On the Prospects of Measuring the Cosmic Dawn 21-cm Power Spectrum using the Upgraded Giant Meterwave Radio Telescope (uGMRT)

Suman Chatterjee$^{1,2,*}$, Somnath Bharadwaj$^{1,2,†}$

$^1$Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur - 721 302, India.
$^2$Centre for Theoretical Studies, Indian Institute of Technology Kharagpur, Kharagpur - 721 302, India.

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ABSTRACT

A recent observation by the EDGES collaboration (Bowman et al. 2018) shows a strong absorption signal in the global 21-cm spectrum from around a redshift of $z = 17$. This absorption is stronger than the maximum prediction by existing models and indicates that the spatial fluctuations of the HI 21-cm brightness temperature at Cosmic Dawn could be an order of magnitude larger than previously expected (Barkana 2018; Fialkov et al. 2018). In this letter, we investigate the prospects of detecting the HI 21-cm power spectrum from Cosmic Dawn using uGMRT. We find that a $10\sigma$ detection of the enhanced HI 21-cm signal power spectrum is possible within 60, 120 and 350 Hours of observation for an optimistic, moderate and pessimistic scenario respectively, using the Band-1 of uGMRT. This could be an useful probe of the interaction between the baryon and dark matter particles in the early universe.

Key words: Interferometric; cosmology: observations, Cosmic Dawn large-scale structure of Universe

Introduction: Observations with the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) have recently resulted in the detection of an absorption profile with full width half maxima (FWHM) 19 MHz centred at 78 MHz in the sky averaged spectrum of the background radiation in the frequency range 50 − 100 MHz (Bowman et al. 2018). If confirmed by other similar experiments like the Large-Aperture Experiment to Detect the Dark Ages (LEDA; Bernardi et al. 2016), the Sonda Cosmológica de las Islas para la Detección de Hidrógeno Neutro (SCI-HI; Voytek et al. 2014), the Probing Radio Intensity at high $z$ from Marion (PRIZM) and the Shaped Antenna measurement of the background Radio Spectrum 2 (SARAS 2; Singh et al. 2017), this can be interpreted as the neutral Hydrogen (HI) 21-cm absorption profile resulting from the Lyman-$\alpha$ coupling due to the formation of the first stars in the early universe (Pritchard & Loeb 2012). However, the observation indicates a dip with amplitude 0.5 K which is more than a factor of two larger than the largest predictions (Cohen et al. 2017). Barkana (2018) have proposed that it is possible to explain this enhanced dip through a possible interaction between the baryons and dark matter particles (b-DM interaction). Such models (Fialkov et al. 2018) have predicted a 10 fold enhancement of the spatial fluctuations of the redshifted HI 21-cm brightness temperature $\delta T_b(x)$. We note that other alternative explanations have also been proposed (Ewall-Wice et al. 2018; Feng & Holder 2018) to explain the enhanced dip. The latter models incorporate an enhancement in the radio background and they do not predict such enhancement in $\delta T_b(x)$.

Upcoming experiments such as the Hydrogen Epoch of Reionization Array (HERA; DeBoer et al. 2017) and the Square Kilometre Array (SKA; Koopmans et al. 2015) have the potential of measuring the HI 21-cm power spectrum from Cosmic Dawn (50 − 100 MHz). Both of these experiments should easily be able to measure the corresponding enhanced HI 21-cm power spectrum predicted by the b-DM interaction models (Barkana 2018).

The Giant Meterwave Radio Telescope (GMRT; Swarup et al. 1991) is one of the largest and most sensitive fully operational low-frequency radio telescopes in the world today. The array configuration of 30 antennas (each of 45 m diameter) spanning over 25 km, provides a total collecting area of about 30,000 sq. m at metre wavelengths. The GMRT is being upgraded (uGMRT, Gupta et al. 2017) to have seamless frequency coverage, as far as possible, from 50 to 1500 MHz. Band-1 of uGMRT, which is yet to be implemented, is expected to cover the frequency range 50 − 80 MHz. Earlier Shankar et al. (2009) envisaged

* E-mail: suman05@phy.iitkgp.ernet.in
† E-mail: somnath@phy.iitkgp.ernet.in
a 50 MHz system developed for GMRT to provide imaging capability in the frequency range 30 – 90 MHz.

In this paper, we investigate the prospects of detecting the redshifted HI 21-cm signal power spectrum from Cosmic Dawn using the uGMRT. For the purpose of this analysis we have considered a functional bandwidth of $B = 20$ MHz centred at $\nu_c = 78$ MHz, consistent with the frequency coverage described in Shankar et al. (2009). Frequencies above 90 MHz are used for FM transmission which restricts the allowed frequency range.

**Methodology** : We have simulated the uGMRT baseline configuration for 8 hours of observation targeted on a field at $+60^\circ$ DEC with 16 s integration time. We assume that the bandwidth $B = 20$ MHz is divided into $N_c = 200$ spectral channels of $\Delta \nu_c = 100$ KHz. Note that the values of $B$, $N_c$ and $\Delta \nu_c$ assumed here are only representative values, and the actual values in the final implementation of the telescope may be somewhat different.

The baselines $u-v$ distribution is gridded at a spacing $D/\lambda_c$, where $D$ is the diameter of each dish and $\lambda_c = 3.82$ m is the wavelength at the center of the band. We use $k_{\perp} = 2\pi U/r$ and $k_{\parallel} = 2\pi m/r' B$ to estimate the Fourier modes at which the brightness temperature fluctuations $\Delta T(k)$ will be measured by this observation. Here $U$ refer to different baselines, $0 \leq m \leq N_c/2$, $r$ is the co-moving distance corresponding to $\nu_c$ and $r = dr/d\nu$ evaluated at $\nu = \nu_c$.

For the Cosmic Dawn HI 21-cm signal we have used the value of the dimensionless HI 21-cm power spectrum $\Delta^2_{HI}$ from Mellema et al. (2013). These values correspond to the standard scenario, we expect a 10 fold enhancement in the brightness temperature fluctuations i.e. a dimensionless power spectrum of $100\Delta^2_{HI}$ in the presence of the b-DM interaction (Barkana 2018; Fialkov et al. 2018). To compute the noise power spectrum we have assumed the system temperature $T_{sys} = 3000$ K. We have binned the $k$-range accessible to uGMRT into 10 logarithmic bins.

We have considered three different cases:

- **Case I**: This is the most optimistic scenario, where we assume that the foregrounds have been removed perfectly and the whole $k$ space accessible by uGMRT is available for measuring the HI 21-cm signal.

- **Case II**: In this moderate scenario we assume that the foreground contributions from angles beyond $18^\circ$ from the center of the field of view are highly suppressed by taping the sky response (Choudhuri et al. 2014). Note that the first null of the uGMRT primary beam pattern at 78 MHz is expected at $\sim 6^\circ$. In this case the Fourier modes $k_{\parallel} \leq 1.813 |k_{\perp}|$ are foreground contaminated and only the modes outside this foreground wedge are used for measuring the HI 21-cm signal.

- **Case III**: In this pessimistic scenario, we assume that the foreground contribution extends till the horizon and the Fourier modes $k_{\parallel} \leq 5.964 |k_{\perp}|$ are foreground contaminated. Only the modes outside this foreground wedge are used for measuring the HI 21-cm signal.

**Result** : Figure 1 shows the signal-to-noise ratio (SNR) which will be achieved for very large observation times, for the situation when only the cosmic variance is considered. For Case I, Case II and Case III SNR $> 5$ can be achieved for $k > 0.02$ Mpc$^{-1}$, 0.04 Mpc$^{-1}$ and 0.1 Mpc$^{-1}$ respectively. We only consider these $k$-modes for our subsequent analysis.

**Figure 1**: This shows the SNR at different $k$-bins for Case I (solid line), Case II (dashed line) and Case III (dotted line). The horizontal dot-dashed line marks the SNR value 5.

We see that in all the three cases there is a reasonably large $k$-range where a detection is possible provided we have sufficiently deep observations.

Figure 2 shows a comparison between the HI 21-cm signal power spectrum and the $r$, $m$, $s$ noise, including $T_{sys}$ and cosmic variance for three different observation times. Note that the cosmic variance here corresponds to $\Delta^2_{HI}$. For Case I we find that $100\Delta^2_{HI}$ and $10\Delta^2_{HI}$ can be detected with 100 and 500 hours of observation for Fourier modes $0.05 < k < 0.4$ Mpc$^{-1}$ and $0.05 < k < 0.25$ Mpc$^{-1}$ respectively. However, a detection of $\Delta^2_{HI}$ will require more that 1000 hours of observation. In Case II, it is possible to detect $100\Delta^2_{HI}$ and $10\Delta^2_{HI}$ in the $k$-range, $0.07 < k < 0.4$ Mpc$^{-1}$ and $0.07 < k < 0.25$ Mpc$^{-1}$ in 100 and 500 hours of observation respectively. For the pessimistic scenario, i.e. Case III, we find that $100\Delta^2_{HI}$ and $10\Delta^2_{HI}$ can be detected in 100 and 1000 hours of observation in the $k$-range $0.1 < k < 0.4$ Mpc$^{-1}$ and $0.1 < k < 0.25$ Mpc$^{-1}$ respectively.

Figure 3 shows the expected SNR for detecting the HI 21-cm signal power spectrum if we combine all the available $k$-modes. The horizontal solid and the dot-dashed lines mark the SNR value of 10 and 5 respectively. For Case I we find that a 10$\sigma$ detection of $100\Delta^2_{HI}$, $10\Delta^2_{HI}$ and $\Delta^2_{HI}$ is possible in $\sim 60$, 500 and 5000 hours of observation respectively. A 5$\sigma$ detection of $\Delta^2_{HI}$ can be achieved in 2000 hours of observation. In Case II and Case III, it takes $\sim 120$, 1200 hours and $\sim 350$, 3500 hours for a 10$\sigma$ detection of $100\Delta^2_{HI}$ and $10\Delta^2_{HI}$ respectively. It is not possible to detect $\Delta^2_{HI}$ within reasonable observation time when we consider the pessimistic scenario.

**Conclusion** : If the proposed b-DM interaction (Barkana 2018; Fialkov et al. 2018) enhances the Cosmic Dawn HI 21-cm power spectrum, it can be detected with the Band-1 of uGMRT within reasonable hours of observation. Such a detection would be an independent confirmation of the enhanced dip reported by Bowman et al. (2018). Observations with the Band-1 of uGMRT hold the prospect of being an interesting probe of the b-DM interaction in the early universe. Even upper limits from a non-detection of this power...
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Figure 2. This shows a comparison of the HI 21-cm signal power spectrum and the r.m.s. noise for an uGMRT observation. The left, middle and right panels show results for Case I, II and III respectively. The HI signal is shown in dashed lines (as mentioned in the figure). The noise r.m.s. for 100, 500 and 1000 hours is shown in solid, dotted and fine-dotted lines respectively.

Figure 3. The left, middle and right panels show the predictions for Case I, II and III respectively when all the available $k$-modes are combined. The dashed, dotted and fine-dotted lines show the predictions for the HI 21-cm signal power spectrum $\Delta^2_{\text{HI}}$, $10\Delta^2_{\text{HI}}$ and $100\Delta^2_{\text{HI}}$ respectively. The horizontal dot-dashed and solid lines mark the SNR of 5 and 10 respectively.

spectrum would impose useful constraints on the proposed b-DM interaction.

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