Diffuse HI and the Evolution of Galaxies: The New Frontier

Felix J. Lockman
NRAO
Green Bank, WV

GBT Collaborations

- Caltech -- CCB
- Univ. Maryland -- Zspectrometer
- Univ. Penn, NIST -- MUSTANG
- UC Berkeley, WVU -- GUPPI
- UC Berkeley -- New Spectrometer
- BYU -- FLAG
- Nanograv
- Caltech, Stanford -- mm-cameras
We’re faced with fundamental questions about the origin, growth and evolution of galaxies like the Milky Way.

**MILKY WAY**
History of star formation
Chemical Evolution
Structure and stability of the disk
The warp

Dynamics of the local group
History of the Magellanic clouds and effects on the Milky Way
Mass and energy flows between the disk, halo, group medium, IGM
Connections between dark and luminous matter
Fossil record of galaxy formation

All need sensitive HI observations
Hydrogen is abundant and observable

Key to understanding the growth and evolution of galaxies

UV absorption lines
H+ emission lines
21cm in the radio

CONCLUSIONS

1) There is a lot to learn from the largely unexplored $N_{\text{HI}} << 10^{19}$ cm$^{-2}$
2) Current facilities can produce exciting results
3) Modest investments give significant improvements
4) The SKA promises even more, but...
5) No Bed of Procrustes for U.S. Astronomy
We know how to make accurate $N_{\text{HI}}$ measurements

Agreement between GBT 21cm and HST Ly$\alpha$ values of $N_{\text{HI}}$

$N_{\text{HI}}(\text{Ly}\alpha)/N_{\text{HI}}(21\text{cm})=1.00\pm0.07$


28 AGN and QSOs
Observing the 21cm line in emission

\[ \sigma_T = \frac{20}{f \left(25000 \times 2 \times t_s\right)^{\frac{1}{2}}} \quad (K) \]

\[ \sigma_T = 90 \; f^{-1} \; t_s^{-\frac{1}{2}} \quad (mK) \]

\[ T_b = 2.1 \; \frac{N_{\text{HI}}}{10^{20}} \; \Omega \; K \]

A 3\(\sigma\) detection takes

\[ t = 1.6 \times 10^{-2} \; f^{-2} \; \Omega^{-2} \; N_{\text{HI}}^{-2} \quad (s) \]

\(\tau\ll1\)

5 km/s channel width

3\(\sigma\) detection

\(\Delta V = 25\) km/s

no bandpass issues

\(f\ll1\) is surface brightness efficiency

\(\Omega\ll1\) is beam dilution
Surface brightness efficiency factors

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBT</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Arecibo</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>EVLA-D</td>
<td>$\sim 10^{-2}$</td>
</tr>
<tr>
<td>EVLA-C</td>
<td>$\sim 10^{-3}$</td>
</tr>
<tr>
<td>EVLA-B</td>
<td>$\sim 10^{-4}$</td>
</tr>
<tr>
<td>ATA</td>
<td>$\sim 10^{-2}$</td>
</tr>
<tr>
<td>ASKAP</td>
<td>$\sim 10^{-3}$</td>
</tr>
</tbody>
</table>
Deep 21cm Surveys

from Popping (2010), PhD thesis, University of Groningen,

<table>
<thead>
<tr>
<th>Survey</th>
<th>Beam [']</th>
<th>Area [deg²]</th>
<th>$\delta v$ [km s⁻¹]</th>
<th>rms(Flux)$^a$</th>
<th>rms($N_{HI}$)$^b$</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHISS</td>
<td>3.3</td>
<td>13</td>
<td>16</td>
<td>0.7</td>
<td>3.5e17</td>
<td>c</td>
</tr>
<tr>
<td>ADBS</td>
<td>3.3</td>
<td>430</td>
<td>34</td>
<td>3.3</td>
<td>1.7e18</td>
<td>d</td>
</tr>
<tr>
<td>WSRT WVF</td>
<td>49</td>
<td>1800</td>
<td>17</td>
<td>18</td>
<td>4.1e16</td>
<td>e</td>
</tr>
<tr>
<td>Nancay CVn</td>
<td>4 x 20</td>
<td>800</td>
<td>10</td>
<td>7.5</td>
<td>5.2e17</td>
<td>f</td>
</tr>
<tr>
<td>HIPASS</td>
<td>15.5</td>
<td>30000</td>
<td>18</td>
<td>13</td>
<td>3.0e17</td>
<td>g</td>
</tr>
<tr>
<td>HI-ZOA</td>
<td>15.5</td>
<td>1840</td>
<td>18</td>
<td>13</td>
<td>3.0e17</td>
<td>h</td>
</tr>
<tr>
<td>HIDEEP</td>
<td>15.5</td>
<td>32</td>
<td>18</td>
<td>3.2</td>
<td>7.4e16</td>
<td>i</td>
</tr>
<tr>
<td>HIJASS</td>
<td>12</td>
<td>1115</td>
<td>18</td>
<td>13</td>
<td>5.0e17</td>
<td>j</td>
</tr>
<tr>
<td>J-Virgo</td>
<td>12</td>
<td>32</td>
<td>18</td>
<td>4</td>
<td>1.5e17</td>
<td>k</td>
</tr>
<tr>
<td>AGES</td>
<td>3.5</td>
<td>200</td>
<td>11</td>
<td>0.7</td>
<td>3.2e17</td>
<td>l</td>
</tr>
<tr>
<td>ALFALFA</td>
<td>3.5</td>
<td>7074</td>
<td>11</td>
<td>1.7</td>
<td>7.7e17</td>
<td>m</td>
</tr>
</tbody>
</table>

Table 1.1: Comparison of Blind $H_1$ Surveys: ($a$): mJy beam⁻¹ at 18 km s⁻¹, ($b$): cm⁻² over 18 km s⁻¹, ($c$): Zwaan et al. (1997), ($d$): Rosenberg & Schneider (2000), ($e$): Braun et al. (2003), ($f$): Kraan-Korteweg et al. (1999), ($g$): Barnes et al. (2001), ($h$): Henning et al. (2000), ($i$): Minchin et al. (2003), ($j$): Lang et al. (2003), ($k$): Davies et al. (2004), ($l$): Minchin et al. (2007), ($m$): Giovanelli et al. (2007)
The Plane of a Spiral Galaxy

$N_{\text{HI}} \geq 10^{22}$

$T_b = 200$ K

$t \approx 10^{-6} \, \text{f}^{-2} \, \text{s}$

Dickey & Lockman 1990, ARAA, 28, 215
Through the spiral arms of galaxies

\[ N_{\text{HI}} = 10^{21.5} \]
\[ T_b = 65 \text{ K} \]
\[ t \approx 2 \times 10^{-5} \text{ f}^{-2} \text{ s} \]

M31 WSRT + GBT

Vertically through the disk at $R_0$.

$N_{\text{HI}} = 10^{20.5}$

$T_b = 6.5 \text{ K}$

$t \approx 2 \times 10^{-3} \text{ f}^{-2} \text{ s}$

*Dickey & Lockman 1990, ARAA, 28, 215*
Brighter parts of high-velocity clouds

Accretion of satellites, fountain, or cold flow?

From Bart Wakker
Brighter parts of high-velocity clouds

GBT Image of Hydrogen in Smith’s Cloud

<table>
<thead>
<tr>
<th>$N_{\text{HI}}$</th>
<th>$10^{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{b}$</td>
<td>$2$ K</td>
</tr>
<tr>
<td>$t$</td>
<td>$\approx 2 \times 10^{-2}$ f$^{-2}$ s</td>
</tr>
</tbody>
</table>

dist = $12.4 \pm 1.3$ kpc
$R = 7.6 \pm 1.0$ kpc
$z = -2.2$ kpc
$M_{\text{HI}} > 10^{6}$ M$_{\odot}$
$M_{\text{H}^+} \approx 3 \times 10^{6}$ M$_{\odot}$
size $\approx 3 \times 1$ kpc
$[\text{N}/\text{H}] = 0.14 - 0.44$

$V_{\text{tot}} \approx 300$ km/s
Will impact the disk in $30$ Myr

The Smith Cloud: Dark Matter Confinement?


\[ N_{HI} = 10^{20} \]
\[ T_b = 2 \text{ K} \]
\[ t \approx 2 \times 10^{-2} \text{ f}^{-2} \text{ s} \]
The ragged edges of HI disks

\[ N_{\text{HI}} = 10^{19.5} \]
\[ T_b = 0.6 \text{ K} \]
\[ t \approx 0.2 \text{ f}^{-2} \text{ s} \]

GBT observations of The Milky Way Warp
\[ N_{\text{HI}} = 10^{19.5} \] at 20° latitude
The ragged edges of HI disks

THINGS VLA Survey
Walter et al. 2008
at 30" resolution $3\sigma=10^{19.5}$
at 6" resolution $3\sigma=10^{20.5}$

$N_{HI} = 10^{19.5}$
$T_b = 0.6 \text{ K}$
$t \approx 0.2 \text{ f}^{-2} \text{ s}$

Structure, Accretion or outflow?
The ragged edges of HI disks

HALOGAS WSRT Survey
Heald et al. 2011, in press
15'' resolution to $N_{\text{HI}}$ limit few $10^{19}$
120 hours per galaxy

$N_{\text{HI}} = 10^{19}$
$T_b = 0.2$ K
$t \approx 2 \, f^{-2} \, s$
The Milky Way disk–halo transition


\[ N_{\text{HI}} = 10^{19} \]
\[ T_b = 0.2 \text{ K} \]
\[ t \approx 2 \text{ } f^{-2} \text{ s} \]
The Milky Way disk–halo transition


\[ N_{\text{HI}} = 10^{19} \]
\[ T_b = 0.2 \text{ K} \]
\[ t \approx 2 \text{ f}^{-2} \text{ s} \]
The Ophiucus superbubble: a starburst in the inner Galaxy?

A coherent structure to more than 3 kpc above the disk.

HI mass $10^6$ Mo
Equal amount in H+ 
Age 30 Myr
E = $10^{53}$ ergs
Cap lags behind Galactic rotation

$N_{HI} = 10^{19}$
$T_b = 0.2$ K
$t \approx 2 f^{-2}$ s

Artist’s conception of the Ophiucus Superbubble drawn to scale
HVCs around other galaxies

**M31 -- GBT**
contours at 0.5,1,2,10,20 $\times 10^{18}$
HI Masses = $10^{6-7}$ M⊙

**M33 -- Arecibo**
lowest contour $2\times 10^{18}$

$N_{HI} = 10^{18.5}$
$T_b = 0.065$ K
$t \approx 16$ f$^{-2}$ s
HVCs around the Milky Way

37% of sky covered with HVC HI to this level

Shull et al. (2009) find 81% coverage from UV lines of ionized gas

\[ N_{\text{HI}} = 10^{18}, \quad T_b = 20 \text{ mK}, \quad t \approx 160 \text{ f}^{-2} \text{ s} \]

Yao et al. (2011)

HVCs around the Milky Way

37% of sky covered with HVC HI to this level

Shull et al. (2009) find 81% coverage from UV lines of ionized gas

Yao et al. (2011)

The tip of the Magellanic Stream

\[ N_{HI} = 10^{17.5} \]
\[ T_b = 6 \text{ mK} \]
\[ t \approx 1600 \text{ f}^{-2} \text{ s} \]

Composite of data from Parkes, the GBT, and WSRT (used as single dishes)

The M81 group the classic example of interactions

Optical + VLA HI + GBT HI
The M31–M33 stream

$N_{HI} = 10^{17}$
$T_b = 2 \text{ mK}$
$t \approx 16000 \text{ f}^{-2} \text{ s}$

WSRT as single dishes
49’ Resolution

Putman et al.
say it’s not real!

Fig. 9. Integrated H I emission from the subset of detected features apparently associated with M 31 and M 33. The grey-scale varies between $\log (N_{HI}) = 17–18$, for $N_{HI}$ in units of cm$^{-2}$. Contours are drawn at $\log (N_{HI}) = 17, 17.5, 18, \ldots 20.5$. 

WSRT as single dishes
49’ Resolution

Putman et al.
say it’s not real!
GBT spectrum of the M31–M33 stream

Free, Lockman & Shields (2011, in prep)

\[ N_{\text{HI}} = 10^{17} \]
\[ T_b = 2 \text{ mK} \]
\[ t \approx 16 \ 000 \ f^{-2} \text{ s} \]

This is the frontier
Hydrogen is abundant and observable

• The potential of HI studies at $10^{17}$
  – Flow of gas into and out of the Milky Way and other galaxies
  – Tracing past interactions
  – The cosmic web?
• The challenge of studies at $10^{17}$
  – Signals are very weak, and yet likely extended
  – Possible with current instruments, it just takes time
• Near term
  – Better receivers -- $T_{sys}=10$ K?
  – Phased array feed receivers -- still not competitive, but...
  – EVLA-E -- $f\approx0.25$
• Long term
  – SKA -- HPBW=2.5’ reaches 1.6 mK over 25 km/s in 1 hour
    (but GBT at 9’ now reaches 0.7 mK over 25 km/s in 1 hr)
## HI brightness and integration times

<table>
<thead>
<tr>
<th>log $N_{\text{HI}}$ (cm$^{-2}$)</th>
<th>$T_b$ (τ&lt;&lt;1) (K)</th>
<th>$3\sigma$ t / $f^2$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>200</td>
<td>$2\times 10^{-6}$</td>
</tr>
<tr>
<td>21.5</td>
<td>65</td>
<td>$2\times 10^{-5}$</td>
</tr>
<tr>
<td>21</td>
<td>21</td>
<td>$2\times 10^{-4}$</td>
</tr>
<tr>
<td>20.5</td>
<td>6.5</td>
<td>$2\times 10^{-3}$</td>
</tr>
<tr>
<td>20</td>
<td>2.1</td>
<td>$2\times 10^{-2}$</td>
</tr>
<tr>
<td>19.5</td>
<td>0.65</td>
<td>0.2</td>
</tr>
<tr>
<td>19</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>18.5</td>
<td>0.065</td>
<td>16</td>
</tr>
<tr>
<td>18</td>
<td>0.02</td>
<td>160</td>
</tr>
<tr>
<td>17.5</td>
<td>0.0065</td>
<td>1600</td>
</tr>
<tr>
<td>17</td>
<td>0.002</td>
<td>16 000</td>
</tr>
</tbody>
</table>

New HI Surveys cover the brighter emission

GASS $\delta \approx 0^\circ 14'$
McClure-Griffiths et al. (2009)

Bonn survey $0^\circ \approx \delta \approx 10'$
Kerp et al. (2011)

---------------
Arecibo Surveys
$0^\circ \approx \delta \approx 40^\circ$
GALFA
ALFALFA

$\Delta v = 25$ km/s
The future?

- 19 dual polarized elements. Cryogenic PAF system
- $T_{sys} \sim 20$ K; Aperture efficiency $\sim 75$ to 80 %
- 7 beams; spacing 0.5 FWHM to 1 FWHM
- Frequency coverage – 1300 to 1800 MHz; Backend for processing signals