Overview of the SKA

The “Square Kilometer Array” is the generic name for the next generation radio telescope facility/ies operating at meter and centimeter wavelengths.

- Total cost for all probably > $5B
- Challenges: mass-produce hardware, computation, power
- Need different technical solutions according to frequency range
- Hence, likely to be three separate facilities:

<table>
<thead>
<tr>
<th></th>
<th>( \lambda )</th>
<th>freq</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKA-low</td>
<td>meter</td>
<td>&lt; 300 MHz</td>
<td>Hydrogen Epoch of Reionization Arrays (HERA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Long Wavelength Array (LWA)</td>
</tr>
<tr>
<td>SKA-mid</td>
<td>2-100 cm</td>
<td>0.3-10 GHz</td>
<td>Radio Synoptic Survey Telescope (RSST)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Allen Telescope Array (ATA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ASKAP, MeerKAT (Amit will discuss)</td>
</tr>
<tr>
<td>SKA-high</td>
<td>0.7-5 cm</td>
<td>5-45 GHz</td>
<td>North American Array (NAA) (core=EVLA)</td>
</tr>
</tbody>
</table>
Overview of the SKA

Reference Design technology

High-Band

> 3 GHz: wide-band feed

Mid-Band

0.3 – 3 GHz: phased array feed

Swinburne/CVA visualization

Low-Band

< 0.3 GHz: sparse aperture array

Innovation path:
dense aperture array

PJ Hall, December 2006
...the end of The Dark Age...
Cut off from view of optical wavelengths!!!

If neutral fraction

\[ \frac{n_{\text{HI}}}{n_{\text{HI}} + n_{\text{HII}}} \gtrsim 10^{-3} \]

Epoch of Reionization....

Z \sim \text{1000}

H^+ 

IONIZED

RECOMBINATION

H^0 NEUTRAL

REIONIZATION

Now

\[ n_{\text{HI}} + n_{\text{HII}} \]

First Stars

Z \sim \text{20}

First QSOs

Z \sim \text{7}

Slide by Frank Briggs
\( \Omega_{\text{HI}} \) = Cosmological Neutral Gas Density

Slide by Frank Briggs
$\Omega_{\text{HI}} = \text{Cosmological Neutral Gas Density}$

Slide by Frank Briggs
Two Experiments

* Global Signal
determine redshift
and amplitude

* Mapping
structure and
fluctuation analysis
Global Signal...

- Gnedin & Ostriker 1997
- Shaver, Windhorst, Madau, & de Bruyn 1999

Brightness Temperature of the Background Radio Sky:

Slide by Frank Briggs
Goal of new telescope: "LOFAR" = Low Frequency Array

Possible site in Western Australia

Slide by Frank Briggs
HERA: HI in the Dark Age/EOR

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Phase</th>
<th>$A_{\text{eff}}$ (km²)</th>
<th># elements</th>
<th>FOV (deg)</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPER</td>
<td>ongoing</td>
<td>0.003</td>
<td>128-512</td>
<td>60</td>
<td>PS detection</td>
</tr>
<tr>
<td>MWA</td>
<td>ongoing</td>
<td>0.01</td>
<td>512</td>
<td>20-40</td>
<td>PS detection</td>
</tr>
<tr>
<td>HERA II</td>
<td>II</td>
<td>0.1</td>
<td>5000</td>
<td>20-60</td>
<td>PS characterization</td>
</tr>
<tr>
<td>HERA III</td>
<td>III</td>
<td>1</td>
<td>50000+</td>
<td>(20-60)</td>
<td>Structure imaging</td>
</tr>
</tbody>
</table>

Challenges:
- Foreground subtraction, esp. polarized MW emission
  - EOR signals should show strong fluctuations over small $\Delta f$
- Earth’s ionosphere and plasmasphere $\Rightarrow$ calibration
  - Can it be done from Earth or do we need to relocate to the Moon?
- Computation
Mid-frequency SKA

0.3 – 10 GHz range

- More conventional hardware but still need to reduce costs and simplify
- “Dishes”
- Combination of aperture arrays (resolution) and phased array feeds (sky coverage) to achieve survey speed.

Many science drivers but let’s stick to cosmology:

- **Cosmological HI Galaxy Survey**
  - HI spectra for > billion galaxies to z > 1.5
  - cosmological parameters (DE) through BAO
  - growth of structure (counts, galaxy evolution)

- **Galaxy Continuum Photometry**
  - cosmic ray continuum in Milky Way-like galaxies
  - weak lensing studies (DE)
  - AGN surveys

- **Magnetic Field Mapping**
  - Faraday rotation mapping
  - intergalactic/primordial fields
Instrumenting the Science

- Science Precursors ($z < 0.5$)
  - Expanded Very Large Array (EVLA)
  - Allen Telescope Array (ATA)
  - Arecibo Observatory (AO)
  - Green Bank Telescope (GBT)
- Pathfinders ($z < 0.8$)
  - ASKAP (Australia)
  - MeerKAT (S. Africa)
- Ultimate Science 2020
  - the Square Kilometer Array (SKA)

"Radio Synoptic Survey SKA": RSSSKA

Slide by Steve Myers
HI Cosmology

• “billion galaxy” HI survey
  - redshifts for gas-rich galaxies out to $z=1.5$ (and beyond)
  - Baryon Acoustic Oscillations (BAO) \( \sigma_w \sim 0.01 \)
  - cosmography of Universe \( d(z), V(z) \Leftrightarrow H(z) \)
  - growth of structure and Cosmic Web
  - HI is critical window on galaxy formation and evolution

• complementarity with “Dark Energy” surveys
  - e.g. JDEM, LSST, DES, SDSS, DES, LSST, PanSTARRS
    - RSSKA is in the DETF as a “Stage IV” project = SKA
  - mutual interest with the DOE & NASA communities
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)
\( \Omega_{\text{HI}} = \text{Cosmological Neutral Gas Density} \)

Slide by Frank Briggs
Cosmic Evolution Indicators

Passive relaxation

Violent accretion

Slide by Frank Briggs
## Outfitting a SKA for Cosmology

- **SKA could see HI galaxies out to redshift** $z > 2$
  - $\sim 10^9$ galaxies for $10^4$ deg$^2$
  - Counts are HIMF dependent
  - Needs sensitivity of SK area
- **Survey Strategy**
  - Tradeoff between wide and deep
  - $1 \text{ Gpc}^3 \text{ comov} = 250 \text{ deg}^2 \text{ } z=1.5$
- **Cosmology**
  - HI galaxies will have different bias to O/IR galaxies
  - We are working on simulations to see results of BAO and galaxy distribution function studies
  - Redshifts are limited only by galaxy HI profile
- **Ref:** Abdalla & Rawlings 2004

---

*Figure 3. Predictions of $dN/dz$ per deg$^2$ for an SKA survey with an exposure time of 4 hours, a signal-to-noise detection limit of 10 and assumptions about the properties of the HI-emitting galaxies and the SKA detailed in Sec. 2. The same linestyles are used as in Fig. 1 to discriminate between the different AR2004 models; the prediction of a ‘no-evolution’ model is shown by the solid (black) line. Also shown (thicker red line) is the surface density of galaxies needed for a survey to be limited by cosmic variance rather than shot noise (AR2004).*
SKA for Dark Energy

- **SKA as $w$-machine**
  - $10^9$ galaxy BAO survey
  - also weak lensing (continuum)
  - target 0.01 in $w$

- **Design Driver**
  - target precision requires survey speed of $4-6 \times 10^9 \text{ m}^4\text{K}^{-2}\text{deg}^2$
  - this is a SK area with 10 deg$^2$ FOV
  - would also like to identify individual galaxies (need arcsecond resolution)
  - survey database for other science

- **Options**
  - might be able to do BAO power spectrum with ultra-compact Hydrogen array/telescope
  - but will not be of general use...
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*Figure 19.* The weighted eigenvalues for the surveys that we used in the joint analysis. Every line represents a survey. All the surveys are marginalized over other parameters including Planck priors. The (black) solid line shows SNe Ia surveys with the filled and unfilled circles indicating PS4 and SNAP, respectively. The (red) dotted lines represents WL surveys with the filled and unfilled stars indicating PS4 and EUCLID, respectively. The (green) dash lines represents BAO surveys with the filled and unfilled triangles indicating WFMOS deep and SKA, respectively. We also show the joint analysis with the (blue) dotted-dash lines; the filled and unfilled squares indicating stage III and IV, respectively.

---

Rawlings et al. SKA Science Book

*Slide by Steve Myers*
Current State of the Art in Surveys

Four published results
1. Eisenstein et al 2005 \textit{(spectro-z)} 3%
   3D map from SDSS
   46,000 galaxies in 0.72 \((h^{-1}\text{Gpc})^3\)
2. Cole et al 2005 \textit{(spectro-z)} 5%
   3D map from 2dFGRS at AAO
   221,000 galaxies in 0.2 \((h^{-1}\text{Gpc})^3\)
3. Padmanabhan et al 2007 \textit{(photo-z)} 5%
   Set of 2D maps from SDSS
   600,000 galaxies in 1.5 \((h^{-1}\text{Gpc})^3\)
   (Same data as above)

HI surveys are currently lagging in numbers of detections
## Complementarity: O/IR Spectroscopic Surveys

<table>
<thead>
<tr>
<th>Surveya</th>
<th>Redshift Range</th>
<th>Sky Area (deg²)</th>
<th>Millions of Galaxies</th>
<th>Effective Volumeb (Gpc³)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADEPT</td>
<td>$1 &lt; z &lt; 2$</td>
<td>29,600</td>
<td>~100</td>
<td>180</td>
</tr>
<tr>
<td>SDSS DR4 Main+2dF</td>
<td>$z &lt; 0.3$</td>
<td>7,000</td>
<td>0.7</td>
<td>0.50</td>
</tr>
<tr>
<td>SDSS LRG</td>
<td>$0.16 &lt; z &lt; 0.47$</td>
<td>3,800</td>
<td>0.047</td>
<td>0.52</td>
</tr>
<tr>
<td>SDSS-II 8-yr LRG</td>
<td>$0.16 &lt; z &lt; 0.47$</td>
<td>7,600</td>
<td>0.094</td>
<td>1.0</td>
</tr>
<tr>
<td>WiggleZ/AAT (220 nights)</td>
<td>$0.5 &lt; z &lt; 1.0$</td>
<td>1,000</td>
<td>0.4</td>
<td>0.64</td>
</tr>
<tr>
<td>APO-LSS</td>
<td>$0.2 &lt; z &lt; 0.8$</td>
<td>10,000</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>FMOS/Subaru (200 nights)</td>
<td>$1.4 &lt; z &lt; 1.7$</td>
<td>300</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>HETDEX</td>
<td>$1.8 &lt; z &lt; 3.8$</td>
<td>250</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>WFMOS/Subaru (150 nights)</td>
<td>$0.5 &lt; z &lt; 1.3$</td>
<td>2,000</td>
<td>2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>WFMOS/Subaru (150 nights)</td>
<td>$2.3 &lt; z &lt; 3.3$</td>
<td>300</td>
<td>0.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

### Notes to the Table:

- **a.** The SDSS surveys in the 2nd and 3rd rows are the only ones completed; the rest are planned or proposed. They are all spectral line surveys. LSST plans a large (~10,000 deg²) photometric redshift survey, perhaps observing $>10^9$ galaxies at $0.5 < z < 3.5$. The photometric redshift errors would degrade the equivalent effective volume of the LSST survey to $< 25$ Gpc³.

- **b.** Effective volume accounts for the limited sampling of the survey volume due to the discrete number of galaxies as a function of redshift. It is evaluated at the scale of the BAO, $k = 0.15 \, h$ Mpc⁻¹.

- **c.** Assumes $h = 0.7$.

### RSSKA in context:

~1000 million galaxies $z<2.5$ in 8-60 Gpc³ comoving!

---

**Warren Moos:** presentation to BEPAC
The Radio Synoptic SKA (RSSKA)

• SKA as Radio Synoptic Survey Telescope
  - radio: HI core 0.4-1.4 GHz (0.3-10 GHz goal)
  - square kilometer: large collecting area for sensitivity
    • high gain/low noise $A/T_{\text{sys}} > 10^4$ m$^2$ K$^{-1}$
  - survey telescope: wide-field for survey speed
    • survey speed FOM $\Omega (A/T_{\text{sys}})^2 > 4 \times 10^9$ deg$^2$ m$^4$ K$^{-2}$

• Built for the Primary Science Goals
  - HI for Cosmology and Galaxy Evolution
  - Deep continuum imaging
  - Transient detection and monitoring

• Commensal Surveys
  - cadences of synoptic observation to accommodate transients
Example: HI Survey Strategies

- Duration of Survey: 20 year mission
  - 5 years Wide, 5 years Deep, 3 years med-deep Galactic plane
  - 2 x 1 year ultra-deep fields (Galactic Center, Virgo deep, other?)
  - 5 years GO or TOO and follow-up (25%)

- Wide “Quarter Sky” = 10000 deg^2
  - 8.64s per deg^2 per day = 4.38 hours per deg^2 in 5 years
  - RD: 19.9h per z=1.5 FOV per year
    - $S_{\text{lim}}=1.75 \mu\text{Jy} \Rightarrow M_{\text{lim}}=4.1\times10^9 M_{\odot}$ at z=1.5 ($\Delta\nu=0.38\text{MHz}$)

- Deep region = 200 deg^2
  - 432s per deg^2 per day = 219 hours per deg^2 in 5 years
  - RD: 110h per z=1.5 FOV per year
    - $S_{\text{lim}}=0.39 \mu\text{Jy} \Rightarrow M_{\text{lim}}=8.8\times10^8 M_{\odot}$ at z=1.5 ($\Delta\nu=0.38\text{MHz}$)

- Ultra-Deep field = 4.5 deg^2
  - 173s per deg^2 per day = 1931 hours per deg^2 per year
  - RD: 1931 hours per z=1.5 FOV per year
    - $S_{\text{lim}}=0.13 \mu\text{Jy} \Rightarrow M_{\text{lim}}=3\times10^8 M_{\odot}$ at z=1.5 ($\Delta\nu=0.38\text{MHz}$)

Slide by Steve Myers
SKA-high

- 5-50 GHz: Shortest cm $\lambda$
- The EVLA is just being completed
  - New receivers
  - New correlator
- SKA high requires baselines 100-1000's of km.

Bandwidth $\Rightarrow$ continuum sensitivity
Short $\lambda$ $\Rightarrow$ highest resolution

Science drivers (partial):
- H$_2$O maser: astrometry for geometric distances
- Gravitational lensing (without obscuration)
- Highly redshifted CO
  - $z \sim 5$: CO(1-2) and (2-1) shifted to 19 and 38 GHz
- Protoplanetary disks: even at IR/mm $\lambda$, opacity is large.
- Time domain (expanding sources, GRBs etc)
SKA Array & Receptor Technologies

Dense Aperture Arrays

3-Core Central Region

Sparse Aperture Arrays

Dishes

Wide Band Single Pixel Feeds

Phased Array Feeds

Artists’ Renditions from Swinburne Astronomy Productions

Slide by Peter Dewdney
Sparse aperture arrays for the lowest frequencies

Replication by Industry

LOFAR (Netherlands et al)

LWA (USA)

MWA (USA, Australia)

Slide by Peter Dewdney
EMBRACE Prototype for Dense Aperture Arrays

Industry already involved in production.

First Fringes (Netherlands)

Slide by Peter Dewdney
Dish Design and Prototyping

**ATA**
42x6m hydroformed dishes

**ASKAP**
36x12m panel dishes

**KAT-7**
7 x12m composite dishes

**CART**
10 m composite prototype

Slide by Peter Dewdney
Multi-pixels at mid frequencies with dishes + phased-array-feeds

ASKAP, Australia

Chequer-board phased array (ASKAP, Australia)

ASkAP chequer board array

APERTIF (Astron, NL)

AO40!

DRAO Canada

Vivaldi arrays

Slide by Peter Dewdney
**$u$-$v$ Coverage**
(Configuration Task Force)

~800 km

20 km

Millenaar, Bolton et al.

Slide by Peter Dewdney
Cost vs DR

- For a fixed-cost telescope, we have a fundamental design question: Where to put the money?
  - Do we design extremely robust sub-systems (antennas, receivers, correlators, etc.), whose characteristics are well-known and stable?
  - Do we design less expensive sub-systems and put funds into back-end computing instead, to calibrate and correct for upstream defects and time-variable errors?

- Major aspect of system design and optimization
  - Probably have to do both things for an extreme sensitivity telescope.
  - Must also err on the side of investing in difficult to upgrade sub-systems (e.g. antennas, AA's).
Other Aspects

- Site conditions:
  - As similar to actual sites as possible.
  - Strong solar, large day-to-night temperature changes.
  - Wind, dust.
  - Test conditions must encompass as many as possible of these effects.

- Beam parameters include polarization properties.
  - Orthogonality, stability.

- Stability across frequency and tuning ranges:
  - Beamshape stability with frequency.
  - Frequency dependence of scattering and sidelobes.

- Other analog components:
  - Bandshape, RF gain components, Analog-to-digital converters.
  - Understanding the behaviour of these components will be very important.
  - Best if already field-qualified, but at least bench qualified.
Need High-Fi Maps of Field Sources

EVLA 3C147 Deep Field @ 1440 MHz

- 12 antennas, 110 MHz bandwidth, 6 hours integration
- Fidelity ~ 400,000:1
- Peak/rms ~ 850,000:1 (59 dB)
- The artifacts are due to non-azimuthal symmetry in the antenna primary beams.
  - Illustrates the need for advanced calibration/imaging software.

Perley et al

Slide by Peter Dewdney
Power Consumption

• Throughout the SKA, power consumption is a major issue:
  • On-site
    - Concentrated loads at the centre.
    - Distributed loads (100's of km from centre).
    - Cooling of equipment is difficult in a desert environment.
  • Off-site
    - Probably a large computing load (Concentrated).
  • Reduction of power consumption and optimisation of the power network will be features of design everywhere.
    - SKA performance may be power limited.