The 21cm probe of Cosmology

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What is the 21cm line

ground state hydrogen atom

Redshifted to 21(1+z) cm

observe w.r.t. radio background: spin temperature

\[
\frac{n_1}{n_0} = 3e^{-\Delta E/k_BT_s} = 3e^{-T_\ast/T_s}
\]

\[
T_s = \frac{T_{CMB} + y_\alpha T_\alpha + y_c T_k}{1 + y_\alpha + y_c}
\]
Why 21cm observation

Ubiquitous: 76% of baryons

The observable Universe in comoving scale

A different perspective

mass relation

Tully-Fisher

Q. Guo et al. (2019), Nature Astronomy
The optical depth of a line passing along X direction
\[ z = 10.1592 \]
\[ Y = 227, Z = 473 \]
Foreground

raw signal to noise ration (SNR) \( \sim 10^{-5} \)

In principle, smooth foreground can be subtracted

V. Jelic et al. (2010)

X. Wang et al. (2006)
Cosmic Dark Ages

Loeb & Zaldarriaga 2004

But:

- The signal is redshifted to very low frequencies, ionosphere absorption—may need to observe from the farside of the moon

- Very strong galactic foreground, need extremely large array to achieve enough sensitivity

- First Step: global signal (DSL, DAPPER)

Barkana & Loeb 2005

\[ N_{21cm} \sim 3 \times 10^{16} \left( \frac{l_{\text{max}}}{10^6} \right)^3 \left( \frac{\Delta \nu}{\nu} \right)(z/100)^{-1/2} \]
Cosmic Dawn

Reionization signal—Emission

Cosmic Dawn signal—Absorption
(XC& J. Miralda-Escude 2003, 2008)

Figure by K. Ahn et al.

Cohen et al. 2017
Model of Reionization

Bubble Model (Furlanetto, Hernquist, Zaldarriaga 2004):

- higher density → form more galaxies earlier
- ionize earlier → produce more ionizing photons

#photon needed = #photon produced

#photon needed = \( n_B V (1+n_{\text{rec}}) \)

#photon produced = \( \xi n_B V f_{\text{coll}} \)
Late Stage of EoR

- Overlapping bubbles—no longer isolated!
- Ionization equation: \#photons = local produced + background

\[
\xi f_{\text{col}}(\delta_M; M, z) + \frac{\Omega_m}{\Omega_b} \frac{\mathcal{N}_{\text{back}} m_H}{M X_H (1 + \bar{n}_{\text{rec}})} < 1,
\]
Stages of Reionization

Based on Minkowski functionals (Chen et al. 2018)

- Ionized Bubble Stage ($x_{HI} > 0.9$)
- Ionized Fiber Stage ($0.9 > x_{HI} > 0.7$)
- Sponge Stage ($0.7 > x_{HI} > 0.3$)
- Neutral Fiber ($0.3 > x_{HI} > 0.16$)
- Neutral Island Stage ($x_{HI} < 0.16$)

Broadly Consistent with Furlanetto & Oh (2016), Yoshiura et al. (2016), Bag et al. (2018)
Reionization

blue: largest ionized region
red: other ionized region
transparent: neutral

from bubble to fiber

From ionized fiber to sponge

blue: largest neutral region
red: other neutral regions
transparent: ionized

neutral island

neutral fiber
**Power spectrum and Bias**

neutral fraction cross power

![Graph showing power spectrum for neutral fraction](image1)

21cm cross power

![Graph showing power spectrum for 21cm cross power](image2)

**Figure 4.** The cross-power spectrum between the neutral fraction and the dark matter density. The solid and the dashed lines represent positive and negative values respectively.

**Figure 5.** The 21 cm brightness temperature and the dark matter density cross power spectrum. Top panel: early BoR, Bottom panel: late BoR. Solid and dashed lines represent positive and negative values respectively.

The density and neutral fraction anti-correlated on large scales

W. Xu et al. (2019)
The Reality: Mode Mixing foregrounds

Data = Instrument Response ✽ Sky + Noise

• The Instrument Response is **frequency dependent** (chromatic beam)
• The Instrument Response is **not smooth** (sidelobe, standing wave, ...)
• Instrument Response only known up to the precision of calibration (polarization leakage and cross-coupling between array elements, Faraday rotation of the polarization, ...)

Nevertheless, people hope to detect the cosmological 21cm signal!
Foreground Subtraction

Data covariance matrix:

\[ C_{\mu \mu'} = \langle T_x(\mu)T_x(\mu') \rangle_x \]

PCA analysis:

\[ C = TT^\dagger \]
\[ Cv_i = \lambda_i v_i \]

Example: GBT (Masui et al. 2013)

Other foreground subtraction methods developed, e.g. ICA (L. Wolz), RPCA (Zuo et al.)
Power Spectra compensation

$$P_{SVD}(k) = T(k)P(k)$$

$$T(k) = \left( \frac{[w_A\Pi_{A+s}(T_A + T_s) - W_A\Pi_A T_A]^T Q_i T_s}{(w_AT_s)^T Q_i T_A} \right)^2$$

cross correlation with WiggleZ (Masui et al 2013)

auto correlation (Switzer et al. 2013)
EoR tomography Experiments

LOFAR

21CMA

PAPER

MWA
EoR 21cm experiments

HERA: 350 x 14m dish, measure the 3D 21cm power spectrum. Regular grid, redundant baseline calibration

SKA-low: 512 x 256 dipole, randomized uv coverage, imaging EoR region
EoR power spectrum

N. Barry et al. arxiv:1909.00561

Beardsley et al. arxiv:1910.02895
Global Spectrum Experiments

EDGES
SCI-HI/PRIZM
BIGHORN
SARAS-2
LEDA
REACH
DSL
How to achieve Precision Calibration

- Internal Calibration
- sky calibration: galaxy up down
EDGES-low result
Interpretation of the Result

The absorption observed by EDGES is much stronger than typical model, even stronger than maximum case!

\[ T_{21}(z) \approx 0.023 \, \text{K} \times x_{\text{Hi}}(z) \left( \frac{0.15}{\Omega_m} \right) \left( \frac{1 + z}{10} \right)^{\frac{1}{2}} \left( \frac{\Omega_b h}{0.02} \right) \left[ 1 - \frac{T_R(z)}{T_S(z)} \right] \]

- foreground contamination (Hills et al. 2018)
- unknown systematics: e.g. underground water reflection, ionosphere
- colder baryons (cooled by interacting dark matter, \( T_S < 3.2 \, \text{K} \))
- extra-radio background \( T_R > 104 \, \text{K} \)
Excess Radio Background

• Maybe in the cosmic dawn, in addition to CMB, there is a radio background generated by early sources AGN, pop star, ... (Ewall-Wice et al. 2018)

• Must be very radio loud (Mirocha & Furlanetto 2018) but at high-z, inverse-Compton stronger, the main radio mechanism-synchrotron likely to be comparatively weaker (Sharma 2018)

• Constrained by reionization redshift, radio and X-ray source count, ...

• If global signal enhanced, fluctuation signal is also strong
Dark Matter Cooling

- DM is cooler than baryon as it decoupled earlier, but need baryon-DM interaction, temperature (energy) dependent, e.g. Coloumb interaction

\[ \sigma(v) = \sigma_c \left( \frac{v}{c} \right)^{-4} = \sigma_1 \left( \frac{v}{1 \text{ km s}^{-1}} \right)^{-4} \]

- Severely constrained by various experiments

Barkana 2018

Berlin et al. 2018
Other Ideas

• Baryonic Universe + MOND (S. McGaugh)

• Early baryon decoupling (so it is colder) by an early dark energy (Hill & Haxter)

• Modify early Hubble parameter by Interacting dark energy (A. Costa et al.)

• Dark photon mixing (M. Pospelov et al.)

• axion Bose-Einstein condensation cooling (Houston et al. 2018)

• Dark matter decay to radio (Fraser et al.)

• Dark matter annihilation to radio (Yang)

• Dark force (Li & Cai)
Space Experiment

Ionosphere refraction and absorption also affects global spectrum.
Space-based low frequency radio observation

- Below 10MHz, due to ionosphere absorption, ground observation is nearly impossible.

Planck map

RAE-2 sky map (1979)
Experiments during CE-4 mission

- CE-4 Lander

- Netherland-China Low frequency Experiment (Relay Satellite)

- Longjiang orbiting satellites (piggy-back on relay satellite launch)—unfortunately, Longjiang-1 malfunctioned

- EMI limited sensitivity, and also work time is very short due to limited power, but still can see moon shield radiation from Earth
Discovering Sky at Longest (DSL) wavelength

- A linear array (5-8) of satellites moving around the moon, take observation at the backside of the moon, then transmit data back at the front side of the moon.

- A mother satellite measure the position of the daughter satellites

- Low frequency aims for imaging of foregrounds, high frequency aims to detect cosmic dawn signal by precise global spectrum measurement
Current mid-redshift Radio Telescopes

- Parkes (64m)
- GBT (105m)
- Arecibo (150m)
- FAST (500m)
- JVLA (27 dish)
- GMRT (27 dish)
- ASKAP (36 dish)
- MeerKAT (64 dish)
FAST survey

Wenkai Hu et al., Forecast for FAST: from Galaxies Survey to Intensity Mapping", arxiv:1909.10946

<table>
<thead>
<tr>
<th>receiver</th>
<th>band(GHz)</th>
<th>Beams</th>
<th>$T_{rec}(K)$</th>
<th>$t_{mw}$(days)</th>
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<tbody>
<tr>
<td>L-band</td>
<td>1.05-1.45</td>
<td>19</td>
<td>20</td>
<td>220</td>
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<tr>
<td>Wide-band</td>
<td>0.27-1.62</td>
<td>1</td>
<td>60</td>
<td>1211</td>
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<tr>
<td>UHFF PAF (future)</td>
<td>0.5-1.0</td>
<td>81</td>
<td>30</td>
<td>135</td>
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</tbody>
</table>

$$\theta = 1.22 \times \frac{21 \text{ cm}(1+z)}{300 \text{ m}} = 2.94(1+z) \text{ arcmin}$$

L-band beams

number density of detected galaxies

DETFF Figure of merit
Dedicated Experiments

• Stable, large field of view (also good FRB searcher)

\[
\frac{S}{N} = \sqrt{\frac{4\pi k^2 dk V_{\text{survey}}}{2(2\pi)^3}} \frac{P_{\text{HI}}}{P_{\text{HI}} + \left(\frac{dT_{\text{sky}} + T_a}{\sigma T_{\text{sig}} \sqrt{\text{int} \Delta f}}\right)^2 V_R + \frac{1}{n}},
\]
The Tianlai (heavenly sound) Experiment

- Cylinder pathfinder: 3x15m x 40m, 96 feeds
- Dish Pathfinder: 16 x 6m

Frequency: 700-800MHz, can be tuned in 600~1420MHz
probe of Large Scale Structure (BAO, PNG, inflation features)

Xu, Wang & Chen (2015)

Xu, Hamann, Chen (2016)
21cm Intensity Mapping Experiments

CHIME (1024 units)

Tianlai (96 units)

HIRAX (1024 units)

BINGO
Near Future: SKA-mid

SKA-1: 197 dish (15m) + 64 MeerKAT dish

SKA-2: ~ 3000 dish
Intensity Mapping
BAO measurements

BAO scales probed by SKA1 – dish versus interferometer

SKA Cosmology Workgroup (http://skacosmology.pbworks.com)
Future Ideas: PUMA

200 \sim 1100\text{MHz}, \ 6\text{m dish}, \ 10^4 \text{ elements}

Slosar et al., arxiv:1907.12559
Outlook

• 21cm experiments are easy (to start) and hard (to detect!)—lots of experiment efforts going on

• Varies approaches: global spectrum, single dish, regular and irregular interferometer arrays

• New and more powerful data analysis method: AI?

• The 21cm auto-correlation is still to be detected, but progresses are being made

• The 21cm cosmology is coming!
Thanks and Enjoy!
Backup slides
Problems with Lunar Array

Traditional imaging algorithm can not work!

- short dipole ($l \ll \lambda$) antenna have very wide field of view (almost whole sky), traditional synthesis algorithm only for small field of view (flat sky, small $w$-term)

- A mirror symmetry w.r.t. orbital plane, can be broken by 3D baselines (produced by orbital plane precession)

- Different baselines have different part of sky blocked by Moon

map-making by inversion

$$V = BT + n.$$  $$T = (B^\dagger N^{-1}B)^{-1}B^\dagger N^{-1}V \equiv B^{-1}V.$$  

Huang et al., arXiv:1805.08259
galaxy detection vs intensity mapping


$L_{SN}$: luminosity scale for voxel shot noise  
$\sigma_L$: rms noise per voxel  
$l_*$: galaxy characteristic luminosity.

<table>
<thead>
<tr>
<th>number</th>
<th>regime</th>
<th>optimal strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$L_{SN} &lt; \sigma_L &lt; l_*$</td>
<td>galaxy detection</td>
</tr>
<tr>
<td>2</td>
<td>$\sigma_L &lt; L_{SN} &lt; l_*$</td>
<td>galaxy detection/intensity mapping$^{a}$</td>
</tr>
<tr>
<td>3</td>
<td>$L_{SN} &lt; l_* &lt; \sigma_L$</td>
<td>intensity mapping</td>
</tr>
<tr>
<td>4</td>
<td>$l_* &lt; L_{SN}$</td>
<td>intensity mapping</td>
</tr>
</tbody>
</table>

$^{a}$ Here the optimal strategy is an intermediate between the intensity mapping and galaxy detection observables.

$$\sigma_{SN}^2(l) = V_{\text{vox}} \phi_* \int_0^l dl' l'^{\alpha+2} e^{-l'}.$$