The HI Distribution of the Milky Way
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(2009)
Summary

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Introduction

- **Neutral atomic hydrogen** (HI) traces the ISM
- **21-cm emission line**: is a key probe of the structure and dynamics of the Milky Way Galaxy (several 21-cm large-scale survey - past decade).
- **All-sky surveys**: shape and $\rho$ of the disk up to its borders
- **HR Galactic plane surveys**: disclose a wealth of shells, filaments, and spurs (connecting two or more spiral arms are a common feature of spiral galaxies).
- **Observational results**: indicate that the HI traces a dynamical Galactic ISM with structures on all scales, from tens of AU to kpc.
Introduction

Scientific research areas considered:

- **The global picture of the HI distribution in the Milky Way**: a quasi-static in large scales
- **The violent ISM**: a dynamical view in small scales
- **HI as part of the multiphase structure of the ISM**: the physical state of the HI distribution
Introduction

SOME APPROXIMATIONS

• most of the derived parameters depend on the adopted Galactic rotation curve. General consensus that a flat rotation curve with $V_{\text{rot}} \sim 220 \text{ km s}^{-1}$.

SOME PREVIOUS RESULTS

• $\rho_{\text{HI}}$ and $\Sigma_{\text{HI}} \propto e^{-R}$ in the midplane
• $h_{\text{HI}} \propto e^{-R}$
• The gaseous disk flares strongly
Introduction

SOME PREVIOUS RESULTS

• At larger radial distances the Milky Way is surrounded by a faint, patchy, and highly turbulent HI distribution that has been traced out to $R \sim 60$ kpc (Kalberla & Dedes 2008).

• The global HI density distribution suggests that in total about 10% of the HI gas is “anomalous” in the sense that it stands out from the main gas layer. This HI gas floats around at large $z$ distances, up to several scale heights above the disk.

• This extraplanar gas layer appears to be approximately corotating with the disk.
Introduction

SOME PREVIOUS RESULTS

• **The Galactic plane surveys**: disclose a wealth of shells, spurs, and chimneys. These structures are the most prominent tracers of the Galactic “ecosystem.”

• **Shells**: are found to be concentrated at mid-plane, and 50% of them at $z \sim < 500$ pc. About 5% of the disk volume appears to be occupied by shells.

• **The HI gas has a two-phase structure**:
  a) characterized by the cold neutral medium (CNM), which has a cloudy structure (40 to 100 K)
  b) warm neutral medium (WNM) with a diffuse distribution
2. INSTRUMENTS AND OBSERVATIONS
Surveys

• ~ 90% of the HI (T ~20 K) is localized within a thin disk. The Sun is within this disk, all single line of sight across the sky has HI gas emission.

• **At high latitudes** most of the HI 21-cm emission lines at low velocities are broad, indicating a high degree of turbulence and T~100K.

• **Toward the Galactic plane:** observations with high angular and spectral resolution are required.

• **Toward high Galactic latitudes** we can study most of the gas properties with moderate angular resolution but high sensitivity.
Surveys

- **Full-sky surveys**: LAB survey (Kalberla et al. 2005) - this is the most sensitive 21-cm line survey with the most extensive coverage

- **Radio Interferometer Galactic Plane Surveys**: The International Galactic Plane Survey (IGPS) comprises many radio telescope surveys to map the ISM in the Galactic plane at various wavelengths.
Sky coverage of different surveys

The background image displays the total volume density of the 21-cm line emission from the LAB survey.
3. HI ON THE GALACTIC SCALE
The Disk

- **Observations of spiral galaxies:** in general that many HI disks have typically three times the extent of their stellar distribution. We use Galactocentric cylindrical coordinates $R$, $z$, and $\phi$.

- Assuming axisymmetric circular rotation yields the well-known relation for the differential rotation velocity (e.g., Burton 1988):

$$v(R, z) = \left[ \frac{R_\odot}{R} \Theta(R, z) - \Theta_\odot \right] \sin l \cdot \cos b.$$  

- Here we use $R_{\odot} = 8.5$ kpc and $= 220$ km s$^{-1}$. 
Differential rotation velocity

\[ v(R, z) = \left[ \frac{R_\odot}{R} \Theta(R, z) - \Theta_\odot \right] \sin l \cdot \cos b. \]
Limitations and results

- The rotation is also poorly known in the outer Galaxy because it is particularly difficult to determine accurate distances there.
- The derivation of such a rotation depends inherently on the baryonic and nonbaryonic matter distribution.

- For the Kalberla et al. (2007) model:
  - Total mass within $R = 60$ kpc is $M = 4.6 \times 10^{11} \ M_{\text{sun}}$
  - Baryons provide $M = 9.5 \times 10^{10} \ M_{\text{sun}}$ and gas fraction of 13%.
  - HI mass is $M = 8 \times 10^9 \ M_{\text{sun}}$
  - The warm ionized medium contributes $M = 2 \times 10^9 \ M_{\text{sun}}$
  - Molecular gas is $M = 2.5 \times 10^9 \ M_{\text{sun}}$
Mean MW rotation curve

- red curves: midplane at the position of the Sun by $|z| = 1$ to $5$ kpc
- Noncircular motions affect rotation velocities significantly for $R < 15$ kpc (thin lines)
• For a description of the global properties of the HI distribution in the Milky Way it is necessary to consider the bending of the Galactic plane.
Taking the warp into account it is possible to derive the \( \rho_{\text{HI}} \) and \( n_0(R) \) at midplane. The radial distribution is \( \sim \) exponential for \( 7 < R < 35 \) kpc (\( n_0 = 0.9 \) cm\(^{-3}\) and \( R_n = 3.15 \) kpc).
Surface density distribution

The average sigma is plotted ($s_0 = 30 \, M_{\odot} \, \text{pc}^{-2}$ and $R_s = 3.75 \, \text{kpc}$).

$$\Sigma(R) \sim s_0 \cdot e^{-(R-R_\odot)/R_s}$$
HI scale height

- The average thickness $h_z(R)$ of the HI disk shows a pronounced flaring that can be approximated by an exponential relation.
- Flaring may be induced by changes of the gravitational potential in the $z$ direction or by variations in the heating/cooling balance of the HI gas and to probe DM models.
HI scale height

- The average scale height $h_z(R)$ of the HI disk depends on the balance between $F_g$ and $p$. 
HI scale height

\[ h_R = h_0 \ e^{(R - R_\odot)/R_0} \]

- \( h_0 = 0.15 \ \text{kpc} \)
- \( R_0 = 9.8 \ \text{kpc} \)
The exponential disk

- The global properties of the HI gas in the disk can be well approximated by exponential distributions.
- **In the outer part of the disk**: this approx. remains valid up to $R \sim 35$ kpc, this radius apparently defines the outer edge of the Galactic disk.

$$R \sim 3 \, R_{25}$$

- $R_{25}$ is half the diameter $D_{25}$ of the $\mu_B = 25$ mag arcsec$^{-2}$ isophote given by de Vaucouleurs et al. 1991.
The Disk-Halo Interface

- Pictures of the HI distribution show numerous filaments extending to high Galactic latitudes (e.g., Hartmann & Burton 1997).
- Individual clouds and coherent cloud assemblies (or complexes) can be distinguished from the Galactic disk emission (Wakker 1991).
Halo clumps

- Lockman (2002b) was the first to study this population at high resolution. In many cases the clumps are embedded in faint diffuse filaments that are connected to the disk.

- Clouds that reach high z distances need large vertical velocities to overcome the gravitational attraction of the Galactic disk. In the median, the clouds have diameters of $\sim 20$ pc, HI densities of a few tens cm$^{-3}$, and HI masses of $50$ M$_{\odot}$.
Halo clumps

- The LAB survey does not allow us to resolve the individual clumps, but provides statistical evidence that about 10% of the HI gas is located outside the disk.

> average HI emission as a function of the radial velocity in the direction toward both Galactic poles for latitudes |b| > 20°.
Halo clumps

• The HI spectra can be fitted by a population of unresolved clouds with a velocity dispersion of $\sigma \sim 74$ km s$^{-1}$ (Kalberla & Dedes 2008).

• This is more than a factor of three larger than the typical velocity dispersion of HI gas, implying that this gas component exceeds the kinetic energy of the disk gas by an order of magnitude.

• Such fast clouds can reach $z$ distances of 4 kpc.
The halo

• We have a smooth transition of temperature, volume density, and pressure with increasing altitude.

• Assuming a hydrostatic equilibrium approximation on a Galactic scale, we can deduce a vertical scale height at the location of the Sun:
  a) $h_{\text{CNM}} \sim 150$ pc
  b) $h_{\text{WNM}} \sim 400$ pc

• HVCs are prominent because they are part of large and massive complexes that are forming coherent structures.

  • HVC: high-velocity cloud
  • CNM: cold neutral medium
  • WNM: warm neutral medium
The outskirts

- Toward the outskirts of the Milky Way, for $R>35$ kpc, the average $\text{HI}$ distribution does not fade off exponentially.

- Milky Way CNM and WNM disks could be also surrounded by a patchy and highly turbulent halo medium. About 10% of the total HI gas may be in this phase (Kalberla & Dedes 2008).
The corotation problem

• For a steady-state gas in an axisymmetric gravitational potential, the average azimuthal streaming velocity $\bar{v}_\phi(z)$ can be derived from Euler’s equation:

$$ (\bar{v} \cdot \nabla) \bar{v} = -\frac{\nabla p}{\rho} - \nabla \Phi, $$

• To the isothermal case $p \propto \rho \sigma^2$. This equation excludes magnetic and viscosity terms.
The corotation problem

- HI observations were interpreted such that in the inner part of the Milky Way corotation is present up to a z distance of 1 kpc.
- Vertical gradient in rotation velocity per unit scale height is dominated by gradients in the gravitational field of the Galactic disk.
- Influences: pressure gradients, magnetic fields, and viscosity terms appear negligible.
The corotation problem