Implication of the Shape of the EDGES Signal for the 21 cm Power Spectrum

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Abstract

We revisit the 21 cm power spectrum from the epoch of cosmic dawn in light of the recent Experiment to Detect the Global Epoch of reionization Signature (EDGES) detection of the 21 cm global signal at frequencies corresponding to \( z \sim 20 \). The shape of the signal suggests that the spin temperature of neutral hydrogen was coupled to the kinetic temperature of the gas relatively rapidly (\( 19 \lesssim z \lesssim 21 \)). We therefore consider models in which the ultraviolet photons were dominantly produced in the rarest and most massive halos (\( M \gtrsim 10^9 M_\odot \)), as their abundance grows fast enough at those redshifts to account for this feature of the signal. We show that these models predict large power spectrum amplitudes during the inhomogeneous coupling, and then inhomogeneous heating by cosmic microwave background and Ly\( \alpha \) photons due to the large shot noise associated with the rare sources. The power spectrum is enhanced by more than an order of magnitude compared to previous models that did not include the shot-noise contribution, making it a promising target for upcoming radio interferometers that aim to detect high-redshift 21 cm fluctuations.

Key words: early universe – galaxies: high-redshift

1. Introduction

At redshifts \( z \sim 20 \)–30, before the epoch of cosmic dawn, the intergalactic medium (IGM) was colder than the cosmic microwave background (CMB), and the spin temperature of the 21 cm line of neutral hydrogen was coupled to the CMB temperature. Subsequently, the spin states were driven toward equilibrium with the thermal motion of the gas due to repeated scattering of the UV radiation from the first stars within the Ly\( \alpha \) resonance (Wouthuysen 1952; Field 1959). This process lowers the spin temperature and leads to an absorption feature in the global radio background.\(^2\)

Recent results from the Experiment to Detect the Global Epoch of reionization Signature (EDGES) suggest that this transition happened at \( z \sim 20 \) (Bowman et al. 2018). Surprisingly, the reported absorption profile (see the top panel in Figure 3) is characterized by abrupt edges and a flattened bottom, which are not seen in any of the prior theoretical models (Cohen et al. 2017b). Although this distinctive shape may have been affected by the choice of the basis functions used to model the foreground, it is sufficiently intriguing to motivate us to explore extreme scenarios of cosmic Ly\( \alpha \) coupling.

Many studies that immediately followed the EDGES detection have focused on the depth of the absorption feature (0.5\(^{+0.5}_{-0.2}\) K at 99% confidence level), which is a factor of \( \sim 2.5 \) larger than the value in any of the standard models of the cosmic dawn. Attempts to explain the size of the signal include either new physics (Barkana 2018; Barkana et al. 2018; Berlin et al. 2018; Fraser et al. 2018; Hektor et al. 2018; Liu & Slatyer 2018; Muñoz & Loeb 2018; Pospelov et al. 2018) or astrophysics (Ewall-Wice et al. 2018; Feng & Holder 2018). At the present time, it is still unclear whether all of these proposed explanations are physically possible and/or consistent with other measurements, as many proposals are already disfavored by more careful analysis.

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\(^2\) See Pritchard & Loeb (2012) for a review of the physics of the cosmic dawn and the 21 cm line.

In this Letter we ignore the depth of the absorption signal, and focus on its shape—the sharp boundary and subsequent flat bottom indicate that Ly\( \alpha \) photons flooded most of the universe within a small fraction of a Hubble time (\( \delta z \sim 2 \) at redshift \( z \sim 20 \)), followed by an extended period (\( \delta z \sim 2 \)) with little to no heating before the gas temperature quickly rose and diminished the absorption signal. Our main objective is to see what observational consequences this feature of the signal has on the expected 21 cm power spectrum. Whatever mechanism might be responsible for the anomalous depth of the signal could also change other characteristics of it, so one might view our study independently of the EDGES results as an exploration of a part of parameter space not yet considered.

In Section 2 we argue that the EDGES signal implies that sources of ultraviolet (UV) emission are hosted in very massive and rare halos. Then, in Section 3 we describe our model of inhomogeneous coupling and heating (ignoring X-ray heating). In Section 4 we discuss the observational consequences of our model, and in Section 5 we briefly compare our results with other studies. Throughout this Letter we use the Planck 2015 cosmological parameters (Planck Collaboration et al. 2016).

2. Order of Magnitude Estimates

The sharpness of the brightness temperature drop between \( z = 21 \) and 19 (see Figure 3) implies that the Ly\( \alpha \) background grows dramatically during this time. In order to estimate by how much the Ly\( \alpha \) background needs to increase we perform the following estimate. Given that the ratio of the rms of the noise to the amplitude of the signal is 0.025/0.5 \( \sim 5\% \) (Bowman et al. 2018), we can definitively say that the amplitude grew from 20\% and 80\% of its maximum in \( \delta z \lesssim 2 \). Because the brightness temperature is proportional to \( x_\alpha/(1+x_\alpha) \), where \( x_\alpha \) is the Ly\( \alpha \) coupling coefficient that is proportional to the Ly\( \alpha \) background, we can conclude that the Ly\( \alpha \) background grew by factor of \( \gtrsim 16 \).

Such a rapid growth within a narrow redshift range can be associated only with dramatic changes in certain properties of the UV sources. One possibility is that the physics of star formation changes with redshift...
formulation abruptly changed, but it is difficult to justify why it occurred within this particular narrow redshift interval. Another plausible explanation, one that we adopt, has to do with the abundance of the host halos of the sources. At any given redshift, the abundance of halos at the massive end of the mass function grows exponentially; from \( z \approx 21 \) to 19 the halos whose abundance increases by more than a factor of 16 satisfy \( \log_{10}(M/M_\odot) \gtrsim 9.3 \) (see the orange boundary in Figure 1). The rapid evolution of the 21 cm signal implies that the UV sources reside in these massive halos.

On the other hand, the UV sources have to be sufficiently abundant for a significant fraction of the universe to be coupled. Given that the light travel distance between \( z = 21 \) and 19 is \( \approx 113 \, h^{-1} \text{Mpc} \), sources should have a number density greater than \( 10^{-6.8} \) halos per \( (h^{-1} \text{Mpc})^3 \). This constraint corresponds to halo masses \( \log_{10}(M/M_\odot) \gtrsim 9.7 \) (see green boundary in Figure 1).

In summary, the two mutually compatible constraints provide us with a mass range \( 9.3 \lesssim \log_{10}(M/M_\odot) \lesssim 9.7 \) for the lightest halos that efficiently formed the first stars. Note that these halos are significantly more massive than the widely accepted minimum halo mass of \( \sim 10^9 M_\odot \) for the first star formation (Bromm 2013). In the next section, we explore the hypothesis of rare UV sources and study how such a scenario can affect the 21 cm power spectrum.

### 3. Inhomogeneous Coupling

The dynamic range of the problem (halos of \( \sim 10^9 M_\odot \), separated by \( 100 h^{-1} \text{Mpc} \)) does not allow us to run a full \( N \)-body dark matter simulation. We instead use an approximate method to populate the volume with halos based on the assumption of log-normal probability density function of galaxy and matter density fields (Coles & Jones 1991; Hand et al. 2017).

We adopt a 256 \(^3 \) mesh in a \( (640 h^{-1} \text{Mpc})^3 \) volume, generate the initial conditions, and evolve them with the Zeldovich approximation to the last epoch of our simulation at \( z = 13 \). We then populate the volume with halos using the mass function and the bias prescription from Sheth et al. (2001). In order to generate halo catalogs at higher redshifts, we modify the halo catalog at \( z = 13 \) by reducing the masses to match the mass function at any given redshift (similar to the abundance matching technique). In other words, we assume gradual growth of all halos through accretion with the rate proportional to their mass. We consider redshifts in range \( 13 < z < 30 \) with time step \( \Delta z = 0.1 \).

We assume that sources are hosted only in the dark matter halos with masses above \( M_{\text{thr}} \), and their emissivity is proportional to their mass.\(^3\) The spectral energy distribution is assumed to be flat between Ly\( \alpha \) and Ly\( \beta \) in terms of number of photons per frequency bin.

At each redshift step and in each cell of the simulation box, we evaluate the Ly\( \alpha \) background as the sum of the UV radiation from all sources that redshift into Ly\( \alpha \) at a given location, taking into account finite speed of light (“light-cone” effect). Knowing the Ly\( \alpha \) background in each cell as a function of redshift and the local linearly growing overdensity, we solve the thermal history and calculate the brightness temperature of the 21 cm line, taking into account both Ly\( \alpha \) and CMB heating using the same technique as in Venumadhav et al. (2018).

For the sake of comparison, we also run a “smooth” simulation in which we distribute the UV sources in all cells according to the clustering bias of their sources, instead of explicitly creating individual halos. This approach assumes the same mass function and bias, and as a result has the same total number of emitted photons as our fiducial simulation. However, by construction this simulation does not incorporate any shot noise.

We can change the duration and the moment of the coupling by adjusting \( M_{\text{thr}} \) and the normalization of the flux. Our fiducial model shown in Figures 2–4 uses \( \log_{10}(M_{\text{thr}}/M_\odot) = 9.4 \). In Figure 5 we show that the model with \( \log_{10}(M_{\text{thr}}/M_\odot) = 9.2 \) cannot fit the detailed shape of the global signal—it either couples fast enough but too early, or starts to couple at the right time but does so too slowly.

One possible caveat is that the choice of the halo mass function can change the quantitative result of this study, because different mass functions can significantly vary at high masses. For example, the value of \( M_{\text{thr}} \) that leads to an order of magnitude change in the abundance over the required period

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\(^3\) This assumption is equivalent to a constant star formation efficiency \( f_s \). Replacing it with a more sophisticated model does not dramatically change our results, as the flux is dominated by halos in a very narrow mass range and the considered time interval is short.
will be slightly different, and the abundance of these halos would change. However, the results that we present should remain qualitatively unchanged.

4. Results and Discussion

The sharpness of the coupling side of the absorption feature tells us that the sources of the UV photons are likely to reside in the massive halos. For our fiducial model we assume that the majority of star formation happens in dark matter halos with masses $\log_{10}(M_{\text{halo}}/M_\odot) > 9.4$. In Figure 3 we show this model can produce a global absorption feature similar to the EDGES best fit scaled by a factor of 0.4, while the models with lower $M_{\text{halo}}$ do not produce a sharp feature at a given redshift (see Figure 5 for an example).

The bottom panel of Figure 3 shows the evolution of the 21 cm power spectrum, which exhibits multiple local maxima. The dimensionless power spectrum at a number of characteristic epochs is shown in Figure 4. The first peak in the power spectrum at $z \sim 19.7$ corresponds to the shot noise due to the finite number of Ly$\alpha$-coupled bubbles (see Figure 2). Subsequently, at $z \sim 15.5$ we have the analogous effect due to the CMB heating, whose amplitude is lower since the number of sources by that moment has greatly increased.

The power spectrum in these peaks is completely dominated by the shot noise. To illustrate this we compare it with that in the “smooth” simulation, in which photon sources are distributed smoothly across the cells according to the clustering bias, i.e., with no discrete halos. By construction, such a simulation does not include any shot noise. In the bottom panel of Figure 5, we compare the amplitude of the fluctuations in the two models. It can be clearly seen that the shot noise amplifies the peak of Ly$\alpha$ coupling by two orders of magnitude, and thus dominates the signal. The model that we explored is one with almost the most prominent effect of shot noise; however, shot noise can be important even in much less extreme models. The shot noise during the Ly$\alpha$ coupling was studied with a full numerical simulation at much lower redshifts ($z \sim 12$) in Kaurov (2017), in which the effect on the power spectrum was estimated to be at $5\%$–$10\%$.

The Astrophysical Journal Letters, 864:L15 (5pp), 2018 September 1
Kaurov et al.

Figure 2. Inhomogeneous brightness temperature (top row) and the kinetic gas temperature (bottom row) at six characteristic epochs in $(640 \, h^{-1}\text{Mpc})^3$ box for our fiducial model with $\log_{10}(M_{\text{halo}}/M_\odot) = 9.4$. From right to left: at $z \sim 24$ no sources have formed yet, and the temperature follows density perturbations that are very small; at $z \sim 22$ the first coupling bubble starts to form, the kinetic temperature is still almost uniform, and the power spectrum (PS) of 21 cm is dominated by one bubble; at $z \sim 19.7$ we have the intermediate stage of coupling with a lot of bubbles, and the PS is dominated by the shot noise; at $z \sim 17.7$ the universe is coupled everywhere and not heated yet, the PS reaches local minimum; at $z \sim 15.5$ the inhomogeneous heating kicks in and produces, again, a signal in the PS dominated by the shot noise; finally, at $z \sim 13.4$ the number of sources is high enough to produce an almost uniform heating.

Figure 3. Top panel: the EDGES best fit for 21 cm line brightness temperature scaled by 0.4 is shown with a red dashed line, and our fiducial model with $\log_{10}(M_{\text{halo}}/M_\odot) = 9.4$ is shown with a blue solid line. Bottom panel: the power spectrum of the 21 cm line at each redshift. Vertical lines correspond to the redshifts that are shown in Figures 2 and 4.

The observation of those two peaks in the 21 cm power spectrum would be a confirmation of the EDGES results, and shot-noise enhancement of the power spectrum makes it a promising observational target.
Figure 4. Dimensionless power spectrum at reference redshifts shown in Figures 2 and 3. At redshifts 19.7 and 15.5, the power spectrum is dominated by the shot noise.

Figure 5. Top panel: the EDGES best fit and our fiducial model with \( \log_{10}(M_{\text{halo}}/M_\odot) = 9.4 \) repeat Figure 3. The orange line shows the “smooth” model with the same number of Ly\( \alpha \) photons, but without the shot noise. The dotted green lines correspond to the model with \( \log_{10}(M_{\text{halo}}/M_\odot) = 9.2 \) and different normalization parameters; they show that they fit into the data much worse compared to the fiducial model. Bottom panel: the fluctuation amplitude of the 21 cm line for \( k = 0.03 \) and 0.1 \( h \) Mpc\(^{-1}\) as a function of redshift for the fiducial model and the “smooth” model.

5. Comparison with Previous Studies

Inhomogeneous Ly\( \alpha \) coupling has been taken into account in many previous studies. The signal from the individual coupled bubbles was studied in Barkana & Loeb (2005). In the simulations by Baek et al. (2009), Vonlanthen et al. (2011), and Zawada et al. (2014) the shot noise is explicitly included in the simulations, but the considered redshifts are much lower.

In a survey of the parameter space for cosmic dawn by Cohen et al. (2017a), the authors adopted a grid with 3 \( h^{-1} \) Mpc resolution and calculated the total flux generated in each cell, assuming a sub-grid model for the local mass function of halos (see the description of the code in Visbal et al. 2012; Fialkov et al. 2014). This approach is similar to our “smooth” simulation and is valid when each cell contains a large number of sources. In the regime implied by the EDGES results, the sources are very sparse, and hence the shot noise necessarily has to be taken into account. For this reason, the amplitude that we have found is more than an order of magnitude larger.

The amplitude of the fluctuations that we have found for the fiducial model is similar to the one found by Ghara et al. (2015), where a DM simulation was used to locate halos in a 100 \( h^{-1} \) Mpc box with masses resolved down to \( \sim 10^9 M_\odot \); and smaller masses accounted for with a sub-grid model. In contrast to that simulation, we have focused on the rapid coupling process at \( z \sim 20 \), and to do so we adopted a larger box in order to capture the rarest halos. In result, we were able to
explicitly show the shot-noise contribution to the power spectrum.

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Software: nbodykit (Hand et al. 2017), hmf (Murray et al. 2013), colossus (Diemer 2017).

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