The future of the HI mass function

Martin Zwaan (ESO)
Luminosity function

Relevance:

- Theories of galaxy formation and evolution
- Luminosity density
- ...
Luminosity function

\[ \Phi(M_r - 5 \log_{10} h) \]

\[ M_r = 5 \log_{10} h \]

SDSS, Blanton et al 2005

Relevance:

- Theories of galaxy formation and evolution
- Luminosity density
- ...
HI mass function

Relevance:

- Theories of galaxy formation and evolution
- Neutral hydrogen gas mass density
- Missing satellites
- Baryon mass functions

HIPASS, Zwaan et al 2005

$\alpha = -1.37$

$log M^*_H = 9.80$

$\theta^* = 0.0060$
**First HI mass functions**

- Based on optical catalogues and assumptions on gas richness (Briggs 1990)

Compare with observations:
Is the Universe filled with dark galaxies?
Low surface brightness galaxies?
Schechter functions

power law slope

HI mass density divergent

'exponential decline'

'flat'

power law
HI mass function from **blind HI Surveys**

- HIMF measured from blind 21-cm surveys:
  - **AHISS**: HI strip Survey (*Zwaan et al* 1997)
  - **AS**: Arecibo Slice (*Spitzak & Schneider* 1998)
  - **ADBS**: Arecibo Dual Beam Survey (*Rosenberg & Schneider* 2000)
  - **ALFALFA**: Arecibo Legacy Fast ALFA Survey (*Giovanelli et al* 2005)
  - **SKA pathfinders**...
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Blind survey covering whole southern sky up to dec=+25°. 5300 detections
HIPASS results

- $M_{\text{HI}} \propto S_{\text{int}} D^2$
- $M_{\text{HI}} = 10^8 M_\odot$ out to $\sim 12$ Mpc
- peak at $\sim 25$ Mpc
- No sharp flux limit $\rightarrow$ complicated completeness corrections
The HI mass function

\[ \alpha = -1.37 \]

\[ \log \ M^* = 9.80 \]

\[ \theta^* = 0.0060 \]

(Zwaan et al 2005)
The HI mass function

\[ \log \Theta(M_{\text{HI}}) [\text{Mpc}^{-3}] \]

\[ \alpha = -1.37 \]

\[ \log M^*_{\text{HI}} = 9.80 \]

\[ \theta^* = 0.0060 \]

\[ \sim 4300 \text{ galaxies} \]

\[ \sim 66 \text{ galaxies} \]
The HI mass function

\log \Theta(M_\text{HI}) = \alpha \log M_\text{HI} + \log M_\text{HI}^* + \theta^*

\alpha = -1.37
\log M_\text{HI}^* = 9.80
\theta^* = 0.0060
The **HI mass function**

The figure shows the HI mass function with a power-law index \( \alpha = -1.37 \) for the faint-end slope. The log of the number of HI masses is given as follows:

- \( \log M_{\text{Hi}}^* = 9.80 \)
- \( \theta^* = 0.0060 \)

The faint-end slope is 'flat'.

- SMC: Very local
- \( M_{\text{Hi}}^* \)
HIMF dependence on galaxy type

- Low mass end of HIMF dominated by Sm-Irr
- High mass end of HIMF dominated by Sbc-Sc
- Trend consistent with optical luminosity function

\[ \theta(M_h) \text{ [Mpc}^{-3}] \]

\[ \log M_h \text{ [M}_\odot] \]

zwaan et al 2003
Environmental effects on HIMF?

- Steeper toward higher densities?
- Density contrast lower in HI samples than in optical samples
- Opposite effect seen by Springob et al (2004), based on optically selected galaxies
HIMF variations

Different surveys probe different depths

Large scale structure causes variations in HIMF?

Or is it differences in analysis?

From Schneider et al 2008
Do larger surveys help?
Do larger surveys help?

- Uncertainties in HI mass function dominated by systematic errors
Do larger surveys help?

- Uncertainties in HI mass function dominated by systematic errors

- Compare optical luminosity function →

Driver et al 2005
Analysis techniques

Completeness  Reliability

• Most detection very close to the noise...

• Put fake sources in your data!
The HIMF and cosmic variance

HIPASS 1000 brightest galaxies
four different quadrants of the southern sky
Future challenges for HI mass function

low mass end

environment  evolution
Future challenges for HI mass function

low mass end

environment    evolution
Future challenges for HI mass function

low mass end

*deep & wide*

environment

*wide*

evolution

*deep*
How to measure space densities

- **Traditionally: $1/V_{\text{max}}$ method** (Schmidt 1968)
  - Summing volumes accessible to objects
  - Sensitive to large scale structure

- **Maximum likelihood methods** (Efstathiou et al 1988, Sandage et al 1979)
  - Find $\theta$ that yields maximal joint probability of detecting all sources in sample
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$$ p(M_{\text{HI},i}|D_i) = \frac{\theta(M_{\text{HI},i})}{\int_{M_{\text{HI},\text{min}(D_i)}}^{\infty} \theta(M_{\text{HI}})dM_{\text{HI}}} $$
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- Minimal detectable HI mass at distance $D_i$ is generally **not defined** for HI selected samples
How to measure space densities

• solution: multi-dimensional stepwise maximum likelihood methods

• Find $\theta(M_{\text{HI}},W)$

• Collapse to find HIMF

• Or, find ML-based effective volume accessible to each galaxy individually
Biases in HI mass determination
Biases in HI mass determination

- Eddington effect
- noise bias
- HI self-absorption
- cosmic variance
- confusion
- inclination bias
- resolve large galaxies
Simulations to test HIMF recovery

- Millennium Simulation (Springel et al 2005)

- 9 million galaxies in the full simulation box (500 Mpc/h on a side)

- Stich several cubes together

- Assume a HIPASS HI mass function

- Low mass \((\log M_{\text{HI}}<8.5)\) cluster around larger ones
Simulations

• Rotational velocity - HI mass relation from Obreschkow & Rawlings (2009)

• Random inclinations -> velocity widths

• Realistic scatter on all parameters

• Select galaxies from simulated boxes, assuming ‘optimal smoothing’
Simulated HI skies

“Wallaby”
all sky shallow

“Dingo”
30deg$^2$ deep
Simulated HI catalogues

~600,000 galaxies in one year

~45,000 galaxies in 1000 hours
Wide field HIMFs

Four different realizations of Wallaby: huge variations in HIMF based on $1/V_{\text{max}}$ method

factor 3 variation!
Without **large scale structure**... but with scatter in M-W relation
The magic of **stepwise maximum likelihood**

Solid: $1/V_{\text{max}}$ method

Open: 2DSWML

(ran 2DSWML only on galaxies $M_{\text{HI}} < 10^8 M_\odot$)

$10^8 M_\odot$ out to $\sim 70$ Mpc
Wallaby-type survey: HIMF expectations

• ~600,000 galaxies (depending on selection technique)

• Can see $M_{\text{HI}} = 10^7 \, M_\odot$ out to ~30 Mpc

• Can measure HIMF down to $M_{\text{HI}} \sim 10^6 \, M_\odot$

• Excellent for measuring HI as function of environment
Dingo HI mass functions

Ten different realizations of Dingo ultradeep: huge variations in HIMF based on $1/V_{\text{max}}$ method
The magic of **stepwise maximum likelihood**

Solid: $1/V_{\text{max}}$ method
Open: 2DSWML
with Dingo to higher redshifts

Can reliably measure HIMF above $M_{\text{HI}}^*$ out to $z=0.3$
Use Dingo to study **HIMF** as function of redshift

Maximum likelihood does not help much

For HIMF evolution, one deep field is dangerous

\[ M_{\text{HI}}^* \text{ out to } z=0.3 \]
Dingo-type survey: HIMF expectations

• ~45,000 galaxies per 30° ultradeep field (depending on selection technique)

• ~12,000 galaxies per 30° deep field

• Can see $M_{\text{HI}} = 10^8 \, M_\odot$ out to $z \sim 0.07$

• Can measure HIMF out to $z \sim 0.3$

• Can measure evolution of $\Omega_{\text{HI}}$ out to higher $z$ using some assumptions/tricks
$\Omega_{HI}$: the cosmic HI mass density

$\alpha = -1.37$

$\log M^*_\text{HI} = 9.80$

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$\Omega_{\text{HI}}$: the cosmic HI mass density

$\alpha = -1.37$

$\log M_{\text{HI}}^* = 9.80$

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Number of **HI atoms** does **not evolve** much

- DLAs are a “phase” not a “reservoir”
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- DLAs are a "phase" not a "reservoir"
- Where is the missing gas?
HI column density distribution evolves slowly
HI column density distribution evolves slowly

- HI distribution in galaxies at $z=3$ similar to that today?
- Star formation laws similar at higher $z$?
Should we be looking at HI or H$_2$?

- Obreschkow & Rawlings (2009): pressure-based models predict that H$_2$ mass density rises quickly
- See also Zwaan & Prochaska (2006)
- Need to follow up part of a deep HI field with ALMA

Obreschkow & Rawlings 2009
What's next? (Before SKA pathfinders?)

- ALFALFA finished~ 2011/2012
- 2 times smaller error bars on HIMF, but uncertainty determined by systematics...

<table>
<thead>
<tr>
<th></th>
<th>HIPASS</th>
<th>ALFALFA</th>
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<tbody>
<tr>
<td>sensitivity</td>
<td>13 mJy</td>
<td>1.7 mJy</td>
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<tr>
<td>beam</td>
<td>15'</td>
<td>3.5'</td>
</tr>
<tr>
<td>area</td>
<td>30000 deg$^2$</td>
<td>7000 deg$^2$</td>
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<tr>
<td>detections</td>
<td>5300</td>
<td>~18000?</td>
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</table>

The Arecibo Legacy Fast ALFA Survey

Predicted detections in ALFALFA (Giovanelli et al 2005)
Conclusions

- HI mass function fairly flat ($\alpha=-1.3$)
  - *but we worry about cosmic variance*
- More sophisticated techniques are essential for volume corrections
  - *but don’t help much with deep field evolution*
- Need to know HIMF as function of environment
  - *also to understand ‘the’ local HIMF*
- Need to know how HI mass function evolves
  - *but all the action is in the molecules?*
Implications for cosmic **SFR density**

SFRD as function of HI and H$_2$ (at $z=0$):

![Graph showing SFRD as function of HI and H$_2$]

Even though H$_2$ has very small cross section, it contributes significantly to $\Omega_{\text{gas}}$ and the SFRD.
HI at **high** and **low** \( z \)

**low redshift**
- 21-cm emission

**high redshift**
- Ly\( \alpha \) absorption
**HI at high and low z**

**low redshift**
- 21-cm emission

**high redshift**
- Lyα absorption

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Image of galaxies and spectrum with peaks labeled.
QSO absorption line statistics from local galaxies:

\[ \frac{dN}{dz} = \frac{c}{H_0} \times \text{Area(HI)} \times \Phi \]
QSO absorption line statistics from local galaxies:

\[
\frac{dN}{dz} = \frac{c}{H_0} \times \text{Area}(\text{HI}) \times \Phi
\]