Cosmology with the Radio Synoptic SKA (RSSKA)

Steven T. Myers

National Radio Astronomy Observatory
Socorro, NM
The RSSKA is part of the SKA Program

- The SKA is an international program to build the next generation of large radio arrays
  - **SKA-low**: 10-300 MHz
    - Epoch of Reionization (EoR) and Dark Ages Telescope (DAT)
    - Pathfinders/Precursors: MWA, PAPER, LWA, GMRT, LOFAR
  - **SKA-mid**: 0.3-10 GHz
    - the RSSKA!
    - Pathfinders/Precursors: ALFA, EVLA, ATA, ASKAP, MeerKAT
  - **SKA-high**: 1-50 GHz
    - Cosmic Star Formation and the “Cradle of Life”
    - Pathfinders/Precursors: EVLA, ATA, ALMA
    - Plan for 2025+?
The Radio Synoptic SKA (RSSKA)

- SKA as Radio Synoptic Survey Telescope (RSST)
  - say “risque”
- The RSSKA is ...
  - radio: HI core 0.4-1.4 GHz (0.3-10 GHz goal)
  - square kilometer: large collecting area for sensitivity
    - high gain/low noise $A/T_{\text{sys}} > 10^4 \text{ m}^2 \text{ K}^{-1}$
  - survey telescope: wide-field for survey speed
    - survey speed FOM $\Omega (A/T_{\text{sys}})^2 > 4 \times 10^9 \text{ deg}^2 \text{ m}^4 \text{ K}^{-2}$
- Built for the Primary Science Goals
  - HI for Cosmology and Galaxy Evolution
  - Deep continuum imaging
  - Transient detection and monitoring
The Synoptic Part

• Revisit the sky regularly
  – if you want to cover $10^4 \text{deg}^2$ with $1\text{deg}^2$ FOV
  – can do so in 1 day with $8s$ per $\text{deg}^2$
  – different parts of survey can have different depths (and thus cadences)

• What cadence? Depends on the science
  – many short visits or fewer longer ones?
  – looking for individual “bursts” or “pulses”?
  – looking for groups or trains of pulses?
  – classical variability curves (e.g. microlensing)?
  – also remember, many compact radio sources are variable (both intrinsic and scintillation)
RSSKA Science
Key science drivers
Cosmology with the RSSKA

- Survey of HI galaxy emission to $z > 1$

A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the “Dark Universe”. Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation.

(Credit: Danail Obreschkow (Oxford) and the SKADS Sky Simulation team.)
RSSKA Science: 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 community
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)
RSSKA for Cosmology

• RSSKA can see HI galaxies out to redshift $z > 2$
  – $> 10^9$ 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

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).
RSSKA for Dark Energy

- **RSSKA 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 $4\times 10^9$ m$^4$K$^{-2}$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
RSSKA Science: Continuum

- Extremely deep (10 nJy) continuum survey
  - “billion” extragalactic radio sources
  - AGN
  - star-forming galaxies
  - SNR and HII regions in galaxies
  - weak lensing

- Census of rare phenomena
  - Gravitational Lenses (e.g. CLASS)

- Polarimetry
  - Rotation Measure (RM) survey
  - galactic and extragalactic magnetic fields
RSSKA Science: Pulsars & Transients

- **Bursty phenomena - a new frontier**
  - giant pulsar pulses out to Virgo
  - brown dwarf flares

- **Variability**
  - compact radio sources
    - intrinsic, IDV, scintillation, etc.
  - flares
  - GRB afterglows

- **Exotica**
  - UHE particles in lunar regolith
  - SETI

- **Pulsars**
  - provide spigot Pulsar Machine attachment

*Pulsars discovered and monitored with the SKA will act like a cosmic gravitational wave detector, allowing the study of ripples in the fabric of space-time that propagate at ultra-low frequencies.*

(Credit: D.Champion, M.Kramer/JBO)
Phase Space for Transients:

Detection limit for SKA:

\[ S_{pk}D^2 > \text{threshold} \]

leftrightarrow Prompt GRBs and GRB afterglows easily seen to cosmological distances

Giant pulses detectable to Virgo cluster

Radio magnetars detectable to Virgo

ET radar across Galaxy

\[ kT_b = \frac{2S_{pk}D^2}{(\nu W)^2} \]

W = pulse width or characteristic time scale
RSSKA Key Science Surveys

• Key Projects (example)
  – Cosmological HI Large Deep Survey (CHILDS)
    • billion galaxies to z~1.5 (and beyond)
    • HI redshift survey for cosmology
    • galaxy evolution
  – Deep Continuum Imaging Survey (DeCoIS)
    • radio photometric and polarimetric survey (static sky)
    • commensal with CHILDS, extracted from spectral data
  – Transient Monitoring Program (TraMP)
    • bursts, variability, pulsars, etc.
    • commensal with other RSSKA surveys – freeloading!

• These are part of one big survey (Big Sur)
Realizing the RSSKA
The RSSKA Roadmap

• RSSKA planning
  – US-SKA and International consortia drafting for Decadal Review

• Science Precursors
  – use EVLA, Arecibo, ATA, etc. to pioneer science areas

• Technology Demonstrators & Pathfinders
  – US-SKA TDP, ATA, EVLA, EOR projects, 1% SKA pathfinders)

• Staged Construction
  – milestones for construction and limited operation
    • e.g. a “10% RSSKA” for HI power-spectra?

• Operations and Staged Upgrade
  – Science Operations (20+ years)
    • US RSSKA Science Center? what is model for community involvement?
  – Upgrade Plan (10 years)
    • build into project (e.g. add multi-beam capabilities, computing upgrades)
Precursors: What we can do Now

- **HI Cosmology Simulations**
  - models to make credible projections
    - $\phi(M,z)$ and $f(M_{HI}/M \mid M,z,\rho,\ldots)$
    - link to halos
  - semi-analytics vs. N-body/hydro
  - galaxy counts vs. emission power spectrum
    - as in CMB (Wyithe & Loeb 2008)

- **Science Precursors**
  - what can we do NOW to pave the way?
  - HI in galaxies at $z=0.5$?
  - how to best use existing facilities?
    - big EVLA surveys (commensal?)
    - beyond ALFA?
    - ATA?
SKA Pathfinders

- ATA
- WSRT
- MWA
- ASKAP
- MeerKAT
- LOFAR
- LWA
- PAPER
- HHA
- FAST

Lister Staveley-Smith (Spineto, 2007)

SKA Pathfinders

- Allen Telescope Array (Blitz talk)
- Australian SKA Pathfinder (ASKAP=MIRANDA=xN MeerKAT (S.Africa))
- MWA (Lonsdale)
- Hubble Hydrogen Array (Peterson)
- FAST (China)
- Aperif WSRT
- LOFAR (de Bruyn)
The SKA Artist’s Concept

- Aperture Array Tiles (low frequency)
- Large Number of Small Dishes (LNSD) (mid and high frequencies)
RSSKA HI: Descoping Issues

- Draft Preliminary Specs v2.7.1
  - 3000 x 15m single-pix survey speed
  - 40x slower than SKA of AR2005
  - could get back w/multi-feed upgrade
  - or implement as separate Aperture Array
    - e.g. 4x scaled-up EOR array
  - also configuration issues (core vs. res)

- HI mass function
  - $z=2$ HIMF steep above $10^{10} M_{\text{sun}}$
  - if $M_{\text{lim}} \times 2$ then $N \times 10^{-3}$ to $10^{-4}$ or worse!
    - in danger of getting < 10 million galaxies at $z>1$
  - **Dark Energy not do-able with PS**
    - need SSFoM > 4-6 $\times 10^9$ m$^4$K$^{-2}$deg$^2$
    - is this important enough?
  - this is a critical issue to deal with in RSSKA DR planning

How do we get to precision “DE” sensitivity?

Figure 1. Predictions of the evolution in the HI mass function from AR2004. The dot-dashed lines show their ‘Model A’ at $z = 1$ (lower, blue) and $z = 2$ (upper, red) with the solid (black) line showing the measured local HI mass function (Zwaan et al. 2003). The dashed lines show their ‘Model B’ at $z = 1$ (rightmost, blue) and $z = 2$ (leftmost, red), and the dotted lines their ‘Model C’ at $z = 1$ (upper, blue) and $z = 2$ (lower, red).

Rawlings et al. SKA Science Book
Example: HI Survey Strategies

• Reference design (RD): 3000 15m antennas
  – only 0.36 of SKA (7500 m²/K vs. 20000 m²/K)
  – 40x slower than SKA for precision BAO (Abdalla & Rawlings 2005)
  – FOV = 0.73deg² at z=0 (1.4GHz) and 4.54deg² at z=1.5 (560MHz) “single pixel”
  – target: 10 deg² or more at z=0 (1.4GHz) - need upgrade!

• 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 deg²
  – 8.64s per deg² per day = 4.38 hours per deg² in 5 years
  – RD: 19.9h per z=1.5 FOV per year
    • \( S_{lim} = 1.75 \mu\text{Jy} \Rightarrow M_{lim} = 4.1 \times 10^9 \text{M}_{\odot} \text{ at } z=1.5 \text{ (} \Delta\nu=0.38\text{MHz}) \)
Example: more HI Survey Strategies

- **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
    - \(S_{\text{lim}} = 0.39 \mu\text{Jy} \Rightarrow M_{\text{lim}} = 8.8 \times 10^8 \text{ M}_\odot \text{ at } z=1.5 \) (\(\Delta \nu=0.38\text{MHz}\))

- **Medium-deep Gal Plane Survey = 750 deg\(^2\)**
  - 115.2s per deg\(^2\) per day = 35 hours per deg\(^2\) in 3 years
  - RD: 25 hours per z=0 FOV

- **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
    - \(S_{\text{lim}} = 0.13 \mu\text{Jy} \Rightarrow M_{\text{lim}} = 3 \times 10^8 \text{ M}_\odot \text{ at } z=1.5 \) (\(\Delta \nu=0.38\text{MHz}\))
RSSKA in Perspective

• A square kilometer array is
  – 100 times the size of the EVLA (10x Arecibo)
  – would take 2700 VLA 25-m dishes
    • take $\sim 10^4$ times the processing of the VLA
  – would take 12000 12-m dishes
    • take $\sim 10^5$ times the processing of the VLA

• Equivalent EVLA data rates $\sim 250$ MB/s
  – RSSKA would be $\sim 2.5$TB/s to 25TB/s
  – data volumes $\sim 200$ to 2000 PB per day
  – there are higher rate modes (transients)
  – cannot store all raw data, only products (images)
    • it will come down to “real time” imaging & processing
Challenges

• Scope of RSSKA
  – current design is as “general purpose” radio array
  – could cut costs by:
    • relaxing upper frequency (10GHz) to 3 GHz
    • possibly by focusing on low-resolution power spectra
    • aperture (dipole) arrays like EOR-SKA (but 1/4 wavelength)

• Costing of RSSKA
  – technology choices, wide-field upgrades, computing

• Data Management
  – is >1/3 the capital cost, and thus must be designed
  – how much processing is “real-time”? 
Great Surveys and the RSSKA
Making a Map of the Universe

• The Whole Universe Telescope
  – must see all the universal constituents
  • luminous matter - stars, HII regions, thermal emissions
  • quiescent gas - HI, molecular clouds and cores
  • planetary objects - exo-planets, proto-planetary & debris disks
  • energetic particles - cosmic rays, “jets”, neutrinos
  • magnetic fields - galactic, intergalactic, cosmological
  • collapsed objects - black holes, AGN, pulsars, gravity waves
  • dark matter - galaxy/cluster cores, gravitational lensing, direct
  • dark energy - cosmological
  • gravity waves - gravitational collapse, GW background

• The RSSKA is part of this future
Great Surveys for a “2020 Vision”

• The SKA is part of a grand vision for the coming decades, including:
  – Large Synoptic Telescope (LSST, Pan-STARRS)
  – Giant Segmented Mirror Telescope (GSMT)
  – Square Kilometer Array (RSSKA, EoR/DAT)
  – Great Space Surveys (JDEM, LISA, ConX, CMBPol)

• These next-generation telescopes are not just great observatories, but are parts of a Great Survey of the Universe
  – These are the instruments that we want to have available to do our science in 2015+
Common Cause

• All these next-generation surveys and telescopes have challenges
  – in particular in the Data Management area!
• The Science is cross-cutting
  – multi-wavelength (or particle) and multi-instrument
  – interest is multi-agency (NSF, DOE, NASA, other)
  – realize the Whole Universe Telescope
• “Great Surveys” Workshop
  – bring together workers from the next-gen projects
  – hold in Santa Fe in November 20-22 2008
  – organization underway
For more information...

- RSST Proto-White Paper (draft)

- my RSST/RSSKA page
  - http://www.aoc.nrao.edu/~smyers/rsst

- SKA Info
  - particularly see the “Science Book”
    - “The Dynamic Radio Sky” by Cordes, Lazio & McLaughlin
    - “Galaxy Evolution, Cosmology, and Dark Energy with the SKA” by Rawlings et al.
    - others...