

THE OUTER DISK OF THE MILKY WAY SEEN IN $\lambda 21$ cm ABSORPTION

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ABSTRACT

Three recent surveys of 21 cm line emission in the Galactic plane, combining single dish and interferometer observations to achieve resolution of $1' - 2'$, $\sim 1 \text{ km s}^{-1}$, and good brightness sensitivity, have provided some 650 absorption spectra with corresponding emission spectra for study of the distribution of warm and cool phase H I in the interstellar medium. These emission–absorption spectrum pairs are used to study the temperature of the interstellar neutral hydrogen in the outer disk of the Milky Way, outside the solar circle, to a radius of 25 kpc. The cool neutral medium is distributed in radius and height above the plane with very similar parameters to the warm neutral medium. In particular, the ratio of the emission to the absorption, which gives the mean spin temperature of the gas, stays nearly constant with radius to ~ 25 kpc radius. This suggests that the mixture of cool and warm phases is a robust quantity, and that the changes in the interstellar environment do not force the H I into a regime where there is only one temperature allowed. The mixture of atomic gas phases in the outer disk is roughly 15–20% cool (40–60 K), the rest warm, corresponding to mean spin temperature ~ 250 –400 K. The Galactic warp appears clearly in the absorption data, and other features on the familiar longitude–velocity diagram have analogs in absorption with even higher contrast than for 21 cm emission. In the third and fourth Galactic quadrants the plane is quite flat, in absorption as in emission, in contrast to the strong warp in the first and second quadrants. The scale height of the cool gas is similar to that of the warm gas, and both increase with Galactic radius in the outer disk.

Key words: Galaxy: disk – Galaxy: structure – ISM: atoms – ISM: clouds – ISM: structure

Online-only material: color figures, extended figure sets

1. BACKGROUND

Surveys of the Milky Way disk using the 21 cm line have been one of the most powerful means of tracing the structure and properties of the Galaxy for over 50 years (reviewed by Burton 1988, 1991; Lockman 2002; Kalberla & Dedes 2008; Kalberla & Kerp 2009). Our knowledge of the outer Galaxy, beyond the solar circle, is particularly dependent on H I emission surveys, as emission from other species in the interstellar medium (ISM) declines faster with Galactocentric radius, R_g . Thus the 21 cm line is much easier to detect and to use as an ISM tracer in the outer Galaxy than lines from molecules like CO, both because the atomic phase of the medium is becoming more and more dominant form of the gas mass with increasing Galactic radius, R_g , and because the H I has a higher spatial filling factor than the molecules.

Since the pioneering H I surveys of the 1950s it has been clear that the Milky Way disk extends to at least 2–3 times the radius of the solar circle, R_o . Surveys covering wide latitude ranges (Burke 1957; Oort et al. 1958) showed that the H I disk in the outer Galaxy is warped: in the longitude range 50° – 130° the middle or centroid of the gas distribution moves toward positive z , where z is the height above the plane defined by

latitude $b = 0^\circ$. In the third and fourth quadrants (longitudes 240° – 310°) there is very little displacement of the gas from this flat plane, at least to $R_g \simeq 25$ kpc. This does not necessarily imply an asymmetry in the Milky Way disk, since our location places us much nearer the warp in the first and second quadrants than its reflection on the other side of the Galactic center, which would be expected at high longitudes in the fourth quadrant (Kalberla et al. 2007; Levine et al. 2006). At the same radii where the warp becomes significant, $R_g \sim 15$ kpc, the gas disk begins to flare, meaning that its scale height increases. This happens at all galactocentric azimuths, ϕ , defined as zero in the direction of longitude zero, i.e., a ray pointing from the Galactic center directly away from the sun.

Although surveys of H I emission at low Galactic latitudes have been done for many years and with many telescopes, surveys of absorption in the 21 cm line have been much less common, because the instrumental requirements to measure absorption are more stringent than for emission, as discussed in Section 2 below. Interferometer and aperture synthesis telescopes like the NRAO Very Large Array (VLA) were used for low latitude absorption surveys in the 1970s and 1980s (Radhakrishnan et al. 1972; Goss et al. 1972; Mebold et al. 1982; Dickey et al. 1983; Kolpak et al. 2002), but interferometers have limited capability to measure the 21 cm emission, so surveys of emission and absorption in these decades were done separately using single dish

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telescopes to measure the emission. This necessarily gave very different effective beam sizes for the emission and absorption spectra, which is problematic for analysis that involves combining the two.

In the late 1990s and early 2000s three large surveys of the 21 cm emission at low latitudes were undertaken: the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003), the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2005), and the VLA Galactic Plane Survey (VGPS; Stil et al. 2006). These surveys were the first to combine data from single dish and aperture synthesis telescopes, for the latter applying the recently perfected mosaicing technique (Sault et al. 1996) for recovering the short-spacing information. This allowed maps of the H I to be made over wide areas with sensitivity to all spatial scales, from many degrees down to the survey resolution of $45''$ (VGPS), $1'$ (CGPS), or $2'$ (SGPS). Thus the survey data is equivalent to a fully sampled map made with a single dish telescope with this beamwidth; such a single dish would have to be 500 m or more in diameter! This resolution allows reasonably accurate measurement of the absorption spectra toward a large number of continuum background sources at low latitudes, with the corresponding emission interpolated from spectra nearby taken with the same resolution. The resulting emission–absorption spectrum pairs are ideally suited for the measurement of the excitation of the 21 cm line from interstellar gas throughout the Galactic plane. This paper presents these emission–absorption spectra from the three surveys, and discusses briefly their implications for the thermodynamics of the hydrogen in the outer disk of the Milky Way. A preceding paper in this series (Strasser et al. 2007) presents a preliminary study of the absorption data from these surveys, and discusses the morphology of the cool gas complexes seen at large R_g .

The main motivation to measure emission and absorption spectra with the same resolution in the same directions is in order to determine the excitation temperature of the 21 cm line, called the spin temperature, $T_{\text{sp}} = \frac{T_{\text{EM}}}{1 - e^{-\tau}}$ where $T_{\text{EM}}(v)$ is the brightness temperature of the H I line as a function of radial velocity in the emission spectrum and $\tau(v)$ is the optical depth of the H I line. In the Galactic environment T_{sp} is generally close to the kinetic temperature (see Furlanetto et al. 2006, for a review of the astrophysics of the spin temperature in various environments). Blending of different regions with different temperatures along the line of sight can make the interpretation complicated, as discussed briefly in Section 4 below, and more fully by Dickey et al. (2003). Because of this blending of warm and cool gas at the same velocity, the measured value of T_{sp} is generally higher than the temperature of the cool clouds that are responsible for most of the absorption, T_{cool} . This bias is independent of distance. Surveys of emission and absorption at low latitudes make it possible to map the spin temperature throughout the Galaxy, using radial velocity as a kinematic distance indicator. In the outer Galaxy this is of particular interest, since the physical processes that dominate heating and cooling in the atomic phase may change drastically with R_g . Going from the solar circle to $R_g \simeq 20$ kpc the density of stars in the disk drops by more than an order of magnitude, and the acceleration due the gravity of the disk, K_z , drops similarly, which is the cause of the flaring or thickening of the gas layer. Although the ISM is not necessarily in hydrodynamic equilibrium with the gravitational potential of the disk on small scales, at least on long timescales the gas pressure cannot be very different from that set by the gravitational force on the gas above (Spitzer 1956).

Thus the average pressure at midplane must drop by more than an order of magnitude in the outer Galaxy compared to its solar circle value. Depending on the metallicity gradient, the standard theory of H I thermodynamic equilibrium (Wolfire et al. 1995, 2003) could predict that this pressure drop would lead to an overall phase change, with all the cool neutral medium (CNM) converting to warm neutral medium (WNM) at some R_g . A major result of this study, described in Sections 3 and 4, is therefore something of a surprise, as we find that the mixture of CNM and WNM is robust, with little or no change in the relative fractions of these two phases with R_g out to nearly 3 times R_o or 25 kpc.

2. SURVEY DATA REDUCTION

To measure absorption requires a continuum background source, and a way of subtracting the emission of the gas toward the source so that the optical depth can be determined. Since emission and absorption are mixed in the spectrum toward the background source, an interpolation of the surrounding emission spectra must be used to estimate and subtract the emission at the position of the continuum. The emission at the position of the continuum source is estimated in the following way: (1) the structure of the continuum source is determined from the line-free channels. (2) The absorption is determined on source and (3) the expected emission estimated from the close surroundings of the source. Accurate estimates for emission requires a combination of single dish and interferometer data. At low Galactic latitudes the H I emission shows random spatial variations on all angular scales, so a small telescope beam is required in order for this interpolation to be made over angles of a few arcminutes or less. Typically the mean square emission fluctuations on a given angle, θ , are proportional to θ^{-3} to θ^{-4} (Dickey et al. 2001), so the error in the interpolated emission profile depends on the beamwidth to a power between 1.5 and 2. For a given level of error in this interpolated emission spectrum, the resulting error in the absorption $(1 - e^{-\tau})$ goes inversely as the continuum antenna temperature due to the background source. This continuum antenna temperature is given by the source flux density times the telescope gain (G in K Jy^{-1}), which itself is inversely proportional to the square of the beamwidth. Thus the error in the measured absorption introduced by emission fluctuations decreases with decreasing beamwidth to a power between 3 and 4. This effect dominates other sources of error such as ordinary radiometer noise in most 21 cm absorption surveys, particularly at low latitudes. For example, the Arecibo telescope, with beamwidth of $3.2'$, is able to measure absorption spectra toward continuum sources of a few Jy or stronger at high and intermediate latitudes (Heiles & Troland 2003a), but for latitudes below about 10° even this beam size is too large to give a sufficiently accurate interpolated emission profile.

Absorption spectra may suffer more from emission fluctuations than the emission spectra do, because an error in the interpolated emission that is subtracted from the spectrum toward the continuum source can cause a large fractional error in the optical depth. Aperture synthesis telescopes can solve the problem of fluctuations in the emission by performing a high-pass spatial filtering of the brightness distribution as set by the uv plane sampling function of the telescope baselines. Thus telescopes like the VLA and the Australia Telescope Compact Array (ATCA) can measure absorption toward compact continuum sources brighter than a few tens of mJy, because

Table 1
Galactic Plane Survey Parameters

Survey	Area	Angular Resolution	Velocity Resolution	rms Noise in T_{EM}	Number of Absorption Spectra with σ_τ		
					<0.02	0.02–0.05	0.05–0.1
VGPS ^a	$18^\circ < l < 67^\circ$ $-1.3^\circ < b < +1.3^\circ$	1'	1.56 km s ⁻¹	2 K	15	64	49
CGPS ^a	$65^\circ < l < 175^\circ$ $-3.6^\circ < b < +5.6^\circ$	1'	1.32 km s ⁻¹	3 K	32	108	256
SGPS ^b	$253^\circ < l < 358^\circ$ $-1.5^\circ < b < +1.5^\circ$	2'	1.0 km s ⁻¹	1.6 K	30	42	54

Notes.

^a Data are available from <http://www2.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/cgps/>.

^b Data are available from <http://www.atnf.csiro.au/research/HI/sgps/queryForm.html>.

the longer baselines of these telescopes are sensitive only to structure smaller than a few arcseconds. This spatial filter can also reduce the continuum emission of the background source, depending on its angular size, so except for the most compact continuum sources there is a point of diminishing returns in the spatial filtering by using longer and longer baselines to measure 21 cm absorption. The SGPS data have been spatially filtered to improve the accuracy of the absorption spectrum (but not for the emission spectrum, of course), the radius of the spatial filter is adjusted to leave the most continuum while minimizing the spectral line emission that leaks through the spatial filter due to small angle emission variations. The effect of these emission fluctuations in the absorption spectra is obvious because they generate spurious “absorption” lines with a symmetric distribution around zero in $(1 - e^{-\tau})$, i.e., equal numbers of spurious negative and positive peaks in the optical depth.

Details of the techniques for doing the interpolation of the emission and so measuring the emission and absorption are given by Strasser & Taylor (2004); Dickey et al. (2003); McClure-Griffiths et al. (2001); Strasser (2006). These techniques are slightly different for the different surveys. For the SGPS and VGPS surveys the continuum was measured together with the spectral line channels, but for the CGPS the continuum was measured separately. So for the CGPS absorption spectra the absolute calibration of the optical depth has some errors in overall scale factor, typically this is less than 5% but in a few cases as high as 10%. Table 1 gives observational parameters of the different surveys. Note that the survey data provided by the web servers on Table 1 have had the continuum subtracted, whereas the analysis described here was necessarily done with data from an earlier stage of the reduction, before the continuum subtraction.

The spectra are grouped according to the continuum antenna temperature of the background source, which sets the noise in $(1 - e^{-\tau})$, as measured at frequencies away from the Galactic velocities where there is no emission or absorption in the 21 cm line. For the brightest continuum sources, the noise in $(1 - e^{-\tau})$ is $\sigma_\tau \sim 10^{-2}$. There are 77 spectrum pairs with $\sigma_\tau < 0.02$ in the three surveys combined. Numbers with σ_τ below 0.05 and 0.10 are given in Table 1. Although the spectra in the third group ($0.05 < \sigma_\tau < 0.1$) are not of high enough quality to measure accurate values for T_{sp} in each velocity channel, they can give useful results for the integral of $(1 - e^{-\tau})$ over broader ranges of velocity, particularly when averaged together with others in a sample of many spectra. The critical point is that both for radiometer noise and for errors in the absorption spectra due to fluctuations in the emission, there is no bias toward positive or negative values of $(1 - e^{-\tau})$.

The emission and absorption spectrum pairs are shown in Figures 1–3, ordered by longitude, for the three groups defined by $\sigma_\tau \leq 0.02$, $0.02 < \sigma_\tau \leq 0.05$, and $0.05 < \sigma_\tau \leq 0.10$. The print edition shows just the first and last pair for each survey in each group. The left-hand panel shows the emission and absorption spectra, with LSR velocity scaled across the bottom, and absorption $(1 - e^{-\tau})$ scaled on the left-hand axis. To provide as much detail as possible in the absorption profile, the velocity scale is expanded to cover only the range where the emission is nonzero, which necessarily includes all the absorption.

The emission spectra (plotted in gray, or in gold in the online edition) are offset upward from the absorption spectra for clarity, and scaled in K of brightness temperature on the right-hand axis of the left-hand panel, which is the same scale as the vertical axes of the right-hand panel. The bottom axis of the right-hand panel is again $(1 - e^{-\tau})$. Thus the right-hand panel shows emission plotted against absorption. These plots are crowded in many cases, but the points on the right panel can be identified with velocity channels on the left panel by drawing a horizontal line through the T_{EM} axis between the two panels. Analysis of the separate loops on the right-hand panel allows the temperature of the cool gas traced by the absorption to be determined, the remaining emission is due to warm gas blended in velocity with the cool gas, some of which may be associated with the cool clouds and some not (Mebold et al. 1997; Dickey et al. 2003). This analysis is beyond the scope of this paper, but it has been performed by Strasser (2006) for all the absorption features in all the spectra.

3. RESULTS

3.1. Longitude–Velocity Diagrams

The absorption spectra are necessarily taken where the background sources are, which does not give a regular and fully sampled map of the optical depth. In order to study the Galactic distribution of the cool gas that causes the absorption, we bin the spectra into grids of longitude and velocity as shown in Figure 4. These show pairs of longitude–velocity diagrams, using the emission–absorption spectrum pairs, with all spectra contributing to each bin averaged together. The longitude step size is 1.8 deg and the velocity step size is 2 km s⁻¹. Typically, more than one spectrum contributes to each bin. Spectra from the full latitude range of each survey are included.

The longitude–velocity diagrams of the emission (Figure 4) are similar to plots from emission surveys (e.g., McClure-Griffiths et al. 2005) which allow structures in the

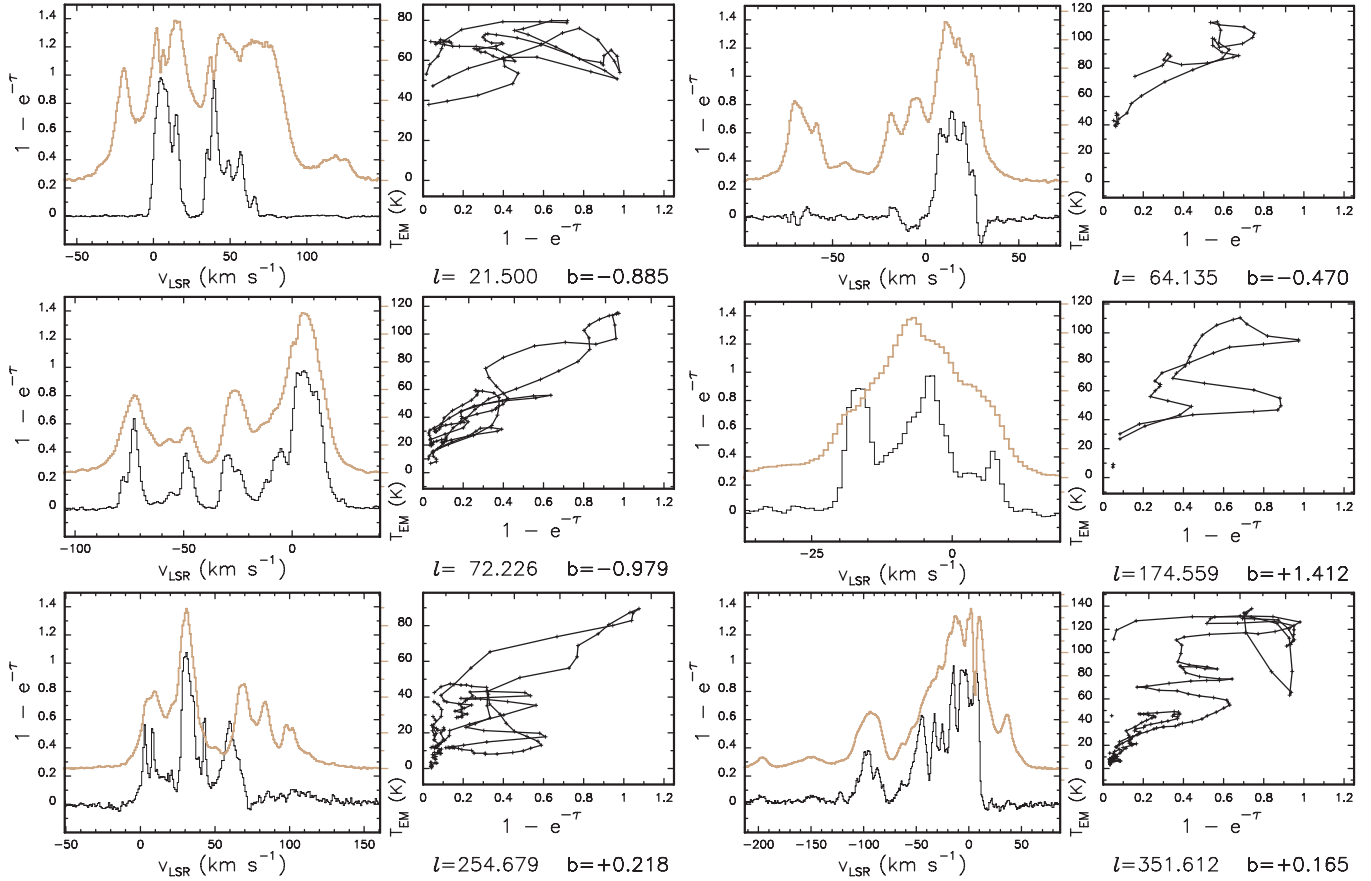


Figure 1. Sample spectra from the three surveys with $\sigma_\tau < 0.02$. Top row shows the first and last spectrum in this group from the VGPS, the middle row shows the first and last spectrum in this group from the CGPS, and the bottom row shows the first and last spectrum in this group from the SGPS. The left panel shows the absorption spectrum plotted as $(1 - e^{-\tau})$, with the corresponding vertical scale on the left, and the emission spectrum, T_{EM} , offset up and scaled on the right-hand axis, between the two panels. In the online edition the emission is shown in gold. The right-hand panel shows the emission plotted vs. the absorption, with the y-axis again the scale for T_{EM} , and the x-axis the scale for $(1 - e^{-\tau})$. In the online edition all spectra are included, from all the three surveys. In the online edition Figure 1 includes 15 pairs of spectra from the VGPS, 32 from the CGPS, and 30 from the SGPS.

(An extended figure set is available in the online journal.)

density and velocity distributions of the ISM to be studied in many ways (reviewed by Burton 1988). In this case, the relatively sparse sampling provided by the background continuum source directions makes the l - v diagram appear crude by modern standards, but the major features are clear. Figure 4 shows two versions of each l - v diagram, with two different gray scales, to make these visible. On the upper panel, curves of constant galactocentric distance, R_g , are indicated, based on a flat rotation curve outside the solar circle. The flat rotation curve approximation gives simple equations for the kinematic distance, $d(v)$, and hence for R_g and ϕ from the laws of cosines and sines, respectively:

$$\frac{d}{R_0} = \cos \lambda + \sin \lambda \sqrt{\left(\frac{v}{\cos b} + \sin l\right)^{-2} - 1} \quad (1)$$

$$\frac{R_g}{R_0} = \sqrt{1 + d^2 - 2d \cos \lambda} \quad (2)$$

$$\phi = \arcsin\left(\sin \lambda \frac{d}{R_g}\right), \quad (3)$$

where $d(v)$ is the distance (from the Sun) as a function of the observed radial velocity, v , in units of $v_o \equiv 220 \text{ km s}^{-1}$, is the LSR velocity around the solar circle (which is assumed

to be the circular velocity for all $R_g > R_0$), and λ is equal to the longitude, l , in the first and second quadrants but $\lambda = -l$ in the third and fourth quadrants. Here, d and R are both in units of $R_o \equiv 8.5 \text{ kpc}$. Note that R_o and v_o are simply scale factors that do not otherwise effect the analysis, and even the choice of a flat rotation curve is not much more significant than a choice of scale. Using any other smooth monotonic function for the circular rotation velocity versus R would cause a smooth stretching of the scale of R , but otherwise the results of the analysis would be unchanged. The upper right panel of Figure 4 shows for comparison distances derived from a rotation curve that is flat to 15 kpc and then drops as a Keplerian. This certainly underestimates the distance to gas at a given radial velocity, but the displacement of the curves is less than 20 km s^{-1} compared with those on the top left.

The lower panels of Figure 4 show, with different gray scales, the longitude-velocity diagram of $(1 - e^{-\tau})$, the optical depth of the 21 cm line. The structures seen in the absorption correspond to structure seen in emission, but with more contrast between arm and interarm regions. This is clear in spite of the higher noise level in the optical depth. This may be partly due to the fact that the line widths seen in absorption are narrower than those of H I emission lines; typically the full width at half maximum (FWHM) of an absorption line is 4 km s^{-1} whereas emission features have widths of 10 – 20 km s^{-1} . In

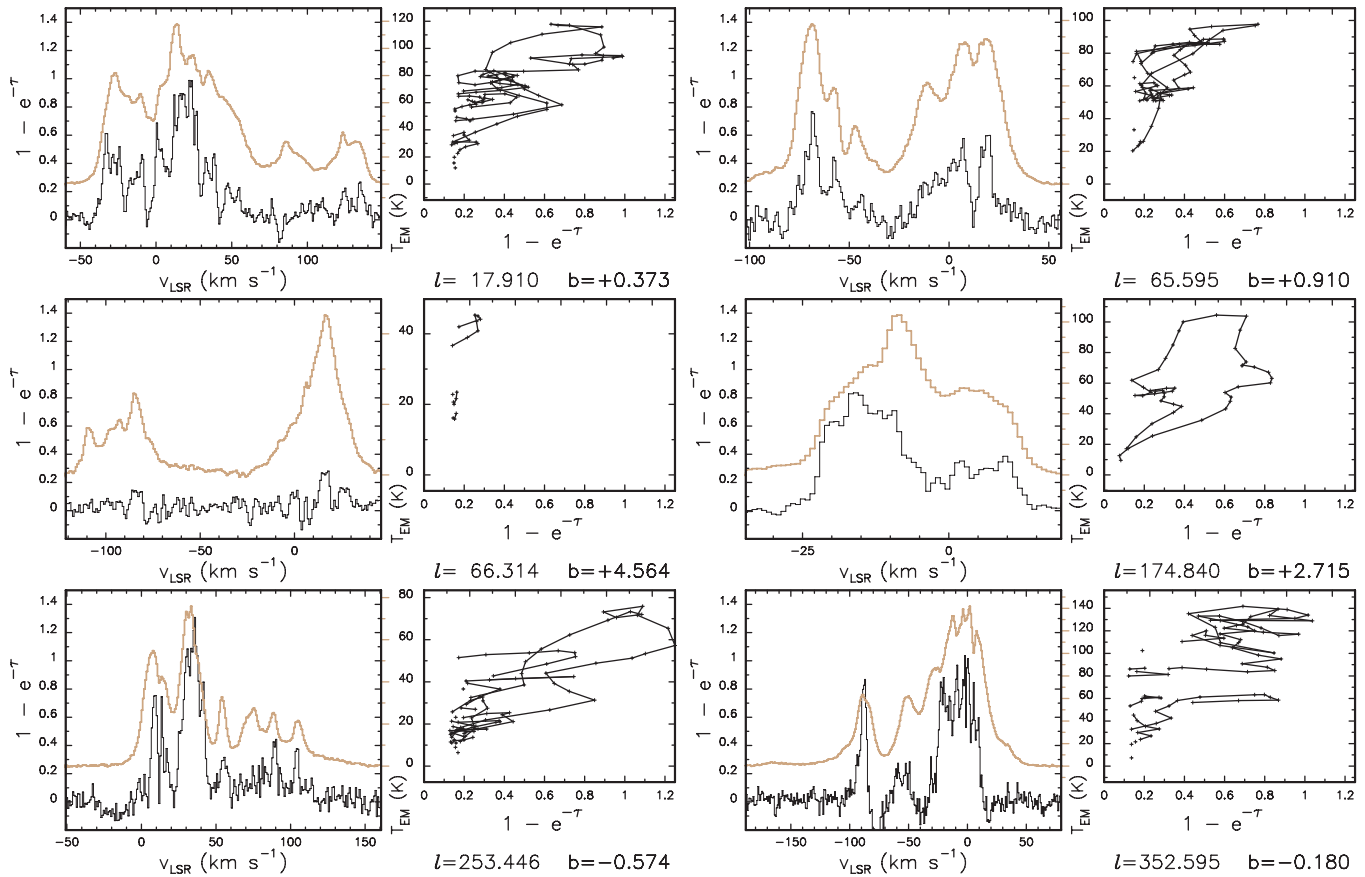


Figure 2. Sample spectra from the three surveys with $0.02 \leq \sigma_\tau < 0.05$. The layouts of the panels are the same as in Figure 1, with the first and last spectra from the VGPS on the top line, the first and last from the CGPS on the second line, and the first and last of the SGPS on the third line. In the online edition Figure 2 includes 64 pairs of spectra from the VGPS, 108 from the CGPS, and 42 from the SGPS.

(An extended figure set is available in the online journal.)

addition, the volume filling factor of the CNM that causes the H I absorption is much less than that of the WNM seen in emission, roughly 3–5% versus roughly 50% (Kalberla & Kerp 2009). So for many reasons the H I absorption traces better than the emission the structures seen in cold gas, on large scales as seen on the l - v diagram as well as on smaller scales in individual spectrum pairs. In this way the 21 cm absorption has some of the characteristics of molecular line tracers such as ^{12}CO and ^{13}CO emission (Jackson et al. 2002).

The l - v diagrams of the emission and absorption are shown in a different format by Strasser et al. (2007, Figure 3). Comparison between that technique, which simply plots the absorption spectra at their respective longitudes with color-coding for the depth of the absorption, and the binning technique used in Figure 4 is interesting. In Strasser et al. (2007), the corresponding l - v diagram of the emission includes all data, not simply the directions toward the background sources used for the absorption, so it has much finer resolution in longitude. As discussed in that paper, absorption surveys provide vital information for tracing large-scale features in the outer disk, such as spiral arms.

3.2. Radial Distribution of the Opacity

To study the distribution of the CNM on the largest scales in the outer Galaxy, we transform the velocity into distance from the Galactic center using Equations (1)–(3), and then average over annuli of constant R_g . This gives Figure 5. On each

figure the data from the three surveys is plotted separately. This separates data from the lower longitudes in the first quadrant, $18^\circ \leq l \leq 65^\circ$ in the VGPS from the higher longitudes in the first and second quadrant, $65^\circ \leq l \leq 170^\circ$ in the CGPS, and the third and fourth quadrant, $255^\circ \leq l \leq 357^\circ$ of the SGPS. These are plotted in gold, black, and red, respectively, on the online edition. The x -axis of Figure 5 shows R_g ranging from 8.5 to 25 kpc in steps of $0.1 R_o$ or 0.85 kpc. The y -axis on the top panel of Figure 5 plots the log(base 10) of the average of the emission brightness temperature (in K), times the spectral channel bandwidth, Δv in km s^{-1} , divided by the line of sight path length, ΔL in kpc, corresponding to that range of velocity:

$$\left\langle \frac{T_{\text{EM}} \Delta v}{L} \right\rangle = \frac{\sum_i T_i \frac{\Delta v}{\Delta L} w_i}{\sum_i w_i}, \quad (4)$$

where the sum is taken over many spectra, and many spectral channels, i , in each spectrum, that correspond to the given range of R_g , and w_i is a weight factor set by the inverse of the noise in each absorption spectrum. The path length corresponding to the velocity width of one spectral channel is $\Delta L = |d(v + \Delta v) - d(v)|$ at the longitude and velocity of channel i . We experimented with different choices for noise weighting, w_i , converging on the inverse of the rms noise in $(1 - e^{-\tau})$ as the most robust. Of course this weighting is designed to optimize the signal to noise of the resulting average only for the *optical depth*, shown in the middle panel of Figure 5, but we use the same weighting for the emission so that the two

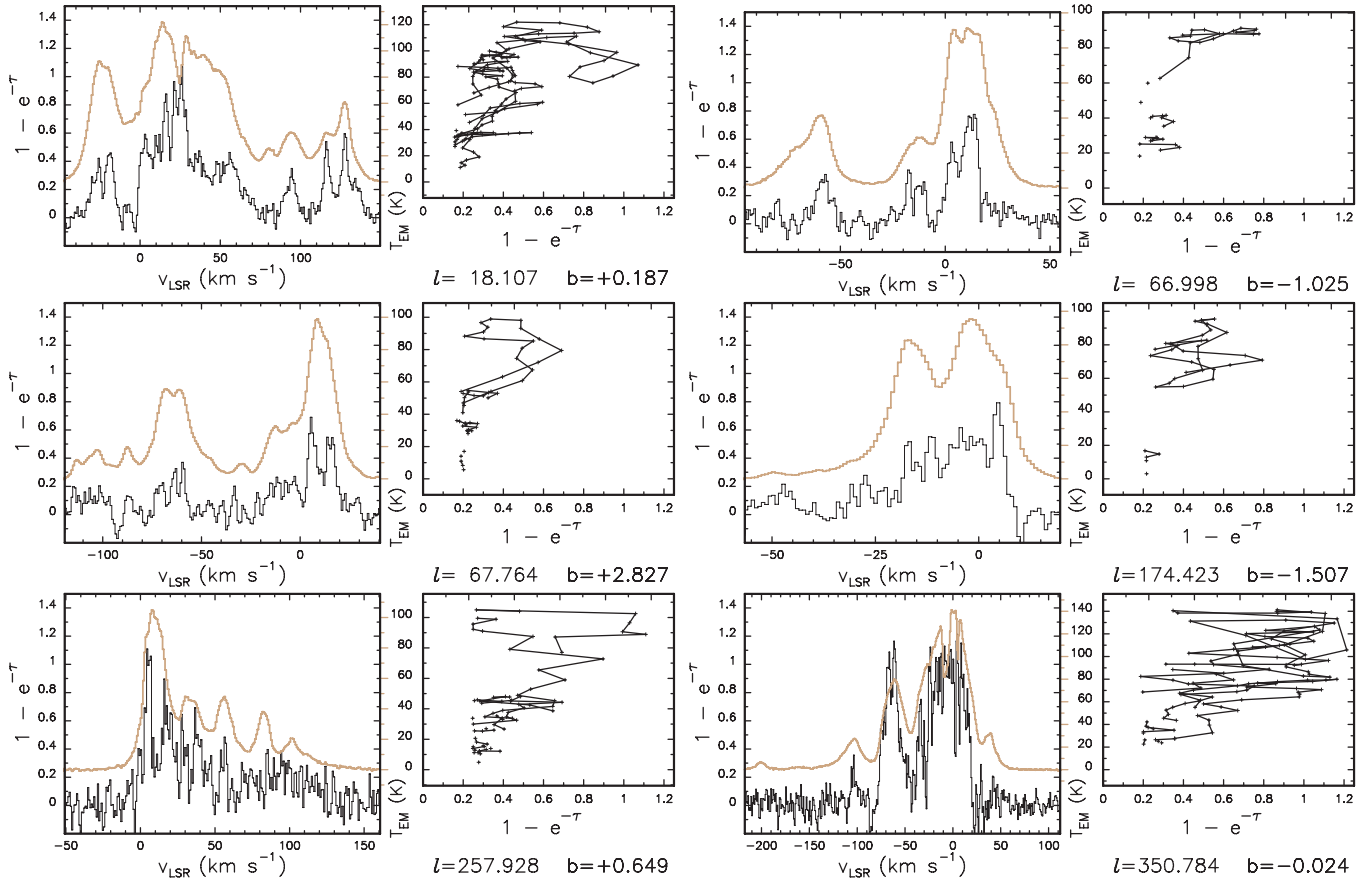


Figure 3. Sample spectra from the three surveys with $0.05 \leq \sigma_\tau < 0.10$. The layouts of the panels are the same as in Figure 1, with the first and last spectra from the VGPS on the top line, the first and last from the CGPS on the second line, and the first and last of the SGPS on the third line. In the online edition Figure 3 includes 64 pairs of spectra from the VGPS, 108 from the CGPS, and 42 from the SGPS.

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averages can be directly compared with all other parameters kept the same.

The brightness temperature average in Equation (4) has units $\text{K km s}^{-1} \text{ kpc}^{-1}$, but this can be converted to density of H I since the brightness temperature averaged over a velocity step traces the column density of gas (for optically thin 21 cm emission):

$$\left\langle \frac{n_H}{\text{cm}^{-3}} \right\rangle = \frac{N_H}{\Delta L} = 5.9 \times 10^{-4} \left\langle \frac{T_{\text{EM}} \Delta v}{\text{K km s}^{-1}} \left(\frac{L}{\text{kpc}} \right)^{-1} \right\rangle \quad (5)$$

with ΔL the path length interval, N_H the column density of H I, and n_H the average space density along this path. Thus, the value 3 on the y-axis of the top panel in Figure 5, meaning $10^3 \text{ K km s}^{-1} \text{ kpc}^{-1}$, corresponds to density 0.59 cm^{-3} , which is roughly the midplane density at the solar circle. The density drops rapidly outside the solar circle, with exponential scale length about 3.1 kpc. This is generally consistent with the much better determined values for these numbers from large-scale H I emission surveys (Kalberla & Dedes 2008). The strong departures from a smooth radial decrease in the CGPS and VGPS data in Figure 5 are due to a combination of the Perseus arm, which increases the H I density above its mean value at $R_g \simeq 10\text{--}15 \text{ kpc}$ in the first and second quadrants, and the warp, that strongly reduces the H I density in the VGPS longitude range at $R_g > 15 \text{ kpc}$. The SGPS data show weaker departures from the underlying exponential decrease, because the effects of the warp are much less significant in the third and fourth quadrants.

The middle panel of Figure 5 shows the radial variation of the opacity in the H I line, i.e., the absorption equivalent width per unit line of sight length, $\langle \kappa \rangle$, which is the major new result of this study. The y-axis now plots the average of the absorption, $(1 - e^{-\tau})$, per spectral channel, weighted in exactly the same way as for the emission in Equation (4), giving the average of the ratio of the density divided by the spin temperature:

$$\begin{aligned} \left\langle \frac{n_H}{T_{\text{sp}}} \right\rangle \left(\frac{\text{K}}{\text{cm}^{-3}} \right) &= \left\langle \frac{N_H}{T_{\text{sp}} L} \right\rangle \left(\frac{\text{K cm}}{\text{cm}^{-2}} \right) \\ &= 5.9 \times 10^{-4} \left\langle \frac{\tau \Delta v}{\text{km s}^{-1}} \left(\frac{L}{\text{kpc}} \right)^{-1} \right\rangle \quad (6) \end{aligned}$$

with the quantities as in Equation (5), and T_{sp} the excitation temperature of the 21 cm transition. The term in brackets in the right-hand expression in Equation (6) is the opacity, $\langle \kappa \rangle$, where the brackets denote a line of sight average over all phases of the ISM. In this analysis, we work with the directly observed quantity $(1 - e^{-\tau})$ rather than τ , so that the noise is not amplified at velocities where the optical depth is significant, this substitution causes the values to be slight underestimates. This is not significant in the outer Galaxy where the optical depth is generally much less than 1. On the y-axis of the middle panel of Figure 5, the value 1, meaning $\langle \kappa \rangle = 10^1 \text{ km s}^{-1} \text{ kpc}^{-1}$, now corresponds to, e.g., density 0.59 cm^{-3} and spin temperature 100 K. The average of T_{sp} over WNM and CNM at the solar circle is between 150 and 250 K (Dickey et al. 2000), so the

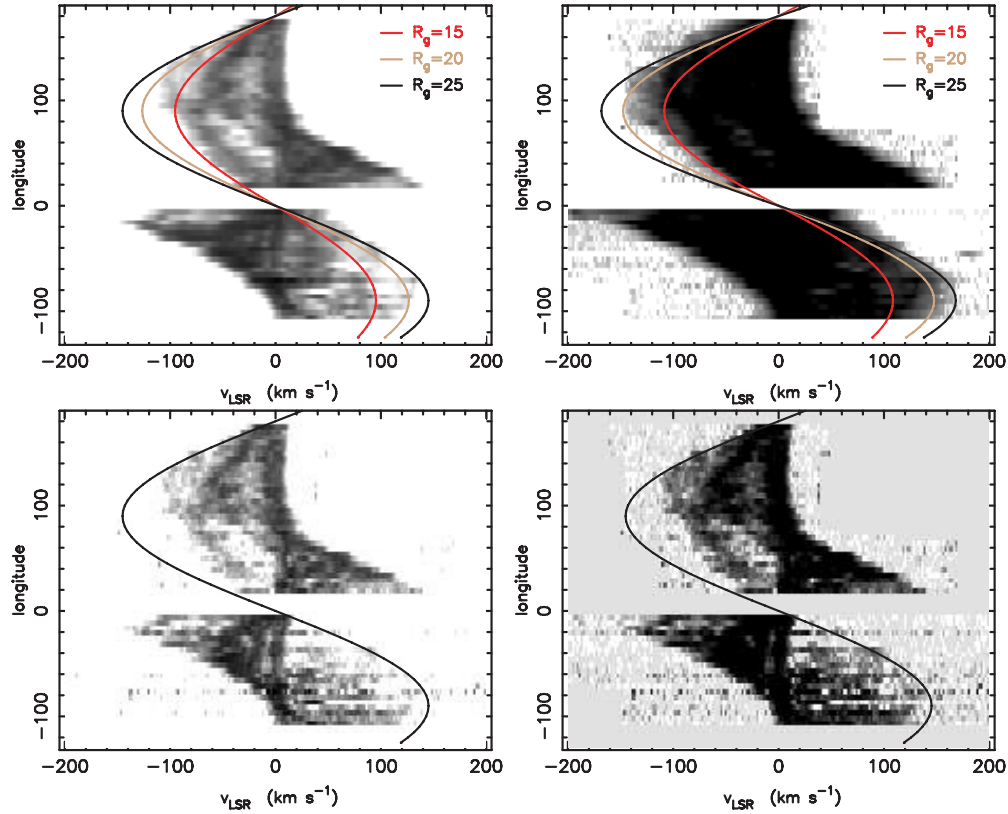


Figure 4. Longitude–velocity diagrams for emission, T_{EM} , and absorption, $(1 - e^{-\tau})$. The upper panels show the emission, with two different levels of gray scale. The lower panels show the absorption. The upper panels have lines of constant R_g indicated. The left panel has the prediction of the flat rotation curve used here (Equations (1)–(3)), the right panel shows similar curves for a rotation curve that stays flat to 15 kpc and then decreases as a Keplerian. The left-hand panels have a shallower grey-scale transfer function than the right-hand panels, to better show the structure at different levels. The lower panels have the curve for $R_g = 25$ kpc from the flat rotation curve repeated from the upper left panel.

(A color version of this figure is available in the online journal.)

expected value for $\frac{n}{T_{\text{sp}}}$ is about $3 \times 10^{-3} \text{ cm}^{-3} \text{ K}^{-1}$, corresponding to 0.7 on the left-hand axis of Figure 5, middle panel. Absorption surveys of the inner Galaxy typically give numbers of $5\text{--}10 \text{ km s}^{-1} \text{ kpc}^{-1}$ for $\langle \kappa \rangle$, which is consistent with the data from the three surveys at the left edge of the middle panel of Figure 5 (Kolpak et al. 2002; Garwood & Dickey 1989).

The radial distributions of the emission and the absorption can be combined into an effective spin temperature by dividing the azimuthal averages of the emission brightness temperature per unit line of sight distance, shown on the top panel of Figure 5, by the optical depth per unit distance shown in the middle panel. The result is shown in the bottom panel. The y-axis now is the average excitation temperature, computed not by dividing the emission by the absorption channel-by-channel, but by dividing the averages of many channels from many spectra that fall in the same radial bins. The result is surprisingly constant with Galactic radius. Whereas the emission and absorption alone decrease by some 2 orders of magnitude over the radial range 10–25 kpc, including departures from the smooth exponential by at least a factor of 3 at certain longitudes, yet their ratio stays constant within a factor of 2 over this entire radial range, with the exception of the VGPS at $R_g > 17$ kpc, for which the optical depths are so small, due to the warp displacing the plane out of the survey area, that the absorption is not detected above the noise in this survey at these radii.

In the bottom panel of Figure 5, the SGPS and VGPS show very good agreement with $\langle T_{\text{sp}} \rangle \simeq 400 \text{ K}$ for $10 \leq R_g \leq 17$ kpc. The CGPS shows significantly cooler values of $\langle T_{\text{sp}} \rangle \simeq 250 \text{ K}$

over the same range. It is possible that this is due to the geometry of the warp, or some other factor that makes the CNM more abundant in the CGPS area than in the areas covered by the other surveys. It may also reflect in part a bias in the continuum estimate used to compute the optical depth in the CGPS survey that could arise from the separate processing of the spectral line and continuum images in that survey. For this reason, the absolute calibration of the absorption spectra from the VGPS and SGPS is probably more reliable than that of the CGPS, even though there are many more lines of sight sampled in the CGPS, which leads to smaller error bars in the lower two panels of Figure 5.

In all the three panels of Figure 5, the error bars represent the rms dispersion of the results for the three groups of spectra, those with $\sigma_\tau < 0.02$, those with $0.02 \leq \sigma_\tau < 0.05$, and those with $0.05 \leq \sigma_\tau < 0.1$, averaged without weighting by σ_τ . The small symbols mark the weighted average of all spectra from all the three groups.

3.3. Variation of the Opacity with Azimuth, ϕ

The radial distribution of the H I opacity, $\langle \kappa \rangle$, shows broad general agreement among the surveys, but the effect of the warp is clearly quite significant in the VGPS longitude range, and in the lower longitudes of the CGPS as well. To see this better, we bin the data in radius and azimuth, as shown in Figures 6(a) and (b). Here the disk is plotted as seen face-on from above the North Galactic Pole. The blank circle at the center has radius R_0 , and the maximum radius plotted is $R_g = 25$ kpc. These figures

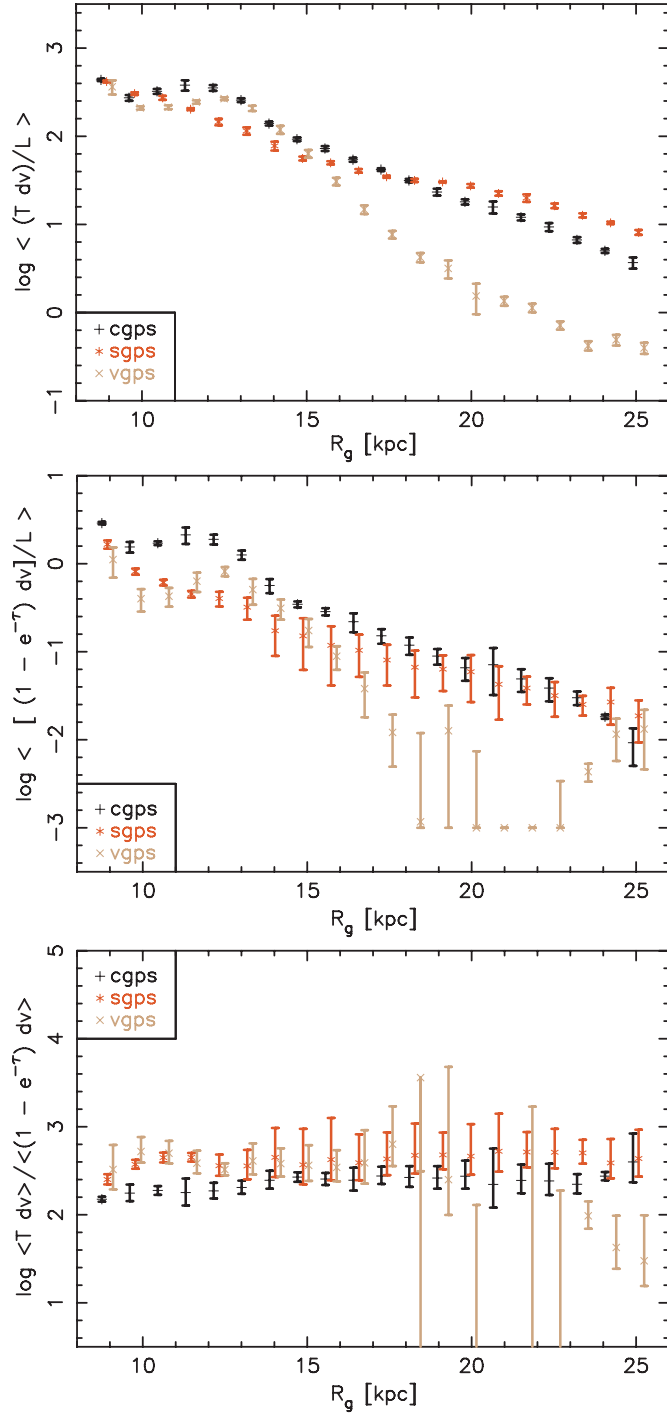


Figure 5. The radial dependence of the 21 cm emission per unit path length (top panel, proportional to $\langle n_H \rangle$), the 21 cm absorption per unit path length ($\langle \kappa \rangle$, middle panel), and the ratio of emission to absorption, (T_{sp} , bottom panel). (A color version of this figure is available in the online journal.)

show in grey-scale the same quantities plotted on the y-axis of the upper two panels of Figures 5, i.e. the log of the 21 cm emission per unit path length, proportional to n_H , and the log of the 21 cm absorption per unit path length, proportional to $\frac{n_H}{T_{sp}}$.

The gray scale extends over a range of $\sim 10^3$ in each quantity, slightly less than the full scale on the y-axes of the upper two panels on Figure 5. The effect of the warp in the first and second quadrants is seen as the white boxes in the lower right corners of each figure.

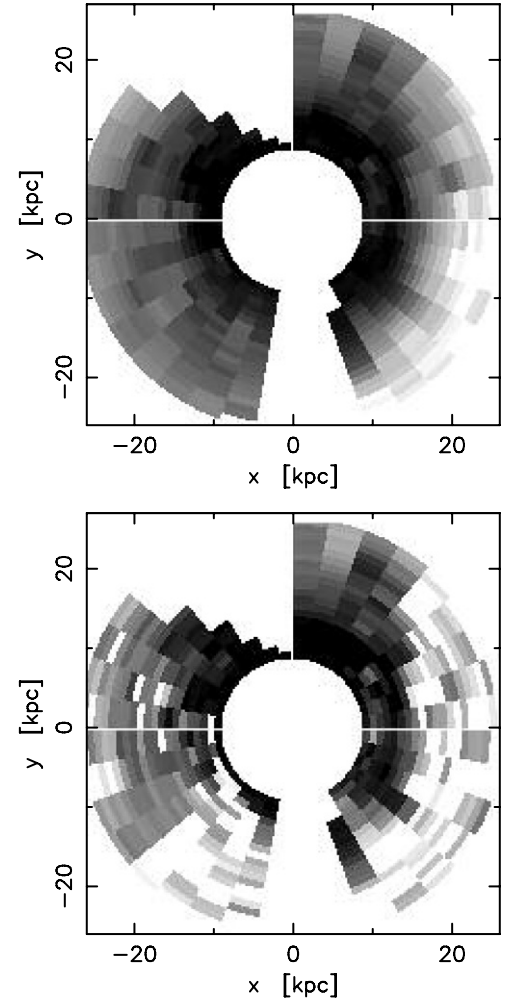


Figure 6. The azimuthal distribution of the emission, shown on the upper panel (a), and the opacity shown on the lower panel (b). The effect of the warp is evident in the empty region in the lower right. The Perseus Arm is clearly visible in the first and second quadrants as the dark feature just outside the solar circle. The gray scale is logarithmic, with range +2.5 (black) to -0.5 (white) in the upper panel, and 0 to -2.5 in the lower panel, with units as in the upper two panels of Figure 5. The axes are labeled in kpc, assuming $R_0 = 8.5$ kpc.

The azimuthal bins on Figures 6(a) and (b) are ten degrees in angle by 0.1 times R_0 in radius. Even with this relatively coarse sampling, the number of lines of sight passing through some bins is not very large, so there is quite a bit of fluctuation from bin to bin, due to small number statistics. The overall radial trend shown on Figure 5 is clearly evident, as is the Perseus Arm in the first and second quadrant, which doubles both the H I density and opacity. In the third and fourth quadrant there is weak indication of the distant arm mapped in 21 cm emission by McClure-Griffiths et al. (2004).

3.4. Variation with Height Above the Plane, z

Figures 7(a) and (b) show the dependence of the H I density and opacity on z , the height above or below the plane defined by $b = 0^\circ$. In order to have a sufficiently large number of measurements contributing to each 100 pc wide interval in z , the data in these figures are averaged over ranges in azimuth and radius. Figure 7(a) shows a histogram of the distribution of the density of H I from Equations (4) and (5), as a function of z over the range $-1.1 < z < +1.1$ kpc. The different panels show averages over separate regions of R_g and ϕ , with the top row

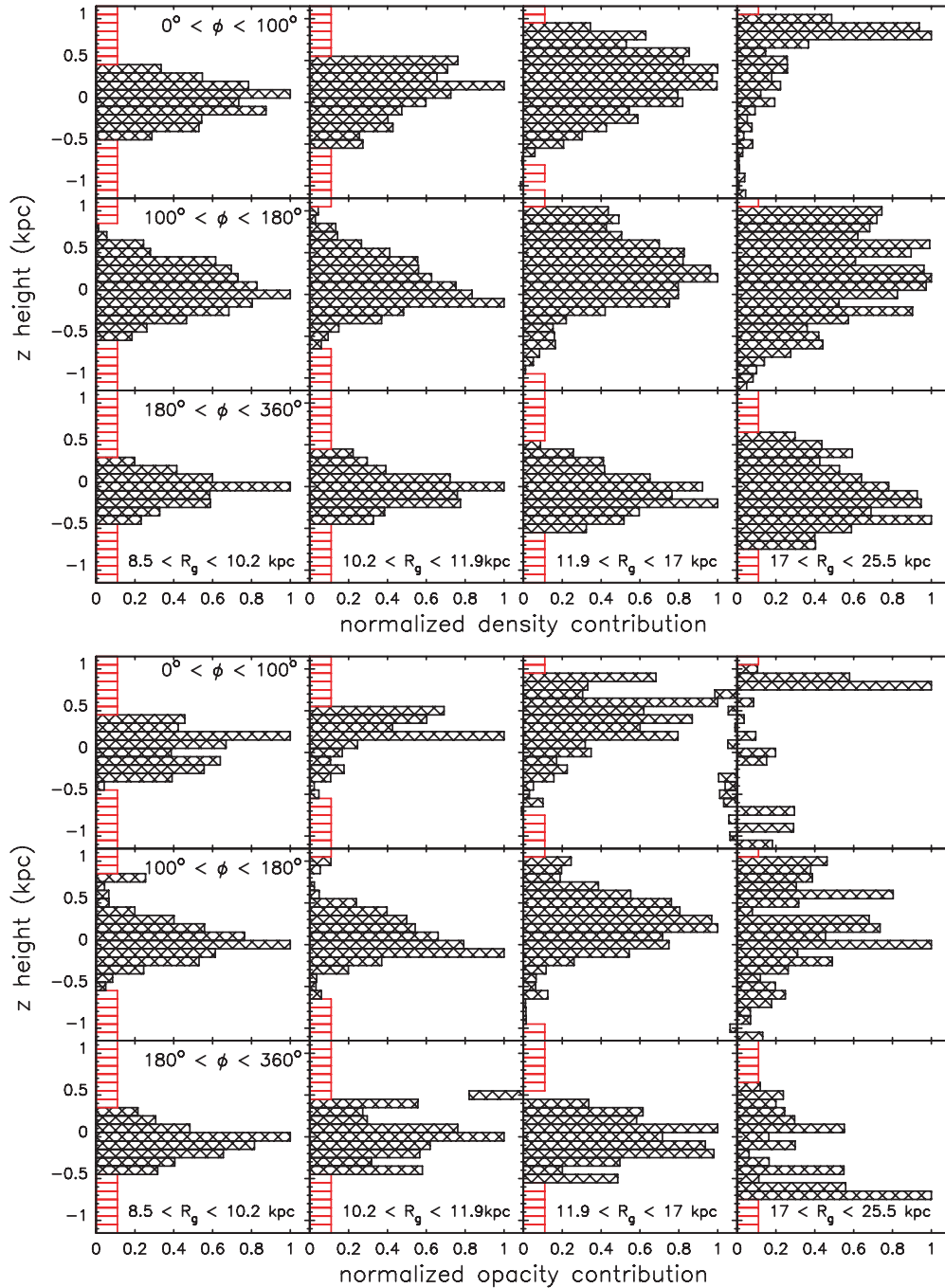


Figure 7. Histograms of the distributions of HI density and opacity with z in different regions of the outer Milky Way disk. The shaded rectangles are histograms, rotated so that the z -axis is vertical, where the height of each bar represents the amount of gas in each 100 pc wide bin in z , from -1.1 to $+1.1$ kpc. The unshaded rectangles (red in the online edition) mark regions where the number of samples is too small to give reliable results. The different panels contain data from separate regions, with the rows showing different ranges of azimuth, ϕ , and the columns showing different ranges of Galactic radius, R_g , as indicated. The upper figure (a) shows the distribution of HI density, measured by the emission per unit path length, and the lower panel (b) shows the opacity, $\langle \kappa \rangle$. The flaring of the disk is evident as a widening of the distributions with increasing R_g at all azimuths. The warp is most clearly seen in the top row, as the median z increases with increasing R_g in both the emission and the absorption. In all the panels the histograms have been scaled so that the largest bar has unit height. This means that the rightmost column has scale factor more than 30 times larger than the leftmost column in absolute units.

(A color version of this figure is available in the online journal.)

using only data with $0^\circ \leq \phi < 100^\circ$, the middle row using only data with $100^\circ \leq \phi < 180^\circ$, and the bottom row using only data with $180^\circ \leq \phi < 360^\circ$. The data is also separated into four radial ranges, corresponding to the four columns. The left column uses data from the range $1.0 < \frac{R_g}{R_0} \leq 1.2$, the next uses data from the range $1.2 < \frac{R_g}{R_0} \leq 1.4$, the next uses data from

the range $1.4 < \frac{R_g}{R_0} \leq 2.0$, and the right column uses data from the range $2.0 < \frac{R_g}{R_0} \leq 3.0$. Figure 7(b) shows the distribution of $\langle \kappa \rangle$, the mean opacity in Equation (6), for the same ranges of ϕ and R_g .

The histograms on Figures 7(a) and (b) indicate the relative amounts of gas at each height, z , in each region. They are all

normalized so that the largest bar has value 1.0. The empty boxes, drawn in red in the online edition, indicate that the number of measurements in that bin is zero, or too small to give a reliable average. Note that the absolute scale is such that the sum of the histograms in each column would match the corresponding radial averages in Figure 5, thus the scale expands by a factor of ~ 30 going from the left column to the right column. The rightmost column shows the effects of noise in the optical depth, as there are several negative histogram bars as well as positive ones.

The shapes of the histograms in corresponding panels of Figures 7(a) and (b) show a strong similarity, meaning that the distributions of the emission, proportional to n_H , and of the opacity, proportional to $\frac{n_H}{T_{\text{sp}}}$, are very similar. This is surprising, since at the solar circle and in the inner Galaxy the scale height of the CNM is smaller than that of the WNM (Dickey & Lockman 1990; McClure-Griffiths & Dickey 2007). The implication is that the flaring or thickening of the disk in z as R_g increases in the outer galaxy, that makes the widths of the distributions increase going from left to right in Figures 7(a) and (b), is a process that affects the WNM and CNM with equal strength. As Liszt (1983) shows, some of the warm phase gas must be associated with the cool gas, while some is in a more widely spread, neutral intercloud medium. The fact that the scale height of the absorption is only slightly smaller than that of the emission in the outer Galaxy suggests that the scale heights of these two warm H I components are not very different.

The effect of the warp is seen strongly in the top row of panels in both Figures 7(a) and (b). The first moment or mean value of z increases with R_g , finally moving out of the survey window altogether for $R_g > 15$ kpc. This is the same effect that causes the empty bins in the lower right area of Figures 6(a) and (b). In the SGPS data, shown in the bottom row of panels in Figures 7(a) and (b), there is very little departure from the midplane in the averages over $180^\circ < \phi < 360^\circ$.

4. CONCLUSIONS

The constancy of the mean spin temperature with Galactic radius from R_0 to $3 \times R_0$, as shown on the bottom panel of Figure 5, indicates that the mixture of CNM and WNM is roughly the same throughout the outer Milky Way disk. This is surprising, given that the physical conditions, in particular the gas pressure, the supernova rate, the radiation field, and the heavy element abundance, are all decreasing with R_g , and these variations must influence the balance of heating and cooling that determines the thermal phases of the H I.

The mean spin temperature should be interpreted not as a physical temperature, but as a parameter that measures the mixture of WNM and CNM. This is because the kinetic temperature in the H I varies over a very wide range, from 20 K to 10^4 K (Kulkarni & Heiles 1988). Blending of warm and cool gas at the same velocity along the line of sight to a background source gives a density-weighted harmonic mean of this quantity,

$$\langle T_{\text{sp}} \rangle = \frac{T_{\text{EM}}}{(1 - e^{-\tau})} = \frac{\int n \, ds}{\int \frac{n}{T_{\text{kin}}} \, ds}, \quad (7)$$

where the integrals in the third expression are taken along the line(s) of sight, s , including only gas with radial velocity that places it into a given velocity channel or range of channels. Making the assumption that the CNM temperature is roughly constant at some typical value T_{cool} , and that the WNM

temperature is high enough that it does not contribute to the optical depth in the denominator of Equation (7), gives

$$\langle T_{\text{sp}} \rangle = T_{\text{cool}} \frac{n_{\text{WNM}} + n_{\text{CNM}}}{n_{\text{CNM}}}, \quad (8)$$

where the ratio of CNM density to total H I (WNM plus CNM) density in this two-phase approximation can be denoted as $f_c = \frac{n_{\text{CNM}}}{n_{\text{WNM}} + n_{\text{CNM}}} = 1 - f_w$ (Dickey et al. 2000). Detailed fitting of the line profile shapes for corresponding features in the emission and absorption spectra can give a good estimate for the CNM temperatures, T_{cool} , which typically vary between 20 K and 100 K for distinct absorption lines with peak optical depths of 0.1 or higher. The mean value for T_{cool} is about 50 K, as measured by different techniques in different surveys with different telescopes (Heiles & Troland 2003b; Dickey et al. 2003). Similar analysis by Strasser (2006) of the absorption lines in the CGPS suggests that T_{cool} does not change significantly or systematically with increasing R_g . The constancy of T_{sp} with R_g thus shows that f_c is also roughly constant in the outer Galactic disk. Since the bottom panel of Figure 5 shows a value of ~ 400 K from the SGPS data from 12 to 25 kpc in R_g , this gives f_c in the range 10–25% for $T_{\text{cool}} = 40$ –100 K.

This invariance of f_c with R_g is surprising in comparison with the apparently strong variation of f_c with z in the inner Galaxy. The CNM and WNM seem to have quite different distributions in z , with the WNM density showing a long tail reaching to $|z| \sim 1$ kpc (Lockman & Gehman 1991), while the CNM has scale height of only 100–150 pc (Crovisier 1978, Malhotra 1995, but see Stanimirović et al. 2006 and Pidopryhora et al. 2007 for studies of H I clouds, at heights of 0.5–1 kpc in z , that contain significant amounts of CNM). The difference in these scale heights has been explained by variation in the gas pressure with z , which shifts the equilibrium values of n and T_{cool} for which the total heating and cooling rates are equal (Wolfire et al. 2003).

One way to understand the difference between CNM scale heights in the inner and outer Galaxy is to identify a part of the CNM in the inner Galaxy with the molecular cloud population. The molecular clouds are the dominant form of ISM mass in the inner Milky Way, particularly in the molecular ring $3 < R_g < 6$ kpc. In the outer disk the molecular phase makes only a small contribution to the total ISM mass, with the neutral and ionized phases playing the dominant role. The molecular clouds certainly have a different distribution from the atomic gas, with the scale height of the disk being much narrower as traced in CO than in H I, for example. Molecular gas is usually surrounded by and/or mixed with partially atomic gas which shows 21 cm absorption and so appears as CNM (Goldsmith et al. 2007). Molecular line cooling is so efficient that the H I gas in a molecular cloud is cooler than in the atomic-only CNM (~ 20 K vs. ~ 50 K; Goldsmith 2001), thus molecular clouds contribute disproportionately (compared to their H I column density) to 21 cm absorption surveys of the inner Galaxy (Kalberla & Kerp 2009, Section 5). In the outer Galaxy this source of 21 cm absorption is insignificant, so f_c shows the mixing ratio of CNM to WNM without confusion by H I in molecular clouds. In the outer disk the evidence on Figures 7(a)–(c) suggests that the scale heights of the WNM and CNM are nearly the same.

A more profound question is how the CNM can coexist with the WNM as a familiar two-phase medium, in an environment where the gas pressure, set by the depth of the disk potential and the overburden of gas at higher z , is as low as it must be

in the far outer Galaxy. We see from Figure 5 that the density at $R_g \sim 20\text{--}25$ kpc is a factor of nearly 100 smaller than at the solar circle, and since the temperatures are similar this means that the gas pressure is less than $100\text{ cm}^{-3}\text{ K}$. The lowest value of the gas pressure that allows the cool phase to exist, even in the environment of the outer disk studied by Wolfire et al. (2003), is $\sim 250\text{--}300\text{ cm}^{-3}\text{ K}$. Supplementing the pressure of the gas with other forms such as magnetic pressure does not necessarily help, since it is the collision rate that sets the cooling in the equilibrium calculation, and so heating–cooling equilibrium is set by the product of the density and random velocity, not by the total pressure.

A similar theoretical problem is posed by cool H I clouds in the Magellanic Bridge and in the far outskirts of the Magellanic Clouds (Kobulnicky & Dickey 1999), and in many examples of HI absorption beyond the edges of the disks of other galaxies. Probably the explanation in most cases is that the local space density, n_H , is increased by an order of magnitude or more above the average, $\langle n_H \rangle$, due to shocks, either from supernova explosions or from converging large-scale gas flows ultimately driven by gravity. The supernova rate is undoubtedly very low in this environment, but converging flows may be common. As long as the cooling time of the H I is shorter than the dynamical timescale of the large structures on the edges of the Milky Way and other galaxies, the H I may be driven from warm to cool and back to warm as the pressure responds to the larger scale gas dynamics.

As Strasser et al. (2007) show, the spatial distribution of the gas causing the absorption in the outer Galaxy is not random; the CNM is gathered in large, coherent structures that in turn follow patterns on the l – v diagram that may connect to the spiral arms of the inner Galaxy. This suggests that departures from circular rotation caused by gravitational perturbations initiate the runaway cooling that precipitates the cool, atomic gas out of the WNM.

A powerful probe of the gas in and around galaxies at high and intermediate redshifts is 21 cm absorption (reviewed by Carilli 2006). An important question in interpreting such lines is how to translate the measured optical depth to H I column density. The results of this study suggest that using a value for T_{sp} of 250–400 K would be appropriate for the Milky Way seen at an impact parameter of 10–25 kpc. This is significantly higher than the values of 100–150 K often used on the basis of the relative abundances of CNM and WNM inside the solar circle.

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