HI beyond the Milky Way

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An HI view of a section of the MW, some 2000 l.y. (700 pc) across

Credit: Dominion Radio Astronomy Observatory
Multiwavelength Milky Way

- 408 MHz
- 2.7GHz
- MIR (6-10m)
- NIR (1.2-3.5 m)
- Optical
- X-ray (0.25-1.5KeV)
- Gamma (300 MeV)
Galactic Components

- Spiral arms
- Bulge
- Disk
- Halo
- Extreme disk
- Thick disk
- Thin disk
- Sun
- Galactic center
- NGP
- SGP
- Plane of rotation
- 8.5 kpc
- Galactic center
- 30,000 pc
- 500 pc
Very near extragalactic space...
The Magellanic Stream

Discovered in 1974 by Mathewson, Cleary & Murray

Putman et al. 2003
How much of the HI stuff do we detect in the Universe?
The Universe is Flat:

\[ \Omega = 1 \]

The current expansion rate is \( H_0 = 70 \text{ km/s/Mpc} \)
less than that...
Do all galaxies have lots of HI?
**Elliptical vs Spiral**

Galaxies can be classified based on appearance

<table>
<thead>
<tr>
<th>Ellipticals</th>
<th>Spirals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth falloff of light</td>
<td>Bulge+disk+arms</td>
</tr>
<tr>
<td>Not forming stars now</td>
<td>Lots of star formation</td>
</tr>
<tr>
<td>Dominant motion: random orbits</td>
<td>Dominant motion: circular orbits in disk</td>
</tr>
<tr>
<td>Prefer cluster cores</td>
<td>Avoid cluster cores</td>
</tr>
</tbody>
</table>
Morphology-Density Relation

The fraction of the population that is spiral decreases from the field to high density regions.

[Dressler 1980]
Disk Formation: a primer

- Protogalaxies acquire angular momentum through tidal torques with nearest neighbors during the linear regime [Stromberg 1934; Hoyle 1949]
- As self-gravity decouples the protogalaxy from the Hubble flow, \([l/(d l/d t)]\) becomes very large and the growth of \(l\) ceases
- N-body simulations show that at turnaround time values of \(l\) range between 0.01 and 0.1, for halos of all masses
- The average for halos is \(l = 0.05\)
- Only 10% of halos have \(l < 0.025\) or \(l > 0.10\)
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\[\lambda = \frac{\omega}{\omega_{\text{circ}}} = \left(\frac{L}{MR^2}\right) \left(\frac{GM}{R^3}\right)^{-1/2} = \frac{L |E|^{1/2}}{GM^{5/2}}\]

- Baryons collapse dissipatively within the potential well of their halo. They lose energy through radiative losses, largely conserving mass and angular momentum
- Thus \(l\) of disks increases, as they shrink to the inner part of the halo

\[\frac{R_h}{R_{\text{disk}}} = m_d \left(\frac{\lambda_{\text{disk}}}{\lambda_h}\right)^2\]

- If the galaxy retains all baryons \(\Rightarrow m_d \sim 1/10\), and \(l_{\text{disk}}\) grows to \(\sim 0.5\),

\[R_{\text{disk}} \sim 1/10 R_h\]

[Fall & Efstathiou 1980]
Some galaxies form through multiple (and often major) mergers.

The orbits of their constituent stars are randomly oriented.

Kinetic energy of random motions largely exceeds that of orderly, large-scale motions such as rotation.

These galaxies have low “spin parameter”.

**Elliptical galaxies**
Other galaxies form in less crowded environments. They accrete material at a slower pace and are unaffected by major mergers for long intervals of time.

Baryonic matter ("gas") collapses slowly (and dissipatively — losing energy) within the potential well of Dark matter, forming a disk.

Baryonic matter has high spin parameter: large-scale rotation is important.
The Antennae
Toomre & Toomre 1972

Restricted 3-body problem
A Computer Simulation of the Merger of two Spiral galaxies
Sensing Dark Matter
Just as we use observations of the orbits of stars near the center of our Milky Way to infer the presence of a Supermassive Black Hole...
The $M(r)$ at the center of the Galaxy is best fitted by the combination of:
- point source of $2.6+/-0.2 \times 10^6 \ M_{\odot}$
- and a cluster of visible stars with a core radius of 0.34 pc and $\rho_0=3.9 \times 10^6 \ M_{\odot}/pc^3$

Schoedel et al (2002)
Research Note

Comparison of Rotation Curves of Different Galaxy Types

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Summary. Rotation curves extending to large radial distances are now available for 3 spiral galaxies, each of a different type. Differences in shape of the rotation curves indicate a mass distribution that is related to structural type and is in the same sense as the luminosity distribution for these galaxies. The shapes of the rotation curves at large radii indicate a significant amount of matter at these large distances and imply that spiral galaxies are larger than found from photometric measurements.

Key words: galaxies – rotation curves
M31
Effelsberg data

Roberts, Whitehurst & Cram 1978
Dark Matter is needed to explain the Milky Way (and other galaxies') dynamics.

The fractional contribution of the Dark Matter to the total mass contained within a given radius increases outwards.

The total mass of the Galaxy is dominated by Dark Matter.

The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a dark matter halo.
Fig. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (dots with error bars). The scale length of the disk has been taken equal to that of the light distribution (60°, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0) = 0.0040 \, M_\odot \, pc^{-3}$. 

[Van Albada, Bahcall, Begeman & Sancisi 1985]
Fig. 13. Mass model for NGC 5585 using the “maximum-disk” method. The contribution of each component is plotted. The stellar disk has (\(\mathcal{M} / L_B\))_\* = 0.5 \(\mathcal{M}_\odot / L_\odot\), the dark halo has \(r_c = 3.1\) kpc and \(\sigma = 52.7\) km s\(^{-1}\).

Fig. 12. Mass model for NGC 5585 using the “best-fit” method. The contribution of each component is plotted. The stellar disk has (\(\mathcal{M} / L_B\))_\* = 0.2 \(\mathcal{M}_\odot / L_\odot\). The dark isothermal halo has a core radius \(r_c = 2.8\) kpc and a velocity dispersion \(\sigma = 53.4\) km s\(^{-1}\).

[Cote’, Carignan & Sancisi 1991]
A page from Dr. Bosma’s Galactic Pathology Manual
We use HI maps of galaxies to infer their masses, their dynamical circumstances, to date their interactions with companions, to infer their star formation ("fertility") rates...
HI Deficiency in groups and clusters
Morphological Alteration Mechanisms

I. Environment-independent
   a. Galactic winds
   b. Star formation without replenishment

II. Environment dependent
   a. Galaxy-galaxy interactions
      i. Direct collisions
      ii. Tidal encounters
      iii. Mergers
      iv. Harassment
   b. Galaxy-cluster medium
      i. Ram pressure stripping
      ii. Thermal evaporation
      iii. Turbulent viscous stripping
Virgo Cluster

HI Deficiency

HI Disk Diameter

Arecibo data

[Grebowelli & Haynes 1983]
Virgo Cluster

VLA data

[Cayatte, van Gorkom, Balkowski & Kotanyi 1990]
VIRGO Cluster

Dots: galaxies w/ measured HI

Contours: HI deficiency

Grey map: ROSAT 0.4-2.4 keV

Solanes et al. 2002
Galaxy “harassment” within a cluster environment

Credit: Lake et al.

Credit: Moore et al.
Way beyond the stars
DDO 154

Arecibo map outer extent [Hoffman et al. 1993]

Extent of optical image

Carignan & Beaulieu 1989

VLA D-array HI column density contours
Fig. 14.—(a) Ratio of the local total (luminous and dark) mass to the stellar mass $M_*$ and to the H I mass $M_{HI}$. (b) Complete mass model for DDO 154 using the rotation curve of Table 5. When not indicated, the errors are smaller than the size of the symbols. The contribution of the H I component was calculated using the surface densities of Fig. 9. The total H I mass is $2.7 \times 10^8 M_\odot$. The stellar disk has $(M/L_B)_* = 1.0$, giving a total mass of $5.0 \times 10^7 M_\odot$. The halo parameters are $r_e = 3.0$ kpc and $\rho_0 = 0.015 M_\odot$ pc$^{-2}$. The total mass (dark and luminous) at the last observed velocity point (7.6 kpc) is $3.8 \times 10^9 M_\odot$. 

Carignan & Beaulieu 1989
... and where there aren’t any stars
Figure 1. The Leo Ring System.
HI: Arecibo single dish map, 3.3' resolution, contours=2 x 10^18 cm^-3 x 2".
Optical: DSS, FOV=70' x 100'.
Notes: Labeled galaxies have redshifts similar to the HI ring.

Schneider, Helou, Salpeter & Terzian 1983

Schneider et al 1989   VLA map

Arecibo map

M96 Ring
... and then some Cosmology
Perseus-Pisces Supercluster

~11,000 galaxy redshifts: Arecibo as a redshift machine
Perseus-Pisces Supercluster
SCI : cluster Sc sample
I band, 24 clusters, 782 galaxies
Giovanelli et al. 1997

“Direct” slope is –7.6
“Inverse” slope is –7.8
Measuring the Hubble Constant

A TF template relation is derived independently on the value of $H_{\text{not}}$. It can be derived for, or averaged over, a large number of galaxies, regions or environments. When calibrators are included, the Hubble constant can be gauged over the volume sampled by the template.

From a selected sample of Cepheid Calibrators, Giovanelli et al. (1997) obtained $H_{\text{not}} = 69 +/- 6$ (km/s)/Mpc averaged over a volume of $cz = 9500$ km/s radius.
Given a TF template relation, the peculiar velocity of a galaxy can be derived from its offset $Dm$ from that template, via

$$V_{pec} = cz(1 - 10^{0.2 \Delta m})$$

For a TF scatter of 0.35 mag, the error on the peculiar velocity of a single galaxy is typically $\sim 0.16cz$.

For clusters, the error can be reduced by a factor $\sqrt{N}$, if N galaxies per cluster are observed.
CMB Dipole

$\Delta T = 3.358 \text{ mK}

V_{\text{sun}} \text{ w.r.t CMB:}

369 \text{ km/s towards}
\ l = 264^\circ , \ b = +48^\circ

Motion of the Local Group:

$V = 627 \text{ km/s towards}$
\ $l = 276^\circ \ b = +30^\circ$
Convergence Depth

Given a field of density fluctuations \( d(r) \), an observer at \( r=0 \) will have a peculiar velocity:

\[
V_{\text{pec}} = \frac{H_0 \Omega^{0.6}}{4\pi} \int \delta(\vec{r}) \frac{\vec{r}}{r^3} d\vec{r}^3
\]

where \( W \) is \( W_{\text{mass}} \)

The contribution to \( \vec{V}_{\text{pec}} \) by fluctuations in the shell \( (R_1, R_2) \), asymptotically tends to zero as \( R \to \infty \)

The cumulative \( \vec{V}_{\text{pec}} \) by all fluctuations Within \( R \) thus exhibits the behavior:

If the observer is the LG, the asymptotic \( \vec{V}_{\text{pec}} \) matches the CMB dipole
The Dipole of the Peculiar Velocity Field

The reflex motion of the LG, w.r.t. field galaxies in shells of progressively increasing radius, shows:
convergence with the CMB dipole, both in amplitude and direction, near $cz \sim 5000$ km/s.
(Giovanelli et al. 1998)