Future Science at cm wavelengths, Chicago II, Aug 2006, C.Carilli

Major efforts: EVLA I+II, ATA…

Science with the Square Kilometre Array
Editors: Christopher Carilli, Steve Rawlings

• Three year process: Quantified ‘experiments’ for future large area cm telescopes – not just radio astronomy reviews

• 50 chapters, 90 contributing authors, 25% theorists, but
Key Science Projects: (i) Address key questions, (ii) Unique role of radio, or complementary but critical, (iii) Excites broad community

Science with the Square Kilometre Array

Cosmic reionization and first light

HI + continuum survey: galaxy evolution and dark energy

Cosmic magnetism: origin and evolution

Strong field tests of GR using pulsars

Cradle of Life: protoplanetary disks on (sub)AU scales + astrobiology + SETI
Many other areas of interest:

- Dynamic radio sky (SNe, GRBs, XRBs, ++)
- Discovery space: ‘exploration of the unknown’
- μas Astrometry
- CRs, Jets/AGN, Abs lines, Sun/stars, S-Z, planetary science…
- DSN
KSP I: Cosmic magnetism (Gaensler/Beck)

**STRUCTURE:** Strength & structure of fields in ISM, ICM & IGM? Interplay between small-scale (turbulent) and large-scale (ordered) fields?

**EVOLUTION:** Field generation and amplification in galaxies & clusters over cosmic time?

**ORIGIN:** Primordial seed field generation? Connection between field formation and structure formation in the early Universe?

SKA All Sky Polarization/Rotation measure survey

- Image the full sky to $\sigma \approx 0.1$ $\mu$Jy at 1.0 to 1.4GHz
- 1 hour per pointing, FOV = 1 deg$^2$, time = 1 yr
- 2e7 extragalactic RMs, spaced by $\sim 90''$ (vs. 1500 currently)
- 2e4 pulsars (vs. 300 currently)
Magnetic Field of the Milky Way

300 Pulsar RMs (Han et al 2002)

SKA pulsar simulation: 2e4 pulsars (Cordes 2001)
Nearby Galaxies: test dynamo models
synchrotron + RM

Polarized synchrotron emission

5000 RM-probes through M31
Nearby and distant clusters: ICM fields on kpc to Mpc scales – embedded and background radio sources

300 RM-probes through Abell 2255

1138-262: $z=2.2$

RM=624 rad/m$^2$

-3000 +4000 rad/m$^2$
Magnetic field evolution in galaxies over cosmic time:
Ly-\(\alpha\) Absorbers at \(z \sim 1 \sim 6\)

- RMs of distant quasars
  - trend of RM vs \(z\) probes evolution of \(B\) in Ly-\(\alpha\) clouds
  - dominant error: Galactic contamination
    \(\rightarrow\) currently very coarse sampling = 150’ source spacing
    \(\rightarrow\) SKA survey gives 1.5’ spacing

- Quasar RMs with SKA:
  - 1e7 RM measurements
  - redshifts: SDSS & successors
  - accurate foreground removal using RM grid
  - Ly-\(\alpha\) forest: RRM vs \(z\)
    Damped Ly-\(\alpha\): RM vs N(HI)
The Magnetized IGM: cosmic web

- Detection & polarimetry of synchrotron emission from filaments also possible
  - signal > 10uJy on degree scales
  - direct estimate of strength & degree of ordering of magnetic fields
  - three-dimensional geometry of magnetic field & filaments
KSP II: Full sky HI + continuum survey: galaxy evolution and dark energy (Rawlings+)

Goal 1: Galaxy evolution – conversion gas to stars

- HI survey: 0.5 – 1.4GHz; 1year; 1e4 channels; 10 deg^2 FoV at 1.4, subarcsec res.
- Total area=2e4 deg^2; rms line = 2uJy; rms cont = 30nJy
- Expect: 1e9 HI galaxies to z=1.5
- Required complement to LSST
Goal 2: Dark energy – Baryon oscillations (Blake)

- Standard (comoving) rod, $S$, fixed by sound horizon (acoustic oscillations) at recombination – measured as acoustic peaks in CMB fluctuations
- Follow evolution of $S$ down to lower redshift through source clustering → measure angular diameter distance (‘fossilized’ acoustic oscillations vs. $z$)
- Accelerating universe: Effect of $w(z)$ (‘Dark Energy’) most pronounced at lower $z$
- SKA: determine clustering power spectrum vs. $z$ using HI emission from $1e9$ galaxies to $z=1.5$: very large number stats, very large scale (full hemisphere) → variance limited
Goal 3: Weak lensing of radio continuum sources – cosmic shear: growth of dark matter power spectrum. SKA advantages: very wide fields (linear regime), well controlled PSF

SKA as Dark Energy Machine: $w = \frac{P}{\rho} = -1$? Func$(z)$?

\[
W(z) = W_0 + W_1 z
\]
Goal 4: Hubble constant through direct measurement: Water Maser Disks (Greenhill)

- Future 1% measures of CMB and related require 1% measure of $H_0$ for fully constrained cosmological parameters: covariance

- Water masers disks into the Hubble flow can provide direct measure of $H_0$ to 1%
Gunn-Peterson + pol CMB

$\Rightarrow z_{\text{reion}} = 6$ to $11$

$\Rightarrow$ opaque at $\lambda_{\text{obs}} < 0.9\mu m$
HI 21cm signal from the IGM: large scale structure

Power spectrum: pathfinders are critical

Tomography: only SKA
- $\Delta T_B(2') = 10's \text{ mK}$
- SKA rms (100hr) = 4mK
- LOFAR (1000hr) = 80mK
Cosmic web before reionization: HI 21Forest – small scale structure

- radio G-P (τ=1%)
- 21 Forest (10%)
- mini-halos (10%)
- primordial disks (100%)

Radio Sources? Expect 0.05 to 0.5 deg^{-2} at z> 6 with S_{151} > 6 mJy
**SDSS J1148+5251: Observing first light at radio wavelengths**

\[ 1 \times 10^9 \text{M}_\odot \text{ in dust}, \ 1 \times 10^{10} \text{M}_\odot \text{ in mol. gas} \Rightarrow \]

- Hyper luminous IR galaxy (FIR = \(1 \times 10^{13} \text{L}_\odot\)):
  \[ \text{SFR} = 1 \times 10^3 \text{M}_\odot/\text{yr} ? \]
- Coeval formation of SMBH/galaxy?
- Dust formation by massive stars?
- Break-down of \(M-\sigma\) relation at high \(z\)?

- Early enrichment of heavy elements (\(z_{sf} > 8\))
- Integration times: hours to days on HLIRGs
Complementarity: Line sensitivity

0.1×Arp220: CO lines at z=5

Line sensitivity (300 km/s, 12hrs)

Low order transitions

High order, C+...

SFR=10M$_{\text{sun}}$/yr

z=5
Complementarity: continuum sensitivity

0.1 \times \text{Arp220} -- 12hr Continuum

Flux density (Jy)

Frequency (Hz)

AGN, star formation

dust

Stars, ionized gas
Case for frequencies up to 45 GHz: Thermal objects

Rayleigh-Jeans curve implies thermal objects are a factor four stronger (in Jy) at 45GHz relative to 22 GHz

=> a 10% demonstrator becomes 40% of the SKA
SKA specifications implied by Key Science Project goals.

<table>
<thead>
<tr>
<th>Topic</th>
<th>$A_{\text{eff}}/T_{\text{sys}}$ (m² K⁻¹)</th>
<th>Frequencies (GHz)</th>
<th>Max Baseline (km)</th>
<th>Special</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>20000 at 1.4 GHz timing array</td>
<td>0.5–15</td>
<td>3000</td>
<td>multifielding desirable? (TBD); significant central core</td>
</tr>
<tr>
<td>Dark Ages</td>
<td>10 000 at 0.1 MHz &amp; 20 GHz</td>
<td>0.1–20</td>
<td>3000</td>
<td>35 GHz for CO studies; central core for HI; full FOV imaging at 1.4 GHz</td>
</tr>
<tr>
<td></td>
<td>CO emission at $z &gt; 6$ (M 82)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HI structure at $6 &lt; z &lt; 13$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetism</td>
<td>20000 at 1.4 GHz RM grid</td>
<td>0.3–10</td>
<td>300</td>
<td>-40 dB polarization purity; central core; full FOV imaging at 1.4 GHz</td>
</tr>
<tr>
<td>Cradle of Life</td>
<td>10 000 at 20 GHz</td>
<td>$\geq 20$</td>
<td>3000</td>
<td>100 pencil beams within FOV for targeted searches; central core</td>
</tr>
<tr>
<td></td>
<td>10 K rms at 1 mas in 100 km</td>
<td>terrestrial planet formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evolution &amp; LSS</td>
<td>20 000 at 1.4 GHz</td>
<td>0.3–1.4²</td>
<td>300</td>
<td>dedicated beam with FOV of 200 deg² at 0.7 GHz is highly desirable to increase survey speed</td>
</tr>
<tr>
<td></td>
<td>$M_\odot$ galaxy at $z = 2$</td>
<td>galaxies to $z = 4$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All require sensitivity: $A/T \geq 1 \times 10^4$ m² K⁻¹
- Most require frequencies $\geq 10$ GHz
- Many require $> 1$ deg² FoV at 1.4 GHz
- Some require $> 1000$ km baselines
- A few require multibeamung
## Pathfinders

<table>
<thead>
<tr>
<th>Facility</th>
<th>Freq (GHz)</th>
<th>Year</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVLA I</td>
<td>0.3 – 50</td>
<td>2012</td>
<td>Broad, thermal</td>
</tr>
<tr>
<td>eMERLIN</td>
<td>1 – 30</td>
<td>2010</td>
<td>High resolution</td>
</tr>
<tr>
<td>ATA</td>
<td>1 – 10</td>
<td>2008?</td>
<td>Wide fields</td>
</tr>
<tr>
<td>DSN</td>
<td>8, 32</td>
<td>2010?</td>
<td>Telemetry</td>
</tr>
<tr>
<td>LWA</td>
<td>0.03–0.08</td>
<td>2009</td>
<td>Low freq window</td>
</tr>
<tr>
<td>LOFAR</td>
<td>0.08 – 0.3</td>
<td>2009</td>
<td>EoR++</td>
</tr>
<tr>
<td>MWAd</td>
<td>0.1 – 0.3</td>
<td>2009</td>
<td>EoR+</td>
</tr>
<tr>
<td>PAPER</td>
<td>0.1 – 0.2</td>
<td>2008</td>
<td>EoR</td>
</tr>
<tr>
<td>SKADS (Europe)</td>
<td>0.1 – 25</td>
<td>2015++</td>
<td>HI survey (aperture array)</td>
</tr>
<tr>
<td>xNTD (Oz)</td>
<td>0.7 – 1.4</td>
<td>2010</td>
<td>HI survey (FPA)</td>
</tr>
<tr>
<td>South Africa</td>
<td>0.7 – 1.4</td>
<td>2010</td>
<td>HI Survey (FPA)</td>
</tr>
<tr>
<td>SKA-TDP (USA)</td>
<td>0.3 – 25</td>
<td>2010</td>
<td>Nd</td>
</tr>
</tbody>
</table>
SKA into the EoR: low order molecular lines, star formation, and AGN

1148+5651: Hyperluminous IR galaxies

- Detect low order CO emission in seconds, including imaging on subkpc scales.
- Detect high dipole moment molecules (HCO+, HCN…) in minutes (critical densities > 1e5 cm^-3).
- Image non-thermal emission associated with star formation and/or AGN at mas resolution.

**Studying 1st galaxies**

- Detect ‘normal’ (eg. Ly α), star forming galaxies, like M51, at z>6, in few hours
- Determine redshifts directly from molecular lines