Cosmic dawn and Epoch of Reionization with 21cm line

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Galaxy-IGM workshop (08/08/2018, Tsukuba)
Contents

• Introduction of cosmic dawn and reionization

• 21cm signal

• Observations of 21cm signal
**Dark Ages** • • • No luminous object exists. (z>~30?)

**Cosmic Dawn** • • • First stars and galaxies form. (z~20-30?)

**Reionization** • • • UV photons by luminous objects ionize IGM. (z~6-15?)
**History of the Universe**

**Dark Ages**
- No luminous object exists. ($z > \sim 30$?)

**Cosmic Dawn**
- First stars and galaxies form. ($z \sim 20-30$?)

**Reionization**
- UV photons by luminous objects ionize IGM. ($z \sim 6-15$?)
Hierarchical formation of first stars

\(\Lambda\)-CDM cosmology

- Primordial density fluctuations
- Growth of fluctuations
- Dark matter halo

Baryon (gas) physics

- Molecular gas cloud
- Protostellar core
- First stars (Pop III)

(Hirano et al 2014)
Cosmic Dawn

After first luminous objects (first stars, galaxies, black holes) had formed • • •

IGM is • • •

• heated

Ross et al (2016)

• (re) ionized

Physics of IGM heating

The time evolution of gas temperature

\[
\frac{dT_K}{dt} = -2HT_K + \frac{2}{3k_B} \sum_j \frac{\epsilon_j}{n}
\]

adiabatic cooling of the gas

\[ \epsilon_j : \text{heating rate for the process } j \]

IGM heating is mainly driven by X-ray sources (X-ray binaries, supernovae remnant and so on).
Physics of reionization

Simple analytic reionization model

Barkana & Loeb (2001)

\[
\frac{dQ_{\text{HII}}}{dt} = \frac{1}{n_0^0} \dot{n}_{\text{ion}}^\gamma f_{\text{esc,ion}} - \alpha_B C (1 + z)^3 n_0^0 Q_{\text{HII}}
\]

**Ionizing** vs. **Recombination**

- $Q_{\text{HII}}$: volume fraction of HII
- $n_0^0$: hydrogen number density
- $\dot{n}_{\text{ion}}^\gamma$: ionising photon number density
- $f_{\text{esc,ion}}$: escape fraction of ionising photon
- $\alpha_B$: case B recombination rate
- $C$: clumping factor
What do we want to know?

- When did first generation objects (e.g., first star, black hole) form?
- What are the properties of first generation objects (e.g., IMF of first stars, SED of X-ray sources)?
- What is the environment of first galaxies (e.g., escape fraction)?
- When did reionization start?
- What is the main source of heating and reionization of the IGM?
- How do ionised regions evolve?

...etc
Current observations tell us

- Ly alpha emitter galaxies
- Ly alpha forest
- CMB-electron Thomson scattering

Konno et al (2014)

QSO cloud

(http://pages.astronomy.ua.edu/keel/agn/forest.html)
Current observations tell us

ionisation history

(Greig et al 2017)
How do we observe IGM at the EoR and cosmic dawn beyond current limits?
21cm line radiation: Neutral hydrogen emits the radiation due to the hyperfine structure.

$\Delta E = 5.9 \times 10^{-6}$ eV

$z=6 \rightarrow 202 \text{ MHz}$

$z=20 \rightarrow 68 \text{ MHz}$

We can observe the distribution of neutral hydrogen atom in the IGM at the EoR and cosmic dawn as 3D tomography.
Spin temperature

\[
\frac{n_{\uparrow\downarrow}}{n_{\uparrow\downarrow}} = 3 \exp \left(- \frac{h\nu_{21\text{cm}}}{kT_S} \right) \quad \Rightarrow \quad T_S^{-1} = \frac{T_{\text{CMB}}^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}
\]

Spin temperature is determined by

- interaction with **CMB photons** \((T_{\text{CMB}})\)
- collision with **hydrogen atom** \((T_K, x_c)\)
- interaction with **Ly-alpha photons** \((T_c \sim T_K, x_\alpha)\)

Relevant astrophysics

- X-ray sources
- Properties of PopIII (II) star.
Spin temperature

Spin temperature includes astrophysical information

- Interaction with CMB photons ($T_{\text{CMB}}$)
- Collision with hydrogen atom ($T_K$, $x_c$)
- Interaction with Ly-alpha photons ($T_c \sim T_K$, $x_\alpha$)

Spin temperature is determined by:

\[ n_{\uparrow\uparrow} = 3 \exp \left( -\frac{h\nu_{21\text{cm}}}{kT} \right) \]

\[ T_a^{-1} = \frac{T_{\text{CMB}}^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{T_{\text{CMB}} + x_c T_K + x_\alpha T_c} \]

X-ray sources

Properties of PopIII (II) star.
Wouthuysen-Field (WF) effect

Ly-alpha photon excites the 21cm line via transitions involving n=2 level

Solid line $\rightarrow$ Change spin state

Dashed line $\rightarrow$ Not change spin state

WF effect is related to $\mathcal{X}_\alpha$
We actually observe brightness temperature, not spin temperature.

\[ T_\gamma > 0 : \text{emission} \]
\[ < 0 : \text{absorption} \]
against CMB

\[ \delta T_b = \frac{T_S - T_\gamma}{1 + z} (1 - \exp(-\tau_\nu)) \]
\[ \sim 27x_H(1 + \delta_m) \left( \frac{H}{dv_r/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_m h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) [\text{mK}] \]
Brightness temperature

\[ \delta T_b = \frac{T_S - T_\gamma}{1 + z} (1 - \exp(-\tau_\nu)) \]

\[ \sim 27x_H (1 + \delta_m) \left( \frac{H}{dv_r/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_m h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) [mK] \]

Red: cosmology  Blue: astrophysics

Brightness temperature has characteristic peaks and troughs according to key epochs
We can see bubble topology with time evolution by 21cm imaging.

See bubble with other telescopes (ALMA, Subaru, JWST etc)
Imaging with 21cm line

Required specification for imaging

⊙ ∼ a few arc-minutes resolution  ⊙ ∼ a few degree FoV
21cm power spectrum

We first aim to detect 21cm signal statistically.

21cm power spectrum (PS) : \( \langle \delta T_b(k) \delta T_b(k') \rangle = (2\pi)^3 \delta(k + k')P_{21} \)

Pober et al (2014)
Statistical challenge

Cosmology

CMB map  \rightarrow (\text{angular}) \text{ power spectrum}  \rightarrow \text{cosmological parameter}

21cm

21cm 3D map  \rightarrow 21cm \text{ power spectrum}  \rightarrow \text{astrophysical parameter}

(Mesinger 2018)
Machine learning with 21cm signal

Recently, some works have focused on Artificial Neural Networks (ANNs) with 21cm signal analysis.

- Emulate 21cm power spectrum (Kern et al 2017, Schmit et al 2018)
- We can quickly perform MCMC calculation.
- Parameter estimate (Shimabukuro et al 2017, Gillet et al 2018)

21cm signal $\rightarrow$ EoR parameters

Shimabukuro et al (2017)
How do we detect 21cm signal?
The measurement by radio interferometer is based on **time delay** between antennae.

We actually measure

- "Visibility"
- Fourier transform
- "Brightness temperature"
The measurement by radio interferometer is based on time delay between antennae.

Resolution

$$\theta = \frac{\lambda}{D}$$

Sensitivity

(effective collecting area)  
(thermal noise)
Current observations

- **MWA** (Australia)
  - $z=6-11.4$
  - Resolution: 2 arcmin
  - Array diameter: $\sim 3$ km
  - Effective collecting area: 3500 m$^2$

- **LOFAR** (Netherlands)
  - $z=7-12$
  - Resolution: 3 arcmin
  - Array diameter: $\sim 2$ km (core)
  - Effective collecting area: 18000 m$^2$

- **PAPER** (South Africa, USA)
  - $z=7-12$
  - Resolution: 30 arcmin
  - Array diameter: $\sim 200$ m
  - Effective collecting area: 1100 m$^2$
Current upper limits on 21cm PS

\[ k \sim 0.2 \text{Mpc}^{-1} \]
SKA

- **SKA** (Australia)
- $z=6-28$
- Resolution: $\sim 7$ arcsec
- Array diameter: $\sim 80\text{ km}$
- Effective collecting area: $\sim 300'000 \text{ m}^2$

*High resolution & High sensitivity*
Redshift evolution

Scale dependence

z = 8.95

Koopmans et al. (2014)

z = 15.98

Pritchard et al. (2014)

SKA covers wide epoch and range of the 21cm PS!!
We did it?

EDGES (Bouman et al 2018)

Too deep trough

flatten trough
We did it?

Did we detect the 21cm global signal?

EDGES (Bouman et al 2018)

Exotic physics?

Foreground?

Systematic error?

Did we detect the 21cm global signal?
We need to wait for other experiment results, but....
We need to wait for other experiment results, but....

The era of 21cm cosmology is around the corner!
References

• SKA science books (https://www.skatelescope.org/books/)

• SKA-JAPAN science book (in JAPANESE) (http://ska-jp.org/science.html)

• Japanese Cosmic Dawn/Epoch of Reionization Science with the Square Kilometre Array (arxiv:1603.01961)
Summary

• Cosmic dawn and EoR are milestones of the Universe.

• The 21cm signal will open the window and give fruitful information on cosmic dawn and EoR.

• Some on-going and future observations target to detect 21cm signal.
Backup
Spin temperature

![Graph showing spin temperature as a function of Z with different temperature scales on the y-axis.]
Component of 21cm PS

\[ \Delta_{21}(k) [\text{mK}^2] \]

\[ k = 0.13 \text{Mpc}^{-1} \]