HI Galaxy Science with the SKA

Martin Meyer

on behalf of the HI SWG
Overview

HI Galaxy Science with the SKA
• science chapters, priorities

SKA Capabilities for HI
• rebaselined SKA1

Key Science Observations
• what kinds of HI surveys do we want to carry out?
Fuelling Galaxies over Cosmic Time

**HI surveys key to unlocking galaxy evolution**

- galaxy evolution studies dominated by optical/NIR (stars)
- need to understand how galaxies fuelled (gas)
- HI the fundamental baryonic building block

**Understanding of HI in galaxies remains limited**

- HIPASS, ALFALFA: single dish, $z < 0.06$
- Only few hundred galaxies detected in HI beyond the local Universe
- SKA and its pathfinders will revolutionise
Fuelling Galaxies over Cosmic Time

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SKA1 HI Science Priorities

- Resolved HI kinematics and morphology of ~10^{10} M_☉ mass galaxies out to z~0.8
- High spatial resolution studies of the ISM in the nearby Universe.
- Multi-resolution mapping studies of the ISM in our Galaxy
- HI absorption studies out to the highest redshifts.
- The gaseous interface and accretion physics between galaxies and the IGM

### SKA1 science goals

<table>
<thead>
<tr>
<th>Science Goal</th>
<th>SWG</th>
<th>Objective</th>
<th>SWG Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - I. Imaging</td>
<td>1/3</td>
</tr>
<tr>
<td>2</td>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - II. Power spectrum</td>
<td>2/3</td>
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<tr>
<td>3</td>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)</td>
<td>3/3</td>
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<tr>
<td>4</td>
<td>Pulsars</td>
<td>Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>Pulsars</td>
<td>High precision timing for testing gravity and GW detection</td>
<td>1/3</td>
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<tr>
<td>6</td>
<td>Pulsars</td>
<td>Characterising the pulsar population</td>
<td>2/3</td>
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<tr>
<td>7</td>
<td>Pulsars</td>
<td>Finding and using (MiliSecond) Pulsars in Globular Clusters and External Galaxies</td>
<td>2/3</td>
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<td>8</td>
<td>Pulsars</td>
<td>Finding pulsars in the Galactic Centre</td>
<td>2/3</td>
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<tr>
<td>9</td>
<td>Pulsars</td>
<td>Astrometric measurements of pulsars to enable improved tests of GR</td>
<td>2/3</td>
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<td>10</td>
<td>Pulsars</td>
<td>Mapping the pulsar beam</td>
<td>3/3</td>
</tr>
<tr>
<td>11</td>
<td>Pulsars</td>
<td>Understanding pulsars and their environments through their interactions</td>
<td>3/3</td>
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<tr>
<td>12</td>
<td>HI</td>
<td>Mapping the Galactic Structure</td>
<td>3/3</td>
</tr>
<tr>
<td>13</td>
<td>HI</td>
<td>Resolved HI kinematics and morphology of <del>10^{10} M_☉ mass galaxies out to z</del>0.8</td>
<td>1/3</td>
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<tr>
<td>14</td>
<td>HI</td>
<td>High spatial resolution studies of the ISM in the nearby Universe.</td>
<td>2/3</td>
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<tr>
<td>15</td>
<td>HI</td>
<td>Multi-resolution mapping studies of the ISM in our Galaxy</td>
<td>3/3</td>
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<tr>
<td>16</td>
<td>HI</td>
<td>HI absorption studies out to the highest redshifts.</td>
<td>4/3</td>
</tr>
<tr>
<td>17</td>
<td>HI</td>
<td>The gaseous interface and accretion physics between galaxies and the IGM</td>
<td>5/5</td>
</tr>
<tr>
<td>18</td>
<td>Transients</td>
<td>Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State</td>
<td>1/4</td>
</tr>
<tr>
<td>19</td>
<td>Transients</td>
<td>Accessing New Physics using ultra-Luminous Cosmic Explosions</td>
<td>1/4</td>
</tr>
<tr>
<td>20</td>
<td>Transients</td>
<td>Galaxy growth through measurements of Black Hole accretion, growth and feedback</td>
<td>3/4</td>
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<tr>
<td>21</td>
<td>Transients</td>
<td>Detect the Electromagnetic Counterparts to Gravitational Wave Events</td>
<td>4/4</td>
</tr>
<tr>
<td>22</td>
<td>Cradle of Life</td>
<td>Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc</td>
<td>1/5</td>
</tr>
<tr>
<td>23</td>
<td>Cradle of Life</td>
<td>Characterise exo-planet magnetic fields and rotational periods</td>
<td>2/5</td>
</tr>
<tr>
<td>24</td>
<td>Cradle of Life</td>
<td>Survey all nearby (~100 pc) stars for radio emission from technological civilisations.</td>
<td>3/5</td>
</tr>
<tr>
<td>25</td>
<td>Cradle of Life</td>
<td>The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc</td>
<td>4/5</td>
</tr>
<tr>
<td>26</td>
<td>Cradle of Life</td>
<td>Mapping the sub-structure and dynamics of nearby clusters using maser emission.</td>
<td>5/5</td>
</tr>
<tr>
<td>27</td>
<td>Magnetism</td>
<td>The resolved all-sky characterisation of the interstellar and intergalactic magnetic fields</td>
<td>1/3</td>
</tr>
<tr>
<td>28</td>
<td>Magnetism</td>
<td>Determine origins, maintenance and amplification of magnetic fields at high redshifts - I.</td>
<td>2/3</td>
</tr>
<tr>
<td>29</td>
<td>Magnetism</td>
<td>Detection of polarised emission in Cosmic Web filaments</td>
<td>3/5</td>
</tr>
<tr>
<td>30</td>
<td>Magnetism</td>
<td>Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.</td>
<td>4/5</td>
</tr>
<tr>
<td>31</td>
<td>Magnetism</td>
<td>Intrinsic properties of polarised sources</td>
<td>5/5</td>
</tr>
<tr>
<td>32</td>
<td>Cosmology</td>
<td>Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.</td>
<td>1/5</td>
</tr>
<tr>
<td>33</td>
<td>Cosmology</td>
<td>Angular correlation functions to probe non-Gaussianity and the matter dipole</td>
<td>2/5</td>
</tr>
<tr>
<td>34</td>
<td>Cosmology</td>
<td>Map the dark Universe with a completely new kind of weak lensing survey - in the radio.</td>
<td>3/5</td>
</tr>
<tr>
<td>35</td>
<td>Cosmology</td>
<td>Dark energy &amp; GW via power spectrum, BAO, redshift space distortions and topology</td>
<td>4/5</td>
</tr>
<tr>
<td>36</td>
<td>Cosmology</td>
<td>Test dark energy &amp; general relativity with fore-runner of the 'billion galaxy' survey</td>
<td>5/5</td>
</tr>
<tr>
<td>37</td>
<td>Continuum</td>
<td>Measure the Star formation history of the Universe (SFHU) - I. - Non-thermal processes</td>
<td>1/8</td>
</tr>
<tr>
<td>38</td>
<td>Continuum</td>
<td>Measure the Star formation history of the Universe (SFHU) - II. Thermal processes</td>
<td>2/8</td>
</tr>
<tr>
<td>39</td>
<td>Continuum</td>
<td>Probe the role of black holes in galaxy evolution - I.</td>
<td>3/8</td>
</tr>
<tr>
<td>40</td>
<td>Continuum</td>
<td>Probe the role of black holes in galaxy evolution - II.</td>
<td>4/8</td>
</tr>
<tr>
<td>41</td>
<td>Continuum</td>
<td>Probe cosmic rays and magnetic fields in ICM and cosmic filaments.</td>
<td>5/8</td>
</tr>
<tr>
<td>42</td>
<td>Continuum</td>
<td>Study the detailed astrophysics of star-formation and accretion processes - I.</td>
<td>6/8</td>
</tr>
<tr>
<td>43</td>
<td>Continuum</td>
<td>Probing dark matter and the high redshift Universe with strong gravitational lensing.</td>
<td>7/8</td>
</tr>
</tbody>
</table>

Table 1. Collated list of science goals. Within each science area, the entries are ordered in the rank provided by the SWG Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.

Braun et al, 2014, SKA1 Science Priority Outcomes
SKA1 HI Science Priorities

- Resolved HI kinematics and morphology of $\sim 10^{10}$ M$_\odot$ mass galaxies out to $z \approx 0.8$.

- High spatial resolution studies of the ISM in the nearby Universe.

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SKA Science Case Update

New HI Chapters:

• The Hydrogen Universe with the SKA (Staveley-Smith) - includes rebaselining
• Neutral Hydrogen and Galaxy Evolution (Blyth)
• The ISM in Galaxies (de Blok)
• The Galaxy and Magellanic System (McClure-Griffiths)
• The IGM (Popping)
• Cool Outflows and HI absorbers (Morganti)
• Galaxy Formation Models (Power)
• Connecting the Baryons (Meyer)
• SMBHs and galaxies (Marconi)
• SKA as Doorway to Angular Momentum (Obreschkow)
• Physics of Cold Neutral Medium (Oonk)
• **Mass properties**: $\Omega_{\text{HI}}$ & HI mass function; baryon cycle; DM dependencies

• Environment: gas inflow and removal

• Angular momentum/kinematics: scaling relations, Tully-Fisher relation

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![Graph showing the HI mass function and its evolution with redshift](image)

- Logarithmic scale for both axes
- Dotted and solid lines represent different redshifts (z=0, z=0.2, z=0.6, z=0.8, z=1, z=1.5)
- Three panels compare different ranges of halo mass: 
  - $\log(M_{\text{halo}}/h^{-1}M_\odot) < 11$
  - $\log(M_{\text{halo}}/h^{-1}M_\odot) < 12.7$
  - $\log(M_{\text{halo}}/h^{-1}M_\odot) > 14.5$

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*Click on the image for a full view of the graph.*
HI & Galaxy Evolution

- Mass properties: $\Omega_{\text{HI}}$ & HI mass function; baryon cycle; DM dependencies
- Environment: gas inflow and removal
- Angular momentum/kinematics: scaling relations, Tully-Fisher relation

SKA will enable unprecedented **resolved** image analyses

VIVA survey; Chung, 2009; Yoon in prep;
HI & Galaxy Evolution

- Mass properties: $\Omega_{\text{HI}}$ & HI mass function; baryon cycle; DM dependencies
- Environment: gas inflow and removal
- Angular momentum/kinematics: scaling relations, Tully-Fisher relation

![Diagram](PoS(AASKA14)138)

Obreschkow et al, 2015, PoS, AASKA14, 138
Deep studies in local Universe also needed to understand HI physics

- Enable **high spatial resolution** (sub-kpc) and **low column density sensitivity** (sub $10^{20}$)

- What is the connection between star formation on small scales and global scaling laws?

- How do galaxies acquire sufficient gas to sustain their star formation rates?

de Blok et al, 2015, PoS, AASKA14, 129
MW and Magellanic clouds allow studies of gas content in greater detail than anywhere else

- How is gas exchanged with surrounding IGM?
- How is warm surrounding diffuse gas cooled into molecular clouds, stars?
- SKA will have surface brightness sensitivity, point source sensitivity and angular resolution to understand Milky Way gas all the way from the halo down to the formation of individual molecular clouds.
HI at High-z: Absorption Studies

• HI 21-cm absorption spectroscopy provides a unique probe of cold neutral gas in normal and active galaxies from redshift \( z > 6 \) to the present day.

• Associated HI 21cm absorption content of individual galaxies, structure of the central regions and the feeding and feedback of AGN.

• Intervening HI 21cm absorption constrain the evolution of cold gas in normal galaxies over more than 12 billion years of cosmic time.

Morganti et al, 2015, PoS, AASKA14, 134
Galaxy-IGM Connection

- How are galaxies re-fuelled from the IGM?
- What is the nature of diffuse intergalactic gas?
- Requires observations at column densities $n_{\text{HI}} \lesssim 10^{18}$

Figure 1: Simulation of the cosmic web from Popping et al. (2009), left panel shows column densities of the total Hydrogen gas component ($\text{HII} + \text{HI}$), the right panel shows the neutral gas component ($\text{HI}$) that can potentially be detected by radio telescopes using the 21-cm line.

When looking at the density of neutral hydrogen 10 billion years ago above redshift $z \approx 2$ (e.g. Prochaska & Wolfe (2009)), the total amount of gas that is locked in galaxies is less than the mass which is locked in stars today. Recent simulations support this picture of continuous gas accretion. Due to the gravitational collapse of dark matter dense structures and filaments are created. The primordial atomic gas falls into the gravitational potential wells of the dark matter.

There are two modes in which gas falls onto galaxies, dubbed hot-mode and cold-mode accretion (Kereš et al. 2005). In the case of hot mode accretion the gas falling on the dark matter filaments is shock heated to temperatures up to $10^7$ Kelvin and forms a quasi hydrostatic equilibrium halo; the warm-hot intergalactic medium (WHIM) (e.g. Davé et al. (2001)). At some evolutionary stage this hot virialized gas cools rapidly while loosing its pressure support and settles into the centrifugally supported disks or the spiral arms of a galaxy. In the case of cold mode accretion the gas is never heated to these high temperatures, but smoothly accretes directly into the galaxies. The empirical deviation between the two accretion modes is around $2 \times 10^5$ K. Recently simulations have converged to a cosmological model where cold mode accretion dominates gas infall at all cosmic times and hot mode accretion is mostly relevant for galaxies that reside in halos with masses above $10^{12}$ solar masses (Kereš et al. 2009; Dekel et al. 2009).

2.3 The Circumgalactic Medium

Surrounding the direct environment of galaxies is the circumgalactic medium (CGM) which is the interplay between galaxies and the IGM. The gaseous haloes of 44 galaxies between $z = 0.15$ and 0.35 has been investigated using background QSOs observed with the Cosmic Origins Spectrograph (Tumlinson et al. 2013). The galaxies span both early and late types and the sight-lines of the QSO spectra pass within 150 kpc of the galaxies. The authors find that the circumgalactic medium exhibits strong HI, with a 100% covering fraction for star-forming galaxies and 75% covering for passive galaxies. The kinematics of this gas indicate that it is bound to the host galaxy and the bulk of the detected HI arises in a bound, cool, low-density photoionized diffuse medium. This gas may...
SKA1 Capabilities

Beam vs Survey Speed (declination=-30 robust=-2)

Survey Speed (deg² mJy² s⁻¹)

beam (arcsec)

SKA1-MID
ASKAP-36
MeerKAT
ASKAP-30, low η

Popping performance plots
SKA1 Capabilities

Beam vs Survey Speed (declination=-30 robust=-2)

- **ASKAP-36**
- **MeerKAT**
- **ASKAP-30**, low $T_{\text{sys}}/\eta$

Increased Survey Speed
SKA1 Capabilities

New High Resolution Studies

Beam vs Survey Speed (declination=-30 robust=-2)

Survey Speed (deg^2 mJy^2 s^-1)

- SKA1-MID
- ASKAP-36
- MeerKAT
- ASKAP-30, low T.sys/\eta

beam (arcsec)
SKA1 Surveys: Resolution @ $10^{20}$ cm$^{-2}$

- Resolve galaxies over large redshift range
- Study role of mergers, feedback, local environment
- carry out detailed studies of galaxy kinematics & angular momentum
- high resolution studies of ISM in nearby galaxies ($< 100$ pc)
• HALOGAS type studies beyond local Universe
• understand how galaxies acquire their gas: role of environment/accretion
• New studies of the disk-halo-IGM interface
### Possible SKA1 Surveys

1,000 hour projects

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area</th>
<th>Freq</th>
<th>Resolution</th>
<th>N</th>
<th>$&lt;z&gt;$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium wide</td>
<td>400</td>
<td>950-1420</td>
<td>10&quot;</td>
<td>34,000</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Medium deep</td>
<td>20</td>
<td>950-1420</td>
<td>5&quot;</td>
<td>25,000</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Deep</td>
<td>1</td>
<td>600-1050</td>
<td>2&quot;</td>
<td>2,600</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Targeted</td>
<td>-</td>
<td>1400-1420</td>
<td>3&quot;-1'</td>
<td>50</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td>Galaxy Emiss.</td>
<td>600</td>
<td>1418-1422</td>
<td>10&quot;-1'</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Galaxy Absorp.</td>
<td>400</td>
<td>1418-1422</td>
<td>5&quot;</td>
<td>4,000</td>
<td>0</td>
<td>0</td>
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<tr>
<td>ExGal Absorp.</td>
<td>1000</td>
<td>350-1050</td>
<td>2&quot;</td>
<td>5,000</td>
<td>1</td>
<td>3</td>
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<tr>
<td></td>
<td>1000</td>
<td>200-350</td>
<td>10&quot;</td>
<td>?</td>
<td>4</td>
<td>6</td>
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</tbody>
</table>

Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167
## Possible SKA1 Surveys

### 10,000 hour projects

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg)</th>
<th>Freq (MHz)</th>
<th>Resolution</th>
<th>N</th>
<th>$&lt;z&gt;$ (z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-sky</td>
<td>20,000</td>
<td>950-1420</td>
<td>15&quot;</td>
<td>550,000</td>
<td>0.06 (0.3)</td>
</tr>
<tr>
<td>Wide</td>
<td>5,000</td>
<td>950-1420</td>
<td>10&quot;</td>
<td>340,000</td>
<td>0.1 (0.5)</td>
</tr>
<tr>
<td>Ultra deep</td>
<td>1</td>
<td>450-1050</td>
<td>2&quot;</td>
<td>23,000</td>
<td>0.7 (2)</td>
</tr>
</tbody>
</table>

*Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167*
Multi-λ for the SKA

“Connecting the Baryons”
Meyer, Robotham, et al, 2015, PoS, AASKA14, 131

https://asgr.shinyapps.io/ganttshiny

excellent coverage: optical and NIR imaging (LSST and Euclid/WFIRST), low S/N redshift emission spectra (4MOST)
significant follow-up possible: IFU, gas-phase emission spectra, mm
potential weaknesses: UV/FIR imaging, stellar-phase absorption spectra
SKA1 1,000 hr surveys
SKA1 10,000 hr surveys
Full SKA Surveys