Neutral Hydrogen in Galaxies from Low to High $z$

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In collaboration with:
A. Bouchard, K. van der Heyden, E. de Blok, W. van Driel, RC Kraan-Korteweg, D. Obreschkow
Outline

• HI-stacking techniques: measuring HI in galaxy surveys

• Application to the nearby Universe

• Probing higher z with MeerKAT

• Summary and Outlook
HI: Big Questions

How do galaxies evolve over cosmic time?

• How does $\Omega_{\text{HI}}$ evolve over time?
• How is HI distributed in galaxies, and how does this vary over time?

Lah et al., MNRAS 376: (2007)1357-1366

still large uncertainties
HI: Big Questions

How do galaxies evolve over cosmic time?

• How does $\Omega_{\text{HI}}$ evolve over time?
• How is HI distributed in galaxies, and how does this vary over time?

still large uncertainties

not much known in this regime

Only known for $z \approx 0$ - how does it change with $z$?

LaH et al., MNRAS 376: (2007)1357-1366

Zwaan et al., MNRAS 359 (2005) L30
How to Measure?

Galaxy in Abell 963, $z = 0.21$

Observing time: 20x12 hours on WSRT
How to Measure?

To measure HI at cosmological distances we need:

1. Different techniques to optimise observation timing:
   - measure the average HI content ($\Omega_{\text{HI}}$) of galaxies for different $z$-ranges
   - co-add / stack individual spectra to increase S/N

   (being used by various groups: Zwaan (2000), Chengalur et al. (2001), Lah et al. (2007), Verheijen et al. (2007)
State of the Art

With current telescopes, HI is hard to find at intermediate z, even with stacking...

**Lah et al. (2007)**

$z = 0.24$, GMRT

signal: $2.6\sigma$

**Verheijen et al. (2007)**

$z = 0.206$, WSRT

S/N not quoted
How to Measure?

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How to Measure?

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1. **Different techniques to optimise observation timing:**
   - measure the average HI content ($\Omega_{HI}$) of galaxies for different z-ranges
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     - (being used by various groups: Zwaan (2000), Chengalur et al. (2001), Lah et al. (2007), Verheijen et al. (2007))

2. **Larger more sensitive radio telescopes with large FoV and frequency coverage:**
   - SKA
   - SKA pathfinders (*MeerKAT, ASKAP ...*)
HI Stacking/Co-adding

Since the HI signal is weak, we use independent measurements of galaxy $z$ before stacking:

- **STEP 1:** extract spectra using known positions and $z$
HI Stacking/Co-adding

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- **STEP 2:** Using known $z$ values, shift all lines to common channel

![Diagram showing RA and $\delta$ axes with spectral lines at different velocities.](image)
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$$M_{HI} = \frac{236}{(1+z)} \left( \frac{S_v}{\text{mJy}} \right) \left( \frac{d_L}{\text{Mpc}} \right)^2 \left( \frac{\Delta V}{\text{km/s}} \right)$$
HI-stacking the Nearby Universe

**NIBLES**: W. van Driel et al.

- **Nancay Interstellar Baryon Legacy Extragalactic Survey**
- **AIM**: Find and quantify the density of baryons in the Local Universe
- Targeted survey of 3000 SDSS galaxies with $(900 < cz < 12000 \text{ km/s})$
- $0.5 \ M_z$ bins
- ~35 mins per pointing

**CRUMBS**: Blyth, Bouchard et al.

- Characterizing Radio-Undetected Masses in Baryonic Surveys
- **AIMS**: ‘Squeeze’ any/all remaining ‘drops’ of HI information out of the NIBLES non-detections
- Inform NIBLES observing strategy
- non-detections = all NIBLES spectra with $< 3\sigma$ HI lines
Picking up the CRUMBS...

Preliminary results based on 884 NIBLES galaxies:

- non-detections = all NIBLES spectra with < 3σ HI lines
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NIBLES data:
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Preliminary results based on 884 NIBLES galaxies:

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Preliminary results based on 884 NIBLES galaxies:
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To understand how the non-detections were distributed, we implemented a red-blue colour cut as a morphology handle:

\[ C_{ur}^{\prime} (M_r) = 2.06 - 0.244 \tanh \left( \frac{M_r + 20.07}{1.09} \right) \]
Picking up the CRUMBS...

Preliminary results based on 884 NIBLES galaxies:

To understand how the non-detections were distributed, we implemented a red-blue colour cut as a morphology handle:

- Number of blue galaxies drops off with distance
- Red non-detections mostly more distant
Stacking results

e.g. blue non-detections:
Stacking results

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\[ \langle M_{\text{HI, red}} \rangle = 1.26 \times 10^8 \pm 1.24 \times 10^7 \, M_{\odot} \]
\[ \langle M_{\text{HI, blue}} \rangle = 6.73 \times 10^7 \pm 8.59 \times 10^6 \, M_{\odot} \]
More preliminary results...

### Colour

- $g-i$ (mags) vs. number of galaxies

### Magnitude

- $M_r$ (mags) vs. number of galaxies

### Radius

- Radius (kpc) vs. number of galaxies
More preliminary results...

Colour

Magnitude

Radius

![Graphs showing data for Colour, Magnitude, and Radius.](image-url)
More preliminary results...

### Colour

- Significance (nσ)
- Color-magnitude diagram

### Magnitude

- Significance (nσ)
- Magnitude-magnitude diagram

### Radius

- Significance (nσ)
- Radius-magnitude diagram
More preliminary results...

- $<M_{HI}>_{\text{red}} > <M_{HI}>_{\text{blue}}$
- Non-detection bias:
  - sampling HI-poor blue galaxies
  - sampling bright red galaxies
More preliminary results...

- Colour: 
  - $<M_{\text{HI}}>$\text{red} > $<M_{\text{HI}}>$\text{blue}
  - Non-detection bias:
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- Magnitude:
  - Brighter galaxies: larger $<M_{\text{HI}}>$
  - expect drop-off for $M_G$ fainter than $\sim -19$

- Radius:
More preliminary results...

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- \(<M_{\text{HI}}>_{\text{red}} > <M_{\text{HI}}>_{\text{blue}}\)
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  - sampling HI-poor blue galaxies
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We have used a simulated galaxy catalogue from Obreschkow & Rawlings et al., (arXiv:0904.2221v2):

• Obreschkow et al. simulate cosmic evolution of neutral gas (HI and H$_2$) based on the virtual galaxy catalogue by De Lucia on Millenium simulation (Springel et al., 2005)

• Produce catalogue of 6 x10$^7$ galaxies (0 < z < 9.7), complete for M$_{(HI+H_2)}$ > 10$^8$ M$_{sun}$
  ▸ galaxy properties incl. parameters of realistic velocity profiles, (W$_{20}$, W$_{50}$, $F_{peak}$ etc.)

\[ \phi / \text{Mpc}^3 \]

\[ M_{HI} / M_\odot \]

Includes evolving HIMF
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Stacking Experiments for MeerKAT

We have simulated 3 survey scenarios for a single pointing observation with MeerKAT:

- Using sensitivities based on MeerKAT, 80 dish layout (E. de Blok’s talk)

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  - 22.3 km/s at $z = 0.1$
  - 38.5 km/s at $z = 0.9$
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- Set channel width = 0.096 MHz:
  - 22.3 km/s at z = 0.1
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Simulation parameters

- FoV = 0.47 deg x 0.47 deg (= 25% MeerKAT FoV)
- Simulate ‘real’ MeerKAT bandwidth of 512 MHz & 16k channels
- Set channel width = 0.096 MHz:
  - 22.3 km/s at z = 0.1 & 38.5 km/s at z = 0.9

- Binned galaxies in z = 0.1 chunks

Caveat:

- Assume ALL galaxy redshifts known (i.e. ‘perfect’ optical data)
Quick comparison at $z=0.4$

S1: 3 month, single pointing

S3: 1 year, single pointing
Preliminary results: towards $\Omega_{\text{HI}}$

Output $\langle M \rangle$ vs. Input $\langle M \rangle$

- Stacking technique recovers input $\langle M \rangle$ well
Preliminary results: towards $\Omega_{\text{HI}}$

- Stacking technique recovers input $<M>$ well
- More refinements yet to come, but looking promising!
Summary & Outlook

• HI-stacking is a promising technique to use for targeted HI surveys to ‘squeeze’ out additional information from non-detections

• HI-stacking will be useful technique to use for high-z surveys with MeerKAT

Next Steps

• Scale CRUMBS up to the full NIBLES dataset
• Stack non-detections from other surveys...

• Refine simulations for MeerKAT planning:
  • investigate luminosity cuts / biases
  • inclinations, etc.
Thank you to:

W. van Driel & the NIBLES team (especially to T. Joseph and M. Ramatsoku at UCT for data reduction)

D. Obreschkow & Oxford team for the use of their galaxy simulations catalogue

My UCT colleagues for all your input
Extra slides
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More preliminary results...

### Colour
- Number of galaxies vs. $g-i$ (mags)
- Significance vs. $g-i$ (mags)
- Mean $M_r$ vs. $g-i$ (mags)

### Magnitude
- Number of galaxies vs. $M_r$ (mags)
- Significance vs. $M_r$ (mags)
- Mean $M_r$ vs. $M_r$ (mags)

### Radius
- Number of galaxies vs. Radius (kpc)
- Significance vs. Radius (kpc)
- Mean $M_r$ vs. Radius (kpc)
More preliminary results...

**Colour**

- Graph showing the relationship between $g-i$ (mags) and the number of galaxies.

**Magnitude**

- Graph showing the relationship between $M_r$ (mags) and the number of galaxies.

**Radius**

- Graph showing the relationship between radius (kpc) and the number of galaxies.
Significance of simulations

![Graph showing significance vs. redshift](image.png)
Number dist. for simulations
Input Mass dist. vs. z
Input Mass dist. vs. z

![Graphs showing mass distribution vs. redshift (z)]