Extra-planar H I in the Inner Milky Way

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Abstract.

The extra-planar H I in the inner parts of the Milky Way has been discovered to contain numerous cloud-like structures when observed in the 21cm line with the Green Bank Telescope. These halo clouds have motions consistent with Galactic rotation and do not seem to be related to the classic high-velocity clouds. They are found to distances >1 kpc from the plane and can contain hundreds of $M_\odot$ of H I. Spectra of many of the halo clouds show evidence of coexisting cool and warm HI phases. A preliminary high-resolution study of one of the clouds suggests that it consists of a diffuse envelope and a few dense cores, with a peak $N_{HI}$ reaching $4 \times 10^{20}$ cm$^{-2}$. The clouds are often organized into larger structures, one example of which was discovered near $\ell = 35^\circ$ rising higher than 2 kpc above the Galactic plane. New observations should answer some fundamental questions about the nature of these clouds.

1. Introduction

The Milky Way provides an opportunity to study extra-planar gas in great detail, yet the view is often confused and uncertain: at high latitudes where spectra can be simple, there is rarely any way to estimate a distance to the gas being measured, while at low latitudes, where Galactic rotation can separate gas kinematically, spectra are blended and confused. Neutral gas in significant amounts has been found far from the Galactic plane, and measurements in optical, radio, and UV absorption lines have provided detailed information on its physical properties, but the data do not form a consistent picture, do not reveal the structure of the material, and leave us with questions about how to generalize from one observation to the next (Münch & Zirin 1961; Savage & de Boer 1981; Lockman 1984; Lockman, Hobbs, & Shull 1986; Savage, Edgar & Diplas 1990; Spitzer & Fitzpatrick 1993; Albert et al. 1993; Sembach & Savage 1994; Fitzpatrick & Spitzer 1997; Kalberla et al. 1998; Howk et al. 1999).

Our understanding of the lower halo changed dramatically upon commissioning of the new Green Bank Telescope (GBT) (Lockman 1998; Jewell 2000) whose 9' angular resolution and superb sensitivity to low surface brightness emission revealed structures in Galactic HI which were only hinted at in earlier 21 cm data. We now know that much of the extra-planar HI in the inner parts
of the Milky Way is organized into discrete objects, some of which look like archetypical diffuse interstellar clouds (Lockman 2002, 2004). The distance to many of the clouds can be estimated with some accuracy, allowing us to derive quantitative information on their temperature, density, and mass. We are now in a new era in the study of the Galactic halo: it may come to be the model for the disk-halo interface in other systems as well.

2. HI Clouds in the Halo

Figure 1 shows the 21cm HI emission measured with the GBT along a cut through the Galactic plane at $\ell = 24\degree$. The fainter emission displayed in the gray scale has a distinctive cloudy structure. The Figure illustrates several key points about extra-planar HI in the inner Milky Way:

- HI emission is seen to at least $10^\circ$ from the plane over the same velocity range as is found in the disk. This extra-planar or halo HI is kinematically well behaved and its velocity arises mainly from Galactic rotation.

- Much of the HI away from the Galactic plane seems concentrated into discrete structures which are isolated in position and velocity: clouds.

- Clouds and cloud-like structures are seen even at low latitudes, but they are usually heavily blended, and difficult to distinguish.

- Many halo clouds have a narrow linewidth indicating that they contain cool gas.

Another aspect of Galactic extra-planar HI, though not so apparent in Fig. 1, is that clouds are sometimes found in groups connected by a common diffuse envelope or filament, and occasionally are organized into larger structures on scales $\sim 1$ kpc. The remainder of this paper will expand on these points and their implications.

3. Kinematics

It is clear from Fig. 1 that HI above and below the plane shares the same kinematics as material in the disk and thus its motion is predominantly due to Galactic rotation. The gas considered here is therefore not related to the classic `high-velocity’ clouds whose kinematics have a large anomalous motion (Wakker & van Woerden 1997). This fact makes it possible to determine reasonably accurate distances to some of the emission features.

At the longitude of Figure 1, Galactic rotation produces $V_{LSR} \lesssim 120$ km s$^{-1}$ (this is established from observations of giant molecular clouds in the disk, e.g., Clemens 1985). In the first Galactic quadrant, the rotation projects a maximum LSR velocity $V_t$ at the tangent point, whose distance is known from simple trigonometry: $r = R_0 \cos(\ell) = 7.7$ kpc. Thus the gas in Fig. 1 at $V_{LSR} \approx 120$ km s$^{-1}$ (marked with the vertical line) probably lies close to the tangent point where each degree in latitude corresponds to a displacement of about 135 pc from the Galactic plane.
Neutral Hydrogen emission observed with the Green Bank Telescope at 9′ angular resolution along a cut through the Galactic plane at longitude 24°4. The bright emission is marked with contours at 5, 10, 20, 35, 50 and 80 K, while the emission between zero and 5 K is displayed on a gray scale. In this direction Galactic rotation produces LSR velocities up to ≈120 cos(b) km s⁻¹ at the tangent point (the vertical line), which lies at a distance $r = R_0 \cos(\ell) = 7.7$ kpc.

There may be a component of halo HI whose velocity lags behind the rotation of the disk, as is observed in a number of systems described elsewhere in these Proceedings. Such lagging halo gas would lie at $V_{LSR} < V_t$ and be confused with other emission. The existence of a lagging halo is the subject of another work – here we concentrate on gas whose kinematics follows Galactic rotation, and specifically on HI which is likely to be near the tangent point where distance uncertainties are the smallest.
Figure 2. GBT observations of 21cm HI emission from several halo HI clouds at $V_{LSR} = 124 \text{ km s}^{-1}$ in a field around $l,b=25^\circ-5^\circ$. This velocity is slightly beyond that due to Galactic rotation, so the clouds are probably quite near the tangent point at a distance $z = -700 \text{ pc}$ from the Galactic plane.

4. Clouds

We describe the extra-planar HI as ‘cloudy’ because that is exactly how it looks. Many clouds have a spheroidal shape or are resolved into quasi-spherical objects. Figure 2 shows a group of three clouds near $24^\circ-5^\circ$ and a fourth fainter one at $25^\circ-6^\circ$. The cloud at $24^\circ-5^\circ$ appears also in the velocity-latitude cut of Figure 1. The chain of three clouds is about 100 pc long and lies 700 pc below the Galactic plane. The individual clouds have identical LSR velocities to within 2 km s$^{-1}$. The total HI mass of the structure is 1350 M$_{\odot}$, about 70% of which is in the clouds and the remainder in a diffuse envelope which surrounds them. Individual clouds have HI masses of 410, 170 and 350 M$_{\odot}$ right to left. The cloud at $25^\circ-6^\circ$ seems unrelated to the others. It contains 70 M$_{\odot}$ of hydrogen and is unresolved by the GBT. It must have a diameter $\leq 20 \text{ pc}$.

Clouds from a sample of 40 detected with the GBT at longitude $29^\circ$ at a median distance from the plane of $-940 \text{ pc}$ have a median HI mass of 50 M$_{\odot}$ and a median diameter of a few tens of pc (Lockman 2002). Some contain lines so narrow that their kinetic temperature must be $< 1000 \text{ K}$. The internal
structure of halo clouds has recently been measured at higher angular resolution, and preliminary results are discussed in §5.

Some halo clouds are dense, cool, concentrations embedded in filamentary structures of broad-line HI which contain most of the mass (Lockman 2004). It is an open question as to the fraction of the total halo HI concentrated in discrete structures, though it appears to be the majority in some regions. Considerable progress on this issue can be expected in the next year as observations of increased sensitivity are made.

5. Internal Structure

The spectra of many halo clouds consist of at least two components, one broad and one narrow, with typical linewidths (FWHM) of 20 and 6 km s\(^{-1}\), respectively. This suggests that neutral hydrogen in the clouds is in two phases, one warm and one cool, a structure which is seen in some high-velocity clouds, and which is expected theoretically at certain pressures (Ferrara & Field 1994; Wolfire et al. 1994). Systematic differences in the internal structure of halo clouds with location in the Galaxy and distance from the plane are now being observed. The clouds may be unique probes of physical conditions in the halo.

Figure 3. Preliminary VLA 21cm HI channel map at 1\′ angular resolution of the halo cloud at \(\ell, b = 19\degree 4+6\degree3\) (Pidopryhora et al. 2005). This map is in equatorial coordinates: the Galactic plane is toward the lower left side of the Figure. The cloud lies 2.8 kpc from the Galactic center and 900 pc above the Galactic plane.

Very recently several halo clouds have been observed with the VLA in the 21cm line at an angular resolution of about 1\′, which corresponds to a linear resolution of a few pc. The data are not yet fully analyzed, but a preliminary channel map for one cloud is shown in Figure 3. The brightest part of this cloud has a peak \(N_{HI} = 4 \times 10^{20} \text{ cm}^{-2}\) and a core with a linear size of about
7 pc, giving an average density \( \langle n \rangle = 20 \text{ cm}^{-3} \). The line at this position has a FWHM = 6 km s\(^{-1}\), limiting the kinetic temperature to \( T \leq 800 \text{ K} \). These values can be used to estimate a thermal pressure \( P/k = n/T \leq 16000 \text{ cm}^{-3} \text{ pc} \).

A preliminary accounting suggests that perhaps half of the 8 \( 00 M_\odot \) of H I in this cloud is contained in its denser central structure, with the remainder distributed more broadly. The three most compact cores hold about 110, 70 and 10 \( M_\odot \).

The typical halo cloud studied so far has a peak \( N_{HI} \) below the \( 5 \times 10^{20} \text{ cm}^{-2} \) required to allow formation of molecular hydrogen \cite{BohlinSavageDrake1978}, but there may be denser regions in some clouds and a significant molecular component.

6. Large-Scale Organized Structures

While there are many H I clouds in the halo which appear as discrete isolated objects, near longitude 35\(^{\circ}\) there is an enormous coherent structure of gas rising from the Galactic plane to heights of more than 2 kpc (Figure 4). This ‘whisker’ of gas contains more than \( 10^5 M_\odot \) of H I. In its lower regions it appears more like a ‘turbulent network’ \cite{ChappellScalo2001} than a set of discrete clouds, but by \( b \gtrsim 10^\circ \) (\( z \gtrsim 1200 \text{ pc} \) is appears to break up into clusters of clouds. Some of the ‘whisker’ clouds are seen even to latitudes higher than \( 20^\circ \) (\( z > 2 \text{ kpc} \)) — the record height for the halo clouds discovered so far. A preliminary study indicates that while ‘mid-latitude’ (\( b \approx 10^\circ \)) ‘whisker’ clouds share the two-component spectral structure of most halo clouds, high-latitude clouds have only the broad component (FWHM \( \gtrsim 20 \text{ km s}^{-1} \)). This may indicate that only a warm ISM phase survives at \( z \gtrsim 2 \text{ kpc} \).

Study of the ‘whisker’ feature is just beginning; it may be a local counterpart to the vertical dust lanes seen in galaxies like NGC 891 \cite{HowkSavage2000}.

7. The Origin of a Cloudy H I Halo

From the GBT observations of the inner Galaxy we get the definite sense that nature likes to gather hydrogen into clouds. There is even evidence that the population of halo clouds extends right down into the plane \cite{LockmanStil2004,StilTaylorLockman2005}. Where did the clouds come from and what keeps them together?

The clouds do not appear to be self-gravitating, yet their dynamical time (size/linewidth) is only a few million years. If the clouds are long-lived they must be confined by an external medium, presumably the Galaxy’s hot halo \cite{Spitzer1956, MünchZirin1961}. Even if they are in pressure equilibrium, they are denser than their surroundings by orders of magnitude and should be dropping toward the plane like stones, with a free-fall time of a few \( 10^7 \text{ years} \). Are they constantly reforming from condensing hot gas in a galactic ‘fountain’ \cite{ShapiroField1976,Bregman1980,HouckBregman1990}? Or are they fragments of structures launched upward from below, as the morphology of the ‘whisker’ suggests (cf. the models of \cite{Cortile2000})?

Hints of core-envelope structure combined with indications of mixed ISM phase coexistence, and even the size and mass range of the clouds are remi-
Figure 4. A large HI structure rising out of the Galactic plane near longitude 35°. This image shows GBT data averaged over 3 km s\(^{-1}\) around +79 km s\(^{-1}\). At the location of this ‘whisker’ one degree of latitude corresponds to about 120 pc, so the structure extends more than 2 kpc above the plane.

niscient of theoretical models like those of McKee & Ostriker (1977), but we do not know if the halo clouds are evaporating or accreting mass, we do not even know if they are rising, falling, or steady in place. Nor do we know the relationship, if any, between the halo HI and the Galaxy’s thick ionized layer (Reynolds 1990). Dwarakanath (2004) has recently proposed that the halo clouds are the distant analog of the ‘high velocity-dispersion’ cloud population observed in local optical and 21cm absorption lines (Routly & Spitzer 1952; Rajagopal, Srinivasan & Dwarakanath 1998). If the local clouds could be de-
tected in 21cm emission maps, a direct comparison of their properties with the halo clouds might settle this issue.

Studies of HI above the Galactic plane in the inner Galaxy have thus far measured only co-rotating gas \cite{Lockman1984, DickeyLockman1990}. If there is a significant lagging component, estimates of the mass and extent of the neutral halo are too low. Questions far outnumber answers today, but there are good prospects for rapid progress as new observations continue to reveal more details of the Milky Way’s fascinating extra-planar gas.

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