LOFAR and the Epoch of Reionization

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Overview

- Introduction
- The Astrophysics (Andrea’s Talk)
  - Reionization:
    - What do we know?
    - What do not we know?
- The Physics
  - the 21 cm emission.
  - The spin and brightness temperature.
- The LOFAR-EoR project
  - The measurement
  - The simulations
  - Signal & Systematics.
  - The data products.
- Summary
Introduction

Epoch of Reionization

1st Stars about 400 million yrs.

Quantum Fluctuations

Inflation

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

Afterglow Light Pattern 400,000 yrs.

Big Bang Expansion 13.7 billion years

Credit for picture: WMAP team
What do we know?

- The Lyman-alpha forest: At $z<6$ the Universe is completely ionized.
- The Universe has completed its ionization by redshift 6: SSDS quasars.
- The WMAP polarisation measurement suggest that ionization has happened at about $z \sim 10$. 
What don’t we know?

- When did the reionization happen?
- What are the sources of ionizing radiation? Stars, miniqsos, decaying DM, exotic physics,…
- How fast did it spread and in what fashion?
- How did the reionization influence the subsequent galaxy and structure formation in the Universe?
The physics of the 21 cm transition

- The 21 cm hyperfine transition is a forbidden transition between the two $^1S_{1/2}$ ground level states of hydrogen.
- The relative population of the two states is given by the spin temp. $T_s$, i.e.,
  \[ \frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{T^*}{T_s}\right) \]  with $T^* = 0.068$ k
- The value of the spin temp. is given by the following equation:
  \[ T_s = \frac{T_{CMB} + \gamma_c T_K + \gamma_\alpha T_K}{1 + \gamma_c + \gamma_\alpha} \]

Field 1958
Lyman-alpha Coupling

- The Wouthuysen-Field effect, also known as Lyman-alpha pumping.

Dominant in both in the case of stars and Black-holes, due to photo and collisional excitations, respectively.
Collisional Coupling

- H-H collisions that excite the 21 cm transition. This interaction proceeds through electron exchange.
- H-e collisions. Especially important around primordial X-ray sources (mini-quasars).
  - This effect might also excite Lyman-alpha transition which adds to the $T_s - T_{CMB}$ decoupling efficiency.

Chuzhoy et al. 06
Zaroubi et al. 06
The Global evolution of the Spin Temperature

At $z \sim 10$ $T_s$ is tightly coupled to $T_{CMB}$. In order to observe the 21 cm radiation decoupling must occur.

Loeb & Zaldarriaga 04
The brightness temperature: The measured quantity

- The quantity that is measured with radio telescopes along a given line of sight and is given by:

\[
\delta T_b(l,b,v) \approx 28 \text{mK} \ (1+\delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{1/2}
\]

- The sources that ionize are probably the same as the ones that decouple

Field 1958
Possible ionization sources

The first stars

Form favourably very massive stars very early on.

- First stars are different creatures from the ones we see in the local universe (no metals).
- Atomic cooling is efficient in halos with \(T_{\text{vir}} > 10^4 \text{K}\) (~\(10^9 \text{M}_{\odot}\)). At smaller masses \(\text{H}_2\) cooling probably produces very massive stars.
- Efficiency of producing stars!! In our environment the main question is why star formation is so inefficient.
Simulations

- Most simulations assume stellar ionization sources.

Ciardi & Ferrara.
Gnedin
Mellema et al.
Khan et al.
and many others

Iliev et al. 07
Possible decoupling sources

The first massive black holes

Quasars with black-hole masses of $\sim10^9 M_{\text{sun}}$ are seen at $z\sim6.7$

BHs with intermediate masses ($10^3-6 M_{\text{sun}}$) could ionize the Universe and heat it up.

Thomas & Zaroubi 07
Decoupling through Miniquasars X-ray radiation

• The X-ray radiation from miniqsos results in $T_s - T_{CMB}$ decoupling through collision heating and excitation.

• Since the mean free path of X-ray photons is quite large, the spin temperature will have different properties relative to that around stars.

Kuhlen, Madau & Montgomery 06
Zaroubi, Thomas, Sugiyama Silk. 2006
The Brightness temp. Around a single miniqso

\[ M_{BH} = 50 - 10^4 M_\odot \]
LOFAR – The Instrument & Relevant Requirements for the EoR KSP

- Frequency range: 115 – 205 MHz (30MHz settings of 195 subbands)

- Spectral resolution: 1 KHz within sub-band (RFI excision)
  10 KHz for storage (dt=10 sec)
  100 KHz for analysis

- HBA station: 96 tiles (4x4 dua pol. dipoles)
  40-50 m diameter station

- Sensitivity: rms=300 mK after 3 hrs (core; ΔΘ~3-5')
  (Δv=1MHz) rms= 30 mK after 300 hrs.
The EoR key project: Scientific goals

- The plan is to statistically measure the EoR signal and as the data collection proceeds to refine our measurement and produce a full power spectrum and eventually maps.
- High order statistics
- The environment of very high z quasars.
- Cross correlate with other data sets:
  - CMB (Planck data).
  - Lyman-alpha emitters.
  - Other complementary data.
- The 21 cm forest (if a strong enough background source is found).
Neutral IGM

“Dark Ages”

First UV sources

Proto-galaxies

Galaxies

Faint radio-loud quasars

Clusters

Galactic synchrotron emission

LOFAR
The Ionosphere and the calibration problem

Wedge Effects: Faraday rotation, refraction, absorption below 5 MHz

Wave and Turbulence Effects: Rapid phase winding, differential refraction, source distortion, scintillations
Dynamic ionospheric phase-screen mapping: 
--> 2-D phase \textit{screen}
The ionosphere

Simulations by
O. Smirnov
The UV Coverage

uv coverage at zenith, 12 hrs int.
The foregrounds

- **galactic synchrotron emission** (~70%)
- **galactic thermal (free-free) emission** (~1%)
- **integrated emission from extragalac. Sources** (~27%)
  - radio sources/AGNs, clusters

Shaver at al., di Matteo et al., Santos et al.
Simulating the data

Foregrounds + ionosphere + Instrument

\[ \sim P(s) \times 10^4 \]

Thomas et al. 07
The Measurement Equation

\[
\vec{V}_{ij}(u,v) = \sum_k \int df \int dt \left( J_{ik} \otimes J_{jk}^* \right) S \, \vec{I}_k
\]

- Hamaker-Bregman-Sault formalism
- Station-pair (i,j): Vector of 4 ‘correlations’
- Matrix equation: full polarization
- Instrumental Jones matrices J (2x2)
- Stokes matrix S (4x4)
- Sum over sources (k): Flux [I,Q,U,V]
- Integral over time-freq domain

See Panos’ Talk
For more detail
Measurement

- **Sensitivity**
  - about $0.15 \text{k}$ for 1 hour integration at 120 MHz

- **Data Model**
  \[ \Delta T^N = \frac{1}{\eta_e} \frac{T_{\text{sys}}}{\sqrt{\Delta \nu t_{\text{int}}}} \]

\[ R_k = A_k B A_k^+ + \sigma^2 I \]

- $B$ is the brightness vector.
- $A$ is the response
- $\sigma$ is the noise
Data Simulation Pipeline

Data³

Signal Extraction
Tomography of the Reionization Process: What will we learn?

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<th>The dark ages: Fluctuations PS at $z \sim 10$. (Non)-Gaussianity, Universe’s Geometry (AP test).</th>
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<td>During</td>
<td>- First objects and their properties.</td>
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<td>- How fast and in what fashion did reionization spread.</td>
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<td>Post</td>
<td>Influence on subsequent galaxy and structure formation in the Universe.</td>
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