HI observables: fluctuations versus imaging

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&
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Content

• Imaging vs statistical measurements
  • Regimes for imaging
  • Science with imaging
Cosmic Dawn & Reionization with SKA

• Redshifted 21cm signal

\[ \delta T_b \approx 27x_{\text{HI}}(1 + \delta) \left( \frac{1 + z}{10} \right)^{1/2} \left( 1 - \frac{T_{\text{CMB}}(z)}{T_s} \right) \left( \frac{\Omega_b}{0.044} \frac{h}{0.7} \right) \left( \frac{\Omega_m}{0.27} \right)^{1/2} \times \left( \frac{1 - Y_p}{1 - 0.248} \right) \left( 1 + \frac{1}{H(z) \frac{dv_\parallel}{dr_\parallel}} \right)^{-1} \text{ mK,} \]

• Different analysis methods:
  • Statistical methods (e.g., power spectrum)
  • Imaging methods
Imaging vs Statistical Measures

- Cosmic Microwave Background signal

- All sky signal.
- One epoch $\rightarrow$ one map
- Gaussian distribution.

Planck team (2013)

Power spectrum
Imaging vs Statistical Measures

- Redshifted 21cm signal ($\delta T_b$)

$\delta T$ (mK) at $z=7.02$ (117 MHz) with [5',0.8 MHz]

- All sky signal.
- Many epochs $\rightarrow$ many maps (tomography)
Imaging vs Statistical Measures

- Redshifted 21cm signal ($\delta T_b$)

$\delta T$ (mK) at $z=7.02$ (117 MHz) with [5',0.8 MHz]

- All sky signal.
- **Non-gaussian** distribution.
Imaging vs Statistical Measures

- Redshifted 21cm signal ($\delta T_b$)

$\delta T$ (mK) at $z=7.02$ (117 MHz) with [5',0.8 MHz]

Simulated 21cm map

Gaussian distribution

Same power spectrum
How?

- Imaging requires sufficient S/N per pixel ($\theta$).

- For a fixed $A_{\text{eff}}/T_{\text{sys}}$ and filled uv plane:

$$S/N \propto (\Delta t \Delta v)^{\frac{1}{2}} (\theta)^2$$

For SKA_Low what pixel size gives ~1 mK noise?
Resolution for 1 mK noise

- $A_{eff}/T_{sys}$ for 1 mK noise for different pixel sizes.

- Hashed area: SKA range (0.25 – 2.5 SKA1).

- Typical resolution:
  - EoR: ~5’
  - EoH: ~10’
  - EoC: ~20’

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CD/EoR White Paper, Mellema et al. (2013)
Regimes for Imaging

- 21cm signal has fluctuations due to: $x(\text{HI}), \delta, T_s$

<table>
<thead>
<tr>
<th>Epochs</th>
<th>Main source of fluctuations</th>
</tr>
</thead>
<tbody>
<tr>
<td>EoR: Epoch of Reionization</td>
<td>$x(\text{HI})$ and $\delta$</td>
</tr>
<tr>
<td>EoH: Epoch of Heating</td>
<td>$T_s (= T_k)$ and $\delta$</td>
</tr>
<tr>
<td>EoC: Epoch of Coupling</td>
<td>$T_s$ and $\delta$</td>
</tr>
</tbody>
</table>

- Smoothing: reduces noise and reduces fluctuations.
Fluctuations due to $\delta$

- Fluctuations (in mK) in density field $\delta$:

<table>
<thead>
<tr>
<th>resolution</th>
<th>1’</th>
<th>3’</th>
<th>5’</th>
<th>10’</th>
<th>15’</th>
</tr>
</thead>
<tbody>
<tr>
<td>z=7</td>
<td>47</td>
<td>17</td>
<td>9</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>z=10</td>
<td>37</td>
<td>13</td>
<td>7</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>z=15</td>
<td>25</td>
<td>8</td>
<td>4</td>
<td>1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- Optimal combination of noise/resolution needs investigation, but needs 1 – 2 mK noise.
- Best prospects for EoR frequencies (with SKA2_Low).
Fluctuations due to $x(\text{HI})$

- Resolved HII regions during EoR have average contrast

\[ 27 \left( \frac{1 + z}{10} \right)^{\frac{1}{2}} \text{mK}. \]

- Can be imaged with $\sim 5 \text{mK}$ noise.
Fluctuations due to $T_s$

- Fluctuations (mK) due to spin temperature $T_s$:

\[ 27 \left( 1 - \frac{T_{CMB}(z)}{T_s} \right) \left( \frac{1+z}{10} \right)^{\frac{1}{2}} \text{ mK}. \]

- **EoH**: cold ($\sim 10$ K) vs hot regions at $z \sim 15$: $\sim 150$ mK
- **EoC**: cold coupled vs uncoupled regions at $z \sim 20$: $\sim 200$ mK

- Can be imaged with $\sim 10 - 30$ mK noise.
Resolution for 10 mK Noise

- $A_{\text{eff}}/T_{\text{sys}}$ for 10 mK noise for different pixel sizes.
- Hashed area: SKA range (0.25 – 2.5 SKA1).
- Typical resolutions:
  - EoR: ~3’
  - EoH: ~5’
  - EoC: ~10’

CD/EoR White Paper, Mellema et al. (2013)
Science with Imaging

Having access to images allows the following science:

- Global signal
- Study of special areas
- Bubble sizes
- Density field
Global Signal during EoR

- Ionized regions during EoR have 0 K intrinsic signal.
- For large FoV interferometer maps this to $-\langle \delta T_b \rangle$

Measurement of Global 21cm Signal!
Special Areas

- Location and shape of ionized regions: connect with other observations: **Galaxies & QSOs**.

- Example: HII region around a bright QSO (Datta, Friedrich, GM et al. 2012)

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21cm signal @ z=7.57, without and with QSO

Datta, Friedrich, GM et al. (2012)
Distinguishing HII Regions
Bubble Sizes

- Distribution, size evolution and topology of ionized regions: break degeneracies in power spectrum measurements.

- Example: study of the topology (e.g. genus) of the signal.
Density Field

- EoR last period that most baryons in Universe could be observed!

Masked analysis of cosmological density field \( \sim 0.5 \text{ – } 1 \text{ Gyr after Epoch of Recombination.} \)

Simulated image, no noise. 3’ synthesized beam, 0.5 MHz BW.
Conclusion

- Imaging/Tomography gives access to unique information and will truly make SKA a transformational telescope.

- Imaging/Tomography of EoR is possible at ~1 mK noise level for ~5 arcmin resolution.
- Imaging/Tomography of EoH/EoC is possible at ~10 mK noise for ~5 – 10 arcmin resolution.

- Examples of science enabled by imaging:
  - Global 21cm signal
  - Study of special areas/objects
  - Bubble size & topology
  - Cosmological density field
Thank You!
Extra Slides
Special Areas

• Location and shape of ionized regions: connect with other observations: **Galaxies & QSOs.**

• Example: HII region around a bright QSO (Datta, Friedrich, GM et al. 2012)
  • Assign QSO to most massive halo \( (M = 1.2 \times 10^{12} \, M_\odot) \) in 607 Mpc volume at \( z=7.76 \) (volume 50% ionized).
    • \( M_{\text{BH}} = 3 \times 10^8 \, M_\odot \) (cf. \( z=7.1 \) QSO \( 2 \times 10^9 \, M_\odot \))
    • \( N_\gamma = 2.4 \times 10^{56} \, \text{s}^{-1} \) (cf. \( z=7.1 \) QSO \( 1.3 \times 10^{57} \, \text{s}^{-1} \))
    • Quasar life time: \( 2.3 \times 10^7 \, \text{yr} \) (\( z=7.76 - 7.57 \))

• Full radiative transfer with H & He photo-ionization.
Impact of QSO on Environment

- Region of most massive halo already contains large HII region before QSO turn on.
- The QSO *does* increase the size of HII region.

21cm signal @ z=7.57, without and with QSO

Interferometer beam, 3’ resolution (no noise).

Datta, Friedrich, GM et al. (2012)
Distinguishing HII Regions
Quasar Properties from Tomography

• For our parameters the QSO
  • Supplies 50% of all photons for HII region
  • Dominates by 5 to 1 over stars during its lifetime.

• From measured size $R_b$:
  • Lower limit of age ($R_b / c$)
  • Upper limit of ionizing photon rate

\[ \dot{N}_{\gamma}^{qso} \lesssim \left( \frac{R_b^2}{3} \pi n_c - \frac{N^*_\gamma}{R_b} \right) c (1 + z) \]

• From measured size $R$ and estimate of luminosity $L$
  • Upper limit on quasar life time

\[ t_{on} = \frac{R_b^3}{3} \frac{4 \pi n_c - N^*_\gamma}{\dot{N}_{\gamma}^{qso}} \]
9 June 2014

Infancy

Tell me about your childhood...

Time line

Adulthood

A Schematic Outline of the Cosmic History

- The Big Bang
  - The Universe filled with ionized gas
- The Universe becomes neutral and opaque
- The Dark Ages start
- Galaxies and Quasars begin to form
- The Reionization starts
- The Cosmic Renaissance
  - The Dark Ages end
- Reionization complete, the Universe becomes transparent again
- Galaxies evolve
- The Solar System forms
- Today: Astronomers figure it all out!

S.G. Djorgovski et al. & Digital Media Center, Caltech
The Universe’s childhood

`'Childhood' phases:
1. **Dark ages**: no sources of radiation; Universe neutral.
2. **Cosmic Dawn**: first stars; Universe mostly neutral.
3. **Reionization**: earliest galaxies; neutral hydrogen starts to disappear.

 `'Adolence/adult' phase:
4. **Post-reionization**: galaxies grow, clusters of galaxies form, Universe filled with ionized hydrogen.
Studying the CD/EoR

- Two complementary approaches:

Find the galaxies

Credit: R. Bouwens

HST, Subaru, JWST, E-ELT, etc.

Find the Intergalactic Medium

LOFAR, MWA, PAPER, GMRT, SKA
Combining Existing Constraints

- Current data: WMAP, SPT, QSO, LAEs/LBGs, ...

Mitra et al. (2012)

Robertson et al. (2013)
The Perfect Tool

- Neutral hydrogen has a forbidden, hyperfine transition between the two $1^2s_{1/2}$ ground level states: $21\text{cm}$.

- The measurable signal, differential brightness temperature $\delta T_b$

$$
\approx 28x_{\text{HI}}(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left(1 - \frac{T_{\text{CMB}}(z)}{T_s}\right)\left(\frac{\Omega_b}{0.042}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m}{0.24}\right)^{1/2}
\left(\frac{1 - Y_p}{1 - 0.248}\right)\left(1 + \frac{1}{H(z)\frac{\text{d}v_\parallel}{\text{d}r_\parallel}}\right)^{-1}\text{mK}
$$

- It is found at radio frequencies below 200 MHz.
The 21cm map

- The signal **fills the sky**.

- It has *intrinsic* fluctuations due to
  - Gas density ($\delta$)
  - Ionized regions ($x_{\text{HI}}$)
  - Excitation variations ($T_s$)

- It has *additional observed* fluctuations due to
  - LOS velocity gradient.

Mellema et al. (2012)

$\delta T_b$ 3’ beam
The 21cm image cube

- The signal is *line* emission: due to Doppler shifting it carries spatial, temporal and velocity information.

The image cube: *tomography* of the Universe

Mellema et al. (2006)
Spin Temperature

Populations of the triplet and singlet states of HI follow Boltzmann distribution, with excitation temperature, a.k.a. the spin temperature.

\[ \frac{n_1}{n_0} = 3 \exp\left(\frac{0.068 \text{ K}}{T_s}\right). \]

Processes affecting spin temperature:

- **Collisions** \( (T_s \rightarrow T_k), \ z > 30 \)
- **Radiative**
  - CMB photons \( (T_s \rightarrow T_{\text{CMB}}) \)
  - Ly-\( \alpha \) photons \( (T_s \rightarrow T_{\text{Ly-\( \alpha \)}} \approx T_k) \) ("Wouthuysen-Field effect")

IGM @ EoR: competition between CMB and Ly-\( \alpha \) photons.
Spin Temperature Regions

- Depending on $T_k$ and local Ly-$\alpha$ flux: different regions of 21cm signals in IGM (for $z<30$).

<table>
<thead>
<tr>
<th></th>
<th>Heated IGM</th>
<th>Unheated IGM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ly-$\alpha$ present</td>
<td>$\delta T_b &gt; 0$</td>
<td>$\delta T_b &lt; 0$</td>
</tr>
<tr>
<td>No Ly-$\alpha$ present</td>
<td>$\delta T_b = 0$</td>
<td>$\delta T_b = 0$</td>
</tr>
</tbody>
</table>

Late EoR: $T_{\text{IGM}} > T_{\text{CMB}}$, and Ly-$\alpha$ present: $\delta T_b > 0$
In this case: $\delta T_b$ independent of $T_s$.

Cosmic Dawn: $T_{\text{IGM}} < T_{\text{CMB}}$, and Ly-$\alpha$ present: $\delta T_b < 0$
Fluctuations due to $T_s$ variations.
History of Temperatures

- $T_{\text{CMB}} \propto (1+z)^{-1}$
- $T_{\text{kin,IGM}} \propto (1+z)^{-2}$

Dark Ages
- $z > 90$: collisions couple $T_s$ to $T_{\text{IGM}} (< T_{\text{CMB}}$ for $z < 160$).
- $z \sim 30-50$: collisional coupling weakens, and $T_s$ tends to $T_{\text{CMB}}$ ($z \sim 30-50$).

Cosmic Dawn
- $z < 25$ (?): Coupling to Ly-$\alpha$ drives $T_s$ back to low $T_{\text{IGM}}$ (Wouthuysen-Field effect).

EoR
- $z < 15$ (?): IGM heated (X-rays, shocks) + substantial ionization.
Analysis 21cm Signal

• Statistical:
  • Variance measurements (as function of frequency)
  • Power spectra
  • Redshift space distortions
  • Higher order statistics

• Tomography:
  • Morphologies of HII regions
  • Special objects (QSOs)
  • Special regions (Galaxy surveys)
  • Density fluctuations

• SKA WP CD/EoR: Mellema et al. (2013)
Evolution of Power Spectrum

- Different models (Pritchard & Loeb 2009): many uncertainties.

- Three phases:
  - Ly-α coupling (CD)
  - X-ray heating (CD/EoR)
  - Photo-ionization (EoR)

Intensity Fluctuations

- EoR
- Cosmic Dawn
- Dark Ages

\[ k = 0.1 \text{ Mpc}^{-1} \]
LOFAR EoR Project

• Observing since December 2012.

• Can deliver for $z < 11$:
  • Variance measurements
  • Power spectra
  • Skewness & kurtosis
  • Redshift space distortions (Jensen et al. 2013).

• A statistical HI detection experiment.
  • Smallest scales: ~4’
  • Largest scales: ~5°
LOFAR Precursor EoR studies

North Celestial Pole

Frequency range 115 – 200 MHz

Images with $10^6$:1 dynamic range.

First statistical detection of EoR HI signal (for $z<11$) by end of 2014?
SKA Transformational

- The SKA, even in Phase I, can deliver
  - Power spectra for the *entire Cosmic Dawn/EoR* period (6 < z < 25).
  - *Tomography* at several arcmin scales for the entire EoR (6 < z < 15).
  - Range of scales: ~5’ to ~5° (frequency dependent).

- Will provide the first ever measurements of
  - The heating of the Universe before redshift 10.
  - The earliest star formation in the Universe.
CD/EoR Science

• Astrophysics:
  • Obtaining a census of earliest star formation and galaxies.
  • Mapping the early development of the cosmic web.
  • Analysing the growth of Black Holes.
  • Establishing the effect of radiative feedback on galaxy growth/formation

• Cosmology:
  • Testing the ΛCDM model of the Universe in new regimes.
  • Measuring the statistics of the Universe’s matter distribution.
  • Imposing constraints on the nature of dark matter.
Summary

• The SKA will allow the first observations of
  • The Cosmic Dawn (15 < z < 25)
  • Tomography of the Epoch of Reionization (z < 15) at arcmin scales.

• The redshifted 21cm data is essential for constraining the reionization process.

• Beyond z=10, the 21cm signal is currently the only observable for our Universe!