the Milky Way interstellar medium far outside the solar circle is in some ways similar to the transition from disk to halo. As the stellar surface density of the disk decreases, its gravitational potential as a function of \(z\) gets smoother and shallower, so the median pressure at midplane must decrease. For heating-cooling balance, when the pressure gets low enough, less than about 300 in units of K cm\(^{-3}\), then the cool phase of the HI should disappear, as there is no density for which equilibrium can be achieved for pressure below this two-phase threshold (Wolfire \textit{et al.} \cite{1995} \cite{2003}). This might lead to a decrease in the amount of HI in the cool phase as \(R_G\) increases, or even possibly an abrupt edge to the cloud population at some critical \(R_G\). Although expected, neither of these effects is seen in this data, at least for \(R_G < 25\) kpc.

2 Data

The absorption and emission spectra are taken from the Canadian Galactic Plane Survey (CGPS, Taylor \textit{et al.} \cite{2003}), the Southern Galactic Plane Survey (SGPS,

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Fig. 1. The radial distributions of the 21-cm line emission brightness temperature, $T$ (top), and optical depth (bottom) both plotted as averages per unit distance along the line of sight, vs. Galactocentric radius, $R_G$. The effect of the warp in the first quadrant is clear in the drop in both quantities in the VGPS data at $R_G > 15$ kpc. The line indicates an exponential with scale length 3.1 kpc. For recent observational reviews of the warp and flare in the HI disk, see Kalberla et al. (2007) and Kalberla and Kerp (2009).

McClure-Griffiths et al. (2005), and the VLA Galactic Plane Survey (VGPS, Stil et al. (2006)). The methods of extracting the absorption spectra, and the corresponding emission spectra in the directions of compact extragalactic continuum sources, are described by Strasser et al. (2007). There are some 650 such sources bright enough to give usable absorption spectra in the three surveys. The analysis
Fig. 2. The radial distribution of the 21-cm line excitation temperature, $\langle T_{sp}\rangle$, averaged over the different phases. The effect of the warp in the VGPS data (gold) at $R_g > 15$ kpc makes these points uncertain, as shown by the large error bars.

below uses data only in these directions, even though there is much more emission data available, to avoid bias that could come from using different samples for the emission and absorption averages. The averages are taken over three independent samples for each survey, the first is the relatively small number of background sources bright enough to give spectra with optical depth noise $\sigma_\tau < 0.02$, the second with $0.02 \leq \sigma_\tau < 0.05$, and the third with $0.05 \leq \sigma_\tau < 0.1$. The numbers of sources in the second and third categories are much larger, although their spectra are relatively less reliable. Error bars on the figures represent the scatter among these three samples.

3 Analysis

Figure 1 shows the radial distribution of the emission (top) and absorption (bottom), using kinematic distances based on a flat rotation curve. The points on figure 1 are computed by dividing the brightness temperature and optical depth in each spectral channel by the line of sight path length corresponding to the velocity width of the channel. The brightness temperature of the 21-cm line traces the column density of the atomic gas in the velocity range of each spectral channel, so dividing by this path length makes the y-axis of the top panel proportional to
the space density, \( n_H \). Converting to cgs units makes the value 3 [meaning \( \log(10^3 \text{ K km s}^{-1} \text{ kpc}^{-1}) \)] correspond to density of 0.59 cm\(^{-3}\). The optical depth is proportional to the average of \( \frac{n_H}{T_s} \), where \( T_s \) is the spin temperature, i.e. the excitation temperature of the \( \lambda21\text{-cm} \) transition, which is normally close to the kinetic temperature in the gas. Thus the quantity displayed on the y-axis of the bottom panel of figure 1 is proportional to the density divided by the spin temperature, \( \frac{n_H}{T_{sp}} \). Here the average \( \langle T_{sp} \rangle \) means that if gas at different temperatures contributes to the same velocity channel of the emission and absorption spectra, then the relevant temperature for the data on figure 1 is the density weighted harmonic mean. Translating the y-axis of the right hand panel of figure 1 to cgs units, the value 1 [meaning \( \log(10^1 \text{ km s}^{-1} \text{ kpc}^{-1}) \)] corresponds to \( \frac{n_H}{T_{sp}} = 5.9 \times 10^{-3} \text{ cm}^{-3} \text{ K}^{-1} \). These quantities are explained in more detail in Dickey et al. (2009).

Figure 2 shows the ratio of the quantities shown on the two panels of figure 1, \( n_H \) divided by \( \frac{n_H}{T_{sp}} \). Now the units are simply Kelvins, as the quantity on the y-axis is simply the mean spin temperature, \( T_{sp} \). The values are remarkably constant with radius, \( R_G \), in the three surveys, with \( \log\langle T_{sp} \rangle \) in the narrow range 2.3 to 2.6, i.e 200 to 400 K. Note that this is not necessarily the physical temperature of the gas, since generally there is a blend of cool clouds (temperature \( T_c \sim 50 \text{ K typically} \)) and warm gas (\( T_{sp} \gg 500 \text{ K typically} \)) in each spectral channel.

The constancy of the mean spin temperature, \( \langle T_{sp} \rangle \), with Galactic radius suggests that the mixture of warm (WNM) and cool (CNM) neutral media is also fairly constant. This depends on the cool phase temperature, \( T_c \), since the fraction of the HI in the cool phase, \( f_c \equiv \frac{n_{\text{CM}}} {n_{\text{WNM}} + n_{\text{CM}}} \), is given by \( f_c = \frac{T_c}{\langle T_{sp} \rangle} \). Here the warm phase temperature is assumed to be much greater than \( T_c \), so that its value is unimportant. This is approximately true in the solar neighborhood, where most of the warm phase gas is 3000 to 10,000 K (Kulkarni and Heiles 1988). The cool phase temperature, \( T_c \), is certainly not constant, as there is a wide range of temperatures in the HI clouds, from below 20K all the way up to the WNM range (see the article by Troland in this volume), but there is a peak in the temperature distribution in the range 40 to 60 K (Dickey et al. 2003, Heiles and Troland 2003). It may be that the peak of this distribution, which we identify as \( T_c \), changes with \( R_G \), and that \( f_c \) also changes, so that their ratio, \( \langle T_{sp} \rangle \), stays constant. But a simpler interpretation of the results on figure 2 is that both \( T_c \) and \( f_c \) are roughly independent of \( R_G \) outside the solar circle.

4 Conclusions

The robust nature of the mean spin temperature, \( \langle T_{sp} \rangle \), is an unexpected result. Somehow conditions even in the far outer disk of the Milky Way support a mixture of cool phase (CNM or diffuse clouds) and warm phase (WNM or inter-cloud medium, although much of it is found in and around the diffuse clouds) that is not very different from that in the solar neighborhood, for which \( f_c \sim 0.25 \) (Kulkarni
and Heiles [1987]. Mebold et al. [1997]. Since the existence of the CNM in heating-cooling equilibrium with the WNM requires that the pressure be above the two phase threshold, and the gravitational potential of the stellar disk at these large values of \(R_G\) will not pressurize the medium sufficiently, the presence of the cool phase is indirect evidence for large scale departures from pressure equilibrium. One cause could be converging flow patterns in the gas, perhaps induced by tidal interactions or by the effect of spiral arms in the inner disk. The morphology of the cool clouds, which appear in very large complexes, 500 pc or more in diameter, in the far outer Galaxy (Strasser et al. 2007) suggests that they result from gas dynamics on very large scales.

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1 Background

The structure of the Milky Way interstellar medium far outside the solar circle is in some ways similar to the transition from disk to halo. For Galactocentric radius $R_G > 8.5$ kpc the disk flares, i.e. the width of the gas in $z$, the height perpendicular to the disk, increases from about 250 pc half-width, to about 750 pc at $R_G = 25$ kpc (Kalberla et al.?). There is also a strong warp that is clearest in the first and second Galactic quadrants, longitude $60^\circ$ to $130^\circ$, but hardly visible in the third and fourth quadrants (Kalberla and Kerp?). As the stellar surface density of the disk decreases, its gravitational potential as a function of $z$ gets smoother and shallower, so the median pressure at midplane must decrease. For heating-cooling balance, when the pressure gets low enough, less than about 300 units of K cm$^{-3}$, then the cool phase of the HI should disappear, as there is no density for which equilibrium can be achieved for pressure below this two-phase threshold (Wolfire et al.?). This might lead to a decrease in the amount of HI in the cool phase as $R_G$ increases, or even possibly an abrupt edge to the cloud population at some critical $R_G$. Although expected, neither of these effects is seen in this data, at least for $R_G < 25$ kpc.

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