The Epoch of Reionization

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“We know more about recombination than about reionization, but it forms the foundation of the present-day Universe.”
Why Study the Universe’s First Gyr?

**Dark Ages**
- DM power-spectrum evolution
- DM annihilation physics
- Baryonic Bulk Flows
- Physics of Gravity/GR

**Cosmic Dawn**
- Appearance of first stars/BHs (PopIII?)
- Ly-\(\alpha\) radiation field
- Impact of Baryonic Bulk Flows
- First X-ray heating sources

**Reionization**
- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Galaxy formation/ Emergence of the visible universe

**Post-Reionization**
- BAO - DE EoS/Gravity
- Intensity Mapping - DE EoS/Gravity
- Galaxy Counts - Mass function ++
Mounting Evidence for Reionization

The last decade has witnessed an enormous growth in observational evidence for reionization happening rapidly at relatively low redshifts (z<10) thanks so many new instrument (HST-WFC, WMAP/Planck, Subaru-HSC, ALMA, etc.).

But the hydrogen itself has not yet been detected … or has it?
Some Selected Observations of the CD/EoR

Observations by Planck (2018) suggest a low Thomson optical depth and hence a low electron density: i.e. the bulk of reionization occurs at low redshifts ($z \sim 8$) when the volume of the Universe was already larger.
Lyman alpha emitters seem to quickly decrease in number density at $z>7$, possibly suggesting that the neutral HI density is increasing and ionised bubbles around these galaxies are small.

No continuum but strong narrow-band emission at $z\sim7.3$
Some Selected Observations of the CD/EoR

High redshift QSO’s (rare) also suggest a high neutral fraction $>0.27$ (2-sigma) at $z=7.5$. 

Banados et al. 2017
A plethora of galaxies (some lensed) in the EoR are becoming available up to $z \sim 11^+$. Largely thanks to drop-out techniques in the IR (e.g. using HST).
Summary of Current Constraints on the CD/EoR

• Scattering optical depths from CMB observations
  Ionised medium causes CMB polarisation: $z_{eor} \sim 8$ (latest Planck results!)

• High-z galaxies/Ly-alpha emitters
  IR drop-outs give SFR/LF to $z \sim 10$: SFR rises fast below $z \sim 10$ but there are not enough UV photons to reionize the Universe
  Ly-alpha emitters seem to drop out already at $z > 7$.

• High-z QSOs
  Gunn-Peterson troughs suggest $>30\%$ neutral HI at $z \sim 7.5$, i.e. the end of reionization occurs close to the highest $z$ QSO/galaxies that we observe

• High-z GRBs
  GRBs traces massive star formation. Currently rare events, but $z \sim 8.2$ GRB has been seen and could be a direct tracer of the SFR.

• Temperature of the IGM
  Extrapolation of the high-z IGM temperature suggest late reionization

• NIR/X-ray backgrounds
  Detection of NIR fluctuations made, but far above predictions.
  X-rays limit AGN contribution to reionization to $\sim 10\%$ max.

• Discovery of the global 21-cm signal from Cosmic Dawn (EDGES2) in 2018 ???
The 21-cm Signal of Neutral Hydrogen

Most evidence points at substantial reionization occurring at $z<10$, being halfway around $z\sim8$ and ending around $z\sim6$.

But the details are largely unknown: a complementary tracer is needed that is volume filling and actually traces what is being ionised and what forms stars/galaxies (i.e. hydrogen itself)
The quantity that is measured with radio telescopes along a given line of sight is given by:

$$\delta T_b = \frac{T_S - T_R}{1 + z} (1 - e^{-\tau_{\nu}})$$

$$\approx \frac{T_S - T_R}{1 + z} \tau$$

$$\approx 27 x_{HI} (1 + \delta_b) \left( \frac{\Omega_b h^2}{0.023} \right) \left( \frac{0.15}{\Omega_m h^2} \right) \left( \frac{1 + z}{10} \right)^{1/2} \times \left( \frac{T_S - T_R}{T_S} \right) \left[ \frac{\partial_{\tau} u_{\tau}}{(1 + z) H(z)} \right] \text{mK},$$

Hydrogen Brightness Temperature

The HI 21-cm intensity is set by a complex interplay between cosmology and (g)astrophysics.

cosmology and (g)astrophysics.
Studying HI Through Cosmic Time

The tomography of HI emission is a treasure trove of information for (astro)physics, cosmology & fundamental physics.

Post-Reionization
HI is found largely in galaxies

Dark Ages/Cosmic Dawn/Reionization
HI has a filling factor of order unity

Credit: Dixon, Illiev et al.
Hydrogen Brightness Temperature

There are (currently) three different ways to analyse the 21-cm signal, each being pursued (or will be):

- **Globally-averaged 21-cm signal**
  - Cheap and fast, using single (auto-correlation) di-/tripole- receivers.
  - Loss of all spatial information but retains spectral/redshift information
  - EDGES, SARAS, LEDA, SCI-HI/PRI²M, BIGHORNS, NCLE, DARE, …

- **Spatial/spectral 21-cm signal intensity fluctuations:**
  - Expensive, using multiple (cross-correlation) receivers (needs large $A_{\text{eff}}$/FoV)
  - Power-spectra, bi-spectra, moments, etc.
  - LOFAR/AARTFAAC, MWA, PAPER, GMRT, LEDA, NenuFar, HERA, SKA, …

- **Tomography/Imaging**
  - Retains all information (if above the noise)
  - SKA (on few to tens of arcmin scales), HERA (on degree scales)
Hydrogen Brightness Temperature
Global Signal

The history of $T_b$ can vary; hence measuring $T_b$ as function of redshift/time, provides a handle on star formation, Ly-α coupling, (X-ray) heating, etc.
Hydrogen Brightness Temperature
Power-Spectrum

Intensity Fluctuations

Sensitivity limits are scale dependent but $\Delta^2_{\text{noise}} \sim \text{few mK}^2$ is where current instruments aim for in $\sim 1000$ hrs. SKA can go to $\Delta^2_{\text{noise}} \sim 0.1$ mK$^2$. 

\begin{align*}
z &= 242.62 \\
\langle x_{\text{HI}} \rangle_v &= 1 \\
\langle \delta T_b \rangle_v &= -16.6 \times 10^{2}
\end{align*}
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Global 21-cm Signal Experiments

Some exciting new results… Remember the year 2018!
Current Global 21-cm Signal Experiments

**Claimed detection (needs confirmation)**

**EDGES**
- Specs: 50-100, 100-200 MHz (left, right)
- Location: Western Australia
  - Rogers & Bowman 2008, 2012; Bowman et al 2018

**SARAS**
- Specs: 50-100, 100-200 MHz (right, left)
- Location: India (Timbaktu/ Himalayas)
  - Singh et al. 2017

**LEDAs @ OVRO-LWA**
- Specs: 30-88 MHz
- Location: OVRO/California, US
  - Bernardi et al. 2016; Price et al. 2018

**NCLE**
- Specs: 0.08-80 MHz
- Location: L2/Behind Moon
  - https://www.isispaces.nl/projects/ncle/
Current Global 21-cm Signal Experiments

BIGHORNS
Specs
- ~10-480 MHz, ~10-300 MHz (left, right)
- Western Australia
  Sokolowski et al. 2015

SCI-HI
Specs:
- 40-130 MHz
  - Isla Guadalupe, Mexico
  Peterson et al. 2014

PRIZM
Specs:
- 30-200 MHz
  - Marion Island, SA
  Peterson, Sievers, Chiang ++

DARE (cancelled)
Specs:
- 40-120 MHz
  - Lunar orbit, 125km above lunar surface
  Burns et al. 2017
In 2018 a detection of the global 21-cm signal of neutral hydrogen seen against the CMB was detected. But signal is too deep and too flat!

Bowman et al. 2018
This result has generated an enormous interest. However, if true it requires some exotic physics such as the cooling of baryons by scattering off dark matter to explain the depth of the signal (-600mK).
EDGES2

But!! The signal however can be explained by many combinations of smooth foreground models and “21-cm signals” some clearly not physical.

EDGES2 results needs confirmation by an independent instrument (e.g. SARAS3)
EDGES2 results motivated the 1000-hr ACE program (PIs: Koopmans & Gehlot) with LOFAR-LBA using AARTFAAC correlator (PI: R. Wijers, UvA, NL).

AARTFAAC correlates all 576 receivers (dipoles or tiles) of LOFAR LBA/HBA at once over a ~3MHz BW.
Netherlands China
Low-Frequency Explorer (NCLE)

Piggy-backing on to the Chines Chang’e 4 lunar lander mission…
Probing the Cosmic Dawn and the Dark Ages.
Netherlands China Low-frequency Explorer

Tripole (5m) receivers on relay satellite; 0.08 - 80 MHz;
Sub-optimal (next to satellite) but very(!) cheap

Onboard Chang’e4 Queqiao relay satellite at Earth-Moon L2
(first part of Chinese lunar far-side lander/rover mission)
If EDGES2 result is correct and also Dark Ages 21-cm signal is -600mK, then NCLE could detect this in ~1 week (>6-sigma level per MHz BW). For the nominal (-60mK) signal it requires the entire mission lifetime of several years. This assumes no systematics, etc.

- Sky noise dominated from 2-60MHz
- First light to be expected in spring
- proof of principle
- if successful, other experiments in the pipeline (DSL)
Many experiments to measure the 21-cm signal are ongoing, but they extremely hard. The signal is very faint and is affected by many effects (RFI, ionosphere, bright polarised foregrounds, instrumental distortions, calibration/ signal processing artefacts, etc.).

Process is made with two steps forward for every step backward.
Current (large) 21-cm Power-Spectrum Detection Experiments

**GMRT**
Epoch of Reionization (EoR) experiment

**Specs**
- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- $z = 8.1-9.2$

Paciga et al. 2013

**MWA**
Murchison Widefield Array

**Specs:**
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $-30^\circ 0^\prime 0^\prime\prime$
- high-band of 30.72 MHz, centered at 182 MHz i.e. $6.2 < z < 7.5$

Dillon et al. 2015

**PAPER**
Precision Array for Probing the Epoch of Reionization

**Specs:**
- 1148 hrs of data
  (8/11/2012 to 23/3/2013)
- 100 to 200 MHz, 1024 chan
- visibility integr.: 10.7 seconds

Ali et al. 2015

**LOFAR**
Low Frequency Array

**Specs:**
- 13 hrs of data; - Feb 11/12 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $90^\circ 0^\prime 0^\prime\prime$
- high-band of 115-189 MHz

Patil et al. 2017
GMRT: Measurement of a 2σ upper limit of \( \Delta(k) < 248 \text{ mK} \) for \( k = 0.50 \text{ h Mpc}^{-1} \) at \( z = 8.6 \).

Paciga et al. 2013

MWA-128T: Upper limits on the power spectrum from \( z = 6.2 \) to \( z = 7.5 \). The lowest limit is \( \Delta(k) < 192 \text{ mK} \) at 95% confidence at a comoving scale \( k = 0.18 \text{ Mpc}^{-1} \) at \( z = 6.8 \).

Dillon et al. 2015

PAPER 64-antenna: A best 2σ upper limit of \( \Delta(k) < 22 \text{ mK} \) for \( k = 0.15-0.5 \text{ h Mpc}^{-1} \) at \( z = 8.4 \).

Ali et al. 2015

LOFAR: Measurement of a 2σ upper limit of \( \Delta(k) < 80 \text{ mK} \) for \( k = 0.05 \text{ h Mpc}^{-1} \) at \( z = 10.1 \).

Patil et al. 2017
The Low Frequency Array (LOFAR) Reionization Key Science Project
Averaging spherically provides the lowest errors (maximum # of samples per shell).

The "best" upper limit (2-sigma) on the 21-cm PS is currently reached at z~10 at the smallest k-values (scales ~120 cMpc) and reach levels of about 80 mK; EoR signal are expected to be somewhere between few to ten mK so still much deeper.

Physical Limits on the Cosmic Dawn

21CMFAST - varying the X-ray heating luminosity.

Note: Excess noise (I over V) is incoherent (averages away): we assume it drops in the cross-variance and plot the 1-sigma upper limits (in 21CMMC, we double the errors)

Credit: Mesinger & Greig
Physical Limits on the Cosmic Dawn

21CMFAST - varying the X-ray heating luminosity.

Note: Excess noise (I over V) is incoherent (averages away): we assume it drops in the cross-variance and plot the 1-sigma upper limits (in 21CMMMC, we double the errors)
Ongoing Developments
Exciting new 21-cm Power-Spectrum/Tomography Instruments

**NenuFar**

Specs:
- 10-80 MHz/FoV ~ 20°
- 52-96 mini-stations of 19 low-freq. dipoles each
- Baselines: ~10 m - 400 m (plus outriggers)

**HERA**

Specs:
- 50-250 MHz/FoV ~ 9°
- 331x14m wide-band dishes
- Baselines: few m to ~1 km

**SKA-low**

Specs:
- 50-350 MHz/FoV ~ 4°
- 512 stations of 256 wide-band dipoles each
- Baselines: few m to 65 km

Paciga et al. 2013

Dillon et al. 2015
New Extension in Nançay Upgrading
LOFAR: NenuFar

Large number of dipole receivers (96x19 = 1824) leads to extremely high sensitivity at low frequencies (f~1 @ 30MHz); Nançay, France)

Power spectrum sensitivity for a nominal 21-cm model at z=20

Zarka et al. 2015
Hydrogen Epoch of Reionization Array: HERA

Large number of ~13m dish receivers (up to ~350) in a redundant hexagonal configuration but reduced field of view (Karoo, South Africa).

deBoer et al. 2016
The Square Kilometre Array: SKA(1)-Low

Large number of cross-dipole receivers grouped in ~512 stations (w/256 receivers) in a non-redundant configuration with reduced field of view (Western AU).

Koopmans et al. 2015; Labate et al. 2017
A three tiered-survey (3x5,000hrs):
- DEEP: 100sdq with 1000hr/pointing
- MEDIUM: 1000sqd with 100hr/pointing
- SHALLOW: 10000sqd with 10hr/pointing

Deeper is better on small scales (less thermal noise; bubbles)
Wider is better on large scales (less sample variance)
Both are needed (PS+Tomography)
General Summary

• The 21-cm signal from the Dark Ages, Cosmic Dawn and Reionization promises a new and unique probe of the 1st billion year of the Universe.

• Many ongoing/planned global and interferometric experiments
  • All experiments are extremely difficult (technically, (astro)physically, signal processing)
  • Steady progress on all fronts, but requires long-term investments
  • Ground and now also space-based experiments (e.g. NCLE)

• Current Status (selected)
  ‣ Only upper limits on the 21-cm signal, but …
  ‣ EDGES2 claimed detection of the global signal (-600mK @ z~17)
  ‣ LOFAR: deepest (2-sigma) prelim. upper limits on PS (@ k=0.1, z=9)

• Future promises
  ‣ Important for the field: confirm EDGES result w/e.g. SARAS3/LEDA…
  ‣ Detect EoR/CD 21-cm signal power spectra w/e.g. LOFAR/MWA/…
  ‣ Building of SKA, HERA, NenuFar: tomography of the 21-cm signal
  ‣ Going in to space: NCLE/… and going for the Dark Ages.