First Multi-redshift Limits on Post–Epoch of Reionization 21 cm Signal from $z = 1.96$–$3.58$ Using uGMRT

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Abstract

Measurement of fluctuations in diffuse HI 21 cm background radiation from the post-reionization epoch ($z \lesssim 6$) is a promising avenue to probe the large-scale structure of the universe and understand the evolution of galaxies. We observe the European Large Area ISO Survey-North 1 (ELAIS-N1) field at 300–500 MHz using the upgraded Giant Meterwave Radio Telescope (uGMRT) and employ the “foreground avoidance” technique to estimate the HI 21 cm power spectrum in the redshift range $z = 1.96$–$3.58$. Given the possible systematics that may remain in the data, we find the most stringent upper limits on the spherically averaged 21 cm power spectra at $k \sim 1.0$ Mpc$^{-1}$ are $(58.87 \pm 21.30)\,\text{mK}^2$, $(61.49 \pm 21.30)\,\text{mK}^2$, and $(105.85 \pm 21.30)\,\text{mK}^2$ at $z = 1.96, 2.19, 2.62$, and 3.58, respectively. We use this to constrain the product of neutral HI mass density ($\Omega_{\text{HI}}$) and HI bias ($b_{\text{HI}}$) to the underlying dark matter density field, $\Omega_{\text{HI}}b_{\text{HI}}$, as 0.09, 0.11, 0.12, and 0.24 at $z = 1.96, 2.19, 2.62$, and 3.58, respectively. To the best of our knowledge these are the first limits on the HI 21 cm power spectra at the redshift range $z = 1.96$–$3.58$ and would play a significant role to constrain the models of galaxy formation and evolution.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Large-scale structure of the universe (902)

1. Introduction

The redshifted 21 cm line emission from neutral hydrogen (HI) provides a rich tool to map the universe in 3D. The majority of HI is ionized by ultraviolet radiation emanating from early galaxies during a period $z \sim 15$–$6$ (Epoch of Reionization, EoR; Madau et al. 1997). However, below $z \sim 6$ (post-EoR epoch) HI is contained within dense clumps, which are self-shielded from the ionizing radiation. These dense clumps are strongly correlated with overdensity of matter where an abundance of HI are being self-shielded. The distribution of HI is intimately connected to matter distribution of the universe and hence help to understand the large-scale structures at intermediate redshifts in the post-EoR era ($z \lesssim 6$; Bull et al. 2015). Along with that measurement of post-EoR, the HI 21 cm power spectrum can be used to study baryonic acoustic oscillations (BAOs) and the equation of state of the dark energy (Chang et al. 2008; Bharadwaj et al. 2009; Bull et al. 2015).

Several methods exist to measure the neutral HI mass density ($\Omega_{\text{HI}}$) from $z = 0$ to 6, starting from the Ly$\alpha$ line absorption feature in distant quasar spectra by an intervening HI region at $z \gtrsim 1.5$ (Prochaska & Wolfe 2009) to detecting 21 cm line emission from individual galaxies at $z \lesssim 0.1$ (Zwaan et al. 2005; Martin et al. 2010). It is extremely difficult to detect individual galaxies at $z \gtrsim 0.3$, which requires a very deep integration time (Kanekar et al. 2016). Nonetheless, one can obtain information about average properties of neutral gas by coadding the HI 21 cm signal from large number of galaxies with known redshifts (“stacking”) to boost the signal-to-noise ratio (Lah et al. 2007; Kanekar et al. 2016; Bera et al. 2019). However, this method has so far been applied to low redshifts, $z \lesssim 0.4$. Another unique technique is 3D “intensity mapping,” which measures the fluctuations in the diffuse 21 cm background radiation (Bharadwaj et al. 2001; Loeb & Wyithe 2008; Chang et al. 2010; Bull et al. 2015). Previous studies use cross-correlation of the single-dish HI 21 cm intensity map with a deep galaxy survey and put constraints on $\Omega_{\text{HI}}b_{\text{HI}}$ at $[0.6^{+0.23}_{-0.15}] \times 10^{-3}$ at $z \approx 0.8$ (Masui et al. 2013; Switzer et al. 2013). Ghosh et al. (2011a) measure the fluctuations in the faint HI 21 cm background using GMRT for the first time and put an upper limit on $[\Omega_{\text{HI}}b_{\text{HI}}] \leq 2.9[(\Omega_{\text{HI}}b_{\text{HI}}) \leq 0.11]$ at $z \sim 1.32$, where $\Omega_{\text{HI}}b_{\text{HI}}$ is the mean neutral fraction.

The major challenge in detecting HI power spectrum is the presence of the bright synchrotron radiation from galactic and extragalactic sources. Several novel techniques have been developed to remove foregrounds (Ghosh et al. 2011b; Liu & Tegmark 2012; Masui et al. 2013; Wolz et al. 2017; Anderson et al. 2018). Also, foregrounds can be avoided in Fourier space ($k_1$, $k_2$), where the smooth foregrounds coupled with instrument response are localized in a “wedge” shape region (Datta et al. 2010; Parsons et al. 2012b). This method is widely used to detect the HI 21 cm signal from EoR (Kolopanis et al. 2019; Trott et al. 2020). We follow the “foreground avoidance” method to estimate the HI power spectrum at redshifts $z = 1.96, 2.19, 2.62$, and 3.58 with uGMRT. We also put upper limits on the product of $\Omega_{\text{HI}}$ and $b_{\text{HI}}$ at each redshift. The quantity $[\Omega_{\text{HI}}b_{\text{HI}}]$ contains information about the host dark matter halos of HI gas and determines the amplitude of the expected HI power spectrum. It is essential to put tight
constraints on these parameters using observations to predict
the uncertainties in measuring the HI power spectrum for
current and future telescopes (Bharadwaj & Ali 2005; Battye
et al. 2012; Padmanabhan et al. 2015).

2. Observation and Analysis

We observed the ELAIS-N1 field (α2000 = 16h10m1s, δ2000 =
54°30′36″) using uGMRT in GTAC Cycle 32 during 2017 May–
June at 300–500 MHz for a total time of 25 hr (including
calibrators) over four nights. ELAIS-N1 is a well-known field in
the northern sky at high galactic latitude (b = +44.48°) and was
previously studied at different frequencies (see Chakraborty et al.
2019a and references therein). The data were taken with a time
resolution of 2 s and frequency resolution of 24 KHz using an
upgraded digital backend correlator (Gupta et al. 2017). The
detailed analysis of editing bad data, calibration, and imaging is
mentioned in Chakraborty et al. (2019b). However, here we did
not average the data across frequencies to get the maximum
k⊥ modes, which is inversely proportional to the frequency resolution
(Morales & Hewitt 2004). We have used a mask during imaging,
generated via PyBDSF,9 to ensure that imaging artifacts do not
propagate into the model during direction-independent (DI)
self-calibration. This results in building a more accurate sky
model consisting of bright compact sources and allows for the
mitigation of calibration errors in self-calibration. Also, during
the self-calibration, we have excluded the shorter baselines
(<1.5kλ), where the diffuse emission is most sensitive. Hence,
there will not be any significant suppression of the diffuse
emission and the 21 cm signal during self-calibration and
subsequent sky-model subtraction (Patil et al. 2016). After
getting the final image we found that there are 3728 components
(compact sources) present in the model. Then we have subtracted
this point-source model from the calibrated visibility data, using
UVSUB in CASA. These residual data are being used for the power
spectrum analysis. We do not attempt to model and subtract the
diffuse foreground emissions in this analysis to avoid any suppression or loss of the diffuse 21 cm signal.

3. Power Spectrum Estimation

The Fourier transformation of a visibility along the frequency
direction to the η-domain is given as (Morales & Hewitt 2004)

\[ V(U, η) = \int V(U, ν)S(ν)W(ν)e^{i2πην}dν, \]

where \( V(U, η) \) is the measured visibility of a baseline \( U \) as a
function of frequency \( ν \) and \( W(ν) \) is the Blackman–Harris
(BH) window function used to control the visibility spectrum in
the η-domain. \( S(ν) \) contains frequency-dependent sample
weights that result from flagging of frequency channels due to
radio frequency interference (RFI). We use one-dimensional
“CLEAN” (Hög b om 1974) to deconvolve the kernel that results
from the Fourier conjugate of the product of \( [W(ν)S(ν)] \) and
obtain the final spectra (Parsons & Backer 2009).

The cylindrically averaged power spectrum can be estimated
with the use of a proper scaling factor as (Morales & Hewitt 2004;
Parsons et al. 2012b)

\[ P(k_r, k_η) = \left( \frac{\lambda^2}{2k_B} \right)^2 \left( \frac{X^2 Y}{ΩB} \right) |V(U, η)|^2, \]

with

\[ k_r = \frac{2\pi}{D(z)} U, \]

\[ k_η = \frac{2πν_21 H_0 E(z)}{c(1+z)^2} η, \]

where \( λ \) is the wavelength corresponding to the band center, \( k_B \)
is the Boltzmann constant, \( ν_21 \) is the rest-frame frequency of
the 21 cm spin flip transition of HI, \( z \) is the redshift to the
observed frequency, \( Ω \) is sky integral of the squared antenna
primary beam response, \( B \) is the bandwidth, and \( X^2 Y \) is a
redshift-dependent scalar to convert angle and frequency to
cosmological length scales (Morales & Hewitt 2004). Here, \( D (z) \)
is the transverse comoving distance at redshift \( z \), \( H_0 \) is the
Hubble parameter, and \( E(z) \equiv [Ω_m(1+z)^3 + Ω_Λ^{1/2}]. \ Ω_m \) and
\( Ω_Λ \) are matter and dark energy densities, respectively. In
this work, we use the best-fitted cosmological parameters of the
Planck 2018 analysis (Planck Collaboration et al. 2018). The
power spectrum \( P(k_r, k_η) \) is in units of \( K^2 \) Mpc\(^{-3} \). We
spherically averaged \( P(k_r, k_η) \) in \( k \)-bins and estimate the
dimensionless power spectrum as (Datta et al. 2010)

\[ \Delta^2(k) = \frac{k^3}{2π^2} < P(k) >, \]

where \( k = \sqrt{k_r^2 + k_η^2} \).

However, correlating a visibility with itself, as in Equation (2), will result in a positive bias due to the noise
present in the data (Bharadwaj & Pandey 2003). To avoid
the positive noise bias, we cross-correlate all the visibilities among
each other within a \( uv \)-cell, whose dimension is the inverse of
the half-power beamwidth of the primary beam (\( θ_{HPBW} \)). The
off-diagonal terms of the correlation matrix for each \( uv \)-cell
are expected to be free of noise bias and the average of those terms is
being quoted as the estimated power corresponding to that
cell. The method of correlating visibilities within a \( uv \)-cell to
measure the post-EoR 21 cm power spectrum was first proposed by Bharadwaj & Sethi (2001) and further discussed in
Bharadwaj & Pandey (2003) and Bharadwaj & Ali (2005).

The power spectrum uncertainties are estimated by dividing the
noise power by the square root of the number of modes
averaged together in estimating the power spectrum (Tegmark
1997). We calculate the noise power by subtracting the average
of the off-diagonal from the diagonal (self-correlation of
visibilities) components for each \( uv \)-cell. The estimated noise
at the highest \( k_η \) modes (above the horizon limit) is expected to be
dominated by thermal variance (Kolopanis et al. 2019).

4. Results

All of the 200 MHz bandwidth data are divided into 8 MHz
subbands, and we only use projected baselines up to 2 km to
estimate the HI 21 cm power spectrum for each of these
subbands. This choice allows us to restrict to minimal baseline
migration over the subband. Also, the analysis using these
subbands ensures the signal ergodicity within the volume, i.e.,
the cosmological signal does not evolve significantly over the
bandwidth (Datta et al. 2014; Mondal et al. 2020; Trott et al.
2020).
We choose four 8 MHz subbands from the entire observed bandwidth that are relatively less contaminated by RFI and estimate the cylindrically and spherically averaged power spectrum. In Figure 1, we show the cylindrically averaged power spectrum estimated from a 8 MHz subband around 310 MHz corresponding to redshift \( z = 3.58 \). Note that the first and last 4 MHz of the 200 MHz bandwidth have been flagged. Hence, this is the power spectrum of the highest redshift \( z = 3.58 \) probed in this analysis. We find that the spectrally smooth foregrounds coupled with chromatic instrument response are confined in a “wedge” shape region in this 2D space. This cylindrically averaged power spectrum is useful to identify the \([k_{\perp}, k_{\parallel}]\)-modes devoid of foreground contamination. The black line in Figure 1 shows the upper bound of foreground contaminated modes within the horizon \((r = |U| \sin 90^\circ/c)\) limit.

Above the horizon line we find a region in the \([k_{\perp}, k_{\parallel}]\)-space where the power is 2–3 orders of magnitude less than the power inside the horizon limit. We choose the modes bounded by the white dashed curve (see Figure 1) by visually inspecting the less foreground contaminated region and estimate the spherically averaged power spectrum using those modes. The dimensionless spherically averaged stokes-I power spectrum (\(\Delta^2\)) in mK² along with 2σ error bars at \( z = 3.58 \) are shown in Figure 2. We also estimate the theoretical thermal noise power (\(\Delta^2_{\text{thermal}}\)), including the flagging, using the uGMRT baseline distribution, bandwidth, integration time, and system temperature \((T_{\text{sys}}; \text{McQuinn et al. 2006; Parsons et al. 2012a})\). The quantity \(G/T_{\text{sys}}\) as a function of frequency for uGMRT is given as a polynomial,\(^{10}\) where \(G\) is the antenna gain (Gupta et al. 2017). We estimate the \(T_{\text{sys}}\) at the central frequency of the subband using the polynomial and also correct for the sky temperature at the corresponding frequency. The bottom, green dashed line shows the theoretical prediction of HI 21 cm power spectrum at redshift \( z = 3.5 \) taken from Sarkar et al. (2016). We find that estimated \(\Delta^2\) is close to \(\Delta^2_{\text{thermal}}\) at the \(k\) modes probed here. However, the measured \(\Delta^2\) is nearly four orders of magnitude higher than the theoretical expectation of the HI 21 cm power spectrum close to redshift \( z = 3.58 \). Hence, this analysis with \(\sim 13\) hr of on-source data (before flagging) puts an upper limit on the post-EoR HI power spectrum and is limited by thermal noise.

The data was observed over 4 nights and coherently added in the \(uv\)-domain within \(uv\)-cells. We show in Figure 3 the cylindrically averaged power spectrum after combining different nights’ data coherently. The bottom, navy dashed line is the theoretical thermal noise power spectrum for the whole four nights of data. The black data was observed over 4 nights and coherently added in the \(uv\)-domain within \(uv\)-cells. We show in Figure 3 the cylindrically averaged power spectrum after combining different nights’ data coherently. The bottom, navy dashed line is the theoretical thermal noise power spectrum for the whole four nights of data. The black line is the dark matter (DM) power spectrum at \( z = 3.58 \) estimated using CAMB.

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\(^{10}\) http://www.ncra.tifr.res.in:8081/~secr-ops/etc/etc_help.pdf
479 MHz \((z = 1.96)\) and estimate the power spectrum following the same procedure discussed above. The cylindrically and spherically averaged power spectrum plots are being shown in Figure A1 (see Appendix A). The lowest limits, at \(k \sim 1.0\) \(\text{Mpc}^{-1}\), on spherically averaged 21 cm power spectrum are \((58.87\ \text{mK})^2, (61.49\ \text{mK})^2, (60.89\ \text{mK})^2,\) and \((105.85\ \text{mK})^2\) at \(z = 1.96, 2.19, 2.62,\) and \(3.58,\) respectively, and are shown in Figure 4. The values of \(\Delta_f^2\) along with the \(2\sigma\) error bars for all \(k\) at different redshifts are mentioned in Table B1 (see Appendix B).

Note that there are several different ways the foreground free cosmological window above the “wedge” may be contaminated, such as by residual calibration errors, polarization leakage, ionospheric effects, the variation of beam, etc., and affect the estimation of the HI 21 cm power spectrum (Gehlot et al. 2018; Joseph et al. 2020; Kumar et al. 2020). Although the estimated power spectrum for different redshift bins are close to the thermal noise, the resultant power spectrum may still be affected by any plausible residual systematics. We will analyze and present any plausible contamination of the signal window due to different systematics in detail and in future work.

5. Constraints on \([\Omega_{\text{HI}}b_{\text{HI}}]\)

The main observable in 21 cm intensity mapping experiments is the power spectrum of 21 cm brightness temperature fluctuation and given by the expression (Battye et al. 2012; Anderson et al. 2018)

\[
\Delta^2_{\text{HI}}(k, z) = T(z)^2 |b_{\text{HI}}(k, z)|^2 k^3 P_{\text{DM}}(k, z) \frac{2 \pi^2}{},
\]

where the mean brightness temperature \(T(z)^2\) is given by Anderson et al. (2018):

\[
T(z) \simeq 0.39 \left(\frac{\Omega_{\text{HI}}(z)}{10^{-3}}\right) \left[\frac{\Omega_{\text{m}} + \Omega_\Lambda (1 + z)^{-3}}{0.29}\right]^{-1/2} \times \left[\frac{1 + z}{2.5}\right]^{1/2} \text{mK},
\]

where \(b_{\text{HI}}(k, z)\) is the HI bias and \(P_{\text{DM}}(k, z)\) is the dark matter power spectrum.

We use the CAMB\(^{11}\) code to generate the dark matter power spectrum at any given redshift for the \(k\) range probed here. After combining Equations (5) and (6) and using the best limit on the HI power spectrum at \(k = 1.0\) \(\text{Mpc}^{-1}\), the estimated upper limits on \([\Omega_{\text{HI}}b_{\text{HI}}]\) are \(0.09, 0.11, 0.12,\) and \(0.24\) at \(z = 1.96, 2.19, 2.62,\) and \(3.58,\) respectively. Theoretical prediction shows the value of \([\Omega_{\text{HI}}]\) \(\sim 1\) \(\times 10^{-4}\) at this redshift range probed here (Sarkar et al. 2016). Previous observation of DLAs suggests that \([\Omega_{\text{HI}}]\) \(\sim 5 \times 10^{-4}\) at this redshift range using uGMRT.

To maintain signal ergodicity, we divide the whole 200 MHz band into 8 MHz subbands and choose four such less RFI contaminated subbands to put limits on HI power spectrum. We coherently added the data in the \(uv\)-domain and estimate the cosmological HI 21 cm power spectrum properly accounting for the positive noise bias. We use the 1D “CLEAN” algorithm to mitigate the foreground spillover beyond the horizon limit caused by missing channels due to RFI flagging. We estimate the cylindrically averaged power spectrum using proper scaling factors and find that spectrally smooth foregrounds coupled with chromatic instrument response is contained within a “wedge” shape region inside the horizon limit. Using the modes less contaminated by the foregrounds above the horizon limit, we estimate the spherically averaged power spectrum. The upper limits at \(k = 1.0\) \(\text{Mpc}^{-1}\) on spherically averaged 21 cm power spectrum are \((58.87\ \text{mK})^2, (61.49\ \text{mK})^2, (60.89\ \text{mK})^2,\) and \((105.85\ \text{mK})^2\) at \(z = 1.96, 2.19, 2.62,\) and \(3.58,\) respectively.

This analysis with the uGMRT observation is a first attempt to estimate the statistical feature of post-EoR HI signal via autopower spectrum using interferometric data at this redshift range using uGMRT.

6. Summary

In this analysis, using 13 hr uGMRT observation of the ELAIS-N1 field, we put limits on the post-EoR HI power spectrum at redshifts \(z = 1.96, 2.19, 2.62,\) and \(3.58.\) This is the first attempt to estimate the statistical feature of post-EoR HI signal via autopower spectrum using interferometric data at this redshift range using uGMRT.

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\(^{11}\) https://camb.info/

\(^{12}\) http://www.ncra.tifr.res.in/ncra/ort

\(^{13}\) https://chime-experiment.ca/en

\(^{14}\) https://tianlai.bao.ac.cn

\(^{15}\) https://hirax.ukzn.ac.za

\(^{16}\) https://www.skatelescope.org/mfaa/
Appendix A
2D and 3D Power Spectrum at $z = 1.96, 2.19, \text{ and } 2.62$

The cylindrically and spherically averaged power spectrum at $z = 1.96, 2.19, \text{ and } 2.62$.

Figure A1. The cylindrically averaged 2D power spectrum (upper panel) and spherically averaged 3D power spectrum (lower panel) for redshifts $z = 1.96$ (left column), 2.19 (middle column), and 2.62 (right column).
Appendix B
Tabulated Power Spectrum Values at Different Redshifts

The upper limit values estimated power spectrum for redshifts $z = 1.96, 2.19, 2.62,$ and $3.58$.

| $z$ | $k$ | $\Delta^2 L_z$ | $\Delta^2_{err}$ |
|-----|-----|----------------|-----------------|
| 1.96 | 0.99 | $(58.57)^2$ | $(43.54)^2$ |
| 1.64 | $(100.08)^2$ | $(64.11)^2$ |
| 2.73 | $(184.25)^2$ | $(133.92)^2$ |
| 5.74 | $(316.94)^2$ | $(162.87)^2$ |
| 9.60 | $(452.71)^2$ | $(212.27)^2$ |

| $z$ | $k$ | $\Delta^2 L_z$ | $\Delta^2_{err}$ |
|-----|-----|----------------|-----------------|
| 2.19 | 0.97 | $(61.49)^2$ | $(36.50)^2$ |
| 1.67 | $(103.84)^2$ | $(61.38)^2$ |
| 2.92 | $(121.89)^2$ | $(79.52)^2$ |
| 5.12 | $(236.55)^2$ | $(160.70)^2$ |
| 9.02 | $(247.93)^2$ | $(176.01)^2$ |

| $z$ | $k$ | $\Delta^2 L_z$ | $\Delta^2_{err}$ |
|-----|-----|----------------|-----------------|
| 2.62 | 0.95 | $(60.89)^2$ | $(45.49)^2$ |
| 1.68 | $(139.47)^2$ | $(130.72)^2$ |
| 2.99 | $(294.13)^2$ | $(232.13)^2$ |
| 5.36 | $(446.21)^2$ | $(311.65)^2$ |
| 9.59 | $(447.51)^2$ | $(325.50)^2$ |

| $z$ | $k$ | $\Delta^2 L_z$ | $\Delta^2_{err}$ |
|-----|-----|----------------|-----------------|
| 3.58 | 0.99 | $(105.85)^2$ | $(60.34)^2$ |
| 1.64 | $(133.06)^2$ | $(93.46)^2$ |
| 2.73 | $(249.49)^2$ | $(150.38)^2$ |
| 4.54 | $(346.92)^2$ | $(170.44)^2$ |
| 7.58 | $(590.82)^2$ | $(241.76)^2$ |

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