Extra-planar Gas
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Extra-planar Gas in the Leiden/Argentine/Bonn HI Survey

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Abstract. We present a novel approach for a definition of the phase space of the Milky Way HI disk and its associated gaseous halo. We discuss how model and observations can be used to discriminate between disk, disk-halo interface and the more distant halo.

The model is applied to the new LAB galactic 21-cm line survey, a joint Leiden/Argentine/Bonn project. This new all-sky survey merges an updated version of the Leiden/Dwingeloo (LDS) survey with southern sky observations from the Instituto Argentino de Radioastronomìa (IAR). The survey was processed in Bonn and is essentially free from stray radiation and spurious instrumental effects.

These data give evidence that the cloudy HI disk-halo interface, detected recently by Lockman (2002) in the inner Galaxy at $R \sim 5$ kpc is rather extended. The LAB survey shows numerous prominent filaments and cloudy features that stand out clearly against the Galactic disk reaching distances $R \sim 20$ kpc, $z \sim 7$ kpc. One particular interesting region at $R \sim 14$ kpc, $z \sim 4$ kpc was mapped with the Effelsberg telescope. We find isolated cold HI clumps with properties very similar to those in the inner Galaxy.

High velocity clouds populate the most distant part in the Milky Way phase space. Compact high column density features are found to be surrounded by diffuse low column density envelopes. Their lower phase space distance suggests some interaction with the Milky Way.

1. Introduction

The detection of the HI 21-cm line emission, more than 50 years ago, led quickly to a disclosure of the density structure and the kinematics of the Milky Way disk. But it was realized soon that some fraction of the observed HI emission could not be readily explained as disk emission. These features were classified as intermediate and high velocity clouds (IVCs & HVCs respectively). The classification was pragmatic, according to observed velocity regimes (distinguishing between IVCs and HVCs at $v_{lsr} = -70, -90$, later -100 km s^{-1}) and without any prejudice to the interpretation of these phenomena. Several decades later it became evident that HVCs have typical z distances of a few kpc or more while IVCs must be located more closely but well separated from the cold and warm interstellar medium within the disk. Some attempts have been made to distinguish such clouds from the Galactic disk by defining IVCs and HVCs by their deviation-velocity (e.g. Wakker & van Woerden 1997). This proposal, however, found no response in the scientific community.

While the structure of the Galactic halo is a matter of debate, there is a general agreement on the structure of the gaseous Galactic disk. Based on this we define the gaseous disk-halo interface in a bottom-up way. If there is a gaseous halo in the Milky Way then it has to be 1) located well above the disk and 2) it needs to be clearly distinguishable from the gaseous disk. We define the phase space for disk and halo and discuss how far its projection in the observable (l, b, v_{LSR}) space is in agreement with observations.

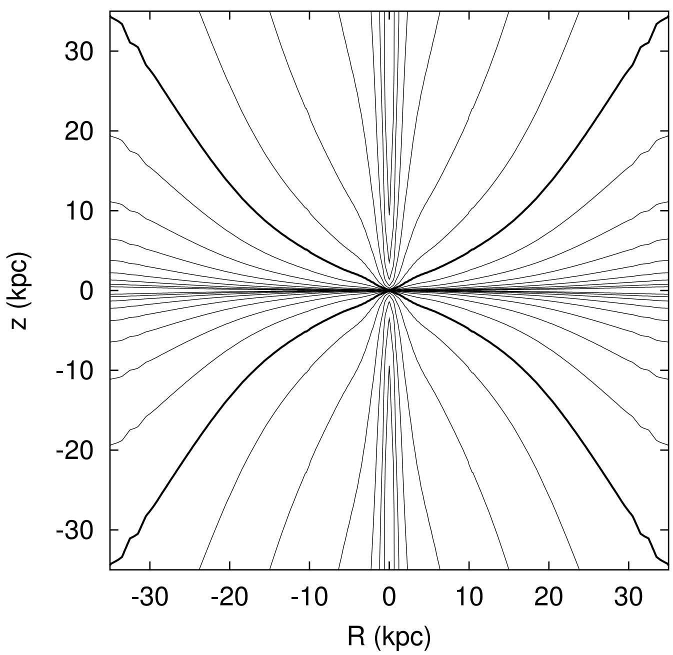

Figure 1. Iso-potentials for the gravitational potential $\Psi(R, z) - \Psi(R, 0)$, normalized relative to the disk. The contours represent locations of constant relative volume density $\rho(z)/\rho(0)$, the thick line displays the scale height of the gaseous halo, locally $h_z = 4$ kpc.

2. The Model

The local scale height of the HI gas is 400 pc (Dickey & Lockman 1990) and there is a general agreement that this layer, as well as the molecular gas layer is flaring. The model used by us (Kalberla 2003) is based on a self-consistent derivation of the gravitational potential in the Milky Way from a sum of isothermal disks. A basic property of this approach is that the solution of the combined Poisson-Boltzmann Eq. leads in a natural way to gas layers with a pronounced flaring. The derived iso-potentials for such a gravitational potential are plotted in Fig. 1. The model deviates strongly from popular plane-parallel models. The strongest deviations are found close to the central bulge. These inner isophotes fit well to the hot gas filaments above the core of NGC 3079, see Cecil et al. (2001) and the conference poster.

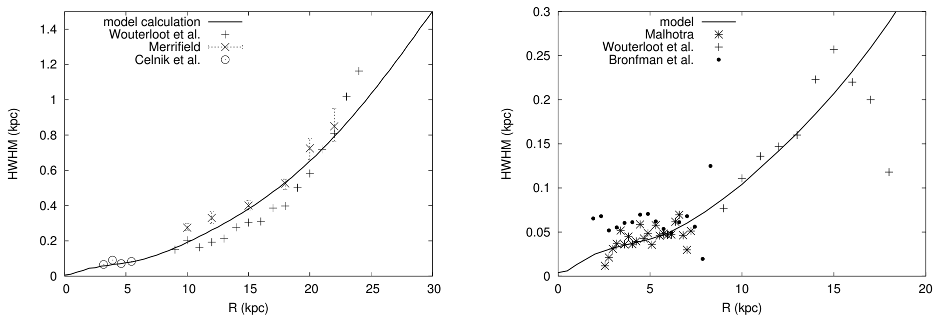

Figure 2. **Left:** Flaring of the HI disk. The data points represent the HWHM of the HI column density as derived by Wouterloot et al. (1990) (+), Merrifield (1992) (X), and Celnik, Rohlfs, & Braunsfurth (1979) (◯). The thick line gives the model prediction. **Right:** Flaring of the molecular disk. The solid line represents the model, the data points give CO scale heights as derived by Malhotra (1994) ($*$), Wouterloot et al. (1990) (+), and Bronfman et al. (1988) ($\bullet$).

In Fig. 2 we compare model predictions for such a potential with the observed flaring of the HI and CO layers in the Milky Way. The shape of the flaring curves is not the result of model fitting, it comes from the constraints of the mass model (Kalberla 2003). The solid lines were derived by matching a single spot, the local scale height at $R = 8.5$ kpc. The agreement between model and observations in Figs. 2 is excellent. We are therefore confident that we may use this mass model to describe the gas distribution in the Milky Way.

Building up a gaseous Milky Way we take into account that the disk is warped (Burton 1988). This effect is important and needs to be clearly distinguished from flaring. We use the warp parameters as determined by Dedes et al. (this volume). The halo gas phase is modeled by a component with a velocity dispersion of 60 km s^{-1} (Kalberla et al. 1998). For the other details of the model we refer to Kalberla (2003, Table 1).

3. The Data

We use the new LAB galactic 21-cm line survey (Kalberla et al. 2004). This consists in the northern sky of a second improved edition of the Leiden/Dwingeloo (LD) survey, the southern sky was observed in Villa Elisa by the Instituto Argentino de Radioastronomìa (IAR) (Bajaja et al. 2004). Both databases have been corrected for stray radiation at the University of Bonn.

The particular advantage of this new survey is that it is sensitive ($70 \lesssim \sigma_{RMS} \lesssim 90$ mK) and essentially unaffected by instrumental effects. The data correspond to observations with a telescope having a main beam efficiency of 99%. Such a survey is ideal to search for global features of a disk-halo interface.

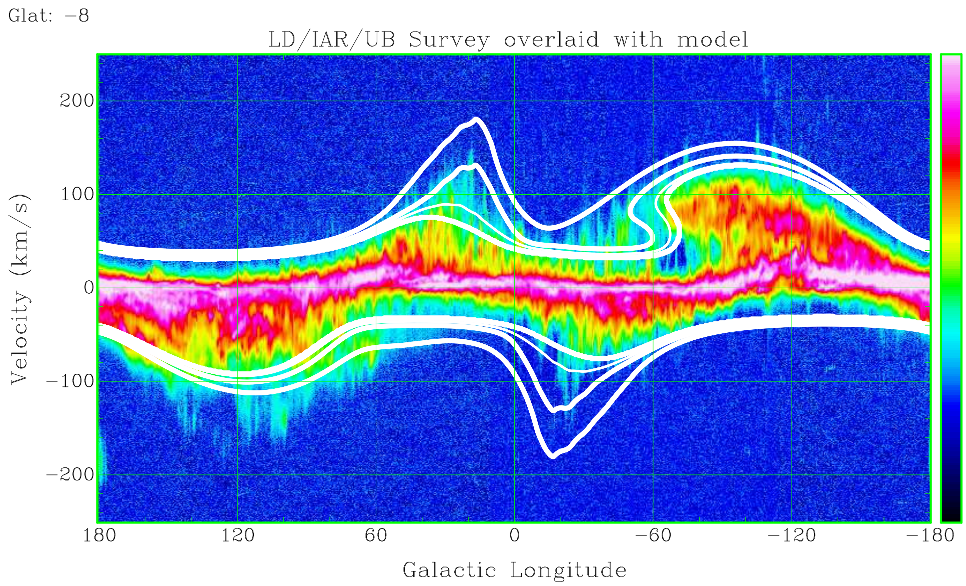

Figure 3. l, v diagram for constant latitude $b = -8°$. The isophotes represent expected halo emission at a mean brightness temperature of 0.1, 0.2 & 0.3K. The inner isophote blanks out emission from the disk whenever this exceeds the halo emission.

4. Model versus Data

The structure of the Galactic disk is most obvious if the data are organized in l, v position-velocity diagrams. In Fig. 3 we plot the HI emission, derived from the LAB survey, at a constant latitude $b = -8°$. Numerous filaments show up and reach velocities $|v_{LSR}| \gtrsim 100$ km s^{-1} . This plot shows a great deal of low velocity gas, considered as disk emission, but also features formally to be identified as IVCs and HVCs. However, distinct velocity limits, separating IVCs and HVCs from the disk are not very obvious. The question arises how to discriminate halo gas from the disk emission.

For this purpose we use the model. We calculate the expected halo emission and at the same time the emission from the cold and warm neutral medium (CNM & WNM) associated with the disk. The overlay in Fig. 3 shows our best guess from the model, the warp has been taken into account. Since we are interested only in the halo gas phase we disregard all regions where the expected disk emission exceeds the halo emission (within the inner isophotes). The outer isophotes span a range in expected mean halo emission from 0.1 to 0.3 K.

Comparing the emission from the LAB survey with the overlay we find only a few windows where unambiguous halo emission is expected to be observable. We conclude that the most prominent emission features at $l \sim 30°$, $v_{lsr} \gtrsim 50$ km s^{-1} in Fig. 3 must originate from the halo and not from the disk.

Lockman (2002) observed this region in more detail with the GBT. He found isolated HI clumps at z distances of 1.5 kpc, significantly above the disk. Lockmans proposed that these clouds are characteristic for a distinct cloudy halo gas phase.

Our model calculations are consistent with this interpretation. The only significant difference between model and data in Figs. 3 is the pronounced clumpiness of the data while the model is smooth. This is expected but cannot be represented in our model. The halo HI clouds are embedded in a hot ($10^{6.2}$ K) plasma. Pressure equilibrium between plasma and neutral clouds implies a volume filling factor of 10% or less (Kalberla & Kerp 1998) in this case. The isophotes in Fig. 3 represent a probability distribution for a clumpy HI halo gas phase.

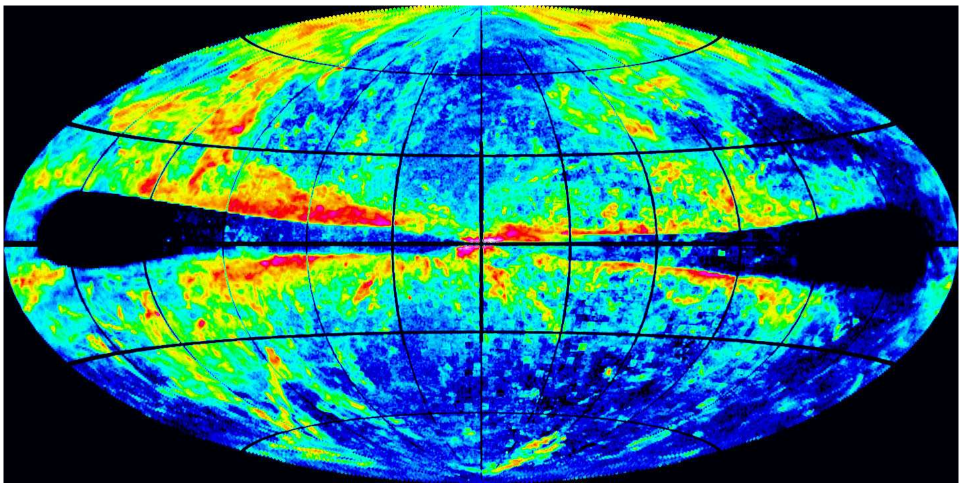

Figure 4. Column density derived from the LAB survey for those regions in the (l, b, v_{LSR}) space that are according to the model dominated by emission from the halo. The Galactic center is in the middle.

We use our model to predict those regions in the observable phase space (l, b, v_{LSR}) of the Milky Way that are dominated by halo gas emission, essentially the region enclosed by isophotes in Fig. 3. We use this prediction to mask the observed HI emission and integrate only over those regions which are expected to contain predominantly halo gas emission.

Fig. 4 shows the derived colum density distribution in Aitoff projection. Numerous filaments are visible. Most of them appear to be associated with the disk but there are also prominent spurs at high latitudes, known as intermediate velocity arcs (Kuntz & Danly 1996).

The current interpretation for the cloudy halo gas phase is that it most probably originates from fountain events (Lockman 2002). According to Fig. 4 there are some doubts that this can be the only source. Galactic fountains are restricted to the inner Galaxy. Gas rising and moving outward has to conserve its angular momentum. The resulting circular velocities of the halo gas in the outer part of the Milky Way must then lag significantly behind the rotation of the disk. We find, however, that the halo gas phase is essentially co-rotating with the disk, only slightly lagging behind. This applies also to the numerous filaments in the outer Galaxy, at large distances from the Galactic center.

Taking Fig. 4 as a finding chart we used the Effelsberg telescope to search for halo emission in the outer Galaxy. Up to now we found 20 isolated HI clumps that appear to belong to a halo gas phase. Derived properties like temperatures

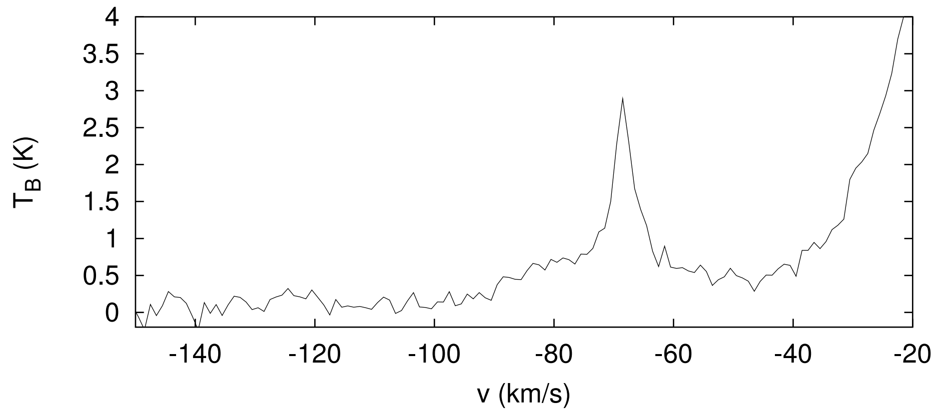

Figure 5. HI line emission from an isolated clump at $l \sim 115°, b \sim 24°$.

and densities are consistent with those determined by Lockman in the inner Galaxy. Fig. 5 shows one particular interesting feature. This isolated HI clump is most probably located at $13 \lesssim R \lesssim 17$ kpc, $3 \lesssim z \lesssim 5$ kpc and has a diameter of ~ 25 pc. The associated broad emission feature is only slightly more extended. The unresolved core appears to be cold, $450 \lesssim T \lesssim 1600$K.

5. The HVC Sky - Gas Most Distant from the Disk in Phase Space

Assigning a probability to a volume element in the observable (l, b, v_{LSR}) space that it belongs to the Galactic disk also implies assigning a distance measure within the phase space of the disk. Low probabilities belong to large phase space distances, large probabilities to low distances.

We may use an upper limit in the expected halo emission to study those parts of the observable HI which are most distant in phase space from the Galactic disk. This means that we exclude any emission from the disk but also most of the emission that can be interpreted as a disk-halo interface. What is left over should essentially be unrelated to the Milky Way disk.

Fig. 6 shows the result after masking the observed emission according to a predicted average emission of the disk-halo interface at a level of 30 and 10 mK (top and bottom). The global structures visible in these plots resemble the well known HVC complexes (Wakker & van Woerden 1997) but there are also significant differences. Some of the HVC complexes are missing, but Fig. 6 also contains some complexes usually classified as IVCs. These differences are due to the fact that our selection criteria are incompatible with the usual HVC/IVC classification according to *fixed* observed velocities.

Most striking is the core-halo structure of the emission in Fig. 6. In the bottom plot we find the most condensed HVC emission, the upper part shows extended emission around many of the compact features. The clumps correspond to gas which is most distant from the phase space occupied by the disk. Envelopes that show up at the top of Fig. 6 are more near-by. This closer part of the HI emission is more diffuse, has low column densities, and surrounds the compact features without any preferential direction.

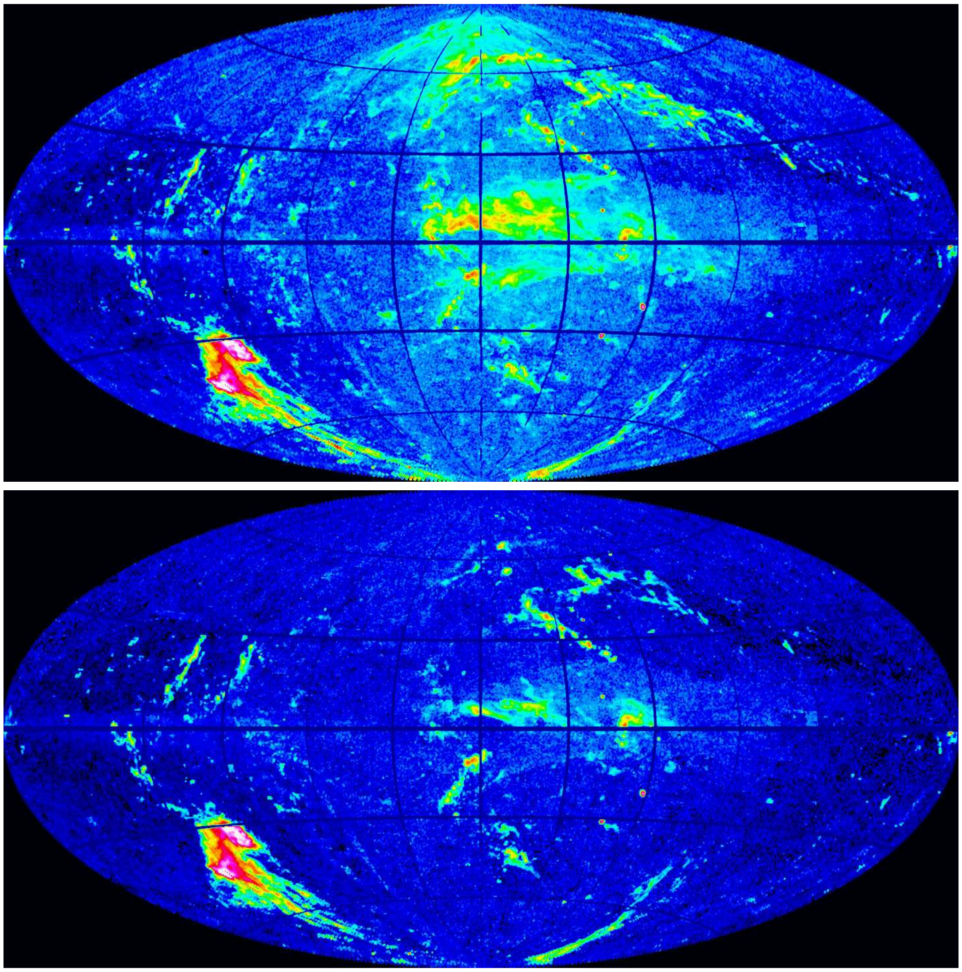

Figure 6. Anti-center view of HI line emission not associated with the disk or the disk-halo interface. The gas in the lower plot is most distant in phase space, the diffuse emission in the upper plot is more nearby.

In general, the HI HVC sky can be separated into condensations and surrounding envelopes by using the appropriate phase space distances to distinguish these features. **All** of the envelopes occupy a phase space which is closer to the disk than the compact cores.

Such a phenomenon is completely unexpected if most of the HVCs are unrelated to the Milky Way disk. If HVCs are at a typical distance of 1 Mpc (Blitz et al. 1999), how do they form such extended envelopes and how do these envelopes know about the phase space of the Galactic disk?

From high resolution observations it is well known that numerous HVCs with condensed cores are surrounded by diffuse envelopes. The surrounding gas usually has lower velocities, implying that this gas has been decelerated or stripped by ram pressure (Brüns et al. 2000). The envelopes visible at the top of Fig. 6 indicate a similar phenomenon, the only difference is that they are one or two orders of magnitude more extended.

6. Summary

We use a multiphase model for the gas distribution within the Milky Way and study how the phase space of the Milky Way is populated by HI gas. Using the new 21-cm LAB survey we find a disk-halo interface with numerous filaments standing out clearly against the disk. At high resolution this cloudy halo breaks up into numerous small and cold HI clumps. Effelsberg observations indicate that clumps at distances of $R \sim 15$ kpc have similar properties as HI halo gas clumps at $R \sim 5$ kpc.

HVCs populate the more distant part of the Milky Way phase space. High column density cores are most distant but surrounded by low column density envelopes, less distant in phase space. Cores and envelopes appear to be related, suggesting some interaction between HVCs and the Milky Way. A deceleration of the envelopes due to ram pressure, caused either by the disk or the disk-halo interface, appears to be the most likely explanation.

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