HI Surveys with APERTIF

Marc Verheijen
Tom Oosterloo
outline

• APERTIF on the WSRT
• Selected surveys
• Role and fate of gas in galaxy evolution
• Examples of existing blind HI synthesis surveys
• Challenges
Salient features of WSRT & APERTIF

- **Westerbork Synthesis Radio Telescope**
  - 14x25m dishes
    - 0.7% of collecting area of SKA
  - 3km regular east-west array
    - baseline redundancy, no w-term in FFT
  - equatorial mounts
    - excellent calibration & polarisation characteristics

- **APERture Tile In Focus**
  - $T_{\text{sys}} = 50K$, 8 deg$^2$ FoV, $A_{\text{eff}}/T_{\text{sys}} = 88 \text{ m}^2/K$
  - 1000–1700 MHz, BW=300 MHz, $\Delta V=16 \text{ km/s}$
## Imaging & Survey speeds

**APERTIF versus other SKA pathfinders**

<table>
<thead>
<tr>
<th></th>
<th>$T_{sys}$</th>
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Not *all* SKA pathfinders can do *all* the science...

Specific surveys for APERTIF on WSRT:

- Efficient pulsar survey machine
  intersecting multiple fan-beams in 8gr8 mode
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regular ‘multi-slit’ diffraction grating
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Heavens et al. 2004

APERTIF will detect the same star forming galaxies as LOFAR.
Not *all* SKA pathfinders can do *all* the science...

➡️ **Specific surveys for APERTIF on WSRT**:

- **Efficient pulsar survey machine**
  intersecting multiple fan-beams in 8gr8 mode

- **Overlap with LOFAR surveys**
  all-sky continuum & polarisation survey at 1.4 GHz

- **Selected HI surveys**
  Galactic Plane survey of the outer galaxy
  Extragalactic HI surveys out to z=0.5
HI self-absorption in DRAO and VLA Galactic Plane Surveys

DRAO - Canadian Galactic Plane Survey

\[ \Theta = 1 \text{ arcmin} , \Delta V = 1.2 \text{ km/s} , \text{FoV} = 107' \]

\[ T_{\text{int}} = 12 \times 12^{\text{hr}}/\text{field}, \ 7 \times 9 \text{m dishes}, \ A_{\text{eff}}/T_{\text{sys}} \approx 5.7 \]

VLA

\[ \Theta = 1 \text{ arcmin} , \Delta V = 1.5 \text{ km/s} , \text{FoV} = 32' \]

\[ T_{\text{int}} = 9^{\text{m}}/\text{field}, \ 27 \times 25 \text{m dishes}, \ A_{\text{eff}}/T_{\text{sys}} \approx 210 \]

Based on \( (A_{\text{eff}}/T_{\text{sys}})^2 \Omega_{\text{FoV}} \):

APERTIF survey speed \( \approx 550 \times \text{DRAO} \)

5 \times \text{VLA}
Extragalactic large-area blind HI surveys

APERTIF HI mass limits versus redshift

5σ detection in HI mass dependent linewidth
Extragalactic large-area blind HI surveys

APERTIF HI detected mass & redshift distributions

all-sky survey, $1 \times 12^{\text{hr}}$ per pointing

![Graph showing HI mass distribution vs. redshift distribution with different survey durations.](image)
Extragalactic large-area blind HI surveys

APERTIF HI detected mass & redshift distributions

Matching SDSS redshift distribution

Z=0.0 0.1 0.2

all-sky survey, 1x12 hr per pointing

SDSS

APERTIF

10x12 hr
WSRT + APERTIF located in northern hemisphere

Take advantage of SDSS

$8^\text{hr} < \alpha < 16^\text{hr}$, $15^\circ < \delta < 60^\circ$

4100 deg$^2 \rightarrow \sim 500$ pointings

4 years @ 30% of time

$0 < Z < 0.25$ (300 MHz)

203,425 optical SDSS redshifts at $z < 0.2$ (DR5)

$M^*_{\text{HI}}$ at $z = 0.08$

expect $\sim 10^5$ HI detections

Spectroscopy completed with DR7
The promise of blind HI synthesis imaging surveys

• Nature of galaxy bimodality
  - How to sustain star formation in the ‘blue cloud’?
  - What happens to galaxies when they migrating to the red sequence?
  - What can we learn from ‘fossil records’ of cold gas in ‘red & dead’ galaxies?
  - Examine cold gas in relation to SFR, age of stellar populations, dust (IRAS) etc

• Environmental dependence of gas content
  - What is the HI Mass Function in different environments
  - What is the origin of HI deficiencies in high density regions (stripping, harassment, ...)?
  - How effective is pre-processing in cluster outskirts and galaxy groups (tidal)?
  - What physical processes dominate gas removal where?

• Resolved galaxy structure and kinematics
  - Obtain an unbiased census of warps, lopsidedness, interactions
  - Determine rotation curves and mass profiles probing dark matter halos
  - Measure spin vectors & angular momentum (cosmic shear, structure formation)
  - ........
central question: What is the role and fate of gas in galaxy formation & evolution?
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Baldry et al 2004
Fraternali et al 2002
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Baldry et al. 2004
Oosterloo & van Gorkom 2005
Fraternali et al. 2002
Oosterloo et al. 2007
Fueling the Blue Cloud
sustaining star formation
building up stellar mass

High Velocity Clouds
in MW and other galaxies

Late stages of gas accretion or
minor mergers

Simkin et al 1987

Sancisi et al 2008
Fueling the Blue Cloud  
sustaining star formation  
building up stellar mass  

High Velocity Clouds  
in MW and other galaxies  

Late stages of gas accretion or  
minor mergers  

APERTIF will provide a full census.
The brightest lenticulars in Ursa Major

Hot action in a cool group

NGC 3998

$M_R = -21.84\, \text{(mag)}$
$M_{HI} = 5.8 \times 10^8\, (M_\odot)$

NGC 4026

$M_R = -21.16\, \text{(mag)}$
$M_{HI} = 1.2 \times 10^9\, (M_\odot)$

NGC 4111

$M_R = -21.44\, \text{(mag)}$
$M_{HI} = 1.3 \times 10^9\, (M_\odot)$

Verheijen et al, 2001
The brightest lenticulars in Ursa Major

Hot action in a cool group

From Spiral to Lenticular through tidal interactions?

\[ M_R = -21.44 \text{ (mag)} \]
\[ M_{HI} = 1.3 \times 10^9 (M_\odot) \]
Stripping in action

NGC 4522 in Virgo

➢ Ram-pressure induced (and truncated?) star formation
HI in the Virgo cluster

VIVA : VLA Imaging of Virgo galaxies in Atomic gas

Chung, van Gorkom, Kenney & Vollmer, 2007

Oosterloo & van Gorkom, 2005
Environmental dependence of gas content.

Verheijen & Sancisi 2001
Westerbork

Cayatte et al 1993
Very Large Array
Environmental dependence of HI Mass Function?

HIMF flattens with increasing density

Springob et al, 2005
Arecibo General Catalogue

HIMF steepens with increasing density

Zwaan et al, 2005
HIPASS
Environmental dependence of HI Mass Function?

HIMF flattens with increasing density

HIMF steepens with increasing density

Springob et al, 2005

Arecibo General Catalogue

Zwaan et al, 2005

HIPASS

APERTIF will blindly survey all densities beyond the local universe.
Blind VLA-D HI survey of Ursa Major.
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collapsing HIMF at $M(HI) < 10^7 M_{\odot}$?

Blind WSRT Survey of CVn
86 deg$^2$, 1372 pointings
60x12 hrs, 80 min/pointing

Where are these low HI-mass dwarfs?

Kovač, 2007 (thesis, Groningen)
collapsing HIMF at $M(\text{HI}) < 10^7 M_{\odot}$?

Blind WSRT Survey of CVn
86 deg$^2$, 1372 pointings
60x12 hrs, 80 min/pointing

Where are these low HI-mass dwarfs?

APERTIF will efficiently survey local volumes to greater depth.

Kovač, 2007 (thesis, Groningen)
HI, ICM, SFR, SP interrelations

Infalling galaxies are clustered in space and velocity
➢ relates to substructures in redshift space
Butcher-Oemler effect

The fraction of blue (starforming?) galaxies in clusters increases with redshift and peaks in cluster outskirts.
The Butcher-Oemler effect

The fraction of blue (starforming?) galaxies in clusters increases with redshift and peaks in cluster outskirts.

Abraham et al, 1996

Butcher-Oemler effect

The fraction of blue (starforming?) galaxies in clusters increases with redshift and peaks in cluster outskirts.

A963

Abraham et al, 1996
A tale of two clusters

Abell 963
Marc Verheijen
Boris Deshev
Jacqueline van Gorkom
K.S. Dwarakanath
Hector Bravo-Alfaro
Aeree Chung
Raja Guhathakurta
María Montano-Castaño

Abell 2192
Glenn Morrisson
Bianca Poggianti
David Schiminovich
Arpad Szomoru
Eric Wilcots
Min Yun
Ann Zabludoff

SDSS images
z=0.206
z=0.188
A tale of two clusters

Abell 963

Abell 2192

SDSS images

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z=0.188
Ultra-deep WSRT observations

- 8x10MHz bands, overlapping to cover 1160–1220 MHz, surveyed volume \( \approx 70,000 \text{ Mpc}^3 \)
- \( Z = 0.164–0.224 \)

- 1600 channels, covering 18,000 km/s velocity range
- 22 km/s velocity resolution (after Hanning smoothing)

- 117x12 hr on Abell 963, 73x12 hr on Abell 2192 (5–10% lost to RFI)

- Measured rms noise: 30 \( \mu \text{Jy} \) and 36 \( \mu \text{Jy} \) at \( R=22 \text{ km/s} \).

\[ M_{\text{HI}} \text{ (min)} = 2 \times 10^9 \left( M_\odot \right) \text{ over 150 km/s profile width.} \]
\[ \text{(4}\sigma \text{ in each of 3 resolution elements)} \]

\[ N_{\text{HI}} \text{ (min)} = 3 \times 10^{19} \left( \text{cm}^{-2} \right) \text{ over 75 km/s profile width at 7}\sigma. \]
Survey Volume & Large Scale Structure

SDSS redshift cone
Survey Volume & Large Scale Structure

combined volume: $7 \times 10^4 \, \text{Mpc}^3$

325 Mpc

Abell 2192

Abell 963

SDSS redshift cone
Survey Volume & Large Scale Structure

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SDSS redshift cone
Abell 2192

\[ \nu = 1205 - 1160 \text{ MHz} \]
\[ z = 0.179 - 0.224 \]
\[ cz = 53.617 - 67.230 \text{ km/s} \]
\[ R = 88 \text{ km/s} \]

1.14x1.14 deg\(^2\)

10 Mpc

6 IFs

\[ \sigma = 17 \mu\text{Jy} \]

99 preliminary 5\( \sigma \) HI detections with optical counterparts.

Abell 963

\[ \sigma = 14 \mu\text{Jy} \]
Abell 2192

1.14x1.14 deg²

σ = 17 μJy

ν = 1205 – 1160 MHz

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R = 88 km/s

99 preliminary 5σ HI detections with optical counterparts.
Detections in pilot observations
Detections in pilot observations

Graphs and images showing frequency, redshift, and distance from center in arcmin.
Revealing the surrounding field

Abell 2192

- ▲: HI detection
- ○: SDSS
- ▲: WIYN/Hydra

- ○ ▲: foreground
- ○ △: cluster (0.180 < Z < 0.195)
- ○ ▲: background

Dec. (J2000)

R.A. (J2000)
Revealing the surrounding field
Colour-Magnitude diagrams

Galaxies with known redshifts only

optical redshifts

○ : SDSS
× : other

HI redshifts

▲ : WSRT
Stacking HI spectra

Average HI mass: $\sim 2 \times 10^9 \, M_\odot$
Probing $\Omega_{\text{HI}}(z)$ of the universe

$\Omega_{\text{HI}}$ at $z=0.2$ from stacking GMRT HI spectra of starforming galaxies with optical redshifts.

(Lah et al, 2007 ; Blyth this meeting)

Soon to be measured from WSRT data, but surveyed volume too small?

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Soon to be measured from WSRT data, but surveyed volume too small?

Still a tough job for APERTIF and ASKAP given $A_{\text{eff}}/T_{\text{sys}}$. 
Challenges

Correlator and pipelined calibration solutions?

How to keep up with the huge data flow?

How to extract HI maps, velocity fields and rotation curves for $10^4$ galaxies and recognize ‘anomalies’?

How to serve the data to the public?
Redshift distributions

Abell 963

Abell 2192
## Trade-offs: Imaging/Survey Speeds & Costs

<table>
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<th>Nbm</th>
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SKA all-sky HI survey

a billion galaxies detected in HI out to z=3

Cosmic large scale structure

Baryonic Acoustic Oscillations from the clustering power spectrum

Chris Blake, 2007
APERTIF
APERture Tile In Focus

A Focal Plane Array for the WSRT

Principal Investigators: Tom Oosterloo
Marc Verheijen

Program Manager: Wim van Cappellen

Engineering team: Laurens Bakker
Marianna Ivashina
Oleg Smirnov
Stefan Wijnholds
Bert Woestenburg
Jan Noordam
Prototype installed in RT5, using the modified LOFAR Initial Test Station

ITS can accept 60 signal chains

Future APERTIF beamforming below apex
APERTIF prototype results

Element patterns  Steerable compound beam
Messier 31

3x3 pointings, 9x20 sec integration time, 6.5° x 6.5° FoV

HI channel maps

integrated HI map

Position–Velocity diagram

HI velocity field
Messier 31

3x3 pointings, 9x20 sec integration time, 6.5° x 6.5° FoV

WSRT primary beam

HI channel maps

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Position–Velocity diagram

HI velocity field

ASTRON, university of Groningen, Kapteyn Astronomical Institute
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ASTRON
university of groningen
Kapteyn Astronomical Institute
3x3 Pointings, \(9 \times 20^\text{sec}\) Integration Time, \(6.5^\circ \times 6.5^\circ\) FoV

**Messier 31**

**HI channel maps**

**Integrated HI map**

**Position-Velocity diagram**

**HI velocity field**
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<td>300</td>
<td>6</td>
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<tr>
<td>ASKAP-30</td>
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<td>30</td>
<td>300</td>
<td>5</td>
<td>6.2</td>
<td>19</td>
</tr>
<tr>
<td>MeerKAT-80</td>
<td>30</td>
<td>1.2</td>
<td>512</td>
<td>29</td>
<td>5.4</td>
<td>28</td>
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<tr>
<td>ATA-42</td>
<td>40</td>
<td>4.9</td>
<td>200</td>
<td>0.43</td>
<td>0.21</td>
<td>0.42</td>
</tr>
</tbody>
</table>
HI SURVEYS OF SDSS AREA

$8^\text{HR} < \alpha < 16^\text{HR}, 15^\circ < \delta < 60^\circ$

$0 < Z < 0.25$ (300 MHz)

$\sim 450 \times 12^{\text{HR}}$

4 YEARS @ 30% OF TIME

203,425 OPTICAL SDSS REDSHIFTS AT $Z < 0.2$ (DR5)

$M_{\text{HI}}^* \text{ AT } Z = 0.08$

$1.5 \times 10^5$ HI DETECTIONS
HI surveys of SDSS area

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4177 deg$^2$

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• HI emission from 41 galaxies at $z \approx 0.2$
  (need SKA for larger redshifts)

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Only SKA can image this at $z=1$
HI deficiencies

- \( D_{\text{HI}} \) at \( N_{\text{HI}} = 10^{20} \) atoms/cm\(^2\)
- \( D_{\text{opt}} \) at \( \mu(B) = 25 \) mag/arcsec\(^2\)

\[
\text{Def} = \langle \text{Log} \sigma_{\text{HI}} \rangle_T - \text{Log} \sigma_{\text{HI}}
\]

\[
\sigma_{\text{HI}} = \frac{M_{\text{HI}}}{\pi(D_{\text{opt}}/2)^2}
\]

- \( D_{\text{HI}}/D_{\text{opt}} \ll 1 \): enhanced central \( N_{\text{HI}} \)  \rightarrow \text{ram-pressure stripping}
- \( D_{\text{HI}}/D_{\text{opt}} \approx 1 \): overall lowered \( N_{\text{HI}} \)  \rightarrow \text{turbulent viscous stripping}
- \( D_{\text{HI}}/D_{\text{opt}} > 1 \): normal \( N_{\text{HI}} \)  \rightarrow \text{never traveled close to center}
So here’s the problem...

We have to live with these bandpass notches...
Radio continuum imaging

**VLA-Cs**
- $\sigma = 24 \, \mu\text{Jy/bm}$
- $\Theta = 16'' \times 15'' = 50 \times 47 \, \text{kpc}$

**GMRT**
- $\sigma = 23 \, \mu\text{Jy/bm}$
- $\Theta = 5'' \times 4'' = 15 \times 12 \, \text{kpc}$

\[
\text{SFR}_{\text{min}}^{3\sigma} = 5.5 \times \frac{L_{21}}{4.0 \times 10^{21} \, \text{WHz}^{-1}} = 9.8 \, \text{M}_\odot/\text{yr} \quad \text{(at field center)}
\]
Radio contours on R-band image

30x30 arcmin

10x10 arcmin

Abell 2192

6.3x6.3 Mpc

2.1x2.1 Mpc
The power of a fully upgraded WSRT

**old VLA**

\[ \frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{182 \text{ m}^2}{\text{K}} \]

2x6.25 MHz

**new WSRT**

\[ \frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{140 \text{ m}^2}{\text{K}} \]

8x10 MHz