Future Extragalactic HI Surveys at Arecibo, SKA/10

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Ongoing Extragalactic HI Surveys at AO

- **ALFALFA**: 7000 sq.deg., 48 sec/beam, 2 mJy/bm, 97% open shutter (P.I.: R. Giovanelli, Cornell, U.S.)
  Fully blind survey, expected N~30,000 det gals

- **AGES**: 300 sq.deg., 300s/beam (P.I.: J. Davies, Cardiff, UK)
  selected fields, expected N (scaling law)~2500

- **AUDS**: 0.36 sq.deg., 50 hrs/bm, 50 μJy/bm (P.I.: W. Freudling, ESO, Germany)
  Fully blind survey, expected N ~ $10^2$ det at z~0.15

- **ZOA**: ~900 sq.deg. (?) Commensal with G-ALFA/P-ALFA surveys
  (P.I.: P. Henning, New Mexico, U.S.)
  Fully blind survey, Zone of Avoidance, expected N ~ few $10^3$ (?)

All programs carried out precursor observations with ALFA in 2004; survey operations for ALFALFA, AGES started in 2005. AUDS, ZOA to start in 2008.
Reality Check...
The minimum integration time in sec, to detect an HI mass $M_{HI}$ at the distance $D_{Mpc}$ with a $T_{sys}/G = 3$ Jy telescope (e.g. Arecibo), is

$$t_s \approx 0.25 \left( \frac{M_{HI}}{10^6 M_{sun}} \right)^{-2} D_{Mpc}^4 \left( \frac{W_{kms}}{100} \right)^\gamma$$

Where $\gamma = 1$ for $W < 300$ km/s and increases to $\gamma \sim 2$ at larger widths.

i.e. the Depth of the survey increases only as

$$D_{Mpc} \propto t_s^{1/4}$$

- While a galaxy with 1% the HI mass of the MW at Virgo distance can be detected in less than 1 min with ALFA,
- A MW HI mass at even moderate $z$ (e.g. $z \sim 0.25$, $D \sim 1$ Gpc) will require many hours of integration [see Catinella’s talk]

⇒ **Only the most massive HI sources are detectable at even moderate $z$**
ALFALFA has already detected more than twice as many objects with $\log M_{\text{HI}} > 10.5$ than all other previous blind HI surveys combined.
Source extraction and identification of counterparts at other wavelength regimes can be a painful experience...

...source centroiding as accurately as possible is thus highly desirable.
Suppose HIPASS detects a source at S/N~6 near 3000 km/s in this field. The position error box will have a radius of ~2.5’. The opt counterpart could be gal #1, 2, 3, 4, 5 or 6.

ALFALFA will detect the same source with S/N~50 and the Arecibo beam is ¼ as wide as the Parkes one

The same source will have an ALFALFA position error of ~ 0.1”

The HIPASS problem evident in this picture will affect also AO, but at higher z.
FPPAs (Focal Plane Phased Arrays)

N~40 beams can be set in Arecibo focal plane.
Survey Speed
Figure of Merit

\[
FoM \propto \left( \frac{A_{\text{eff}}}{T_{\text{sys}}} \right)^2 \Omega_{\text{fov}}BW
\]

Parameters Used:

<table>
<thead>
<tr>
<th>D (m)</th>
<th>Beam</th>
<th>Ntel*Nbm</th>
<th>Tsys</th>
<th>BW</th>
</tr>
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<tbody>
<tr>
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<td>225</td>
<td>3.5’</td>
<td>1x1</td>
<td>25K</td>
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<tr>
<td>ALFA</td>
<td>225</td>
<td>3.5’</td>
<td>1x7</td>
<td>30K</td>
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<tr>
<td>AO40</td>
<td>225</td>
<td>3.5’</td>
<td>1x40</td>
<td>50K</td>
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<tr>
<td>APERTIF</td>
<td>25</td>
<td>30’</td>
<td>14x25</td>
<td>50K</td>
</tr>
<tr>
<td>ASKAP</td>
<td>12</td>
<td>60’</td>
<td>30x30</td>
<td>35K*</td>
</tr>
</tbody>
</table>

(*): The actual performance that FPPAs will deliver is still very uncertain; Tsys values of 35K or 50K are rough expectations. It would be fair to use the same Tsys values for all telescopes ➔ a value of 50K for ASKAP would then apply.
Survey Speed  
Figure of Merit

\[
\text{FoM} \propto \left( \frac{A_{\text{eff}}}{T_{\text{sys}}} \right)^2 \Omega_{\text{fov}} \cdot BW
\]

<table>
<thead>
<tr>
<th></th>
<th>( (A_c)^2 )</th>
<th>( (T_{\text{sys}})^2 )</th>
<th>FoV</th>
<th>BW</th>
<th>FoM</th>
</tr>
</thead>
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<tr>
<td>AO1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>ALFA</td>
<td>1</td>
<td>1/1.4</td>
<td>7</td>
<td>3**</td>
<td>14**</td>
</tr>
<tr>
<td>AO40</td>
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<td>3</td>
<td>30</td>
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<tr>
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<td>1/4</td>
<td>1800</td>
<td>3</td>
<td>33</td>
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<tr>
<td>ASKAP</td>
<td>1/170</td>
<td>1/2*</td>
<td>8800</td>
<td>3</td>
<td>74*</td>
</tr>
</tbody>
</table>

(* For \( T_{\text{sys}}=50K \), the FoM of ASKAP is 37, comparable with AO40 & APERTIF)
Instrumented with a 40 beam FPPA, Arecibo would have a survey speed FoM comparable to ASKAP & APERTIF, with one important advantage: with a collecting area 10% of the SKA, the Arecibo telescope already exists.

One important disadvantage of AO: confusion limit will occur at much lower z than for distributed apertures like APERTIF and ASKAP.

➔ Niche for AO40: large scale surveys at low z

For example:

- ALFALFA++
- AGES++
- VirgoDeep
- Void++

Plus: for targeted surveys, push system to limit
ALFALFA will map 7000 sq. deg.  
ALFALFA++ would complete coverage of the 13000 sq. deg. accessible with AO:  
→ 3500 hrs with ALFA  
→ 600 hrs with AO40

AGES will map 300 sq. deg. at 3x ALFALFA’s sensitivity  
AGES++ would extend coverage to a more extensive set of targets, to a total of 2000 sq. deg.  
→ 10,000 hrs with ALFA  
→ 1500 hrs with AO40
• **VirgoDeep**

VirgoDeep would map 200 sq. deg. Centered on the Virgo cluster with 10x the sensitivity of ALFALFA, to detect $M_{HI} = 2 \times 10^6$ solar at Virgo distance

- 11,500 hrs with ALFA
- 2000 hrs with AO40

• **Void++**

Void++ would map 400 sq. deg. centered on largest nearby void (center at $cz \sim 2500$ km/s, in front of Pisces-Perseus Supercluster), with 10x the sensitivity of ALFALFA. Will also permit detection of $M_{HI} = 5 \times 10^3$ solar and $N_{HI} \sim 2 \times 10^{17}$ cm$^{-2}$ in resolved sources in the Local Group, serendipitously along l.o.s.

- 23,000 hrs with ALFA
- 4000 hrs with AO40
Towards VirgoDeep

ALFALFA finds many low mass, low surface brightness features in the cluster
Combined ALFALFA data around VIRGOHI21
$cz = 1946$ to $2259$ km/s

Towards VirgoDeep
Stream $M_{HI} = 5 \times 10^8$ solar

...new, dramatic events of galaxy harassment, high speed encounters with debris spread over hundreds of kpc, and well beyond the VLA FOV

Fig. 2. Contour maps of NGC 4532/EDG 2550, showing the distribution of HI gas towards VirgoDeep. The beam positions at 100 km s\(^{-1}\) (pointing to the North) and DDO 137, and are drawn at 7.3, 12, and 18 in units of 10\(^{19}\) atoms cm\(^{-2}\).
Towards VirgoDeep

... some stretching over half a Mpc, peppered with possible tidal dwarves at the column density limit
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⇒ 11,500 hrs with ALFA

⇒ 2000 hrs with AO40

**Void++**

Void++ would map 400 sq. deg. centered on largest nearby void (center at cz~2500 km/s, in front of Pisces-Perseus Supercluster), with 10x the sensitivity of ALFALFA. Will also permit detection of $M_{HI} = 5 \times 10^3$ solar and $N_{HI} \sim (a \ few) \times 10^{17}$ cm$^{-2}$ in resolved sources in the Local Group, serendipitously along same l.o.s.

⇒ 23,000 hrs with ALFA

⇒ 4000 hrs with AO40
Extragalactic HI surveys typically favor a special category of objects: baryon-rich but more often low mass, actively star-forming galaxies.

Late bloomers, the targets of HI surveys are today’s fertility flagbearers of a Universe that 5 to 10 Gyr ago used to make stars at a rate nearly one order of magnitude higher than it does now.
Targeted survey of galaxies to $z \sim 0.5$ (6 Gyr look-back time). While multibeam facility not necessary, dual beam option for rfi excision desirable. Big collecting area essential.

- Evolution of $M/L$, $\Omega_{HI}(z)$, gas content
- Evolution of scaling relations, e.g.

\begin{align*}
L & \propto V_{200}^3 \left[ \frac{H(z)}{H_o} \right]^{-1} \\
R_{\text{disk}} & \propto V_{200} \left[ \frac{H(z)}{H_o} \right]^{-1} \\
\Sigma_o & \propto V_{200} \left[ \frac{H(z)}{H_o} \right]
\end{align*}
The cluster A1835, at \( z \sim 0.25 \), has a SZ signature 4’ in diameter, well matched to the AO beam at \( \sim 1100 \) MHz.

A total HI mass of \( 10^{12} \) solar, spread over 1500 km/s, could be detectable at AO in less than 10 hours, provided we can tame systematics.

A pointed survey of integrated cluster emission at redshifts up to \( z \sim 0.5 \) or even higher may be possible.
**HI Mass Density from DLA**

- $\Omega_g$
  - Mass density of the universe in atomic gas
  - Units of $\rho_c$
- Redshift evolution
  - $z>2$ (SDSS)
    - Decline by ~2 from $z=4$ to 2
    - Coincidence of $z=0$ and $z=2$
    - HI mass density is far larger than dwarf galaxies at $z=0$
  - $z=0$ (21 cm)
    - Reasonable agreement with $z=2$
  - $z=1$ (MgII)
    - Total disconnect
    - Reasonable with 0.666 scaling

Slide credit: J. X. Prochaska 2007