Detecting the redshifted 21cm forest during reionization

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21CM FOREST

\[ \tau_{\nu_0}(z) = \frac{3}{32\pi} \frac{h_p c^3 A_{10}}{k_B \nu_0^2} \frac{x_{HI} n_H(z)}{T_S (1 + z)(d\nu_\parallel/dr_\parallel)} \]

\[ \approx 0.009 (1 + \delta)(1 + z)^{3/2} \frac{x_{HI}}{T_S} \]

\[ \times \left[ \frac{H(z)/(1 + z)}{d\nu_\parallel/dr_\parallel} \right] . \]

The factor in square brackets accounts for the peculiar velocity of the gas; we will assume the gas is in the Hubble flow.
\[ T_S^{-1} = \frac{T_{\gamma}^{-1} + x_\alpha T_c^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}, \]

where \( T_{\gamma} \) is the temperature of the CMB, \( T_c \) is the color temperature of the Lyman-\( \alpha \) background, \( T_K \) is the gas kinetic temperature, and \( x_c \) and \( x_\alpha \) are coupling coefficients for collisions and the Wouthuysen-Field effect, respectively.

In our calculations at \( z \lesssim 17 \), we assume \( T_S = T_K \).
Properties of 21 cm forest

- Flux decrement blueward of 21 cm absorption frequency at source redshift.

- Due fluctuation of the IGM state along LoS, small scale variations in flux.

- Deep absorption features due to dense neutral HI clouds in dwarf galaxies and minihalos.
Contrast with Ly-alpha forest

• Occurs at high z (z>7) with respect to Ly-alpha.

• Contains detail information about IGM even when it is largely neutral.

• It in principle can probe very small structures in IGM.

• Much of the information in 21cm forest will come from structures which are in linear regime.
Simulations

Two simulations ---

i) One simulates mean properties of uniform IGM over cosmic time.

ii) Other simulates small scale spatial inhomogenities of IGM.

Mean IGM code incorporates X-ray heating via the following relation between X-ray source luminosity and SFR --

\[ L_X = 3.4 \times 10^{40} f_X \left( \frac{\text{SFR}}{1 \text{ M}_\odot \text{ yr}^{-1}} \right) \text{ erg s}^{-1} \]

where \( f_X \) is an x-ray efficiency factor.
Figure 1. Uniform IGM simulation output plots. (a) Mean IGM ionized fraction $x_i$ as a function of redshift. (b) Gas kinetic temperature (solid line) and CMB temperature (dotted line) as a function of redshift. (c)
Mean 21cm optical depth as a function of redshift. The model shown here has $f_X = 1$ (see Section 4).
Simulations (Inhomogeneous IGM)

Box of size 70 cMpc with $360^3$ grids.

4 random LoS thrown through the box and stitched to get a LoS of length 280 cMpc.

Small scale variation in the redshift range $z= 8 - 9$ generated.

Spectra for a radio source at $z=9$ is thus generated.

Simulation box do have ionized bubbles but do not have collapsed objects of high HI column density, which produces deep absorption spikes in spectra.
Figure 2. Non-uniform IGM simulation output plots. (a) Overdensity $\delta$ and (b) neutral hydrogen fraction $x_{HI}$ in the non-uniform simulation region as a function of redshift, from a two-phase IGM code developed by Geil & Wytche (2008). The size of the simulation box is 70 cMpc cubed, with 360 pixels per sidelength. Multiple slices through the simulation box are used, giving a total of 280 cMpc.
**Effect of X-ray heating**

**Figure 3.** 21cm absorption optical depth. (a) Mean 21cm optical depth $\tau$ as a function of observed frequency, for varying $f_X$ values: from top to bottom curve, $f_X = 0$ (no x-ray heating), 0.01, 0.1, 1 (thick black line), 10, 100.

(b) 21cm forest optical depth as a function of redshift, for varying $f_X$ values: from top to bottom curve, $f_X = 0$ (no x-ray heating), 0.01, 0.1, 1 (thick black line), 10, 100.
SOURCE POPULATION AND DETECTABILITY

The biggest challenge for doing observations of the 21cm forest will be finding sufficiently distant, radio-loud sources. The optical depth to 21cm absorption increases with the redshift, density and neutral fraction of the intervening gas, but decreases with the gas’s spin temperature. Therefore the strongest signals will be found in the spectra of very high redshift sources – those occurring prior to the epoch of reionization. However, the detection of 21cm absorption also becomes more difficult as the radio flux density of the source decreases: dimmer sources offer fewer photons and the difference between regions of the spectrum that are partially absorbed and those that are fully unabsorbed becomes less apparent.
Minimum Flux Density

\[ S_{min} = 160 \text{ mJy} \left( \frac{S/N}{5} \frac{10^{-3}}{\tau} \frac{10^6 \text{ m}^2}{A_{eff}} \frac{T_{sys}}{400 \text{ K}} \right) \times \left( \frac{1 \text{ kHz}}{\Delta \nu_{ch}} \frac{1 \text{ week}}{t_{int}} \right)^{1/2}. \]

The parameters \( A_{eff} \) and \( \Delta \nu_{ch} \) are the effective area of the telescope array and the channel bandwidth, here taken to be those plausible for the SKA, and \( t_{int} \) is the integration time. The system temperature, \( T_{sys} \), is dominated by the Galactic synchrotron foreground at the frequencies of interest. This can be approximated (Carilli 2006) as

\[ T_{sys} \sim 100 \left( \frac{\nu}{200 \text{ MHz}} \right)^{-2.8} \text{ K}. \]
Successful observations will require both a high optical depth to 21cm absorption and a population of very radio-loud sources.
SOURCE POPULATION AND DETECTABILITY

Haiman et al. (2004) present an estimate of the number of radio-loud sources per square degree for a range of flux densities out to redshift $z = 15$. According to this estimate, in the redshift range $8 < z < 12$, there should be $\sim 2000$ sources above $\sim 6$ mJy in the full sky. However, Jiang et al. (2007) have presented evidence that the radio-loud fraction may decrease with redshift, which would make discovery of appropriate 21cm forest background sources less likely. In this work, we have shown that objects with 10-100 mJy at $z \gtrsim 8$ are most favorable as background sources. If they exist, they may have already been discovered in surveys such as FIRST\textsuperscript{7}. Ivezic et al. (2002) have found that $\sim 30\%$ of FIRST sources at 10-100 mJy have no detected optical counterpart within 3" (via SDSS).
Figure 4. Minimum flux density curves for $S/N \gtrsim 5$ detection of the 21cm forest for $f_X = (0, 0.01, 0.1, 1)$ (solid lines), with the redshifted 21cm flux density of a Cygnus A-like source also plotted as a function of redshift (dashed line). The instrument is assumed to be SKA with channel width of 1 kHz and integration time of (a) 1 week and (b) 1
Detection Methods
Difference of variance

Figure 7. Mean binned signal variance as a function of frequency for windows with $w = (50 \text{ kHz}, 100 \text{ kHz}, 500 \text{ kHz}, 1 \text{ MHz}, 5 \text{ MHz})$, for (a) $f_X = 0.1$ and (b) $f_X = 1$. No absorbers are included in this simulation.

$$\sigma_i^2 = \sum_{\nu = \nu_0}^{\nu_0 + w} (F_{N,\nu} - \langle F_{N,i} \rangle)^2$$
Detection Methods

Difference of variance

![Graph showing variance increase over integration time for different values of \( f_X \).](image)

**Figure 8.** Difference in mean variance between unabsorbed and absorbed regions as a function of integration time for a window size of 1 MHz, with \( f_X = 1 \) and no lines added (red symbols with errorbars). Also included, for reference, is the difference in mean variance for \( f_X = 0.1 \) with a window size of 1 MHz, for an integration time of 1 week (blue cross with errorbars).
Inserting strong absorption lines

**Figure 6.** Simulated spectrum for 21cm absorption against the spectrum of a radio source at $z = 9$ with spectral properties similar to that of Cygnus A, with (a) 100 and (b) 500 absorption lines added to simulate the presence of overdense neutral regions along the line of sight. The x-ray efficiency factor in these simulations is $f_X = 0.1$. Observational parameters are as in Figure 5 above.
Gaussian Fitting

Unabsorbed Region

$\mu_{\text{Gaussian}} = 0.0008 \pm 0.0005$

$\sigma_{\text{Gaussian}} = 0.0410 \pm 0.0004$

$\mu_{\text{data}} = 0.0009$

$\sigma_{\text{data}} = 0.0407$

skewness = 0.0339

Absorbed Region

$\mu_{\text{Gaussian}} = -0.0276 \pm 0.0006$

$\sigma_{\text{Gaussian}} = 0.0470 \pm 0.0005$

$\mu_{\text{data}} = -0.0274$

$\sigma_{\text{data}} = 0.0466$

skewness = 0.0015

(a) Absorbed Region

$f_x=0.1$

100 Lines Added

$\mu_{\text{Gaussian}} = -0.0277 \pm 0.0007$

$\sigma_{\text{Gaussian}} = 0.0472 \pm 0.0005$

$\mu_{\text{data}} = -0.0360$

$\sigma_{\text{data}} = 0.1316$

skewness = -16.0105

(b)
**Figure 10.** Difference between the Gaussian mean in the absorbed region and unabsorbed region of the spectrum (flux decrement) for $f_X = 1$ (blue squares) and $f_X = 0.1$ (black diamonds), plotted against the number of absorption lines added to the spectrum. Error bars are derived from a bootstrap resampling of each spectrum.
Figure 11. Difference between the Gaussian standard deviation in the absorbed region and unabsorbed region of the spectrum for $f_X = 1$ (blue squares) and $f_X = 0.1$ (black diamonds), plotted against the number of absorption lines added to the spectrum. Error bars are derived from a bootstrap resampling of each spectrum.