Extragalactic HI Surveys with the Feed Array

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Main Scientific Goals:

- Investigate the faint end of the HI mass function (HIMF)
- Determine the local density dependence of the HIMF
- Map the distribution of luminous and dark matter in the local (z < 0.1) Universe
- Determine the gas-rich membership of nearby groups of galaxies
- Determine the population of gas-rich systems in the Local Group and the periphery of the MW (HVCs)
- Find (rare) OH Megamasers near z=0.25
- Be surprised
A few useful scaling laws...
The minimum integration time $t_s$ required for ALFA to detect a source of HI mass $M_{HI}$ and width $W_{kms}$ at the distance $D_{Mpc}$ is

$$t_s = \frac{1}{4} f_\beta^{-2} \left( \frac{M_{HI}}{10^6 M_\odot} \right)^{-2} (D_{Mpc})^4 \left( \frac{W_{kms}}{100} \right)^{-2\gamma}$$

where

$$\gamma = \begin{cases} 
-3/4 & \text{if } W_{kms} \leq 100 \\
-1 & \text{if } W_{kms} > 100 
\end{cases}$$

i.e. the depth of a survey increases only as $t_s^{1/4}$

Alternatively, the minimum detectable HI mass at distance $D_{Mpc}$ is

$$\left( \frac{M_{HI}}{10^6 M_\odot} \right)_{min} \approx 0.5 f_\beta^{-1} t_s^{-1/2} (D_{Mpc})^2 \left( \frac{W_{kms}}{100} \right)^{-\gamma}$$

(by comparison, HIPASS detects 1 million solar masses at 1 Mpc in 460 sec...)
On comparative advantages: in a survey, is aperture of a larger telescope offset by the larger solid angle which a smaller telescope can sweep per unit time?

\[ A \quad \text{telescope collecting area} \]
\[ \Omega_b \propto A^{-1} \quad \text{telescope beam} \]
\[ G \propto A \quad \text{telescope gain} \]
\[ D_{max} \propto G^{1/2} \propto A^{1/2} \quad \text{max distance at which given HI mass is detectable} \]
\[ V_{beam} = \Omega_b D_{max}^3/3 \propto A^{1/2} \quad \text{volume sampled by beam out to } D_{max} \]

i.e., at fixed total time and bandwidth,

**the volume sampled by a survey scales like the telescope diameter.**
For a given HI mass, the volume sampled by a survey

\[ V_{\text{survey}}(M_{HI}) = \Omega D_{\text{max}}^3 / 3 \]

can be increased by either (a) surveying a larger solid angle \( \Omega \) or (b) integrating longer and increasing \( D_{\text{max}} \).

- Since the time required to complete the survey is \( t_{\text{survey}} \propto (\Omega / \Omega_b) t_s \),
- and \( D_{\text{max}} \propto t_s^{1/4} \),
- then \( V_{\text{survey}}(M_{HI}) \propto \Omega [D_{\text{max}}]^3 \propto \Omega t_s^{3/4} \propto t_{\text{survey}} t_s^{-1/4} \)
- Inverting: \( t_{\text{survey}} \propto V_{\text{survey}} t_s^{1/4} \)

Hence, once \( t_s \) is large enough to make \( M_{HI} \) detectable,

**it is more advantageous to maximize \( \Omega \) than to increase the survey depth.**
Survey simulation ingredients...
\[ \Phi(x) = \frac{dn}{d(\log x)} = (\ln 10) \Phi^* x^{\alpha+1} e^{-x} \]

where

\[ x = \frac{M_{HI}}{M^*} \]

**Zwaan et al. 97:**

\[ \Phi^* = 0.0048h_{70}^3 \]

\[ \log M^*/M_{sun} = 9.86 - 2 \times \log h_{70} \]

\[ \alpha = -1.20 \]

**Rosenberg & Schneider 02:**

\[ \Phi^* = 0.0041h_{70}^3 \]

\[ \log M^*/M_{sun} = 9.94 - 2 \times \log h_{70} \]

\[ \alpha = -1.53 \]
The HI mass of a source at distance $D_{Mpc}$, in solar units, is

$$M_{HI}/M_\odot = 2.356 \times 10^5 D_{Mpc}^2 \int S(V) dV$$

approximated by

$$M_{HI}/M_\odot \simeq 2.356 \times 10^5 D_{Mpc}^2 S_{peak} W_{kms}$$

if we match smoothing to signal width:

$$S/N = \frac{f_\beta S_{peak}}{S_{rms}} \simeq 1.37 \times 10^{-4} t_s^{1/2} \frac{M_{HI}}{M_\odot} D_{Mpc}^{-2} W_{kms}^{-1/2}$$

But $S_{peak}$ is depressed by smoothing. Detection criterion then is:

$$10.1 f_\beta t_s^{1/2} \left( \frac{M_{HI}}{10^6 M_\odot} \right) D_{Mpc}^{-2} \left( \frac{W_{kms}}{100} \right)^\gamma > 5$$

where $\gamma = -3/4$ for $W_{kms} \leq 100$ and $\gamma = -1$ for $W_{kms} > 100$. 

Source-to-beam extent  Integration time in sec  Signal width in km/s
Moreover:

- **The reliability** of a detection depends on S/N. Model the probability $p$, that a “detection” at given S/N will be confirmed, as

$$p = (e^{S/N - S_{1/2}}/\eta + 1)^{-1}$$

where $\eta$ is set to 2.2 and $S_{1/2}$ to 6.

- **Model $W_{\text{kms}}$ as Gauss deviate with dispersion 0.1 dex about**

$$\log(W_{\text{kms}}^c) = 1.8 + 0.397[\log(h_{70}^2 M_{HI}/M_\odot) - 8.1],$$

scramble disk inclination and add turbulent term

- **Model source size as**

$$\log h_{70} D_{HI} = [\log(h_{70}^2 M_{HI}/M_\odot) - 6.53]/1.94,$$
• Simulate random pointing errors and estimate beam dilution factor

• Model suppression of gas infall onto low mass halos due to reionization (e.g. adopting the "filtering mass" criterion of Gnedin & Hui 1998)

Next,

adopt a model for the cosmic density field
Slice of the cosmic Density field along The Supergalactic Plane

You are here
Most of the mass is to be found in regions of density substantially higher than average.

**Caveat:**

But, do low baryonic mass systems trace the cosmic density distribution?
A set of survey simulations:

• All-AO, fast (6-sec) sky survey: ALFALFA
• 300 - sec ZOA ```staring``` survey ZOA
• 60 - sec Virgo Cluster survey VIRGO
ZOA
300 sec
|b| < 10
AO limits
ZO\text{OA}

300 sec

$|b| < 10$

AO limits
ZOAlimits

300 sec

$|b| < 10$

AO limits
What about synergies?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ALFALFA</th>
<th>Virgo</th>
<th>ZOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky Coverage</td>
<td>$12,000 \ (\circ)^2$</td>
<td>$810 \ (\circ)^2$</td>
<td>$2000 \ (\circ)^2 \ (</td>
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<tr>
<td>Spectral Coverage</td>
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<td>100 MHz</td>
<td>100 MHz</td>
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<tr>
<td>Spectral Resolution</td>
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<td>25 kHz</td>
<td>25 kHz</td>
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<tr>
<td>Spectral channels</td>
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<td>$7 \times 2 \times 4000$</td>
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<tr>
<td>Total $t_s$ per beam</td>
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<td>60</td>
<td>300</td>
</tr>
<tr>
<td>Revisits per beam</td>
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<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Number of beams</td>
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<td>$8 \times 10^5$</td>
</tr>
<tr>
<td>Total Survey time</td>
<td>1200 hours</td>
<td>800 hours</td>
<td>10,000 hours</td>
</tr>
<tr>
<td>$S_{rms}$ at 25 kHz</td>
<td>6 mJy beam$^{-1}$</td>
<td>1.7 mJy beam$^{-1}$</td>
<td>0.8 mJy beam$^{-1}$</td>
</tr>
<tr>
<td>$S_{rms}/$HIPASS, ZOA</td>
<td>0.2</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>$5\sigma \ M_{HI, min}/10^6 M_\odot$ at $W_{kms} = 100$</td>
<td>$0.2 D_{Mpc}^2$</td>
<td>$0.06 D_{Mpc}^2$</td>
<td>$0.03 D_{Mpc}^2$</td>
</tr>
<tr>
<td>Size of data set (@ 1 sec dump)</td>
<td>1.2 Tb</td>
<td>0.8 Tb</td>
<td>10.0 Tb</td>
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<tr>
<td>To complete</td>
<td>&lt; 1 yr</td>
<td>~ 2 yr</td>
<td>~ 7 yr</td>
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<td>10</td>
<td>1</td>
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<td>Number of spectra</td>
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<td>$0.9 \times 10^6$</td>
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<td>$10 \times 4.6 \times 10^5$</td>
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What about synergies?

References. — $^1$Only Xgal; $^2$Simultaneous with MW survey;
Useful Relations

- The minimum $t_s$ to detect a source of $M_{HI}$, $W_{kms}$ at distance $D_{Mpc}$ is

$$t_s = \frac{1}{4} f_\beta^{-2} \left( \frac{M_{HI}}{10^6 M_\odot} \right)^{-2} (D_{Mpc})^4 \left( \frac{W_{kms}}{100} \right)^{-2\gamma}$$

- or, alternatively, the minimum HI mass detectable at distance $D_{Mpc}$ is

$$\left( \frac{M_{HI}}{10^6 M_\odot} \right)_{min} \simeq 0.5 f_\beta^{-1} t_s^{-1/2} (D_{Mpc})^2 \left( \frac{W_{kms}}{100} \right)^{-\gamma}$$

(by comparison, HI PASS detects 1 million solar masses at 1 Mpc in 460 sec...)

- The volume covered by the solid angle $\Omega$, out to distance $D_{Mpc}$, is

$$V = \Omega D_{Mpc}^3 / 3$$

- The maximum distance at which a given HI mass can be detected in time $t_s$ is

$$D_{Mpc, max}(M_{HI}) \propto t_s^{1/4}$$
Useful Relations (cont.)

- The time required to complete a survey covering a solid angle \( \Omega \) is

\[
t_{\text{survey}} \propto \left( \Omega / \Omega_b \right) t_s
\]

- The survey volume sampled for a given HI mass is

\[
V_{\text{survey}}(M_{HI}) \propto \Omega [D_{\text{Mpc, max}}(M_{HI})]^3 \propto \Omega t_s^{3/4}
\]

- And

\[
t_{\text{survey}} \propto V_{\text{survey}}(M_{HI}) D_{\text{Mpc, max}}(M_{HI}) \propto V_{\text{survey}}(M_{HI}) t_s^{1/4},
\]

i.e. for a given \( V_{\text{survey}}(M_{HI}) \), which will yield a desired number of detections of clouds of mass \( M_{HI} \), it’s better to maximize the sampled solid angle \( \Omega \) than to increase the depth of the survey \( D_{\text{Mpc, max}}(M_{HI}) \).