Revealing the Physics and Evolution of Galaxies and Galaxy Clusters with SKA Continuum Surveys*

I. Prandoni
on behalf of the SKA Continuum Extragalactic Science WG

*based on the Continuum Science Chapters of new SKA Science Book [see chapter index at arXiv:1412.6942]
SKA Radio Continuum Extragalactic Surveys Science Drivers

- **Deep Fields/Multi-Tier surveys (1-1000 deg²)**
  (in combination with redshift/multi-λ info)
  - Star formation & BH accretion history
  - Role of AGN feedback over cosmic time
  - Evolution of FIR-Radio correlation
  - Role of environment

- **Wide/All-sky Shallower Surveys (1k-30k deg²)**
  (in combination with redshift/multi-λ information)
  - First galaxies, BHs & protoclusters
  - Galaxy clusters, cosmic web
  - RL AGN physics/lifecycle
  - RQ/RL AGN dichotomy
  - ISM and SF physics in nearby galaxies
  - Origin of FIR-Radio correlation
  - Strong lensing

**Commensality:**
- HI Deep Fields
- High-z Magnetism
- Weak Lensing

**Synergy with LSST, Euclid, JWST, eROSITA**
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SKA1 Key Science Goals

Top Priority Objectives for SKA1 selected by SKA Office in consultation with ad hoc Science Review Panel and SEAC → Notional Key Science Projects

| Science Goal | SWG      | Objective                                                                 | SWG Rank |
|--------------|----------|---------------------------------------------------------------------------|----------|
| 1            | CD/EoR   | Physics of the early universe IGM - I. Imaging                           | 1/3      |
| 2            | CD/EoR   | Physics of the early universe IGM - II. Power spectrum                   | 2/3      |
| 4            | Pulsars  | Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection | 1/3      |
| 5            | Pulsars  | High precision timing for testing gravity and GW detection               | 1/3      |
| 13           | HI       | Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8 | 1/5      |
| 14           | HI       | High spatial resolution studies of the ISM in the nearby Universe.       | 2/5      |
| 15           | HI       | Multi-resolution mapping studies of the ISM in our Galaxy               | 3/5      |
| 18           | Transients | Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State | 1/4      |
| 22           | Cradle of Life | Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc | 1/5      |
| 27           | Magnetism | The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields | 1/5      |
| 32           | Cosmology | Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales. | 1/5      |
| 33           | CosmoRay | Angular correlation functions to probe non-Gaussianity and the matter dipole | 2/5      |
| 37 + 38      | Continuum | Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes | 1+2/8    |

Table 2. List of highest priority SKA1 science objectives, grouped by SWG, but otherwise in arbitrary order.
Why radio surveys?

Radio continuum emission reliable tracer of star formation rates unaffected by dust (opt/UV/Hα)

Less confused than IR surveys

SKA 1 can probe both synchrotron and free-free continuum radio emission + redshifted CO lines
Deep Radio Fields dominated by SFGs

Sensitivity is key

Requirement:
→ sub-uJy rms

SKA competitive with opt/IR facilities!

When does SF occur?
What dominates SFRD at each z?

SFH vs gal type
SFH vs gal mass
SFH vs environment

... 8/24/15
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(Ultra-)Deep Fields

SFH vs galaxy mass [sSFRD]

→ SF Main Sequence
   SFR=f(Mass)

→ to be constrained at high z

Requirement:

→ sub-uJy flux limits
   [sensitive to low SFR/low mass systems at high redshift]

1 GHz [BAND 1/2]

Deep (rms 0.2 uJy): \( \lg(M/M_{\odot}) \sim 9 \)
   @ \( z \sim 1-2 \) peak of SFH

Ultra Deep (50 nJy): \( \sim \lg(M/M_{\odot}) \sim 10 \)
   @ \( z \sim 3-4 \)

Full SKA \( \rightarrow \) \( \lg(M/M_{\odot}) \) @ \( z > 5 \)

\[ \text{Jarvis+ 2015} \]
The image contains a slide with text and graphs discussing the relationship between star formation (SF) and environment. The text is as follows:

**Deep+Wide Fields**

**SF vs Environment**

**Requirement:**

10-1000 deg² survey coverage  
(also relevant for AGN studies)

a) Large samples $\rightarrow$ good statistics  
$\rightarrow$ accurate $f(L,z)$ for different source parameters  
$\rightarrow$ sample variance under control

b) Study environment effects  
$\rightarrow$ link between SF activity & Dark Matter Halo underlying distribution

**Jarvis et al 2015**
Band 5 \( \rightarrow \) \(~0.1^{"}\) spatial resolution \((150\text{ km bs})\) \(\rightarrow\) Spatially resolved SF \(\text{(synergy Euclid 0.2")}\)

SKA1 \(\rightarrow\) can resolve 100 \(M_{\odot}/\text{yr}\) SFGs to \(z\sim1\) on sub-kpc scales and to \(z\sim2\) on kpc scales

SKA2 \(\rightarrow\) can push high-z resolved studies to 10 \(M_{\odot}/\text{yr}\) SFGs

\(\rightarrow\) But also unbiased SFR \(\text{(resolution is key to identify and remove embedded AGN cores…)}\)

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Band 5 Deep Fields

Detailed Astrophysics of SF

Murphy, Sargent et al. et al 2015

~150 km bs $\rightarrow$ ~ 1 GHz: 0.5-1” resolution
~10 GHz: 0.05-0.1” resolution

$\rightarrow$ Detailed astrophysics of SF and Accretion

All Sky SKA1-MID survey/Targeted Obs.
Local Universe at 0.5-2 arcsec resolution
to resolve galaxies on several scales

VLBI-mode added value

$\rightarrow$ But also unbiased SFR (resolution is key to identify and remove embedded AGN cores…)

8/24/15 I. Prandoni
Important ingredient in galaxy formation and evolution models

**RL AGN – Radio/Hot Mode**
→ jet-driven mechanical feedback

**RQ-AGN – QSO/Cold Mode**
→ radiation-driven feedback (winds)

RQ-AGN start to appear at uJy levels in deep radio fields → hosted by disk galaxies

Complete census of RL and RQ AGNs
→ complete view of AGN feedback
→ Role of AGN feedback in gal. evol.
Evolution of RL AGN at $z>1$ & $L<10^{24-25}$ W/Hz $\rightarrow$ poorly constrained

$L<10^{24-25}$ W/Hz dominated by LERG $\rightarrow$ Role of radio feedback in gal. evol.

RQ AGNs span a similar radio lum. range
What determine RQ/RL dichotomy?
What triggers radio emission in RQ AGNs?
- Synchrotron radiation from mildly relativistic mini-jets?
- thermal cyclo-synchrotron emission from ADAF/ADIOS?
- thermal free-free emission from the X-ray heated corona or wind

SF and AGN related emission do co-exist

Radio AGN cores
Difficult to detect at uJy levels

~2 kpc size

Requirements:
Multi-band information & Multi-frequency info

Radio-band:
Spatial Resolution & sub-uJy sensitivity

Padovani+ 2011
Separating AGN/SF activity in RQ AGN

RQ-AGN often associated to disk galaxies → Need to separate AGN from SF radio emission → unbiased and complete AGN demography

Requirements: sub-arcsec resolution + uJy/sub-uJy sensitivity

SKA → larger samples & higher redshift

Multi-frequency/Polarization disentangle thermal vs non-thermal emission

Now possible for small samples in local Universe

Courtesy Orienti
Core emission from high-z RQ QSO

Gravitational lensing to study intrinsically faint sources
Requirement: sub-arcsec resolution at ~1 GHz

Left: SDSS J1004+4112 (z=1.7; 6hr JVLA 5GHz, C conf.); quad-imaged radio-quiet quasar of ~1 uJy intrinsic flux

Below: HS0810+2445 (z=1.5, 3hr JVLA 5GHz, C conf.): similarly faint RQ quasar → modelling shows intrinsic extent of RQQ

10-12 mas ≅ 100 pc size
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⇒ All Sky sub-arcsec resolution surveys
SKA1 @ 0.5” → ~7000 lens candidates
Best to be followed up at Band 5/VLBI

10-12 mas ≅ 100 pc size

Courtesy N. Jackson

I. Prandoni
Surface brightness sensitivity + steep spectrum: $ightarrow$ Resolved studies of extended RGs
SKA1 $\rightarrow$ only most extended RGs ($>10$ arcsec)
SKA2 $\rightarrow$ to study full RG population $\rightarrow$ USS dying radio sources $\rightarrow$ 1st generation RL AGNs ($z>6$)
SKA2 $\rightarrow$ <50 MHz
1st generation RL AGNs (z>6)

GPS/CSS thought to be the progenitors of extended RGs

Low frequency emission less affected by radiative losses

Peak moves to low frequency with redshift (150 MHz @z~6)

Afonso et al. 2015
Galaxy Clusters

SKA1-LOW:
Confusion limited @ ~20 uJy/b rms (120 MHz, 10” res.)

Exploit excellent surface brightness
Sensitivity of SKA-LOW in synergy with eROSITA, up to z~0.5

SKA will be sensitive to
**turbulent USSRHs** (low-mass mergers) and **“off-state” hadronic RHs** (relaxed clusters)

SKA2:
For higher-z needs <10” resolution to remove foreground galaxies
**SKA-LOW: All Sky Survey**

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**SKA2:**
For higher-z needs <10” resolution to remove foreground galaxies
SKA can potentially detect non-thermal emission associated to steady-shocks in cosmic web filaments

z~0.02
B=0.1 µG
Vazza et al. 2015
### Outline of SKA1 Key Reference Surveys

*Prandoni & Seymour 2015*

| Science Drivers                  | Freq.            | Tier       | Rms (full BW) | Area     | Res. | Science/Commensality                      |
|----------------------------------|------------------|------------|---------------|----------|------|--------------------------------------------|
| **SFHU Non-thermal**             | ~1 GHz Band 1/2  | Ultra Deep | 50 nJy        | 1 deg²   | ~0.5"| AGN/gal co-evol.                           |
| (gal/AGN co-evol.)               |                  | Deep       | 200 nJy       | 10-30 deg² | ~0.5"| AGN/gal co-evol.                           |
|                                  |                  | Wide       | 1 uJy         | 1000 deg² | ~0.5"| High-z Magnetism                           |
|                                  |                  |            |               |          |      | HI deep field (B1)                         |
| **SFHU Thermal**                 | ~10 GHz Band 5   | Ultra Deep | 40 nJy        | 0.008 deg² | ~0.1"| AGN/gal co-evol.                           |
| (gal/AGN co-evol.)               |                  | Deep       | 300 nJy       | 1 deg²   | ~0.1"| AGN/gal co-evol.                           |
| **Legacy Strong Lensing**        | ~1 GHz Band 2    | All-sky    | 4 uJy         | 31000 deg² | ~2"  0.5"| Magnetism                                  |
| (rare populations)               |                  |            |               |          |      | Cosmology tests                            |
| **Clusters**                     | ~120 MHz         | All-sky    | 20 uJy (confusion) | 31000 deg² | 8"   | EoR                                        |
| (RL AGNs)                        |                  |            |               |          |      | Transients (beam forming)                  |
|                                  |                  |            |               |          |      | HI surveys                                 |
|                                  |                  |            |               |          |      | Our Galaxy                                 |

Revisited after rebaselining (March 2015)
What’s Next: Definition of KSP

Tasks for this meeting and next future:

- Start defining actual KSPs
- Identification of useful ECPs
- Identification of Synergies and Commensality with other SKA WGs
- Exploiting synergies with other upcoming facilities (e.g. LSST, Euclid, JWST, eROSITA, etc.)

- **Observational Setup:**
  Frequency, BW, Area Coverage, rms, observing strategy, etc.
- **Choice of Region/Fields**
- **Pipelines/Data Products:**
  Stokes parameters (IQUV), image/catalogue parameters \(\rightarrow\) spatial/spectral resolution, etc.
- **Resources/Expertise** (strong role played by Precursors)
Commensality: Examples

- **All-Sky Surveys**: All-Sky RM / Local Universe / Legacy / Rare Cosmology tests / HI Intensity Mapping / Our Galay
- **Wide Fields**: SFHU/AGN Evolution / Weak Lensing (MID) / HI Surveys (MID)
- **Deep Fields**: SFHU/AGN Evolution / HI deep surveys (MID) / Deep Polarization Fields (MID)
- **Mid Ultra Deep**: SFHU/AGN Evolution / HI deep surveys

**To be fully exploited:**

- data processing of all I,Q,U,V Stokes parameters,
- data processing with different setups, eg:
  - angular resolution: 0.5” – 2”
  - spectral resolution: full BW, ~MHz channels for RM/spectral index, kHz for line
- different data products, eg:
  - 2D continuum I,Q,U,V + 3D HI images/catalogues
Continuum Radio surveys provide a valuable dust-extinction/gas-obscuration-free tool to study thermal and non-thermal emission from galaxies and galaxy clusters.

SKA sub-uJy sensitivity will make it possible to study high-z SFG and all types of AGN: both the RL and the most common RQ component.

- Added value: sub-arcsec resolution and Band 5

SKA continuum surveys will be competitive with upcoming IR, optical and X-ray surveys [will become important component of multi-band studies and useful to a very broad community].

- Strong synergies to be exploited with other facilities

Existing commensality/synergy with other WGs should be explored. To be fully exploited:

- different obs. modes to be implemented in parallel (e.g. full Stokes, beam-forming, etc.)
- data processing of all I,Q,U,V Stokes parameters, and with different setups:
  - Angular resolution/weighting scheme: from arcsec to sub-arcsec
  - Spectral resolution: from kHz (for line surveys) to ~MHz (for RM/absorption in-band spectral index) to ~GHz (for detection experiments)
THANKS!