Mapping the Universe on the pathway to the SKA

Galaxy Evolution and the role of AGN

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Outline

1. The SKA Framework
   - Science drivers
   - The ramp-up to the SKA: precursors, SKA1, SKA2

2. Radio Continuum Extragalactic Survey Science
   - Cosmology/LSS
   - Galaxy Evolution
   - The role of AGN

3. Designing the best SKA
   - Current Activity in SKA WGs
   - Design Criticalities
   - How one can contribute
SKA Key Science

SKA Science Book (now being update)

- Strong-field Tests of Gravity with Pulsars and Black Holes
  Phase 1 headline science

- Galaxy Evolution, Cosmology, & Dark Energy
  Phase 1 “H I through cosmic time” headline science

- Emerging from the Dark Ages and the Epoch of Reionization
  Phase 1 “H I through cosmic time” headline science

- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of Exploration of the Unknown
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With design philosophy of Exploration of the Unknown

Courtesy R. Braun
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With design philosophy of Exploration of the Unknown

Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

\[ \nu = 1420 \text{ MHz/(1 + z)} \]
\[ \lambda = 21 \text{ cm (1 + z)} \]

Courtesy R. Braun
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With design philosophy of Exploration of the Unknown

Courtesy R. Braun
Science-driven Requirements for the SKA

- Large Frequency Range
  10 MHz - 30 GHz
  [different receivers: SKA LOW & MID]

- High Sensitivity ≈ 1-2 $10^4$ m$^2$ K$^{-1}$
  [low $T_{sys}$ receivers]

- High Survey speed
  ≈ 0.2-60 $10^8$ deg$^4$ m$^4$ K$^{-2}$
  [large FOV, small dishes + PAF technology (1-10s deg$^2$)]

- High spatial resolution
  ≈ 10-100 mas
  [long baselines, >1000 km]
The SKA in Phases

SKA will be implemented in phases:

- **Precursors** (Meerkat, ASKAP)
- **SKA\(_1\)** subset (~10% area) of **SKA\(_2\)**

  - **SKA\(_1\)**-low (sparse AA): Freq. Range: 70 - 350 MHz
  - **SKA\(_1\)**-mid (dish+SPF): Freq. Range: 0.45 – 10 GHz (3 Bands)
  - **SKA\(_1\)**-survey (dish+PAF): Freq. Range: 0.7 – 1.7 GHz
    - PAF for Survey Speed

- **SKA\(_2\)**: full SKA capability between 70 MHz and 10 GHz
- **SKA\(_3\)** (TBD): extension of **SKA\(_2\)** to 30 GHz

Phased construction allows maximum use of advances in technology and incremental fine-tuning of science drivers/technical requirements
SKA Phase 1 (SKA1)  
Cost: €650M, construction start 2017  

Courtesy P. Diamond

SKA1_MID  
254 Dishes including:  
64 x MeerKAT dishes  
190 x SKA dishes

SKA1_LOW  
Low Frequency Aperture Array Stations

SKA1_SURVEY  
96 Dishes including:  
36 x ASKAP  
60 x SKA dishes
ASKAP – Australia’s SKA Pathfinder

Main characteristics:

• Array of 36 12-m antennas
• Phased array feeds (36-feeds, focal plane arrays)
• Wide FoV and High dynamic range imaging capability
• Observing Band: L-band (1.4 GHz)
• Maximum baseline ~8 km
• FoV = 30 sq. deg @ 1.4 GHz
• High survey speed: continuum (10 µJy/beam) 2.2 deg²/h
• Site: Murchison Radio-astronomy Observatory (MRO), Western Australia. Remarkably radio quiet

Timeline:

• Beta Array: in operation + new MkII PAFs
• Early Science: 12 antennas (mid 2015)
• Full system: mid 2016

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**MeerKAT – South Africa’s SKA Pathfinder**

**Main characteristics**
- Array of 64 13.5m receptors
- 48 concentrated in the core area ~1 km in diameter.
- Longest baseline 8 km
- Site: Karoo Region

- 0.58 - 1.015 GHz
- 1 - 1.75 GHz
- 8 - 14.5 GHz
- Single Pixel, high sensitivity ($T_{sys} \sim 20K$)

**Timeline**
- **End 2014**: Four MeerKAT receptors fully assembled, integrated and verified
- **End 2015**: Array of 16 antennas commissioned and ready to do science
- **End 2016**: All 64 antenna positioners will be in place.
- **Mid 2017**: Full array ready to do science.

**27 March 2014: First antenna launched**
What’s up now?

SKA Pathfinders (1% SKA):

• **JVLA:** upgrade of the existing Very Large Array (VLA) - operational
• **eMERLIN:** deep high resolution imaging I,Q,U,V
  [Key Programmes approved in 2009 - started end 2013]
• **Apertif:** PAF mounted on the WSRT (L-band only).
  [Expression of interest for key projects (2010) – 2015]
• **LOFAR** (Key Projects: EoR, Continuum Tiered Survey, Magnetism, Transients, Pulsars)
  [operational (Cycle 0 – 2013; Cycle 1 & 2 – 2014)]
• **MWA** (Australia) – operational
• **eEVN:** real-time VLBI operations
Performance Comparison - Sensitivity

Adapted from Braun, 2014
Performance Comparison - Survey Speed

Adapted from Braun, 2014
Radio Continuum extra-galactic surveys

- Available extragalactic surveys & deep fields with current facilities
- Next generation radio telescopes will push the boundary by a factor of 10-1000
- Need of high sensitivity, together with high survey speed and high spatial resolution to beat confusion
- New region of parameter space will be explored, new discoveries expected
Next Radio-continuum extra-galactic legacy surveys

All-sky (rms 14 µJy)
- ASKAP: EMU (δ<+30°)
  [+ APERTIF: WOODAN]
  (δ>+30°)

Deep fields
Meerkat: MIGHTEE
  Tier 1: 35 deg² 1 µJy rms
  Tier 2: 1 deg² 0.1 µJy rms

Factor 50 deeper

SKA₁ Killer survey:
[Huynh+, work in progress]
Factor 10 deeper

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Astronomy Landscape in SKA Era

Pre-SKA (2015+):
- SKA precursors/pathfinders (1% SKA): LOFAR, JVLA, eMERLIN, ASKAP, Meerkat,…
  → SKA1 needs to make significant scientific advance over pathfinders

SKA1 (2020+):
- Euclid: 15k deg$^2$ HST image (0.2") in optical and near IR, L* gals up to $z=3$, $0.7<z<2$
- LSST: 18k deg$^2$ ugrizy ($r<27.5$; $i<26.8$; $z<26.1$), 4 Billion gals, $<z>\sim 1.2$, photo-z to $z\sim 4$
- JWST: sub-arcsec mid IR imaging + spectroscopy of $z>5$ galaxies

SKA2 (2025+)
- E-ELT: VLBI-like optical/MIR images + spectroscopy, internal dynamics of gals to $z\sim 4$, spectroscopy of $z>7$ galaxies
### Reference SKA 1 Continuum Surveys – mid frequency

<table>
<thead>
<tr>
<th>Topics</th>
<th>Rms (µJy/b)</th>
<th>Area (deg²)</th>
<th>Resolution (&quot;)</th>
<th>Freq. (GHz)</th>
<th>Science</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tier 1 (All sky)</strong></td>
<td>1</td>
<td>20-30k</td>
<td>2</td>
<td>~1</td>
<td><strong>Cosmology tests</strong>&lt;br&gt;Low-z gal/AGN&lt;br&gt;Cluster/diffuse&lt;br&gt;Magnetism&lt;br&gt;Galactic studies&lt;br&gt;Legacy/Rare</td>
</tr>
<tr>
<td><strong>Tier 2 (Wide)</strong></td>
<td>0.34</td>
<td>5k</td>
<td>0.5</td>
<td>~1</td>
<td><strong>Weak lensing</strong>&lt;br&gt;Galaxy/AGN&lt;br&gt;Cluster/diffuse&lt;br&gt;Magnetism&lt;br&gt;Galactic studies&lt;br&gt;Strong lensing</td>
</tr>
<tr>
<td>Feasible @ SKA₁?</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Tier 3 (Deep)</strong></td>
<td>0.05 0.1</td>
<td>10s</td>
<td>0.5</td>
<td>~1</td>
<td><strong>Complete census of SFRD(z), SFG/AGN evolution, SF/AGN interplay</strong></td>
</tr>
<tr>
<td></td>
<td>feasible @ SKA₁</td>
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Radio Continuum Extragalactic Survey Science

• Evolution of galaxies and clusters
  (in combination with HI + multi-λ information)
  - Star formation & BH accretion history
  - Role of AGN feedback over cosmic time
  - Interplay between SF and AGN activity
  - Origin of FIR-Radio correlation
  - Diffuse non-thermal emission in clusters
  - Radio continuum emission from the cosmic web
  - First galaxies, BHs & protoclusters
  - Detailed study of ISM physics in nearby galaxies

• Cosmology (in combination with HI/redshift surveys)
  (Constrain dark energy and non-Gaussianity)
  - Baryonic Acoustic Oscillations
  - Integrated Sachs-Wolfe Effect
  - Magnification Bias
  - Weak lensing
  - HI Intensity Mapping

- Commensality between line/continuum/polarization surveys
- Synergy with surveys in other wave-bands

GALFORM, Benson et al. 2000

Deep fields
10-100 deg²

Shallower wide-area surveys
>1/4 sky
Next generation 1.4GHz Surveys

- SKA$_1$ Surveys designed to give a complete census of galaxies (including MW-like) up to $z\sim3$ and to probe more intense star-forming gals to $z\sim6$

- SKA$_2$ will give complete census of galaxies up to $z\sim6$, and will push galaxy studies into the realm of the EOR ($z>>6$) including RQ AGN

![Graph showing different tiers of surveys]
Galaxy evolution – SF and AGN feedback

Bower+ 2006

No AGN feedback
No dust

Bower+ 2006
Star Formation History

Radio is sensitive tracer of star formation rates unaffected by dust or gas (at ν>> 1 GHz it traces thermal emission)

- SFRD vs redshift
  [Dust enshrouded SFH up to high z]

Region occupied by unidentified sub-mJy radio sources?

What dominates SFR at each z?

Present Day

(From Hopkins et al 2004, Barger et al 2000)
What dominates SFR at each $z$?

$z=1.5$

10 uJy

0.1 uJy

SKA1

SKA2

COSMOS field

Bower+ 2006
SF vs Galaxy Structure

Quenching SF cannot cause a galaxy to transition from blue cloud to red sequence

Do AGN play a role?

Need sub-arcsec spatial resolution

~0.5'' $\rightarrow$ SKA1

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AGN Radio-mode Feedback

From galaxy cluster to individual galaxy scales

1. Spatial relationships between nucleus, jet, warm [OIII] gas and X-ray gas in kpc NLR

2. Some estimates of energy in the multiphase gas
**AGN Radio-mode Feedback**

AGN radio mode feedback vs environment and stellar mass

Radio-AGN heating versus radiative cooling balance in elliptical galaxies

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**Best et al. 2005, 2006, 2007**

RL-AGN~10% $\rightarrow$ jet-driven mechanical feedback or RQ-AGN radiation-driven feedback (winds) important for the overall galaxy evolution?

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Science  
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• RQ-AGN start to appear at uJy levels in deep radio fields
• SKA perspective: Evolution of radio-selected AGN down to RQ regime \( P \approx 10^{21} \text{ W/Hz} \)
• RQ-AGN share many properties with SFGs
  \( \rightarrow \) Mini-jets or SF? Or both?
• Interplay/co-existence of AGN and SF activity?
Separating AGN/SF activity

High resolution sensitive radio observations is the most direct and neat way to securely pinpoint AGN radio emission in deep radio fields.

Need baselines >1000 km (SKA2)

High spatial resolution allows to separate AGN/SF contributions in hybrid sources.

- Overall Energy budget of gals (balance of fusion vs. accretion)
- Interplay between AGN and SF
- Unbiased estimation of SF/BH History especially at high-z
e-MERLIN Galaxy Evolution (e-MERGE) legacy survey

- *e-Merlin's* unique combination of sensitivity and spatial resolution

- 900 hours allocated (about 30% of the total amount of time available): deepest high resolution radio imaging of two well studied extragalactic fields → to be combined with JVLA

- GOODS-N (L + C bands) → SFR & AGN evolution at 1<z<4, with special focus on possible co-existence and co-evolution of the two phenomena

- Abell Cluster (L band) → lensed pop (z>5)

  - Resolution of 50-200 mas in C- & L-Bands respectively (<0.5-1.5 kpc at z>1) → disentangle the contributions of AGN and SF, an essential step given the apparently simultaneous growth of the black holes and stellar populations in galaxies.

(Guidetti, Bondi, IP+ 2012)
Separating SF/AGN Activity

- **Synergies with VLBI**
  \[ \rightarrow \text{will inform the SKA on the need of >1000 km bs} \]

- **Synergies with HI surveys** [see pilot work *Gereb, IP et al. 2013*]
Conclusions

• Valuable continuum science expected in all phases to the full SKA:
  - from Pathfinders to Precursors to SKA1 & SKA2

• Previous phases will provide valuable constraints (both scientific & technological) to better fine-tune following phases
  - Better sky modeling + technology advances

• We don’t need to wait for the full SKA. A lot of work can be done already now!

• Need to address some critical issue in SKA1 design that may limit continuum science