The Warped HI Layer of the Outer Galaxy

T. Voskes

M.Sc. Thesis, University of Leiden
Abstract

Using the Leiden/Dwingeloo Survey (Hartmann & Burton 1997) of the Galactic sky north of $\delta = -30^\circ$ as the principal component of a composite data cube, the structure of the warped HI layer of the outer Galaxy was displayed by converting the data cube from heliocentric ($l, b, v$)–coordinates to galactocentric ($R, \theta, z$)–coordinates. We masked out known high–velocity–cloud complexes which might otherwise have contaminated the resulting description of the warped layer. We considered analogous displays under controlled circumstances by using as input medium a simulation of the same complete ($l, b, v$) data cube corresponding to a modeled HI Galaxy of known morphology and kinematics. By varying this artificial input we were able to check our method of converting the data cube and to put constraints on the global parameters that have been used to explain different asymmetries in the heliocentric data.

This paper was written by Tom Voskes, in fulfillment of the requirements for a Master of Science degree at the University of Leiden, under the supervision of W. Butler Burton. The thesis defense took place in November, 1999. The thesis was given a limited distribution, but was not formally published. A brief preliminary summary of this work was published as “The Large–Scale Structure of the Outer–Galaxy HI Layer”, T. Voskes and W.B. Burton, 1999, in “New Perspectives on the Interstellar Medium”, A.R. Taylor, T.L. Landecker, and G. Joncas, editors, ASP Conference Series 168, 375. A PDF file containing the complete paper, including figures, is available at ftp://ftp.cv.nrao.edu/NRAO-staff/bburton/warp/warp.pdf. Contact: W.B. Burton, bburton@nrao.edu
Contents

1 Introduction 4
2 Data used 5
3 Masking high-velocity-clouds 5
4 Coordinate conversion 6
  4.1 Derived galactic morphology 8
  4.2 Computed input parameters 14
5 Modeling under controlled circumstances 16
  5.1 Circular symmetry 16
    5.1.1 Description of the model 16
    5.1.2 Simulation results 17
  5.2 Circular kinematics with warp 17
    5.2.1 Conversion controlling 18
    5.2.2 Resulting vagaries 20
6 Deviations from circular symmetry 21
  6.1 Asymmetries in the data 23
  6.2 Symmetrical reference data 28
  6.3 Modeled asymmetries 30
7 Observational implications of model asymmetries 31
  7.1 Circular symmetry with asymmetrical warp 31
  7.2 Radial velocity LSR 32
  7.3 Solar elliptical movement 35
  7.4 Global elliptical streaming 36
  7.5 Local streaming 37
  7.6 Decreasing versus constant ellipticity 38
  7.7 Conversion remarkable 39
8 Summary 40
1 Introduction

The early Leiden and Sydney surveys of HI in the Milky Way led to the discovery that the gas layer in the outer reaches of our Galaxy is systematically warped away from the flat plane $b = 0^\circ$. Subsequently, it has become clear that many galactic gas disks are globally warped; indeed, it is difficult to argue that most galactic gas disks are not warped. The embedded perspective which hinders some morphological investigations of our own Galaxy is in fact quite advantageous for studies of the warp. The first descriptions of the Milky Way warp as given by Burke (1957) [3], Kerr (1957) [12], and Oort et al. (1958) [20] have not had to be altered in any fundamental way as investigations based on more modern data became available. The early work led to the recognition that the outer–Galaxy HI layer is warped above the equator $b = 0^\circ$ in the first and the second longitude quadrants, and below it in the third and fourth; the amplitude of the warp is larger in the northern data than in the southern; the total velocity extent in the southern outer–Galaxy layer is larger than in the northern; and the thickness of the gas layer in both hemispheres increases with increasing galactocentric distance.

Although the essentials of the original findings remained unchanged, more recent studies by Burton & te Lintel Hekkert (1986) [7] using principally the Leiden/Green Bank survey of Burton (1985) [6], and by Diplas & Savage (1991) [9] using the Bell Labs horn antenna survey of Stark et al. (1992) [22], have extended the information and have yielded a more quantitative description of the warp parameters. Also, several investigations have pointed out certain spectral asymmetries with respect to the generally adopted approximation of kinematic and spatial circular symmetry to which a set of different explanations have been sought, not always in correspondence with each other (cf. Kerr (1962) [13], Blitz & Spergel, 1991 [2]; Kuijken, 1991 [16]; and Burton, 1991 [8]).

The current project further extends the earlier work by using more sensitive data with more detailed spatial as well as kinematic coverage; it also attempts to account for possible contamination of the results by emission from high–velocity clouds. The data was transformed into galactocentric coordinates using the IAU standards of $R_0=8.5$ kpc and $\Theta_0=220$ km/s, and a wide range of morphological parameters was further quantified. Comparing observationally established spectral asymmetries with respect to kinematic and spatial circular symmetry with similar asymmetries in synthetic spectra for a range of Galactic morphological and kinematic situations, we attempt to identify the response of various aspects of the spectra to small changes
Figure 1: Representative cuts through the all-sky composite datacube. The upper panel shows an \((l,v)\) plot at \(b = -2^\circ\); the lower panel, at \(b = +2^\circ\). The warp at negative latitudes in the third and fourth quadrants causes the emission to extend to larger velocities when probed below the plane \(b = 0^\circ\), and vice versa for the warp at positive latitudes in the first and second quadrants. The peak intensity corresponds to a brightness temperature around 135 K. The lightest greys in these displays correspond to \(T_b = 4\) K, much greater than the sensitivity of the LDS, \(\sigma = 0.07\) K. All \((l,v)\) plots in this paper use the same grey–scale, except for those latitude–averaged.

in these models and to put constraints on the parameters used in them.

2 Data used

The project utilizes the Leiden/Dwingeloo HI survey of Hartmann & Burton (1997) \[10\], which has a greater latitude coverage than that of the Leiden/Green Bank survey (which was restricted to \(|b| \approx 20^\circ\)), and a greater sensitivity (\(\sigma = 0.07\) K); the new data have a more detailed spatial coverage (\(\Delta l = 30', \Delta b = 30'\)) as well as a more detailed kinematic resolution (\(\Delta v = 1\) km/s) than the Bell Labs data and were corrected for contamination by stray–radiation. The Leiden/Dwingeloo data covers the sky north of \(\delta = -30^\circ\). HI data of the full southern sky are not yet available, although the latitude range \(|b| \leq 10^\circ\) at \(\delta < -30^\circ\) is covered by the Maryland/Parkes survey of Kerr et al. (1986) \[14\]; in the region below \(\delta = -30^\circ\) where the survey of Liszt & Burton (1983) \[19\] was available, it was given precedence over the Parkes data because of its higher resolution. The data from the two additional sources were interpolated onto the \((l,b,v)\) grid of the Leiden/Dwingeloo survey and scaled to brightness temperature using the parameters of the S7 standard field given by Williams (1973) \[25\]. In Figure 1 the resulting all–sky data cube was displayed for two cuts through galactic longitude, \(l\), and velocity, \(v\), at constant galactic latitudes of \(b = -2^\circ\) and \(b = 2^\circ\).

3 Masking high-velocity-clouds

The distortions by high–velocity–cloud material were addressed by masking out the principal HVC complexes. We note that in some directions at intermediate latitudes the total HI emissivity contributed by anomalous–velocity gas associated with the high–velocity and intermediate–velocity clouds can be greater than the conventional–velocity emissivity. Unless this material
Figure 2: Rotational situation used in the circularly symmetric velocity–to–distance conversion of the data.

is masked out, the velocity–to–distance analysis in section four would have attributed it to distances calculated according to the normal rotation velocity (unless the HVC velocity were so extreme as to be formally forbidden in terms of the input rotation). To test what the effect of this disturbance is on the displays of the data after conversion to galactocentric \((R, \theta, z)\) coordinates, we masked out the major HVC complexes A, C, H, and AC, as well as the complexes WA, WB, WC, and WD (see e.g. Wakker & van Woerden 1997) \[24\]. Complex G was partially left behind in order not to lose any well–behaved data since it has low deviation velocities. Then the masked data set was subtracted from the observed data and the result was displayed in the \((R, \theta, z)\) coordinates. The differences between the results obtained without masking out the high–velocity clouds and those obtained after masking were minimal. The velocities of the high–velocity cloud complexes are largely forbidden by any reasonable rotation curve. Therefore we conclude that the properties of the Figure 3–6 type of displays are not significantly affected by HVC contamination.

4 Coordinate conversion

The brightness temperatures in the masked data cube of heliocentric coordinates \((l, b, v)\) were then transformed to HI volume densities in galactocentric cylindrical coordinates \((R, \theta, z)\) using a kinematic model of the Galaxy that is circularly symmetric and has a flat rotation curve with \(\Theta(R\geq R_o)=8.5\) kpc\(=220\) km/s. Figure 2 shows a face–on view from the northern side of the Galaxy of the rotational situation. An observer at the sun’s position, embedded in the equatorial plane of the rotating Galaxy, measures a radial velocity along its line of sight towards an object at position \((l, b, R)\) of: \(v(l, b, R)=R_o \sin l[\Theta(R)/R - \Theta(R_o)/R_o] \cos b\). After the velocity–to–distance transformation was carried out, volume densities were derived in galactocentric cylinders, assuming optical thinness. Since at any specified velocity range the optical depth, \(\tau(v)\), and the column density, \(N_{HI}(v)\) (in number of atoms at a particular velocity in a cylinder of cross–sectional area 1 cm\(^2\)), are related by \(N_{HI}(\Delta v) = 1.823 \times 10^{18} \int T_k \tau(v) dv\) [cm\(^{-2}\)], with \(T_k\) the spin temperature of the gas. For the case of optical
thinness, \( T_b(v) = T_k(1 - \exp^{-\tau(v)}) \simeq T_k \tau(v) \), so we can derive the volume density through the integrated intensity observed: \( n_{HI}(\Delta v) \propto \int T_b(v)dv/\Delta r \) [cm\(^{-3}\)]. If, on the other hand, the HI in some direction contributing at a particular velocity is opaque \( (\tau(v) \gg 1) \), the observed brightness temperature does not reveal the number of emitting atoms, but, instead, only a lower limit. It does indicate, however, the gas temperature, because \( T_b(v) = T_k(1 - \exp^{-\tau(v)}) \simeq T_k \). In this case, the profile integral yields an interesting measure: \( \int T_b(v)dv/\Delta r \simeq T_k|\Delta v/\Delta r| \). The expression \( |dv/\Delta r| \) is called the velocity–crowding parameter. It is a measure of how fast the line of sight distance varies for a given radial velocity increment, according to the pertaining kinematics. Emission from regions of high velocity crowding, that is for a low absolute value of \( dv/\Delta r \), is compressed into a short velocity interval making the spectra tend to saturate. This effect is particularly notable in both cardinal directions \( (l = 0^\circ \) and \( l = 180^\circ) \) and also, though somewhat less, in the directions \( l = 90^\circ \) respectively \( l = 270^\circ \).

The volume densities resulting from the conversion are shown in Figures 3 through 6 in cuts through azimuth, \( \theta \), (defined such that \( \theta = l \) for a point at infinity) and vertical height, \( z \), at constant galactocentric radius, \( R \), at azimuth intervals \( \Delta \theta = 1^\circ \), in vertical thickness steps \( \Delta z = 25 \) pc, in cylindrical walls of thickness \( \Delta R = 250 \) pc.

We restricted the use of data to those latitudes that are essential in order to display the warp to any sensible extent in radius. Thus we used data with \( b > -20^\circ \) and \( b < 30^\circ \). This latitude cutoff can be seen clearly in the displays as arcs through \( z \) and \( \theta \) at smaller radii. One immediately also sees the limited extent of the Maryland/Parkes survey of Kerr et al. (1986) [14] \( (|b| \leq 10^\circ) \) as well as that of the Liszt & Burton (1983) [19] survey \( (|b| \leq 10^\circ, \text{with some indentations at the most negative latitudes}) \). Figures 3 through 6 show that these latitude limitations put no major restrictions on the validity of the derived warp parameters, as the data in the northern hemisphere up to \( b = 30^\circ \) seems quite sufficient to display the warp and, due to the warp’s lesser amplitude in the southern hemisphere, so does the data down to \( b = -10^\circ \).

At \( \theta = 0^\circ \) the emission shows a dip. This is not an observed feature, but a consequence of the conversion’s analytics that reach a mathematical singularity at \( \theta = 0^\circ \). Also, although the displays still show non–zero HI densities at radii larger than the last displayed at \( R = 26 \) kpc, they are not shown here because of large systematic errors. At those radii the densities have lessened to such extent that it is difficult to distinguish between a density decrement with increasing radius as a galactic morphological artefact and a density decrement along velocity dispersion wings which is converted
Figure 3: Mean HI volume densities in cylindrical cuts through the composite and HVC–masked data cube at distances of $R = 12$ kpc (upper) and 14 kpc (lower). The cylindrical–coordinate $(R, \theta, z)$ data set was sampled at $1^\circ$ intervals in $\theta$ and 25–pc intervals in $z$; the velocity–to–distance transformation displayed here was circularly symmetric. The darkest grey–scale was scaled to the maximum densities at each radius, to be able to show details even at large $R$, and can be compared with $n_{HI}$ values in Figures 9 and 10.

Figure 4: Same cuts as in Figure 3, at galactocentric distances of $R = 16$ kpc and 18 kpc.

as a progressively smaller amount of gas originating from larger radii (Figure 12). It is further evident in the displays that the heliocentric sampling of space reaches finer gridpoints when getting closer to the sun by noticing that a higher resolution is attained closer towards the anticenter.

In order to follow the transformation process under controlled circumstances, we have simulated the complete observed $(l, b, v)$ data cube on the same grid by solving the radiative transfer pertaining for an ad hoc Galaxy characterized by a plane–parallel, but warped and flaring, gas layer. This both provides an objective control on the conversion method used and gives at the same time useful insight in the disturbing effects on the images in $(R, \theta, z)$ coordinates of velocity crowding, changing degrees of optical thinness, and a finite velocity dispersion of the gas. More on this will follow in sections 5.2.1 and 5.2.2.

4.1 Derived galactic morphology

After conversion, the resulting set of galactocentric representations of the Galaxy, assuming circular symmetry, can be used to obtain a first–order impression of its morphology. For comparison with earlier data we computed several parameters concerning this morphology. At the same time these parameters can be used as the most realistic input values currently available for the simulations of section five. It must be noted, however, that an unavoidable error is being made here inherent to the method, when we make statements on possible galactic morphologies and kinematics as responsible

Figure 5: Same cuts as in Figure 3, at galactocentric distances of $R = 20$ kpc and 22 kpc.
for observed asymmetries on the basis of simulated models that took as input the parameters that were computed assuming circular symmetry. Since all parameters were azimuthally averaged to fit circular data and, moreover, since even in a worst case scenario the errors will typically not exceed a few to at most ten percent, we assume that this has no important effect on the conclusions that follow.

The parameters in the Figures 8 through 12, and 14 and 15 were computed by fitting a Gaussian to the \( z \)-dependent HI density distribution for each fixed \((R, \theta)\) combination, using the GAUSSFIT routine in IDL. We measured for each \((R, \theta)\) combination the height of the Gaussian, its width and the location of its center. From the \( z \) location of its center we determined the parameter plotted in Figures 8 and 9, from its height, the one in Figures 10, 11, and 12, and from its width, the one in Figure 14 and in Figure 15. It should be noted that the Gaussian width corresponds to the dispersion \( \sigma \) and not to a full width at half maximum \((\text{FWHM}=2.36*\sigma)\). The parameter in Figure 13 was computed by integrating all \( z \) values for each point in \((R, \theta)\).

It would be valuable, of course, to be able to determine the total extent of the Milky Way’s HI disk in view of its theoretical consequences for, e.g., the shape of the Galactic dark halo and the Local Group’s dynamics, to name but a few. However, this is not easily established. Not only is there the difficulty to distinguish in the observed spectra between the outer edge of the Galaxy and its less outward velocity dispersed gas (of which the exact dispersion rate at these outer parts is difficult to determine) as is described above, but also is it likely that errors in this determination are superseded by errors in the assumption of the Galactic kinematics as used in the conversion method. It is clearly of influence what type of rotation curve one uses in the velocity–to–distance transformation; currently, there is not one uniquely determined rotation curve found yet. Also, there remains some uncertainty in the correct value found for \( R_0 \). Furthermore, as will be commented upon in section 6.1 and 7.7, some deviations from kinematic and spatial symmetry have important consequences for the perceived Galactic morphology after conversion. In particular, note that it appears that the HI density at large radii is large in the fourth quadrant with respect to the first and that of the second quadrant is large compared to the third. As will be shown (in section 7.7) this effect is also reproduced with slightly elliptical HI streamlines in
Figure 7: Line of sight velocities for emission from increasing radius $R$ in the direction $l = 90^\circ, b = 0^\circ$. The solid line is according to the kinematics used in this investigation ($\Theta(R \geq R_\odot = 8.5 \, \text{kpc}) = 220 \, \text{km/s}$), the dotted line to that in Henderson et al. (1982) [11] and Diplas & Savage (1991) [9] ($\Theta(R \geq R_\odot = 10.0 \, \text{kpc}) = 250 \, \text{km/s}$), and the dashed line corresponds to the kinematics specified by $R_\odot = 8.5 \, \text{kpc}, \Theta_\odot = 220 \, \text{km/s}$, and $\Theta(R) = \Theta_\odot (R/R_\odot)^{0.0382}$ as is used by Wouterloot et al. (1990) [26].

Figure 8: Vertical distance from the plane $b = 0^\circ$ of the gauss-fitted peak HI density at galactocentric distances of respectively $R = 12 \, \text{kpc}$, $16 \, \text{kpc}$, and $20 \, \text{kpc}$. The distribution was smoothed over $10^\circ$ in $\theta$. The central bump near $\theta = 0^\circ$ is not physically significant, due to the smearing of the data in that direction (see the comments on this in the caption of Figure 14).

Galactic simulated spectra. That the data, and the parameters deduced from it, are nevertheless displayed in $(R, \theta, z)$ coordinates, using cylindrical symmetry and the rotation curve as above, is for comparison with earlier data (to which this has the advantages described in the introduction) and by lack of any better established alternative yet. The same arguments lead to the explanation of the absence of error bars on the parameters displayed here, as it is estimated that the systematic errors following from the conversion method are greater than the errors introduced by fitting Gaussians or than errors in the data itself.

It is instructive to compare these new data with the findings of past investigations. For instance, although the shapes of the surface density ($\sigma$) curves of Henderson et al. (1982) [11] in their Figure 4 and that of our Figure 13 are quite similar it can be seen that the peak of their northern surface density profile occurs at a radius of $\sim 14 \, \text{kpc}$, while ours occurs at $\sim 12.5 \, \text{kpc}$. This difference is caused by the choice of the assumed Galactic kinematics in the velocity–to–distance transformation as is illustrated in Figure 7. This scale effect, which is more pronounced for radii nearby to the solar radius, is squared when it enters their analysis of the surface density, using $\Theta(R \geq R_\odot = 10.0 \, \text{kpc}) = 250 \, \text{km/s}$, and leads to an underestimate relative

Figure 9: Vertical distance from the plane $b = 0^\circ$ of the gauss-fitted peak HI density at galactocentric distances of respectively $R = 24 \, \text{kpc}$, $26 \, \text{kpc}$, and $28 \, \text{kpc}$. The distribution was smoothed over $10^\circ$ in $\theta$. 
Figure 10: Azimuthal distribution of HI midplane densities, measured as the gauss-fitted peak of the vertical HI density distribution, at the respective radii of $R = 10$ kpc, $12$ kpc, and $14$ kpc. The distribution was smoothed over $10^\circ$ in $\theta$. The plots show an apparent underabundance of HI gas in those directions ($\theta \sim 0^\circ, \pm 180^\circ$) where due to velocity crowding the total amount of emitting gas is expected to be higher than what is observed by received emission. Note, specifically, the low values around $l = 0^\circ$.

Figure 11: Same azimuthal distribution of HI midplane densities as in Figure 10, at the radii of $R = 16$ kpc, $18$ kpc, and $20$ kpc.

Figure 12: Azimuthally averaged HI midplane densities with increasing radius for the range $20^\circ \leq \theta \leq 160^\circ$ (dotted line) and for the range $200^\circ \leq \theta \leq 340^\circ$ (dashed line). It is difficult, at very large radii, to distinguish between a density decrement with increasing radius as a galactic morphological artefact and a density decrement along velocity dispersion wings which is by the conversion method naturally taken as a progressively smaller amount of gas originating from larger radii.

Figure 13: Azimuthally averaged HI surface densities ($\sigma$) in solar masses per square parsec (upper panel), for the range $20^\circ \leq \theta \leq 160^\circ$ (dotted line) and for the range $200^\circ \leq \theta \leq 340^\circ$ (dashed line). The lower panel gives the logarithmic version from which we deduce that the mean radial scalelength for the HI surface density in the $\theta$-averaged range $20^\circ \leq \theta \leq 160^\circ$ at $R \geq 9$ kpc is $4.3$ kpc and for the range $200^\circ \leq \theta \leq 340^\circ$ $4.9$ kpc. However if we only measure at $15 \leq R \leq 25$ kpc, then we arrive at $3.7$ kpc and $4.2$ kpc, respectively. In view of the low densities at $R > 25$ kpc, it is difficult to determine the significance of the values of $\sigma$ at those radii.

Figure 14: Gaussian dispersion ($h$) of the vertical HI density distribution at distances of $R = 12$ kpc, $16$ kpc, and $20$ kpc. The distributions were smoothed over $10^\circ$ in $\theta$. Note the increase of average scale height with increasing radius. The large values of $h$ near $\theta = 0^\circ$ are spurious, being due to the elongated patch of emission in the Figures 3–6. This is caused by local gas that reaches velocities, due to the finite velocity dispersion, that correspond kinematically with radii in the far outer Galaxy. Note, that it is slightly off-center, as is the elongated patch.
Figure 15: Flaring of the azimuthally averaged gaussian width ($h$) of the vertical HI density distribution for increasing galactocentric radius. The dotted line is the $\theta$–averaged value for the range $20^\circ \leq \theta \leq 160^\circ$, the dashed line is the $\theta$–averaged value for the range $200^\circ \leq \theta \leq 340^\circ$. Finally, the solid line is their average. The 40$^\circ$–bands in both cardinal directions were omitted, because of their unrealistic high values of the scale height as explained in the caption of Figure 14. As mentioned in Figure 13, also here it is difficult to determine the significance of the values of $h$ at $R > 25$ kpc, in view of the very low densities at those radii in Figure 12.

to the analysis we made, using $\Theta(R \geq R_o=8.5$ kpc)$=220$ km/s. Thus the difference in the magnitude of the density, with the current findings coming to a more than 2 solar masses per square parsec higher value than those of Henderson et al. for radii up to about 17 kpc, is at least in part accounted for. This is clearly also the case in the logarithmic plot of $\sigma$ in Figure 8 of Diplas & Savage (1991) [9], who used the same kinematics as Henderson et al. Also, they show in their table 1 that derived scale lengths are expected to be greater when using the kinematics we used than using theirs. They point out that for the Henderson et al. data they estimate $r_s=2.08$ kpc (for $\Theta(R \geq R_o=10.0$ kpc)$=250$ km/s), while they arrive at $r_s=2.49$, 2.60, and 3.98 kpc for values of $\theta$ of $50^\circ$, $90^\circ$ respectively $130^\circ$ corresponding to $r_s=3.14$, 2.74, and 5.55 kpc for $\Theta(R \geq R_o=8.5$ kpc)$=220$ km/s. These three specific values can not be compared directly to the $\theta$–averaged values we found as explained in the caption of Figure 13, though it is clear that ours are significantly higher than the one found from the Henderson et al. data. Since the shape, and particularly the height, of the Galactic surface density curve is very sensitive to the choice of range for averaging in $\theta$, as can clearly been seen in Figures 10 and 11. In the case of the work done by Henderson et al. this range was $30^\circ \leq \theta \leq 150^\circ$ (northern) respectively $210^\circ \leq \theta \leq 330^\circ$ (southern) where we used $20^\circ \leq \theta \leq 160^\circ$ respectively $200^\circ \leq \theta \leq 340^\circ$, some of the difference in surface densities along Galactic radius may also be accounted for by this effect, although the lower densities toward the cardinal directions might in fact argue for a bias in the Henderson et al. data towards higher values with respect to ours, instead of lower. That this effect is significant and can be attributed to velocity crowding alone is shown in the lower panel of Figure 22 in section 5.2. This is also the direct reason for us to leave out a band of 40$^\circ$ in $\theta$ in both center and anticenter direction in our analysis. The data as analyzed by Wouterloot et al. (1990) [26] is more directly comparable to the current results, as can be found in their Figure 5b,
due to the small difference in kinematic distance determination between their method, using R_o=8.5 kpc, Θ_o=220 km/s, and Θ(R) = Θ_o(R/R_o)^0.0382, and ours, as can again be seen in Figure 7. They find for the ranges 120° ≤ θ ≤ 170° (northern) respectively 190° ≤ θ ≤ 240° (southern) equivalent, though slightly lower, magnitudes than ours, where due to a bigger overlap with the region that is most affected by underestimation of density through velocity crowding one would expect these magnitudes to be lower limits, rather than upper. This is almost certainly the case for the Galactic surface density curve shown in their Figure 5e, where they averaged over the complete second and third quadrants and thus included the minimum around l = 180°. As therefore expected, it displays lower σ, especially at radii nearer to R_0=8.5 kpc, which can be understood when taking into account the progressively larger relative minimum in the Figures 10 and 11 for values of R nearer to the solar radius. Their value of radial scalelength, r_s = 4.0 kpc, is, again, equivalent to ours, though slightly lower, in spite of the suppressed density magnitudes at radii close to R_0, which would make it larger. This could be attributable to the fact that at larger radii the difference between the kinematics becomes more pronounced (Figure 7), causing their σ to decline faster.

The flaring of the thickness of the HI layer is demonstrated in Figure 15. Also here it can be seen, from Figure 14, that the exact shape and, in particular, the height of the flaring curve is sensitive to the applied range of θ–averaging. It is remarkable how the data from Wouterloot et al., in their Figure 9, leads to a much smaller thickness near R = 10 kpc of a half width to half maximum of about 200 pc, which roughly equals 170 pc (FWHM=2.36*σ) in Gaussian width (σ), compared to our ~450 pc in σ. However, Diplas & Savage find, using the data of Henderson et al., for a θ–averaging over 90° ≤ θ ≤ 130° about σ=500 pc and for 210° ≤ θ ≤ 250° about σ=400 pc, both at R = 12 kpc, in good agreement with the data here. Their plots of the flaring of the thickness for different particular θ values in this figure, with their wide range in thickness at any particular radius, illustrate the impact of the range of θ included on the flaring curve, as was mentioned above. We choose not to include a band of 40° in θ in both center and anticenter direction in our analysis, since we can see that in these regions the values of h are unrealistically high due local velocity dispersed gas, explained in the caption of Figure 14, as is demonstrated in Figure 22, upper panel, in section 5.2. For all the plots showing the flaring of the thickness, the flaring continues to rise towards higher radii. Only our new data shows a slowing of rise in flaring at very large radii (R > 23 kpc), although one should be careful about the interpretation of the analysis
at these large distances from the Galactic center in view of what was said before about systematic errors.

When looking at the vertical distances from the plane $b = 0^\circ$ of the gauss-fitted peak HI density at very large galactocentric distances in Figure 9 the attention is drawn to a feature, which is referred to in the literature as scalloping (e.g. Kulkarni et al. (1982) [17]), that is most pronounced in the 3rd and 4th quadrants. As mentioned before, carefulness is required for the interpretation of the reality-content of this feature at such large radii. Closer inspection reveals that about 10 periods can be distinguished for a full $360^\circ$ in azimuth, the same number that was found by Kulkarni et al. The scalloping is further remarkable, because it sustains the same regularity through several kpc in galactocentric radius. Currently, it is uncertain, what its cause is. In any case this effect is additional to the global parameters we consider here and shall not be pursued by us any further.

4.2 Computed input parameters

We have constructed a complete set of $(l,b,v)$ spectra based upon an HI brightness temperature distribution according to known input galactic morphology and kinematics. More on this will follow in section 5. Both for the purpose of having a realistic controlled input medium for the heliocentric–to–galactocentric coordinates conversion and for the purpose of showing observational consequences of various different galactic models that have been put forward as a possible explanation of observed spectral asymmetries, it is valuable to have close-to-reality input parameters. Some of these are taken from the literature, others have been computed by using this project’s data and the parameters calculated in the subsection above. We will mention those of the last type here and explain the method by which they were calculated.

The radial scale length was taken as an average of the four values that were found from the lower panel in Figure 13. It was derived to be 4.3 kpc. The vertical scale height in the solar neighborhood was deduced from Figure 15. This is a Gaussian scale factor and it was computed to be 0.40 kpc. The rate of flaring was also taken, azimuthally averaged, from the same plot and amounted to 25 pc in Gaussian width of vertical thickness.
for every kpc radially outward beyond $R = 9$ kpc, the radial edge of the assumed flat and of constant density disk. This central disk HI density was measured at a radius of $R = 9$ kpc and averaged over all $\theta$ values except for 20° regions centered on both the anticenter and center directions in order to avoid an underestimation due to velocity crowding. We found $0.26 \, \text{cm}^{-3}$, which is a lower limit. At a certain point the simulation makes use of a sinusoidal warp that is linearly rising beyond $R = 9$ kpc. That this is a fair first approximation can be seen in Figure 8. To determine the rate of rising of the warp we calculated the magnitude of a sine curve that maps out the same surface in a plot either above or below the plane $b = 0^\circ$. These thus determined sine–fitted warp heights for increasing radius can be found as the solid lines of Figure 16. Their increasing rate was averaged to give 110 pc per kpc radially outward from $R = 9$ kpc. A better approximation involves an asymmetric warp that distinguishes a part at latitudes north of the plane $b = 0^\circ$ and one south of it. This approximation increases not linearly but according to the mathematical fits shown with dashed lines in Figure 16.

In the original $(l, b, v)$ data the warp maximum and warp minimum were defined as the longitudes at which the highest respectively lowest latitudes were attained. This was measured for a velocity–integrated $(l, b)$ plot at $−220 < v < −100 \, \text{km/s}$ for the warp at positive latitudes in the first and second quadrant to include only gas from the outer Galaxy, as well as for $100 < v < 220 \, \text{km/s}$ for the warp at negative latitudes in the remaining two quadrants. This resulted in $l = 103^\circ$ for the warp maximum and $l = 262^\circ$ for the warp minimum. Because of the smaller than 180° spacing between the maximum and the minimum and the known folding–back property of the warp at the southern hemisphere, which is prominent in the velocity range that was sampled here, the measurement was repeated for the range $60 < v < 100 \, \text{km/s}$, which is representative for distances more towards those where the southern warp reaches its minimum, shown in Figure 16. This gave for the warp at $b < 0^\circ$ a quite shallow minimum that extended from $l \sim 240^\circ$ to $l \sim 290^\circ$. A warp maximum for $l = 100^\circ$ implies for the models a galactocentric warp maximum at $\theta \simeq 120^\circ$ spaced from the warp minimum by 180°, assuming that this maximum is observed at $R \sim 20$ kpc or more. However, judging by the line of nodes in Figures 8 and 9 one would come to a warp maximum at $\theta \simeq 95^\circ$. As, from the same figures, it is clear that both orientations represent only in part the real situation, since the shape of the warp is not perfectly sinusoidal, both will be used in the simulations of section five and seven.
Figure 17: General elliptical rotational velocities used in the simulation models, $\Theta_x$ has a negative value, $\Theta_y$ a positive one. Note that in the case $\epsilon = 0$ and $\alpha = 0^\circ$, it will follow that $\psi = \theta$.

5 Modeling under controlled circumstances

We have constructed a complete set of ($l, b, v$) spectra based upon an HI brightness temperature distribution according to known input Galactic morphology and kinematics. This simulation provides a strong check on the analysis procedures, when taken with identical kinematics as those specified in the method used for converting the data to ($R, \theta, z$) coordinates. Changing the input models, it is furthermore possible to monitor the influences this has on both the appearance of the spectra, and on the appearance of plots in ($R, \theta, z$), that were made, while still using the conversion we use in the real data’s case. To be able to include demonstrations of the effects of any possible kinematic ellipticity or other forms of asymmetry, we have used as an input model the general case of a Galaxy with kinematics described by motions in closed elliptical streamlines. That it is reasonable to do so, even though in a non–spherical potential there are no dynamical stable and closed orbits, can be thought of when one realizes that a collection of HI clouds on independent and randomly chosen non–stable orbits are likely to collide and thus to cause shocks, for which there is no observational evidence. The kinematics were therefore chosen without a formal dynamical foundation, with an ellipticity, $\epsilon$, defined for the rotational velocity, $\Theta$, of any object at a certain position angle $\psi$ (which is $\alpha + 180^\circ$ in the case of the sun; see Figure 17). This $\Theta$ is decomposed into a velocity along the $x$-axis (defined by the ellipse major axis), $\Theta_x$, and a velocity along the $y$-axis, $\Theta_y$, where $\Theta_x = -\Theta_0(1 + \epsilon/2)\sin \psi$ and $\Theta_y = \Theta_0(1 - \epsilon/2)\cos \psi$.

5.1 Circular symmetry

5.1.1 Description of the model

The simplest case we consider is that of a plane–parallel circularly symmetric Galaxy, with differential rotation according to $\Theta(R) = \Theta_0[1.0074(R/R_0)^{0.0382} + 0.00698]^{-2.0}$ (km/s), for $R < R_0$, and $\Theta(R) = \Theta_0$, for $R \geq R_0$. The gas layer shows flaring, but is not warped. The midplane is specified by the plane $b = 0^\circ$ and has a volume density of $0.30$ cm$^{-3}$, a little higher than what was found in section 4.2 to compensate for the underestimation of this parameter due to the fact that not everywhere in the Galaxy along the line
Figure 18: Simulated analogue at \( b = 0^\circ \) of Figure 23, upper panel, for a model with complete circular symmetry as described in the text. As in Figure 1, the peak intensity of the display corresponds to a brightness temperature of 135 K; the lightest greys, to \( T_b = 4 \) K.

of sight the opacity is truly far smaller than 1. That this expectation is justified can be seen in the middle panel plot of Figure 21, which bears a fair resemblance to that of Figure 12. The volume density is constant at the midplane up to \( R = 9 \) kpc, but at larger \( R \) it declines with a scale length of \( r_s = 4.3 \) kpc. Moreover, it also declines with vertical \( |z| \) height, with a scale height of \( h_s = 0.40 \) kpc. Due to the flaring of this thickness, this value of \( h_s \) increases with 0.025 kpc for every kpc in radius beyond \( R = 9 \) kpc. All these parameters were derived using the real data after a circularly symmetric conversion as described in section 4.2. The model Galaxy is truncated at \( R = 30 \) kpc. The gas was defined to have a velocity dispersion of \( \sigma = 7.5 \) km/s and a spin temperature of \( T_k = 135 \) K.

5.1.2 Simulation results

The complete observed \((l,b,v)\) data cube is then simulated on the same grid by solving the radiative transfer pertaining for the ad hoc Galaxy, as described above. Figure 18 shows the resulting set of spectra at \( b = 0^\circ \) in a display through \( l \) and \( v \). Note that, apart from the scale factors mentioned above, the input model did not have any structure and that thus all artefacts in this \((l,v)\) plot are due to effects of velocity crowding, i.e. to changing degrees of optical thinness, and a finite velocity dispersion of the gas. Furthermore, the line of sight kinematic point of symmetry with respect to the outer Galaxy is entirely coincident with the location of the sun. Thus, the most extreme velocities occur at galactic longitudes of \( l = 90^\circ \) respectively \( l = 270^\circ \) and show a drop–off in magnitude that is symmetrical with respect to the velocity minima at the center \((l = 0^\circ)\) and anticenter \((l = 180^\circ)\) directions. Note also, how in the 2\textsuperscript{nd} quadrant some emission is present at formally forbidden positive velocities, as is some emission in the 3\textsuperscript{rd} at negative velocities, due to the velocity dispersion of nearby gas.

5.2 Circular kinematics with warp

Since the presence of a warp in the Galactic HI layer will alter the appearance of the velocity cutoff at \( b = 0^\circ \) in those directions were the line of sight will
Figure 19: \((l,v)\) plot at \(b = 0^\circ\), for the simulated data with circular kinematic symmetry, but a symmetrical warp with its maximum at \(\theta = 95^\circ\) (upper panel), as well as a latitude integrated version for \(|b| \leq 10^\circ\) (lower panel), to show the effects this has on the influence of the warp. As in Figure 1, the peak intensity of the upper–panel display corresponds to a brightness temperature of 135 K and the lightest grey–scale corresponds to \(T_b = 4\) K. The lower–panel display was averaged over its \(b\) values and has a deviating grey–scale scaled between minimum and maximum intensities.

leave the gas layer where it warps away maximally from the plane at radii smaller than those for which it reaches its extreme velocities, it is instructive to compare the observed \((l,v)\) plot at \(b = 0^\circ\), with an \((l,v)\) plot of a model Galaxy described as in subsection 5.1.1, only now with a linear sinusoidal warp. The shape of the warp is such that a line through the midplane along a cylindrical wall through \(\theta\) and \(z\) at constant radius \(R\) is a perfect sine curve. The magnitude of the maximum of the warp starts at zero at \(R = 9\) kpc and increases from there with 110 pc for every kpc outwards, as was derived from the real data in section 4.2. For the simulations in this section we put the warp maximum at \(\theta = 95^\circ\).

5.2.1 Conversion controlling

In Figure 19 an \((l,v)\) plot of the sort of Figure 18 was displayed, this time including a linearly rising sinusoidal warp. For comparison with a plot shown in Figure 23 in section 6.1 a latitude integrated version for \(|b| \leq 10^\circ\) was displayed as well. The upper panel shows indentations at the outer–Galaxy velocities in the heliocentric \(l\) directions where we expect the maximum warp along galactocentric \(\theta\). This complete \(T_b(l,b,v)\) data cube was processed in the same manner as the observed data cube to yield volume densities in cylindrical cuts through galactocentric coordinates of the sort displayed in the Figures 3–6. Since, in this case the input kinematics are, for certain, conveniently identical to those used in the velocity–to–distance processing, this should render a Galactic morphology that is consistent with the input model and, furthermore, draw our attention to any vagaries that can only have been inflicted by the method of converting the data cube and that can thus also be expected to blur our view of the Galaxy, displayed in the Figures 3–6. The result of this conversion is displayed in galactocentric cylindrical cuts in Figure 20 for the constant radii \(R = 16\) kpc and \(R = 26\) kpc.
Figure 20: Mean HI volume densities in cylindrical cuts through the simulated data cube with circular kinematic symmetry, but a symmetrical warp with its maximum at $\theta = 95^\circ$ at galactocentric distances of $R = 16$ kpc (upper) and 26 kpc (lower). The cylindrical–coordinate $(R, \theta, z)$ data set was sampled at 1° intervals in $\theta$ and 25–pc intervals in $z$; the velocity–to–distance transformation displayed here was circularly symmetric. The darkest grey–scale was scaled to the maximum densities at each of both radii, to be able to show details even at $R=26$ kpc. Compare, for the exact derived densities, Figure 21 (middle panel). For reference a line tracing the galactic plane at $b = 0^\circ$ was drawn.

Figure 21: Vertical distance from the plane $b = 0^\circ$ of the Gauss-fitted peak HI density of the simulated data cube with circular kinematic symmetry, but a symmetrical warp with its maximum at $\theta = 95^\circ$ at a distance of $R = 16$ kpc (upper), to be compared with Figure 8, a $\theta$-averaged ($20^\circ < \theta < 140^\circ$) HI midplane density with increasing radius (middle) (comparable with Figure 12) and the flaring of the azimuthally averaged Gaussian width of the vertical HI density distribution (lower), comparable with Figure 15. The parameters were calculated in the same manner as their real–data counterparts, that is, after conversion of the data to galactocentric coordinates.

Figure 22: Gaussian width ($h$) of the vertical HI density distribution (upper) of the simulated data cube with circular kinematic symmetry, but a symmetrical warp with its maximum at $\theta = 95^\circ$ at a galactocentric distance of $R = 12$ kpc (comparable with Figure 14) and azimuthal distribution of HI midplane densities, at $R = 10$ kpc (lower) (comparable with Figure 10). Note that these parameters were calculated in the same manner as their real–data counterparts, that is, after conversion of the data to galactocentric coordinates.
5.2.2 Resulting vagaries

A set of morphological parameters similar to those in section 4.1 were computed using the same procedures. They are displayed in Figures 21 and 22. Several remarks can be made about the appearance of the cylindrical cuts in Figure 20 and on these parameters. First, it can be seen that the orientation of the warp is correct and also, at closer inspection, that the line of nodes is exactly at $\theta = 5^\circ$ and $\theta = 185^\circ$ (see also the upper panel of Figure 21). In fact, it was tested how the conversion analytics would deal with a warp maximum at exactly $\theta = 0^\circ$, in view of the apparent coincidence of having the sun–center line so close to the observed line of nodes. It behaved properly and retrieved the exact input situation. Secondly, the gas layer has generally a constant thickness along azimuth and shows flaring from the $R = 16$ to the $R = 26$ plot, as required by the input. A non–input feature is clearly the density indentations at the center and anticenter directions, due to a mathematical singularity in the conversion analytics at $\theta = 0^\circ, 180^\circ$. Also, the striking patches, stretched greatly in $z$, are caused by the processing, rather than inherent to the model. Its origin is of local gas that reaches velocities, due to its finite velocity dispersion, that correspond kinematically with radii in the far outer Galaxy. The densities are then derived from the received intensities according to the multiplefold distances. It occurs only at the cardinal directions, as it is there where the line of sight velocities remain quite small, even at large radii. Note that in the case of kinematic symmetry, as is considered here, the patch is also symmetrically oriented around both directions, whereas in the Figures 3–6 it was displaced. Compare, in this context, for instance, the upper panel of Figure 22 with that of Figure 14. That the patch reaches greater vertical heights above the plane in the center direction can be easily understood in terms of the large kinematic distance that local gas emission at any particular latitude corresponds to, with its corresponding large $z$ height, since it needs to traverse the sun–center radius twice first. Again, in the center direction, and in that of the anticenter to a lesser extent as well, a vagary is observed, at $R = 16$ kpc, displaying a progressive lower volume density when approaching $\theta = 0^\circ$ (and $\theta = 180^\circ$). This effect is even more clear in the lower panel of Figure 22 and is attributable to a non–negligible optical depth due to velocity crowding. This concentrates all emission in a small range of frequencies and thus causes the spectra to saturate, resulting in an underestimation of the true volume density in spatial distribution. Finally, this under abundance near the cardinal directions changes into an overabundance for plots at very large radii; see the cylindrical cut at $R = 26$ kpc.
By the drop in density according to the input scale length, $r_s$, at these distances its magnitude remains only a fraction of the inner constant density disk value, as is illustrated in the middle panel plot of Figure 21. The contribution of emission far into the velocity dispersion wings from gas nearer to the Galactic center becomes non-trivial at such low densities. Generally, the effects induced by velocity crowding and velocity dispersion are stronger in the center direction than in anticenter direction, because there the inner solar radius gas emission conveys at low positive and low negative velocities with the outer–Galaxy emission through its own finite velocity dispersion.

From the middle panel of Figure 21, it can be seen that the input density of $n_{HI} = 0.3 \text{ cm}^{-3}$ yields realistic volume density values after conversion. The lower panel in that figure was shown for the remarkably steep rising scale–height for smaller radii, something that is also observed in the analysis of the real data in this project, as well as in that of others. It is, obviously, not according to the original input, but due to a strong broadening of the elongated patches mentioned before when approaching $R_0$, thus biasing the azimuthally averaged scale height to greater values.

6 Deviations from circular symmetry

There is substantial long–established evidence for bilateral asymmetry in the outer–Galaxy gas layer. The kinematic cutoff at $b = 0^\circ$ corresponding to the far outskirts of the Galaxy occurs at velocities some 25 km/s more extreme in the southern–hemisphere data than in the northern (Burton, 1973 [5]). Additionally, the tightest constraint of radial velocities occurs $6^\circ$ removed from the cardinal direction $l = 180^\circ$; for $l = 90^\circ$, circular symmetry would formally forbid any positive velocities (except those due to velocity dispersion), while, in fact, the emission peaks at $v = +6 \text{ km/s}$ (Burton, 1972 [4]). Early on, Kerr (1962) [13] suggested that the apparent difference between the inner–Galaxy northern and southern rotation curves derived from terminal velocity data could be due to an outward motion of the adopted local standard of rest of about 7 km/s. Blitz & Spergel (1991) [2] reproduced the shape of the difference between velocity contours in the $0^\circ < l < 180^\circ$ and $180^\circ < l < 360^\circ$ regions corresponding to a 1 K isotherm by adopting a 14 km/s radial outward LSR motion and, assuming this to be kinematically equivalent to a more naturally explained radial outward component at the sun’s location along global elliptical streamlines, they put forward a model of gas streamlines with decreasing ellipticity outwards, the outermost gas moving in almost circular orbits, with an angle $\alpha$ between the sun–center
line and the semi–major axis of the gas distribution of $\approx 45^\circ \pm 20^\circ$, and an ellipticity $\epsilon \approx 0.02$, which they found to be consistent with some other observables they examined (e.g. stellar kinematics, molecular gas). Kuijken & Tremaine (1991) and Kuijken (1992) argued that from their examination of the kinematics of the solar neighborhood they found little or no evidence for large–scale nonaxisymmetry. They note, however, that it would be very difficult to detect any ellipticity, if the sun happens to reside near a symmetry axis. These and other investigations were reviewed by Burton (1991).

The dynamical situation responsible for the observed asymmetries remains unclear, as does the extent to which the asymmetries might be spatial rather than kinematic. However, it is clear that even small deviations from kinematic symmetry are likely to have an observable impact on the HI profiles, since their shape is very sensitive to small variations in the streaming motions (Burton, 1972). We will consider in what follows consequences of kinematical asymmetry only, although we note that it seems unlikely that this would be the exclusive cause of the observational situation in view of the common occurrence of true lopsidedness in other nearby spiral galaxies (Baldwin et al., 1980; Richter & Sancisi, 1994). In any case, it is important to realize that many kinematic asymmetries are necessarily joined by a spatial counterpart (e.g. non–zero ellipticity, with the sun–center line anywhere in between the semi–major and semi–minor axes of the ellipsoid) and that a true structural lopsidedness, due to an $m = 1$ harmonic term in the Galactic potential, is always revealed by a perturbation in the line of sight velocity field (Swaters et al., 1999).

We do not go into a full detailed treatment in order to pinpoint a definite Galactic morphology and its kinematics that can account for the observed deviations from circular symmetry, but instead we want to make use of our model simulations as a controlled input, showing the observational implications of assumed real galactic asymmetries that have been suggested as explanations of the observed asymmetries on several aspects of observed spectra at the same time. In fact, this gives us a powerful instrument for putting constraints on various solutions to the asymmetry problem in the literature.

In order to do so, we will first distinguish a set of observed asymmetries and establish a method to measure these asymmetries quantitatively. Then, after having found the real data’s values of these parameters, we will adopt a list of possible morphologies and kinematics and measure the same set of parameters in the data as simulated according to these models. The measurements take place in an ($l, v$)–displayed set of spectra at $b = 0^\circ$. 

Figure 23: \((l,v)\) plot at \(b = 0^\circ\) (upper panel) as well as a latitude integrated version for \(|b| \leq 10^\circ\) (lower panel), which can be considered free of any influence by deviations from the galactic plane. Like in Figure 1, the peak intensity of the upper panel corresponds to a brightness temperature around 135 K and the lightest grey-scale corresponds to \(T_b=4\) K. The lower panel was averaged over its \(b\) values and has a deviating grey-scale scaled between minimum and maximum intensities.

Some measurements shall be taken as well from a \(b\)-integrated \((l,v)\) display, for \(|b| \leq 10^\circ\), to remove most of the warp’s influence on these displays as is demonstrated in the next section.

### 6.1 Asymmetries in the data

We define spectral asymmetry as any feature or property of the \(T_b\) spectral \((l,v)\) images, insofar as not corresponding to those according to simple planar circularly symmetric rotation, with the assumed flat rotation curve as described in section 4.

In the \((l,b,v)\) data we choose to monitor the following set of parameters, when we reproduce galactic spectra according to different models. Most of these have been used before in investigations on Galactic asymmetry and some have been added by us, not always as an asymmetry, but also to put restrictions on the various explanations of observed asymmetry. We explain how we proceed to measure these phenomena and give the according values for the real data.

1. The kinematic or spatial cutoff appears to occur at more extreme velocities in the part of the hemisphere accessible from the south than that from the north.

2. The maximum velocities attained in the north and the south are not centered on \(l = 90^\circ, 270^\circ\) respectively, as would be expected in the symmetrical case.

3. The shapes of the extreme velocity curves in the north and the south differ.

4. The tightest velocity constraint towards the anticenter is displaced by a few km/s into the third quadrant.
5. The centroid or middle of this velocity distribution still appears centered on $l = 180^\circ$.

6. The tightest velocity constraint towards the center is not displaced as it is towards the anticenter.

7. The centroid of the velocity distribution around $l = 0^\circ$ is significantly displaced to positive velocities.

8. Emission extends to higher positive velocities in the second quadrant than to corresponding negative velocities in the third.

9. Finally, it appears that the velocity integrated column depth is large in the fourth quadrant with respect to the first, and that of the second quadrant is large compared to the third.

We can further make remarks on the apparent asymmetries, as observed in the real data after conversion under the assumption of circular symmetry, in the $(R, \theta, z)$ frame, as can be seen in the Figures 3 through 6. They were not measured quantitatively.

1. In general the South is observed to be endowed with a progressively higher abundance of gas with increasing radii than the North.

2. An elongated patch of gas in the center direction, reaching high $z$, is observed to be displaced from $l = 0^\circ$ into the fourth quadrant.

These effects can be real spatial anomalies (which would for point 2 be highly unlikely) or the result of the conversion itself under the, at least in part, wrong assumptions of circular symmetry.

In particular the effect mentioned in point 1 could be reproduced if the kinematic situation would be such that gas on a certain radius from the Galactic center would give rise to a higher velocity along the line of sight in the south than in the north, be this due to its own velocity or due to that of the LSR$^1$.

Furthermore, the effect mentioned in point 2, when centered symmetrically on $l = 0^\circ$, is caused by local velocity-dispersed gas, entering at the center direction into negative velocities for the first quadrant and into positive velocities for the fourth and hence accounted for originating from beyond the solar circle near $l = 0^\circ$ and scaled to densities accordingly (see also the

---

$^1$In the Hartmann & Burton Leiden/Dwingeloo Survey the LSR was defined in terms of the Standard Solar Motion of 20 km/s toward $(\alpha, \delta)^{1900} = (18^h, 30^\circ)$. Productive
6 DEVIATIONS FROM CIRCULAR SYMMETRY

This effect can also be seen in the simulation of section 5.2. The displacement can be easily conceived of by assuming a line of sight net positive velocity between the LSR and the local gas in the center direction, be this due to local streaming or to a radial velocity gradient by a non-circular global streaming.

To quantify all these conditions we measure parameters as follows. For the items 4, 5, 6, and 7, we make use of the IDL routine GAUSSFIT as described in section 4.1 to fit a Gaussian to the velocity distribution in the \((l,v)\) plot at certain longitudes around the cardinal directions \(l = 0^\circ\) respectively \(l = 180^\circ\), after we have removed spectral features that are less than a factor \(e^{-2}\) times the maximum \(T_b\) value at that specific longitude, that otherwise might have contaminated the outcome. The tightest velocity constraints are then taken to be the minima along a plot of the Gaussian widths varying with longitude, while the centroid of the velocity distribution simply is the location of the center of the Gaussian with longitude. For the items 1, 2, and 3, we only make use of the contour in the \((l,v)\) display at \(T_b = 2\) K. Item 1 is the maximum velocity along this contour over a broad longitude range around \(l = 270^\circ\), respectively the minimum around \(l = 90^\circ\). The longitudes where these extremes were recorded represent item 2. A parameter, \(v_{diff}\), is calculated from the difference between the magnitude of the negative velocities at \(l\), for \(0^\circ < l < 180^\circ\), and the positive velocities at their co–longitudes, at \(360^\circ - l\). This parameter corresponds to the shape of the extreme velocity curves, mentioned in item 3, and is positive for larger velocities in the south than in the north at any particular longitude. It is the same parameter that was used by Blitz & Spergel (1991) as the principal indication of their suggested outwardly decreasing ellipticity model. The emission mentioned in item 8 is probably due to local gas that, in a purely circularly symmetrical case, by its velocity dispersion would enter the (for its circular kinematics) forbidden quadrants in equal amounts (as was shown by the simulations of section five), but now has an extra positive line of sight velocity. If the emission were due to gas from larger radii in the second quadrant, shifted sufficiently to positive velocities to show up at \(v > 0\) km/s, it might surprise why this large–scale feature does not extend into the 1st and the 3rd quadrants, but instead disappears at their boundary quite abruptly. Also, it is shown below in section seven that a net radial inward (to the Galactic center) velocity of the LSR would reproduce the desired effect, but this is strongly ruled out by other (global) kinematic measures. Furthermore, a tangential error in the LSR would either increase the extent to which the emission enters the formally forbidden velocities for both quadrants or decrease them at the same time. Finally, item 9 is
Figure 24: Compilation of parameter plots derived from an \((l,v)\) display at \(b = 0^\circ\). The upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width \((\sigma)\) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ - l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\textsuperscript{th} quadrant with respect to the 1\textsuperscript{st}, and of the 3\textsuperscript{rd} with respect to the 2\textsuperscript{nd}.

In addition to this it followed that the most extreme velocity in the first two quadrants along a contour of 2 K in brightness temperature was \(-126\) km/s occurring at \(l = 117^\circ\) (27° displaced from \(l = 90^\circ\)), while for the last two it was \(+144\) km/s occurring at \(l = 281^\circ\) (11° displaced from \(l = 270^\circ\)), which renders their absolute ratio to be 1.1. Furthermore, emission from local gas enters along the same contour the formally forbidden second quadrant at an average velocity of 16.5 km/s, while in the third at \(-11.0\) km/s, establishing an absolute ratio of 1.5.

Quantified by integrating over velocities with \(v < 0\) km/s for \(0^\circ < l < 180^\circ\) and with \(v > 0\) km/s for their co–longitudes, at \(360^\circ - l\). The \(l\) values are then subtracted from the \((360^\circ - l)\) values and this is divided by the \((360^\circ - l)\) values and then multiplied by 100 to give change in column depth in percentages. The integration cutoff at \(v = 0\) km/s does not significantly affect this parameter, \(N_{\text{diff}}\), but instead the plot remains quite similar if we take the cutoff at \(v = \pm 10, \pm 20\) or \(\pm 30\) km/s, as was also shown by Blitz & Spergel.

Figure 24 shows a compilation of parameter plots derived from an \((l,v)\) display at \(b = 0^\circ\) of the composite data cube and Figure 25 shows the same set of parameters for a latitude integrated \((l,v)\) data set in the range \(|b| \leq 10^\circ\). Since the data grid points are separated by half a degree in latitude, this last measurement includes 41 cuts through the data of the sort that was used in the first. The change in the plots from \(b = 0^\circ\) to \(|b| \leq 10^\circ\) was monitored for the integrations \(|b| \leq 1^\circ, |b| \leq 2^\circ, \) and \(|b| \leq 5^\circ\) as well and found to behave continuously and to settle fast towards the situation of the \(|b| \leq 10^\circ\) plots. It can thus be relied upon that this plot reflects the global kinematic (and spatial) situation more accurately than any of the others, moreover so because effects due to the deviation of the HI layer from the plane \(b = 0^\circ\) at larger radii, are being prevented, since emission at intensities large enough to
Figure 25: Same plots from an \((l, v)\)-display at \(|b| \leq 10^\circ\) as in Figure 24 are shown here. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width \((\sigma)\) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ - l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4th quadrant with respect to the 1st, and of the 3rd with respect to the 2nd. Corresponding values for the extreme velocity cutoffs at \(T_b=2\) K are \(-123\) km/s at \(l = 105^\circ\) (15° displaced from \(l = 90^\circ\)) and 132 km/s at \(l = 277^\circ\) (7° displaced from \(l = 270^\circ\)), with a ratio of 1.1. The local gas has averages of 15.2 km/s respectively \(-12.2\), giving 1.2 as an absolute ratio.

have an influence on the parameters under consideration here predominantly originates from within the covered latitude range. The difference between the plots of the centroid around \(l = 0^\circ\) can therefore be attributed to a local irregularity in global streaming in the \(b = 0^\circ\) case, something that is, in center direction, not implausible. It is reassuring for this reasoning that in the direction \(l = 180^\circ\), where great kinematic turmoil is not observed, the velocity centroid of both distributions have almost identical positions. The greater spectral width of the plot of tightest \(v\)–constraint with longitude around \(l = 0^\circ\) in the case of the \(b = 0^\circ\) data cut with respect to the \(|b| \leq 10^\circ\) version, while in the direction of longitudes around \(l = 180^\circ\) they keep identical values, is a feature that appears to be regular and inherent to the dynamical situation and is reproduced in all of the simulations we made in this project. In particular, note the difference between Figure 27 and Figure 28, in this context. The change of the parameter \(v_{\text{diff}}\) along \(0^\circ < |l| < 180^\circ\) indicates that the outer–Galaxy line of sight radial velocities, measured at \(T_b=2\) K, are more extreme in the 4th quadrant, and well into the 3rd, with respect to those from the 1st quadrant, and into the 2nd. At certain directions \((l \approx 110^\circ\) and \(l \approx 250^\circ)\) this reverses and the velocities in the 2nd quadrant become more extreme than those in the 3rd. The column depth \((N_{\text{diff}})\) varies similarly. Here, around \(l = 100^\circ\), there is a high relative peak to be seen of velocity integrated densities in the southern data with respect to the northern, a structure that has attributed to the Carina spiral arm by some authors, as was mentioned by Blitz & Spergel. In any case, this
Figure 26: Same plots from an \((l, v)\) display at \(b = 0^\circ\) as in Figure 24 are shown here for the simulated data according to a circularly symmetric model. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width \((\sigma)\) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ - l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\textsuperscript{th} quadrant with respect to the 1\textsuperscript{st}, and of the 3\textsuperscript{rd} with respect to the 2\textsuperscript{nd}. Corresponding values for the extreme velocity cutoffs at \(T_b=2\) K are \(-156\) km/s at \(l = 90^\circ\) (0\(^\circ\) displaced from \(l = 90^\circ\)) and \(156\) km/s at \(l = 270^\circ\) (0\(^\circ\) displaced from \(l = 270^\circ\)), with a ratio of 1.0. The local gas has averages of 14.1 km/s respectively \(-14.1\), giving 1.0 as an absolute ratio.

sort of large structures seem to suggest that we should be cautious, when we try to explain the shapes of these parameters by global kinematic measures only, omitting other large scale influences like e.g. spiral structure.

6.2 Symmetrical reference data

As a reference to what would be the observational situation in case of perfect circular symmetry or circular kinematic symmetry, but with a linear sinusoidal warp, and as yet another check on the behavior of the synthetic spectra, we performed the same asymmetry analysis as above on the controlled models that were described in section five. When considering perfect circular symmetry, there are indeed no deviations detected of the sorts cataloged in the previous subsection. This can be verified in Figure 26. This situation changes slightly though, with respect to the parameters \(v_{\text{diff}}\) and \(N_{\text{diff}}\), for the model including a linear sinusoidal warp (Figure 27). When we integrate the \((l, v)\) display for \(|b| \leq 10^\circ\), however, this difference almost totally vanishes, since then the warped layer is included as well (Figure 28). Note, as was mentioned above, how this also brings the two different tightest velocity constraints closer together.
Figure 27: Same plots from an \((l, v)\) display at \(b = 0^\circ\) as in Figure 24 are shown here for the simulated data according to a circularly kinematically symmetric model with a linear sinusoidal warp, with its maximum at \(\theta = 95^\circ\). Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width \((\sigma)\) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ - l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\textsuperscript{th} quadrant with respect to the 1\textsuperscript{st}, and of the 3\textsuperscript{rd} with respect to the 2\textsuperscript{nd}. Corresponding values for the extreme velocity cutoffs at \(T_b=2\) K are \(-133\) km/s at \(l = 98^\circ\) (8\(^\circ\) displaced from \(l = 90^\circ\)) and 136 km/s at \(l = 259^\circ\) (–11\(^\circ\) displaced from \(l = 270^\circ\)), with a ratio of 1.0. The local gas has averages of 14.1 km/s respectively –14.1, giving 1.0 as an absolute ratio.

Figure 28: Same plots from an \((l, v)\) display at \(|b| \leq 10^\circ\) as in Figure 24 are shown here for the simulated data according to a circularly kinematically symmetric model with a linear sinusoidal warp, with its maximum at \(\theta = 95^\circ\). Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width \((\sigma)\) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ - l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\textsuperscript{th} quadrant with respect to the 1\textsuperscript{st}, and of the 3\textsuperscript{rd} with respect to the 2\textsuperscript{nd}. Corresponding values for the extreme velocity cutoffs at \(T_b=2\) K are \(-135\) km/s at \(l = 95^\circ\) (5\(^\circ\) displaced from \(l = 90^\circ\)) and 135 km/s at \(l = 265^\circ\) (–5\(^\circ\) displaced from \(l = 270^\circ\)), with a ratio of 1.0. The local gas has averages of 14.1 km/s respectively –14.1, giving 1.0 as an absolute ratio.
6.3 Modeled asymmetries

In general we can distinguish some categories of asymmetries with respect to deviations from simple planar circularly symmetric rotation, with the assumed flat rotation curve as described above.

- Deviations from planar rotation.
- Deviations from a flat rotation curve.
- Deviations in the LSR.
- Deviations from circular streaming.

The only deviation with immediate observational consequences that is quite firmly established is the one that is first mentioned and has for a symmetrical warp been tested already in the previous subsection. The possibilities that were further investigated here were the following:

- Asymmetrical warp
- Radial velocity LSR inward/outward from the GC.
- Global circular streaming, with sun on elliptical movement.
- Global elliptical streaming.
- Small radial velocity of local gas in the solar neighborhood.
- Linear change in ellipticity from solar radius outward.

With respect to deviations from a flat rotation curve, we can comment as follows. A linear or monotonically and smoothly varying rotation curve will cause only scaling effects due to the different velocity–to–distance transformation. Local perturbations with $R$, however, or, for that matter, with $\theta$, certainly will cause the appearance of the spectra and, after conversion, that of the derived Galactic morphology, to change significantly. Since we consider global parameters only here, we did not perform such simulations. During our investigations various different values for the parameters that occur in the models were tried out to monitor the response of the generated spectra to these changes, as will be described in the next section.
### 7 Observational implications of model asymmetries

After having cataloged, in the previous section, a set of observed asymmetries and constraints and listed a number of morphologies and kinematics that could mimic these asymmetries, we will proceed to pursue the observational implications of certain specific models for the observed spectra. It has been shown which properties of the spectra require that the assumptions of circular spatial and kinematic symmetry be abandoned. In this section it will become apparent which modeled asymmetries produce spectra that point in the right direction. For clearness, we will monitor one change with respect to the standard model of section 5.1 at a time, except in 7.7, when we consider global elliptical streaming in combination with an asymmetrical warp. This, to give galactocentric cylindrical plots that are comparable with the real data, since the asymmetrical warp is quite firmly observationally established (and it is the only one in this section to have been so). We are putting limits on a possible error in the determination of the motion of the Local Standard of Rest as well as on possible ellipticity in combination with different orientations of the semi-major axis with respect to the line connecting the sun with the Galactic center. Such galactic asymmetries could mimic some of the observed bilateral asymmetries in the \((l,b,v)\) data. We conclude this section with a consideration of the effects of a velocity–to–distance conversion, using circular kinematics, on the \((l,b,v)\) spectra of a Galaxy that, in fact, rotates along global elliptical streamlines.

#### 7.1 Circular symmetry with asymmetrical warp

The first deviation from the model in section 5.1 is that of an asymmetrical warp. It should be noted that this deviation is less hypothetical than the others that will follow, since it has been accurately measured. Even though this measurement was performed in the data cube that was constructed using circular kinematics instead of some possibly better, but yet unknown, alternative, it cannot be expected to differ more than of the order of, at most, ten percent from reality. The shape of the warp is again sinusoidal, but this time the amplitude differs in the part of the hemisphere that is accessible from the north from that of the south, according to the curves that are plotted in Figure 16. The maximum of displacement from the plane \(b = 0^\circ\) was set to be attained at \(\theta = 120^\circ\). It was separated from the minimum by \(180^\circ\).

An \((l,v)\) plot of the resulting spectra is shown in Figure 29. It is clearly
7 OBSERVATIONAL IMPLICATIONS OF MODEL ASYMMETRIES

Figure 29: Composite spectral image at \( b = 0^\circ \), for a model with circular kinematical symmetry, but asymmetrical warp with its maximum at \( \theta = 120^\circ \), as described in the text. As in Figure 1, the peak intensity of the upper panel display corresponds to a brightness temperature of 135 K and the lightest grey–scale corresponds to \( T_b = 4 \) K.

seen that in the 3\(^{rd}\) and 4\(^{th}\) quadrants, by the folding–back property of the asymmetrical warp in the south, velocities are recorded along the lowest brightness temperature contours that are more extreme than those of the 1\(^{st}\) and 2\(^{nd}\) quadrants. Furthermore, in the compilation of parameter plots, that check for asymmetry, in Figure 30, it is interesting to note the large impact this has on the parameters \( v_{\text{diff}} \) and \( N_{\text{diff}} \), and on the ratio of the extreme velocity cutoffs, for a cross–cut at \( b = 0^\circ \). Taking into account the relative certainty with which we should accept the asymmetrical warp effects, they should be imagined to reside implicitly in the same real data’s \( b = 0^\circ \) parameter plots. However, it was demonstrated earlier (in section 6.2) that for a \( |b| \leq 10^\circ \) plot these effects largely disappear. Also, mind that the distortions of the above mentioned parameters from symmetry due to the asymmetrical warp will have to be superimposed on those resulting from the following investigations, if comparison is to be made with the plots in Figure 24. Particularly, it is encouraging that the \( N_{\text{diff}} \) parameter in this figure is quite indented for the first few tens of degrees in \( |l| \), when compared with its \( |b| \leq 10^\circ \) counterpart, consistent with the curve below 0% of \( N_{\text{diff}} \) in Figure 30. To visualize its asymmetrical character, the warp was also displayed in a cylindrical cut through \( z \) and \( \theta \) at the galactocentric distance of \( R = 20 \) kpc.

7.2 Radial velocity LSR

Superimposed upon the standard flat plane–parallel simulated Galaxy with circular kinematic and spatial symmetry (section 5.1) is the effect of a 10 km/s motion of the LSR radially outward from the Galactic center. Figure 32 shows the spectral situation of this model, again for \( b = 0^\circ \). From this figure and from the compilation of parameter plots in Figure 33 it can clearly be seen that both in the center and in the anticenter directions the centroid of the spectrum has an off–set exactly as great as the initial radial velocity in absolute magnitude. The \( v_{\text{diff}} \) parameter shows a reasonable fit to the real data (Figure 25), although a slightly better fit would be attained for a higher radial outward velocity. This is exactly what Blitz & Spergel derived for the
Figure 30: Same plots for $b = 0^\circ$ as in Figure 24, for the case of circular kinematical symmetry with an asymmetrical warp with a maximum at $\theta = 120^\circ$. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes ($360^\circ – l$), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4th quadrant with respect to the 1st, and of the 3rd with respect to the 2nd. Corresponding values for the extreme velocity cutoffs at $T_b=2$ K are $-111$ km/s at $l = 89^\circ$ ($-1^\circ$ displaced from $l = 90^\circ$) and 156 km/s at $l = 270^\circ$ ($0^\circ$ displaced from $l = 270^\circ$), with a ratio of 1.4. The local gas has averages of 14.1 km/s respectively $-14.1$, giving 1.0 as an absolute ratio.

Figure 31: Mean HI volume densities in a cylindrical cut through the simulated data cube at a galactocentric distance of $R = 20$ kpc, for a model with circular kinematical symmetry, but asymmetrical warp as described in the text. The warp maximum here was set at $\theta = 120^\circ$. From the intersection of the Galactic midplane with the plane established by $b = 0^\circ$ it can be seen that the line of nodes resulting from this warp maximum in the case of a sinusoidal warp is not consistent with what is seen in the real data (Figures 2–5).
Figure 32: Composite spectral image at $b = 0^\circ$, for a model with circular symmetry but a radial outward velocity of 10 km/s as described in the text. As in Figure 1, the peak intensity corresponds to a brightness temperature of 135 K and the lightest grey-scale corresponds to $T_b = 4$ K.

Figure 33: Same plots for $b = 0^\circ$ as in Figure 24, for the case of circular symmetry with a radial outward velocity of 10 km/s. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes ($360^\circ - l$), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4$^{th}$ quadrant with respect to the 1$^{st}$, and of the 3$^{rd}$ with respect to the 2$^{nd}$. Corresponding values for the extreme velocity cutoffs at $T_b = 2$ K are $-157$ km/s at $l = 93^\circ$ ($3^\circ$ displaced from $l = 90^\circ$) and $157$ km/s at $l = 273^\circ$ ($3^\circ$ displaced from $l = 270^\circ$), with a ratio of 1.0. The local gas has averages of 7.4 km/s respectively $-20.9$, giving 0.4 as an absolute ratio.

same parameter in their simulations. As a best fit they found $v_{\text{rad}} = 14$ km/s outward. However, our other parameters strongly oppose such an outcome. For, not only would this increase the velocity of the centroid with respect to the center direction, which is not desirable in view of Figure 25, but also, and this is most important, does it contradict the observational evidence of little or no velocity with respect to the anticenter of the spectral centroid found there. On the other hand it is possible to reconcile $N_{\text{diff}}$ with the observations, but it will be shown below that this is also possible for other models. The same is true for $v_{\text{diff}}$. Finally, by itself not conclusive, but still a matter of concern, is that the ratio of the average local gas velocities shows a directly opposite movement to what is observed. Note, that in case of an inward velocity all effects would be the same, but reversed. Through the above mentioned reasoning we rule out any correction to the LSR used in the Leiden/Dwingeloo survey greater than a few km/s.
7 OBSERVATIONAL IMPLICATIONS OF MODEL ASYMMETRIES

7.3 Solar elliptical movement

In the case of a solar elliptical movement, but keeping the remainder of the Galaxy identical to that in section 5.1, the effects mimic in part those for a solar radial velocity. The rotational situation is shown in Figure 34 for a face–on view of the Galaxy as seen from the north pole. In Figures 35 and 36 the results are shown for the case of an ellipticity of $\epsilon = 0.05$ and an angle between the sun–center line and the semi–major axis of its orbit of $\alpha = 45^\circ$. The line of sight component of the sun’s orbital velocity immediately creates a non–acceptable shift with respect to the anticenter centroid and even a double shift in the center direction. At the same time the ratio of the local gas average velocities again moves in the wrong direction. Any measure to reduce both shifts in order to get within reach of the real observables, reduces the effects on $v_{diff}$ and $N_{diff}$ correspondingly and thus seems not very fruitful. These measures include a decrease in ellipticity and a change of $\alpha$ towards both 0$^\circ$ and 90$^\circ$. For these reasons, we rule out the solar elliptical movement according to the model as discussed as a natural explanation of the observed asymmetries.

We must note that all alternatives that imply a motion of the LSR with respect to its immediate neighborhood are likely to be refuted by the same constraints mentioned above, since the bigger part of all the 21 cm intensity is emitted by gas that resides within a few kpc distance from the sun. The parameter $v_{diff}$ on the other hand originates from the outer Galaxy only. As we shall see, is in the case of global elliptical streaming the velocity difference with respect to the immediate solar neighborhood limited, whereas with respect to the region outside the sun–center radius in the direction of $l = 0^\circ$ it is considerable. This is in direct correspondence with the observed data.
Figure 36: Same plots for $b = 0^\circ$ as in Figure 24, for the case of circular kinematics with the sun moving on a slightly elliptical orbit, with $\epsilon = 0.05$ and $\alpha = 45^\circ$. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes ($360^\circ - l$), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4th quadrant with respect to the 1st, and of the 3rd with respect to the 2nd. Corresponding values for the extreme velocity cutoffs at $T_b = 2$ K are $-161$ km/s at $l = 92^\circ$ ($2^\circ$ displaced from $l = 90^\circ$) and $151$ km/s at $l = 272^\circ$ ($2^\circ$ displaced from $l = 270^\circ$), with a ratio of 0.9. The local gas has averages of 10.5 km/s respectively $-17.6$, giving 0.6 as an absolute ratio.

Figure 37: Construction of the rotational situation used in the global elliptical streaming simulation. For clearness, the ellipticity is greatly exaggerated.

7.4 Global elliptical streaming

The model incorporating global elliptical streaming is further clarified in Figure 37. Reviewed here is the situation for $\epsilon = 0.05$ and $\alpha = 45^\circ$. Figures 38 and 39 show the results of its analysis. It is immediately seen that this model combines positive results for all parameters. Thus, it causes the required positive velocity displacement for the centroid in the center direction, and still keeps that in the anticenter direction fixed at zero. Both $v_{diff}$ and $N_{diff}$ show a distortion that can, in combination with that of the asymmetrical warp, be united with the situation for the real data. On top, the ratio of the local gas average velocities agrees more here to that observed. We cannot give a fixed set of variables here that represent a best fit, but it is clear that this is the only one of our models that accounts for the general trends without contradicting others. In fact, it has not been found possible by any other model than global elliptical streaming, through the simulations we used, to reproduce the required positive velocity of the center direction centroid and at the same time keep the centroid in the anticenter direction fixed at $v = 0$ km/s within a few km/s. Finally, if the angle $\alpha$ were to be set at negative values all plots would show the same curves, but inverted. It is interesting to see that the conclusion resulting from this subsection
Figure 38: Composite spectral image at $b = 0^\circ$, for a model with global elliptical streaming as described in the text. As in Figure 1, the peak intensity of the upper panel display corresponds to a brightness temperature of 135 K and the lightest grey–scale corresponds to $T_b=4$ K.

Figure 39: Same plots for $b = 0^\circ$ as in Figure 24, for the case of global elliptical streaming. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes $(360^\circ - l)$, such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4th quadrant with respect to the 1st, and of the 3rd with respect to the 2nd. Corresponding values for the extreme velocity cutoffs at $T_b=2$ K are $-166$ km/s at $l = 90^\circ$ ($0^\circ$ displaced from $l = 90^\circ$) and 147 km/s at $l = 271^\circ$ ($1^\circ$ displaced from $l = 270^\circ$), with a ratio of 0.9. The local gas has averages of 14.1 km/s respectively $-14.1$, giving 1.0 as an absolute ratio.

invokes a ellipticity and an orientation of the inflicted morphology, that is consistent with the model that Blitz & Spergel put forward. Although it can be seen that their assumption, that the kinematic influence on $v_{diff}$ of a radial component of the solar motion along elliptical streamlines is identical to a true radial velocity of the LSR, is not generally valid.

7.5 Local streaming

Since there was no global model found that could naturally explain the greater than one value of the absolute ratio of local gas average velocities without going against other strong constraints, a non–global explanation was thought of that could. This was that of local streaming. The model is again the Galaxy of section 5.1, only this time with an area around the sun’s location within a radius of 250 pc that has a velocity radially outward from the Galactic center of 7 km/s. It is important to realize that by our parameters in the compilation of Figure 41 only the response of the data in the anticenter direction is monitored, and that, in fact, in the center direction the reasoning around the asymmetrical, elongated patch of gas (section 6.1)
7 OBSERVATIONAL IMPLICATIONS OF MODEL ASYMMETRIES

Figure 40: Composite spectral image at $b = 0^\circ$, for a model with local streaming as described in the text. As in Figure 1, the peak intensity corresponds to a brightness temperature of 135 K and the lightest grey-scale corresponds to $T_b=4$ K.

Figure 41: Same plots for $b = 0^\circ$ as in Figure 24, for the case of local streaming. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes $(360^\circ - l)$, such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the $4^{th}$ quadrant with respect to the $1^{st}$, and of the $3^{rd}$ with respect to the $2^{nd}$. Corresponding values for the extreme velocity cutoffs at $T_b=2$ K are $-156$ km/s at $l = 90^\circ$ ($0^\circ$ displaced from $l = 90^\circ$) and $156$ km/s at $l = 270^\circ$ ($0^\circ$ displaced from $l = 270^\circ$), with a ratio of 1.0. The local gas has averages of $18.2$ km/s respectively $-11.0$, giving 1.6 as an absolute ratio.

would argue for a motion away from the sun. In Figures 40 and 41 it can be seen that local streaming reaches the right objectives and yet leaves the other observables almost unaffected. When we increase the radius of the local area that is given a net velocity, the parameters increasingly respond to it in accordance with an error in the LSR, as more overall HI intensity is taken to have a distorted velocity. As a local effect one would need to incorporate all local effects that are associated with the solar neighborhood on such scales, in order to derive valid conclusions about Galactic properties. As such it is not meant to describe the solar neighborhood in this section. However this model is taken to be suggestive of a remarkability in the analysis of the parameters we monitor, in view of an observed asymmetry.

7.6 Decreasing versus constant ellipticity

Finally, we comment upon the difference of constant ellipticity versus decreasing ellipticity, as advocated by Blitz & Spergel. The same global elliptical model as in the subsection 7.5 above was altered to let the ellipticity decrease linearly beyond $R = 9$ kpc to zero at $R = 25$ kpc. A parameter compilation plot was made, as shown in Figure 42, comparable to that in
Figure 42: Same plots for $b = 0^\circ$ as in Figure 24, for the case of an outward decreasing elliptical streaming. Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width ($\sigma$) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes ($360^\circ - l$), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4th quadrant with respect to the 1st, and of the 3rd with respect to the 2nd. Corresponding values for the extreme velocity cutoffs at $T_B=2$ K are $-160$ km/s at $l = 92^\circ$ ($2^\circ$ displaced from $l = 90^\circ$) and $160$ km/s at $l = 272^\circ$ ($2^\circ$ displaced from $l = 270^\circ$), with a ratio of 1.00. The local gas has averages of 14.0 km/s respectively $-14.2$, giving 1.0 as an absolute ratio.

Figure 39. The slight differences might be pleading in favor of the decreasing ellipticity, though not very strongly on the basis of our analysis. For comparison, we tried a version with increasing ellipticity from the solar radius onwards, with negative results.

7.7 Conversion remarkabilities

There is a compelling argument that could make it worthwhile to test a conversion to galactocentric ($R, \theta, z$) coordinates from heliocentric ($l, b, v$) coordinates taking as an input model a combination of the best options of the alternatives that we went through in the subsections above. This would be a combination of the asymmetrical warp and the global elliptical streaming with $\alpha = 45^\circ$ and an ellipticity of $\epsilon=0.05$. This argument is, of course, that if our Galaxy were to be of such morphology, with corresponding kinematics, then at the velocity–to–distance conversion, assuming the wrong type of kinematics, errors would be made with respect to the distances that are then attributed to certain emissivities and, what is at least as bad, volume densities are calculated accordingly. As in section 5.2, we thus constructed the complete ($l, b, v$) data cube for the combined model mentioned here. Resulting plots for spectra through $v$ and $l$ for $b = 0^\circ$ and for $|b| \leq 10^\circ$ are shown in Figure 43. Compare the two compilation parameter plots in Figures 44 and 45 that were derived from them. It is instructive to note that the velocity of the centroid of the spectrum in the center direction is
Figure 43: $(l,v)$ plot at $b = 0^\circ$, for the simulated data with elliptical streaming and asymmetrical warp with its maximum at $\theta = 95^\circ$ (upper panel), as well as a latitude integrated version $|b| \leq 10^\circ$ (lower panel), to show the effects this has on the influence of the warp. As in Figure 1, the peak intensity of the upper panel display corresponds to a brightness temperature of 135 K and the lightest grey-scale corresponds to $T_b=4$ K. The lower panel display was averaged over its $b$ values and has a deviating grey-scale scaled between minimum and maximum intensities.

lessened significantly when averaged over several (41 to be exact) cross-cuts in latitude. Compared to Figure 25, this ellipticity suddenly does not seem very large anymore, but instead quite appropriate. Also, note, how the effect of the asymmetrical warp is greatly reduced for the case $|b| \leq 10^\circ$. Now let us consider the remarkabilities concerning the velocity–to–distance data processing. As one can see in Figure 46, the discrepancy between the input model and its display in $(R, \theta, z)$ after conversion is by far greater than that, as described in section 5.2.2, of the case of identical model and conversion kinematics. Since, in addition to some of the vagaries that were commented upon there, we see some striking new ones. First, it appears that, just as in the Figure 3–6 displays, the $4^{th}$ quadrant is overabundant in gas with respect to the $1^{st}$ and similarly the $2^{nd}$ quadrant displays a higher volume density than the $3^{rd}$, especially for larger radii. Secondly, the rise to high $z$ from the $2^{nd}$ quadrant to the $1^{st}$ of the HI gas layer and its subsequent detachment of that in the $4^{th}$ quadrant. A feature that, again more towards higher radii, is also seen in the real data. Finally, the apparent larger overall volume densities of the southern hemisphere data with respect to the northern. This is perceived to be due to the kinematic effect that was explained in section 6.1.

8 Summary

In this project the Leiden/Dwingeloo data was used as a main constituent in a composite data cube to display the outer reaches of our Galaxy. To account for any possible distortion of the warp description due to anomalous velocity gas the principle HVC complexes as identified by Wakker & van Woerden were masked out before the velocity–to–distance conversion took place. For this conversion we used the IAU standards of $R_0=8.5$ kpc and $\Theta_0=220$ km/s. Due to the properties of the Leiden/Dwingeloo survey, at the same time a
Figure 44: Same plots from an \((l,v)\) display at \(b = 0^\circ\) as in Figure 24 are shown here for the simulated data according to a model with elliptical streaming and asymmetrical warp with its maximum at \(\theta = 95^\circ\). Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width (\(\sigma\)) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ – l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\(^{th}\) quadrant with respect to the 1\(^{st}\), and of the 3\(^{rd}\) with respect to the 2\(^{nd}\). Corresponding values for the extreme velocity cutoffs at \(T_b = 2\) K are \(-133\) km/s at \(l = 98^\circ\) (8° displaced from \(l = 90^\circ\)) and \(136\) km/s at \(l = 259^\circ\) (−11° displaced from \(l = 270^\circ\)), with a ratio of 1.0. The local gas has averages of 14.1 km/s respectively −14.1, giving 1.0 as an absolute ratio.

Figure 45: Same plots from an \((l,v)\) display at \(|b| \leq 10^\circ\) as in Figure 24 are shown here for the simulated data according to a model with elliptical streaming and asymmetrical warp with its maximum at \(\theta = 95^\circ\). Again the upper–left and middle plots show the net radial velocity of the peak 21 cm emission with respect to the LSR towards the center respectively anticenter. The lower–left and middle plots show the width (\(\sigma\)) of the total spectral distribution along any galactic longitude in the center respectively anticenter direction. The upper–right plot shows the difference in velocity of a 2 K contour of longitudes versus their co–longitudes \((360^\circ – l)\), such that it is positive for larger velocities in the southern hemisphere. Finally, the lower–right plot is a measure of the percentage of excess column depth of the 4\(^{th}\) quadrant with respect to the 1\(^{st}\), and of the 3\(^{rd}\) with respect to the 2\(^{nd}\). Corresponding values for the extreme velocity cutoffs at \(T_b = 2\) K are \(-135\) km/s at \(l = 95^\circ\) (5° displaced from \(l = 90^\circ\)) and \(135\) km/s at \(l = 265^\circ\) (−5° displaced from \(l = 270^\circ\)), with a ratio of 1.0. The local gas has averages of 14.1 km/s respectively −14.1, giving 1.0 as an absolute ratio.
Figure 46: Mean HI volume densities in cylindrical cuts through the simulated data cube with elliptical streaming and asymmetrical warp with its maximum at \( \theta = 95^\circ \) at galactocentric distances of \( R = 16 \) kpc (upper) and 26 kpc (lower). The cylindrical-coordinate \((R, \theta, z)\) data set was sampled at 1° intervals in \( \theta \) and 25–pc intervals in \( z \); the velocity–to–distance transformation displayed here was circularly symmetric. The darkest grey–scale was scaled to the maximum densities at each of both radii, to be able to show details even at \( R = 26 \) kpc. For reference a line tracing the galactic plane at \( b = 0^\circ \) was drawn. The warp maximum here was set at \( \theta = 95^\circ \).

more sensitive and more detailed description of the warp and its flaring nature was given than had been possible before. A range of warp parameters was further quantified and compared to previous investigations. In order to follow the method of converting from heliocentric \((l, b, v)\) coordinates to galactocentric \((R, \theta, z)\) coordinates a complete set of synthetic spectra was constructed on the same grid as the Leiden/Dwingeloo survey and subsequently processed in identical manner as the real data. Several observational vagaries that resulted from this test conversion have been identified in the real spectra. In addition controlled conversion has been done for a range of hypothetical Galaxy models to search for resulting remarkabilities that can be associated with the observational situation, since it has been long established that the spectra show asymmetries with respect to global circular spatial and kinematic symmetry. In order to monitor this quantitatively, we choose a fixed set of parameters in the \((l, b, v)\) data and plotted their measured values in a single compilation display. This was done for the real data as a reference as well. It appeared that many different models create an effective significant motion of the LSR, which is by our parameter plots strongly confined to very low velocities. Judging on a global scale these models can therefore be ruled out. To the observational situation, both directly in heliocentric coordinates and in a more subtle (kinematical) way in galactocentric coordinates (after conversion using circular symmetry), remarks can be made that agree with those that follow from a modeled elliptical input Galaxy. This outer Galaxy ellipticity is consistent with that found by Blitz & Spergel. We note, furthermore, that it has the same orientation as the gas streamlines that resulted from the modeling of the motions in the inner few kpc by Liszt & Burton (1980) [18]
References

[1] Baldwin, J.E., Lynden–Bell, D., Sancisi, R. 1980, Monthly Notices Roy. Astron. Soc. 193, 313

[2] Blitz, L., Spergel, D.N. 1991, Astrophys. J. 370, 205

[3] Burke, B.F. 1957, Astron. J. 62, 90

[4] Burton, W.B. 1972, Astron. Astrophys. 19, 51–65

[5] Burton, W.B. 1973, Pub. Astron. Soc. Pacific 85, 679

[6] Burton, W.B. 1985, Astron. Astrophys. Suppl. Ser. 62, 365

[7] Burton, W.B., te Lintel Hekkert, P. 1986, Astron. Astrophys. Suppl. Ser. 65, 427

[8] Burton, W.B. 1991, The Galactic Interstellar Medium, Saas–Fee Advanced Course 21, ed. D. Pfenniger and P. Bartholdi (Berlin: Springer–Verlag), 126

[9] Diplas, A., Savage, B.D. 1991, Astrophys. J. 377, 126

[10] Hartmann, D., Burton, W.B. 1997, Atlas of Galactic Neutral Hydrogen (Cambridge: Cambridge University Press)

[11] Henderson, A.P., Jackson, P.D., Kerr, F.J. 1982, Astrophys. J. 263, 116–122

[12] Kerr, F.J. 1957, Astron. J. 62, 93

[13] Kerr, F.J. 1962, Monthly Notices Roy. Astron. Soc. 123, 327–45

[14] Kerr, F.J., Bowers, P.F., Jackson, P.D., Kerr, M. 1986, Astron. Astrophys. Suppl. Ser. 66, 373

[15] Kuijken, K., Tremaine, S. 1991, Dynamics of Disc Galaxies (Sweden: Varberg Castle), 71

[16] Kuijken, K. 1992, Pub. Astron. Soc. Pacific 104, 809–811

[17] Kulkarni, S.R., Blitz, L., Heiles, C. 1982, Astrophys. J. 259, L63–L66

[18] Liszt, H.S., Burton, W.B. 1980, Astrophys. J. 236, 779
REFERENCES

[19] Liszt, H.S., Burton, W.B. 1983, Astron. Astrophys. Suppl. Ser. 52, 63

[20] Oort, J. H., Kerr, F.J., Westerhout, G. 1958, Monthly Notices Roy. Astron. Soc. 118, 379

[21] Richter, O.-G., Sancisi, R. 1994, Astron. Astrophys. 290, L9

[22] Stark, A.A., Gammie, C.F., Wilson, R.W., Bally, J., Linke, R.A., Heiles, C., Hurwitz, M. 1992, Astrophys. J. Suppl. Ser. 79, 77

[23] Swaters, R.A., Schoenmakers, R.H.M., Sancisi, R., van Albada, T.S. 1999, Monthly Notices Roy. Astron. Soc. 304, 330

[24] Wakker, B.P., van Woerden, H. 1997, Annu. Rev. Astron. Astrophys. 35, 217

[25] Williams, D.R.W. 1973, Astron. Astrophys. Suppl. 8, 505

[26] Wouterloot, J.G.A., Brand, J., Burton, W.B., and Kwee, K.K. 1990, Astron. Astrophys. 230, 21–36