The Distribution of Disk-Halo HI Clouds in the Inner Milky Way

J.M. Lattimer

Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800

ABSTRACT

Studies by Ford et al., concerning the physical properties and distribution of HI clouds in the inner Milky Way using 21 cm HI observations from the Parkes Radio Telescope’s Galactic All-Sky Survey, are reviewed. Individual clouds were identified in regions centered on tangent points at galactic longitudes 25° (quadrant I; hereafter Q1) and 335° (quadrant IV; hereafter QIV) and within 20° of the galactic plane. Clouds in the two regions have similar physical properties and random velocities relative to galactic rotation but are 3 times more populous with double the scale height in Q1 than in QIV. These asymmetries are attributed to their formation from gas lifted from star formation regions of the spiral arms in the disc by superbubbles and stellar feedback or from fragmenting supershells.

Subject headings: Milky Way, HI clouds

1. Introduction

The neutral atomic hydrogen (HI) in the Milky Way lies in a thin disc layer a few hundred parsecs thick (see Schmidt 1957 for a review). The densest and coolest gas is confined closer to the plane than the hotter, more diffuse gas, but their relative temperatures cannot account for their observed scaleheights. Turbulence is likely to provide the necessary support for the hotter gas. However, in the inner Galaxy, there exists an HI component that has an exponential scale height of 400 pc (Dickey & Lockman 1990) and turbulence cannot explain this. Rather, this component may be involved with circulation of gas between the disc and halo and may contain the majority of the kinetic energy of the ISM (Kulkarni & Fich 1985). It has been discovered (Lockman 2002) that the transition region between the disc and halo contains many discrete HI clouds (called disc-halo clouds). Despite the fact that they represent a major component of the Galaxy, their origin, lifetime, evolution
and connection with other interstellar components is unknown. A series of studies by Ford and collaborators (Ford et al. 2008, 2010) investigated the disc-halo cloud population. This review summarizes their findings and inferences.

2. Identifying a Disc-Halo Cloud Population

The data used by Ford et al. (2008, 2010) are from the Galactic All-Sky Survey (GASS), an H I survey of the entire southern sky with declination $\delta \leq 1^\circ$ made with the Parkes Radio Telescope (McClure-Griffiths et al. 2009). GASS is fully sampled at an angular resolution of 16', and covers frequency channels corresponding to velocities relative to the local standard of rest ($V_{\text{LSR}}$) ranging from -400 km s$^{-1}$ to +500 km s$^{-1}$ at a channel spacing of 0.82 km s$^{-1}$. To define a sample of disc-halo clouds with well-determined properties, the study was limited to those clouds located near tangent points in the first (Galactic longitude $\ell$ between 0$^\circ$ and 90$^\circ$) and fourth ($\ell$ between 270$^\circ$ and 0$^\circ$) Galactic quadrants. A tangent point is the location, for a given longitude $-90^\circ \leq \ell \leq 90^\circ$, where the largest velocity magnitude (the so-called terminal velocity $V_t(\ell)$) occurs as the line of sight reaches the minimum distance from the Galactic center. For these Galactic longitudes, a right triangle exists with vertices at the Galactic center, the Sun and the tangent point, with a right angle at the tangent point. Ford et al. (2008) analyzed the HI disc-halo cloud population in the fourth Galactic quadrant of longitude (QIV) between 324.7$^\circ \leq \ell \leq 343.1^\circ$. Ford et al. (2010) analyzed the HI disc-halo cloud population in the first Galactic quadrant of longitude (QI) between 16.9$^\circ \leq \ell \leq 35.3^\circ$. These two regions are mirror-symmetric about the Sun-Galactic center line. Both samples were restricted to Galactic latitude $|b| \leq 20^\circ$.

In the absence of random motions, an object in pure Galactic rotation with $V(R)$ at any tangent point has the maximum radial velocity magnitude $V_t(\ell) = V(R_0 \sin \ell)$, and objects with lower radial velocity magnitudes lie either closer or farther from the Sun. But there are random motions, and it will be seen that the velocity dispersion is of order $\sigma_{cc} = 18$ km s$^{-1}$. If this dispersion was instead interpreted solely as a distance effect, to 1$\sigma$ this would be equivalent to choosing a cutoff velocity $V_c = 18$ km s$^{-1}$ smaller than $V_t(\ell)$. The velocity $V_t(\ell) - V_c$ denotes two specific distances along a longitude line for objects in pure Galactic rotation, which gives a sense of how large a region is actually sampled. Note that the distance to the tangent point is $d_t(\ell, b) = R_0 \cos \ell / \cos b$, where $R_0 = 8.5$ kpc is the Galactocentric distance. The approximate inner and outer sampling distances are found by assuming pure Galactic rotation and are given (in the Galactic plane) by

$$d_{\pm}(\ell) = d_t(\ell) + \frac{R_0 \sqrt{2V(R)V_c}}{V(R) - V_c} \sqrt{1 - \frac{V_c}{2V(R)}} \sin \ell_{\pm}.$$  

(1)
Fig. 1.— A schematic view of the QI and QIV tangent point regions. The longitude boundaries are indicated by the dotted arrows. The locus of tangent points is represented by the dashed circle that connects the Sun and the Galactic center. The solid lines enclose the area around the tangent points bound by the longitude limits and a kinematic distance ±18 km s\(^{-1}\) away from \(V_t\) assuming a flat rotation curve. It will be shown that most of the selected clouds lie within these regions. Figure is taken from Ford et al. (2008).

If one uses the fact that \(V_c/V(R) \ll 1\) and also the approximation of uniform rotation \(V(R) \simeq V_0\) for the inner Galaxy, where \(V_0 = V(R_0) \simeq 220\) km s\(^{-1}\),

\[
d_{\pm}(\ell) = d_t(\ell) + R_0 \sqrt{\frac{2V_c}{V_0}} \sin \ell_{\pm} \simeq 7.7 \pm 1.4 \text{ kpc},
\]

where the center latitudes \(\ell_+ = 25^\circ\) and \(\ell_- = 335^\circ\) were used. The tangent point regions are shown in Fig. 1.

Of course, clouds are characterized by a cloud-cloud velocity dispersion \(\sigma_{cc}\) and are also not located exactly at the tangent points so that an observed cloud in the direction \((\ell, b)\) will have a radial velocity, relative to \(V_t(\ell, b)\), of \(V_{dev} = V_{LSR} - V_t(\ell, b)\). (Note that we are treating \(V_{LSR}\) as a positive quantity in this discussion, which is true in QI, but in QIV it is actually negative.) Thus \(V_{dev}\) is a measure of the difference between a cloud’s LSR velocity and
Fig. 2.— Left: Crosses indicate selected clouds in the QIV region, which satisfy $V_{LSR} \leq -V_t(\ell)$ km s$^{-1}$. Open circles show other clouds. The solid line is the adopted terminal velocity $V_t(\ell)$ from HI and CO observations near the Galactic plane. Taken from Ford et al. (2008). Right: The selected clouds in the QI region, which satisfy $V_{LSR} \geq V_t(\ell) - 0.8$ km s$^{-1}$. Taken from Ford et al. (2010).

the maximum expected from Galactic rotation in that direction. Clouds with significantly negative $V_{dev}$ are likely located far from the tangent point, i.e., very close to or very far from the Sun, but those with positive $V_{dev}$ are likely located very close to the tangent points. The actual volume sampled will depend on $\sigma_{cc}$, but as long as the longitude, latitude and velocity limits are reasonably small, $V_{dev}$ is a reasonable measure of the cloud velocity relative to pure Galactic rotation close to the tangent points. In practice, since the channel spacing is 0.8 km s$^{-1}$, the tangent point sample was taken in QI to consist of those clouds along a line of sight with velocities $V_{LSR} \geq V_t - 0.8$ km s$^{-1}$. In the QIV region, the selected clouds have velocities $V_{LSR} \leq -V_t$. The clouds selected in QI and QIV are shown in Fig. 2.

Terminal velocities $V_t(\ell, b = 0)$ were taken, for QIV, from McClure-Griffiths & Dickey (2007) and Luna et al. (2006), and, for QI, from McClure-Griffiths & Dickey (2011) and Clemens (1985), and are shown in Fig. 3. The fact that the number of clouds declines steeply for $|V_{LSR}| >> V_t$ is consistent with the cloud populations being dominated by Galactic rotation.

The procedures used to detect and measure clouds are summarized in Ford et al. (2008, 2010). The individual cloud properties, such as velocities, radii, and masses, can first be determined assuming they all are located at tangent points, meaning $V_{dev}$ can be determined for each. Errors are assigned based on estimated errors in $V_t$. A simulated cloud population
was derived from the assumptions of a flat rotation curve and co-rotation (i.e., there is no $z$ dependence), and a random line of sight component drawn from a Gaussian with a dispersion $\sigma_{cc}$. Due to the non-zero velocity dispersion of the clouds, other fundamental characteristics such as their distances and scale heights can only be estimated by also assuming a random population of clouds as a function of $R$ (Galactic radial distance) and $z$ (Galactic azimuthal distance) to represent the observed populations. Quite a large volume of the Galaxy has to be simulated to include all clouds likely to end up with observed velocities. Consider the clouds within a small volume at a tangent point. This ensemble has a mean velocity $< V_{LSR} > = V_t$, but half of them have $V_{LSR} > V_t$. Moving closer than the tangent point, one finds $< V_{LSR} > < V_t$ but a considerable fraction still have $V_{LSR} > V_t$. The assumed cloud distribution in cylindrical coordinates $(R, z)$ was taken to be

$$n(R, z) = \Sigma(R) \exp(-|z|/h),$$

where $\Sigma(R)$ is the surface density and $h$ is the exponential scale height. The surface density was taken to be binned in zones of spacing 0.25 kpc from 2.5 to 6.5 kpc. K-S tests were used to maximize the quality of fits to determine the parameters $h$, $\sigma_{cc}$ and $\Sigma(R)$. Details and the determination of errors are discussed in Ford et al. (2008, 2010).
3. Comparison of the Properties of the Disc-Halo Clouds

81 clouds were detected at the tangent points for QIV and 255 for QI. The best-fit velocity dispersions were $\sigma_{cc} = 14.5 \pm 2 \text{ km s}^{-1}$ for QI and $\sigma_{cc} = 18 \pm 2 \text{ km s}^{-1}$. The surface density $\Sigma(R)$ was consistent with a uniform distribution for the QI sample, but was more consistent with a somewhat concentrated distribution around Galactic radii of $R \sim 3 - 4 \text{ kpc}$ in the QIV sample. The vertical distributions were best fit by a scale height $h = 800 \pm 100 \text{ pc}$ for the QI sample and $h = 400 \pm 100 \text{ pc}$ for the QIV sample. The internal velocity dispersions within clouds was about $\Delta v = 10.5 \text{ km s}^{-1}$ for QI and $\Delta v = 12.8 \text{ km s}^{-1}$ for QIV. The distributions of cloud radii and masses were roughly the same for the two samples. The median radius is about 28 pc (with a nominal spread of $\pm 10 \text{ pc}$) and mass in H I is 700 $M_\odot$ (with a nominal spread of 0.5 in log $M$).

Using the value $V_c \simeq \sigma_{cc} \simeq 18 \text{ km s}^{-1}$, the tangent point regions are shown overlaid on an artist’s conception of the Milky Way (NASA/JPL-Caltech/R. Hurt (SSC-Caltech), as reproduced in Ford et al. (2010)), as derived from the Galactic Legacy Infrared Mid-Plane Survey Extraordinare (GLIMPSE) using the Spitzer Space Telescope (Benjamin et al. 2003). The two regions studied, though selected to be symmetric with respect to the Sun-Galactic center line, sample two very different parts of the Galaxy. The QI area covers the near tip of the Galactic bar where a major spiral arm originates, while the QIV area contains only a minor arm.

4. Origin of the Observed Asymmetries

The individual clouds have very similar physical properties, but the cloud populations have three major asymmetries. There are 3 times as many clouds in the QI sample as in the QIV sample, the QI sample has twice the scale height of the QIV sample, and the radial velocity dispersions are dissimilar. The fact that the QI sample is located in a region near the tip of the Galactic bar where a major spiral arm is located, while the QIV sample contains only a minor arm, probably accounts for these asymmetries. The sparseness of the QIV region compared to the QI region accounts for the relative numbers of clouds as the clouds mirror the spiral structure. The concentration of clouds near 4 kpc in QIV seems to be connected to a weak spiral feature, the Norma spiral arm. On the other hand, the more nearly uniform radial distribution of clouds in QI is accounted for by the richer portion of the Galaxy where the near end of the Galactic bar merges with the beginning of the major Scutum-Centaurus arm. This suggests an intimate relation between the clouds and the spiral features, including star formation. The origin of the scale height differences, however, are not as clear, but could be connected to the relative star formation rates. Ford et al. (2010)
Fig. 4.— Artist’s conception of the Milky Way as derived from GLIMPSE survey infrared data, taken from Ford et al. (2010). The longitude boundaries of the QI and QIV regions are the dotted arrows while the locus of tangent points is represented by the dashed circle. The solid lines enclose the area around the tangent points bound by the longitude limits and a kinematic distance ±18 km s\(^{-1}\) away from \(V_t\) assuming a flat rotation curve. The artist’s conception image is from NASA/JPL-Caltech/R. Hurt (SSC-Caltech).

argues that the observed differences in numbers of clouds or scale heights are not due to kinematic selection effects.

5. Inferences and Conclusions

The physical properties of the clouds in the two samples are similar, suggesting they belong to the same population with similar origins and evolutionary histories. If the clouds evolved in the Galactic potential without disruption, the random motions implied by \(\sigma_{cc} = 16 - 18\) km s\(^{-1}\) would suggest a scale height of only 90 pc (Ford et al. 2008), which is inconsistent with the observations. If these clouds were self-gravitating, they would have
to have a mass of order $r\Delta v^2/G$ where $r$ is their radii, but this mass is several orders of magnitude larger than observed. These results indicate the clouds are not an equilibrium population. The clouds must be either pressure-confined or transitory. In the absence of pressure information, it is unknown if they are pressure-confined. Unless there is some sort of confinement, however, their lifetimes must be significantly less than their thermal evaporation timescale, about 100 Myr (Stanimirović et al. 2006), or their internal dynamical timescale, $r/\Delta v \sim 3$ Myr.

The standard explanation for the existence of disc-halo clouds is that they are formed by the cooling and condensing of hot gas that has been expelled from the disc which then falls back to the plane (Shapiro & Field 1976; Bregman 1980). However, the hot gas is expected to be fairly uniform in the halo so this model cannot account for the observed QI-QIV asymmetries.

Ford et al. (2010) instead proposes that the disc-halo clouds are related to areas of star formation and result from stellar feedback and superbubbles that have swept gas into the halo. The clouds are formed in the lower halo. The scale height differences could be accounted for by the greater star formation rate and number of superbubbles in QI as compared with QIV. But the time delay between the specific events producing superbubbles and cloud formation means that there should be no direct correlation with other details of star formation in the disc, as observed.

The sheer number of clouds detected means that these clouds are a major component of the Galaxy. Their concentration toward the Galactic plane and tight coupling to Galactic rotation and spiral structure preclude the possibility that they are created through tidal stripping of satellite dwarf galaxies or infalling primordial gas. These clouds play an important role in Galaxy evolution and the exchange of gas between the disc and halo. They are likely common in external galaxies but will be extremely difficult to detect there for many years.

**REFERENCES**


