Maximum Absorption of the Global 21 cm Spectrum in the Standard Cosmological Model

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Abstract

The absorption feature in the global spectrum is likely the first 21 cm observable from the cosmic dawn, which provides valuable insights into the earliest history of structure formation. We run a set of high-resolution hydrodynamic simulations of early structure formation to assess the effect of nonlinear structure formation on the maximum absorption level (i.e., assuming the spin temperature coupling is saturated) of the global 21 cm spectrum in the standard cosmological framework. We ignore the star formation and feedbacks, which also tend to reduce the absorption signal, but take into account the inevitable nonlinear density fluctuations in the intergalactic medium (IGM), shock-heating, and Compton-heating, which can reduce the absorption level. We found that the combination of these reduced the maximum absorption signal by \(\sim 15\%\) at redshift 17, as compared with the homogeneous or linearly-fluctuating IGM. These effects have to be carefully accounted for when interpreting the observational results, especially when considering the necessity of introducing new physics.

Unified Astronomy Thesaurus concepts: Reionization (1383); Radio astronomy (1338); Cosmic background radiation (317); Large-scale structure of the universe (902)

1. Introduction

The spectrum of the sky-averaged 21 cm brightness temperature, or the so-called global 21 cm signal, provides valuable information on the early history of structure formation, from the dark ages to the cosmic reionization (e.g., Pritchard & Loeb 2012). The EDGES experiment has reported the detection of an absorption trough with a depth of \(\delta T_{21} = -500^{+200}_{-500}\) mK (99% confidence level) corresponding to the cosmic dawn (Bowman et al. 2018), which is unexpectedly large as compared with theoretical predictions from the standard model. Although the claimed signal may be affected by instrumental effects (e.g., Bradley et al. 2019), mis-modeled foregrounds (e.g., Hills et al. 2018), or data analysis systematics (e.g., Singh & Subrahmanyan 2019), various theoretical works have been trying to explain the signal level by introducing new physics. These models invoke a variety of mechanisms to explain the large absorption, e.g., extra cooling of the cosmic gas (e.g., Barkana 2018; Muñoz & Loeb 2018; Fialkov et al. 2018; Barkana et al. 2018; Slatyer & Wu 2018; Hirano & Bromm 2018; Muñoz et al. 2018; Houston et al. 2018; Li et al. 2018), extra source of early radio background in addition to the cosmic microwave background (CMB) (e.g., Feng & Holder 2018; Ewall-Wice et al. 2018; Fraser et al. 2018), or modified Hubble expansion rate (Costa et al. 2018; Wang & Zhao 2018).

Many other experiments with a variety of designs are also trying to measure the global 21 cm signal, such as the SARAS (Singh et al. 2018a), PRIZM (Philip et al. 2019), SCI-HI (Voytek et al. 2014), BIGHORNS (Sokolowski et al. 2015), LEDA (Price et al. 2018), and ASSASSIN (McKinley et al. 2020) from ground, and the planned DAPPER (Burns et al. 2021) and Discovering the Sky at the Longest wavelengths (DSL) (Chen et al. 2020) from space. In particular, the SARAS-2 has already put some constraints on the 21 cm spectrum, and disfavors models that feature weak X-ray heating along with rapid reionization (Singh et al. 2018b).

To correctly interpret the observations, it is important to calculate the 21 cm absorption level precisely, taking into account various effects. Although the absorption feature in the global 21 cm spectrum is produced by gas that is still quite homogeneous during the cosmic dawn, where the volume fraction of collapsed halos are still small, the budding inhomogeneity can still affect the result. Xu et al. (2018) investigated the effect of gas inhomogeneity on the maximum absorption level of the global 21 cm spectrum. It was found that the nonlinearity of the gas density fluctuations induced by the structure formation, and the associated adiabatic heating, suppress the signal level significantly.

Note that the 21 cm absorption feature is produced by the neutral hydrogen with a spin temperature lower than the CMB temperature at that epoch (Chen & Miralda-Escudé 2004, 2008). The neutral hydrogen spin temperature would generally fall somewhere between the gas kinetic temperature and CMB temperature, depending on the intensity of the Ly\(\alpha\) background, which couples the spin and kinetic temperatures of the gas. By maximum, we are referring to the case that the spin-kinetic coupling of the gas is saturated, such that the spin temperature is equal to the kinetic temperature, and the largest amount of absorption is produced. In realistic models, by the time a strong Ly-\(\alpha\) background is set up by star formation and black hole accretion, some amount of ionization and heating would have already taken place. The ionized gas would not contribute to the 21 cm signal, while the neutral gas heated above the CMB temperature would appear in the 21 cm emission, reducing the total amount of 21 cm absorption. The
ionization and radiation induced heating would, however, depend on many modeling details, which results in a variety of spectrums (Cohen et al. 2017). However, to assess the necessity of new physics, we can focus on the maximum absorption case. As all of these effects reduce the absorption, one can obtain a very conservative limit if we ignore them.

However, the analytic estimates in Xu et al. (2018) should only be taken qualitatively, as the large-scale clustering of halos and the structure formation shocks that are inevitable during the cosmic dawn are not easy to model analytically. Also, the adopted density profile for the intergalactic medium (IGM) around collapsed halos from the infall model only applies to density peaks (Barkana 2004). Applying it to the whole IGM of any environment requires an artificial normalization, which may result in an inaccurate level of gas density fluctuations and the resultant 21 cm signal. Recently, Villanueva-Domingo et al. (2020) has also investigated, analytically, the maximum amplitude of the high-redshift 21 cm absorption feature, accounting for 21 cm heating, Lyα heating, and the density fluctuations. Adopting the nonlinear density distribution of the MHR00 model (Miralda-Escudé et al. 2000), they found that the density fluctuations result in a decrement in the absolute value of ~10% in the maximum 21 cm absorption.

In this work, we focus on the maximum signal level of 21 cm brightness from cosmic dawn within the standard framework, i.e., assuming neither extra cooling nor extra radio background from new physics, a fully neutral IGM before reionization, and saturated coupling between the spin temperature of neutral hydrogen and the kinetic temperature of gas. However, we do consider the inevitable standard model evolutions, such as nonlinear structure formation and Compton–heating. To incorporate more reliable density profiles of gas in the IGM, for both over-dense and under-dense regions, and to include the clustering effect of nonlinear structures, we use a set of high-resolution hydrodynamic simulations to compute the expected global 21 cm signal at high redshifts, and discuss various effects that impact the signal level.

This paper is organized as follows. We describe our simulations set and present some basic results in Section 2, and then we discuss the effects of density profiles, the shock-heating and Compton-heating, and the large-scale clustering in Section 3. We conclude in Section 4. Throughout this paper, we adopt the ΛCDM model with the Planck 2018 cosmological parameters (Planck Collaboration et al. 2020).

2. Simulation and the Maximum Signal

We use hydrodynamical simulations to investigate the effects of nonlinear structure formation on the global 21 cm signal from cosmic dawn. In this section, we will first describe our simulation setup, and make some checks.

2.1. Simulation

We carry out our cosmological simulations by the publicly available code GADGET-2 (Springel et al. 2001; Springel 2005), which uses the smoothed particle hydrodynamics (SPH) method to solve the gas dynamics equations. The publicly available version does not involve radiative heating/cooling and the chemistries that are necessary for correctly modeling the gas temperature evolution. We add the evolution of the free electrons, H and He ions, and the associated cooling/heating processes. Free electrons are essential in the global IGM temperature evolution. The initial free electron abundance and gas temperature are computed from the epoch of recombination using the RECFAST code (Seager et al. 1999). We ignore, here, the formation of H2 and the cooling it induced, as we are focusing on the nonlinear structures that have not yet experienced star formation processes. The homogeneous gas temperature and ionization state are evolved by solving the equations

\[
\frac{dT_{K}}{dt} = -2H(z)T_{K} - \frac{2(\Lambda_{\text{net}}(T_{K}))}{3k_{B}n_{\text{tot}}},
\]

\[
\frac{dn_{\text{HII}}}{dt} = -3n_{\text{HII}}H(z) + \gamma_{\text{HII}}(T_{K})n_{\text{HII}}n_{e} - \alpha_{\text{HII}}(T_{K})n_{\text{HII}}n_{e},
\]

\[
\frac{dn_{\text{HeII}}}{dt} = -3n_{\text{HeII}}H(z) + \gamma_{\text{HeII}}(T_{K})n_{\text{HeII}}n_{e} - \alpha_{\text{HeII}}(T_{K})n_{\text{HeII}}n_{e},
\]

\[
\frac{dn_{e}}{dt} = \frac{dn_{\text{HII}}}{dt} + \frac{dn_{\text{HeII}}}{dt},
\]

where \(n_{\text{HII}}, n_{\text{HeII}}, n_{\text{HeII}}, \text{ and } n_{e}\) are the physical numberdensities of neutral hydrogen, ionized hydrogen, neutral helium, singly ionized helium, and electrons, respectively; \(\gamma_{\text{HII}}\) and \(\gamma_{\text{HeII}}\) are the recombinations rates; \(\alpha_{\text{HII}}\) and \(\alpha_{\text{HeII}}\) are the collisional ionization rates that are in fact negligible, and \(\Lambda_{\text{net}}\) is the net cooling rate. In the gas temperature evolution, we include the Compton scattering and Bremsstrahlung, as detailed in Maselli et al. (2003).

In Figure 1, we plot the evolution of the mean gas temperature in a simulation that has a box size of 4 Mpc \(h^{-1}\), 800^3 dark matter particles, and 800^3 gas particles, respectively. The filled circles show the arithmetic mean temperature of all

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5 https://wwwmpa.mpa-garching.mpg.de/gadget/

6 https://www.astro.ubc.ca/people/scott/recfast.html
gas particles, including those within and near halos that are shock-heated, while the dashed line corresponds to the average over gas particles with density contrast $|\delta| < 0.05$, which is likely less affected by the shock-heating.

The expected temperature evolution for the homogeneous gas solution of Equation (1) is plotted with the blue solid line in the same figure. The simulation correctly captures the global temperature evolution trend for the mean-density gas, and it shows that the shock-heating effect becomes significant at $z \lesssim 25$. Note that the arithmetic mean temperature is significantly boosted by the small number of gas particles with high temperatures in the halos. As will be discussed later (Section 4), there is still no real consensus on the exact magnitude of the shock-heating effect. Our following results are based on the GADGET-2 simulation that adopts the SPH algorithm, and predicts a reasonable evolution of the mean gas temperature.

For monoatomic gas that experiences only adiabatic compression without shock-heating, radiative heating/cooling, or any change of chemical species, a relation between the gas temperature and the density builds:

$$T_K(\Delta) = T_0 \Delta^{2/3},$$

where $T_0$ is the temperature of the mean-density gas. This adiabatic relation is widely adopted when estimating the IGM temperature analytically. However, during the cosmic evolution, even before the formation of any luminous objects, the Compton-heating that arises from the scattering with the CMB photons and the shock-heating in the over-dense regions that are undergoing nonlinear structure formation can affect the gas temperature and break this relation. The left panel of Figure 2 shows the probability distribution of particles on the $T_K - \Delta$ plane from our simulation at $z = 17$. The right panel shows the probability distribution of particles on the $(1 - T_{\text{CMB}}/T_K) - \Delta$ plane, which is more closely related to the 21 cm brightness temperature. The color denotes the number density of particles in the corresponding spaces. It is seen from the left panel that the power-law relation is clearly broken in the simulation. For $\Delta \lesssim 1$ the deviation is mainly due to the Compton-heating, while for $\Delta \gtrsim 1$ the shock-heating is the main source of heating. It is, therefore, essential to take the Compton-heating and shock-heating into account.

Note that, however, the shock-heated gas only occupies a small volume fraction. If we define the shock-heated region as those overdense regions with temperatures higher than the adiabatic temperature of Equation (2) by a fraction of 30%, 50%, or 100%, then the shock-heated volume fractions are 3.5%, 2.5%, and 1.5%, respectively.

### 2.2. The Maximum 21 cm Signal

We convert the particle field into the density field with the Cloud-in-Cell method, and calculate the global 21 cm signal from the simulation. The 21 cm brightness temperature from a uniform cell in the simulated box is

$$\delta T_{21} = \frac{T_S - T_e}{1 + z} (1 - e^{-\tau}),$$

where $T_S$ is the spin temperature of the neutral hydrogen, $T_e$ is the brightness temperature of the background radiation, and $\tau$ is the 21 cm optical depth. In the absence of any extra radio background at cosmic dawn (e.g., Ewall-Wice et al. 2018), the only radio background is the CMB, so that $T_e(z) = T_{\text{CMB}}(z)$. As the peculiar velocity has only negligible effect on the sky-averaged 21 cm signal (Xu et al. 2018), the optical depth can be written as

$$\tau = \frac{3}{16} \frac{h c^3 A_{10}}{k_B \nu_{21}^2 T_S} n_{\text{HI}} H(z),$$

where $A_{10} = 2.85 \times 10^{-15} \text{s}^{-1}$ is the Einstein coefficient for the spontaneous decay of the 21 cm transition, $\nu_{21} = 1420.4 \text{MHz}$ is the frequency of the transition, and $n_{\text{HI}}$ and $H(z)$ are the local neutral hydrogen number density and the Hubble parameter, respectively. In the present work, we focus on the maximum absorption signal of 21 cm that is achievable in the standard $\Lambda$CDM model. Therefore, in all the following calculations, we assume saturated coupling between the spin temperature of hydrogen and the kinetic temperature of the gas, so that $T_S = T_K$. The 21 cm global signal is computed by averaging the
21 cm brightness temperature over all the cells in the simulation. The spectra of the maximum 21 cm absorption from several simulations are plotted in Figure 3. The shaded regions of the same color as the corresponding lines indicate the jackknife errors in the corresponding spectra. The expected spectrum from the homogeneous IGM, with the homogeneous solution for the gas temperature (the blue solid line in Figure 1), is plotted with the dotted line for comparison. It is seen that the nonlinear structure formation affects the 21 cm absorption level obviously; the homogeneous assumption of the IGM would overestimate the absorption. The effect gets more and more significant for lower redshifts, as more nonlinear structures form.

The solid and dashed lines with different colors in Figure 3 show results from simulations of different box sizes and resolutions. As the redshift decreases, the large-scale perturbations become more and more important, and a limited box size would underestimate the effect of nonlinear structure formation because of the delayed structure formation. This is seen from the solid magenta line predicted by the simulation with a box size of 0.4 Mpc\(^{-1}\), 8 Mpc\(^{-1}\), and 4 Mpc\(^{-1}\), respectively. The solid and dashed lines correspond to results from simulations with particle numbers of 2 \times 800\(^3\) and 2 \times 400\(^3\), respectively. The black dotted line represents the maximum signal level expected from the homogeneous IGM. The shaded regions of the same color as the corresponding lines indicate the jackknife error.

In the following analysis, we will take the simulation with 4 Mpc\(^{-1}\) size and 2 \times 800\(^3\) particles as the fiducial simulation. From the fiducial simulation, at \(z = 17\), where the EDGES absorption trough locates, the 21 cm absorption signal is \(-190\) mK. The absorption amplitude is reduced by 15% with respect to (w.r.t.) the homogeneous IGM case at this redshift, when the nonlinear structure formation is taken into account. The effects are more significant as the IGM becomes more nonlinear.

### 2.3. Under-resolved Signal

In order to survey a large parameter space and investigate the various effects on the global 21 cm spectrum, a set of semi-numerical simulations is usually used to compute the signal (e.g., Cohen et al. 2017). This kind of simulation usually covers a sufficiently large volume while not having a high enough resolution to resolve nonlinear structures, such as halos and their ambient gases, though the shock-heating effects could be implemented with a sub-grid algorithm. Therefore, it is necessary to see the effect of losing small-scale structures while keeping large-scale fluctuations just as a semi-numerical simulation does.

In Figure 4, we compare our high-resolution hydrodynamic simulation with the low-resolution ones typically used for semi-numerical simulation. The thick dashed line shows the expected signal from a simulation with a box size of 600 Mpc\(^{-1}\) and a particle number of 2 \times 600\(^3\), a typical resolution of a semi-numerical simulation. It shows that, in the low-resolution simulation with only linear density perturbations, it would overestimate the global 21 cm signal significantly, predicting an absorption level similar to the homogeneous IGM case. Therefore, one needs to achieve a resolution of nonlinear scales, or to implement a sub-grid algorithm for the shock effects (e.g., Furlanetto & Loeb 2004), to account for the small-scale effects on the sky-averaged signal.

### 3. Dependence on Different Effects

We now look more closely at the various aspects, including the density and temperature dependence, and the large-scale clustering, that would have impacts on the maximum signal level of the global 21 cm spectrum.
3.1. The IGM Density

In Xu et al. (2018), by assuming the analytical infall model, we found that the weakly nonlinear gas around collapsed halos is adiabatically heated and could affect the global absorption signal. Now we study the dependence on the local over-density and density profiles of the IGM in this section.

Figure 5 shows the averaged optical depth (left panel) and the 21 cm brightness temperature (right panel) averaged over over-dense pixels (all pixels with $\delta > 0$, blue dashed line) and that averaged over under-dense pixels (all pixels with $\delta < 0$, red dotted–dashed line). The thick solid line shows the averaged values over all pixels in the simulation, and the thin solid line in each panel represents the spectrum expected from the homogeneous IGM.

The gas in halos is shock-heated to a temperature close to the halo virial temperature, suppressing substantially its contribution to the 21 cm absorption, and the main contribution to the 21 cm absorption signal during the cosmic dawn comes from the gas in the less-heated IGM. The formation of dark matter halos, however, enhances the gas density surrounding them, resulting in nonlinear density fluctuations in the vast IGM. Here we investigate how the detailed density profiles affect the predicted global 21 cm signal.

In Figure 6, we plot the density profiles of halos with $M \sim 10^6 M_\odot$ at redshift $z = 17$. Right: the density profiles of halos with $M \sim 10^7 M_\odot$ at $z = 17$.

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including the halo position and mass information, from the hydrodynamic simulation, but assign an artificial density profile to the IGM around each halo as prescribed by the infall model, further normalized such that the minimum density is zero, and the mean density equals the cosmic mean. Note that the infall model is appropriate for halo surroundings that are located in density peaks, but may not be applicable for under-dense environments. By introducing this artificial normalization, we mimic the existence of under-dense regions while keeping the cosmic mean density. However, we caution that this artificial density profile, as shown by the blue dotted-dashed lines in Figure 6, is unphysical, and here we only use it to investigate the effect of a steeper density profile on the global 21 cm signal.

A mock adiabatic temperature is assigned to each pixel according to the local density using the adiabatic relation of $T_k \propto \rho^{2/3}$ for the ideal gas, with the mean-density gas having a temperature of 6.46 K at redshift 17, consistent with the homogeneous gas temperature calculated with Equation (1), i.e., the blue solid line in Figure 1. We call this temperature the mock adiabatic temperature as it accounts for the adiabatic heating or cooling according to the local density, but the Compton-heating is taken into account when determining the mean-density gas temperature, which is not purely adiabatic.

The resulting 21 cm signal is $-208$ mK ($\sim 7\%$ decrement in the absolute value w.r.t. the homogeneous IGM case) at $z = 17$, as compared to $-213$ mK ($\sim 5\%$ decrement in the absolute value) at the same redshift if we adopt the density field from the hydrodynamic simulation with the corresponding mock adiabatic temperature. We find that the steeper density profile, or equivalently a higher level of density fluctuations, results in weaker absorption in the 21 cm signal, but the effect is only moderate.

### 3.2. Gas Temperature

In Section 2.1, we have seen that the shock-heating and Compton-heating can make the gas temperature deviate significantly from the $T_k \propto \Delta^{2/3}$ relation (Figure 2). These effects may play a significant role in determining the 21 cm signal level during the cosmic dawn. Here we run another two simulations with the same initial condition as the fiducial simulation; in one simulation, we turn off the shock-heating (in GADGET-2, this is controlled by a parameter named artificial viscosity), and in the other one, we remove both the shock-heating and the Compton-heating terms. We make a detailed comparison between the temperature profiles from the hydrodynamic simulations with or without these heating effects and test their impacts on the 21 cm signal.

Figure 7 shows the gas temperature profiles of the IGM surrounding halos with mass $\sim 10^6 M_\odot$ (top panels) and $\sim 10^7 M_\odot$ (bottom panels) at redshift $z = 17$. For each panel, we plot the temperature profiles from the fiducial simulation, the simulation without shock-heating, and the simulation without either shock-heating or Compton-heating, respectively. In each row, the left panel shows the median gas temperature at the various distances with the error bars being the standard deviation of the median temperature, while the right panel shows the 90% upper limit of the temperature distributions and the corresponding standard deviation. As a reference, we also plot the mock adiabatic temperature profile derived from the infall model. Although the scatter among halos is quite large, it is clear that the shock-heating significantly increases the gas temperature in over-dense regions near halos, and the Compton-heating dominates the heating effect in the vast under-dense regions. As a result, the adiabatic assumption for the IGM temperature would substantially overpredict the 21 cm absorption level, as shown in Figure 8, which compares the global 21 cm spectrum from the fiducial simulation (thick solid line) with the mock adiabatic gas temperature (dashed line). Because of the shock-heating and the Compton-heating incorporated in the hydrodynamic simulation, the 21 cm signal at redshift 17 is further suppressed to be $-190$ mK ($\sim 15\%$ decrement in the absolute value w.r.t. the homogeneous IGM case), as compared to $-213$ mK ($\sim 5\%$ decrement in the absolute value) in the case considering only the gas density fluctuations and the mock adiabatic temperature.

Interestingly, in Figure 7, we find that between $\sim 0.01 - 1 h^{-1} Mpc$, the temperature profile in the fiducial simulation has large scatters. It implies that the gas in these regions experienced complicated dynamical processes. The shock-heating makes this over-dense gas optically thin for the 21 cm signal. However, it is very hard to observationally resolve these shocked regions. During the cosmic dawn, the shock-heated regions only occupy a small volume fraction, but they result in $\sim 10\%$ decrement in the global 21 cm signal. The global 21 cm signal may provide some clue on these shock effects.

To investigate the heating effect in regions with different densities, we divide the box into $4 \times 4 \times 4$ sub-boxes. Each sub-box has the same size of $1 Mpc h^{-1}$ and a different local density $\delta_{\text{local}}$. In Figure 9, we plot the mean 21 cm brightness temperature of the sub-boxes as a function of their local mean overdensity at $z = 17$, for our fiducial simulation (black dots), and for the case with the fiducial density field and the mock adiabatic temperature (blue triangles). The stars of the corresponding colors indicate the average values over the whole box. The black solid line in the figure indicates the 21 cm brightness expected from a homogeneous IGM for comparison, while the cyan curve shows the 21 cm signals with the scaling of $\delta T_{21} \propto \rho^{1/3}$, which is expected for the cold gas ($T_9 \ll T_{\text{CMB}}$) in the linear regime. We find that, at under-dense regions, the scaling between the 21 cm brightness and the local overdensity is close to $\delta T \propto \rho^{1/3}$ if we assume the mock adiabatic temperature, while at over-dense regions, the relation deviates from this scaling significantly. The Compton-heating and shock-heating effects further suppress the 21 cm signal, which is more prominent in over-dense regions.

For the fiducial simulation and the mock adiabatic case, we find that a relation between the maximum 21 cm signal and the local overdensity of the form

$$\delta T_{21} = -\alpha \Delta_{\text{local}}^{\frac{1}{3}} \text{mK}$$

holds between $-0.2 < \delta_{\text{local}} < 0.2$. At redshift 17, we find $\log_{10} \alpha = 2.28$ and $\beta = 0.091$ for the fiducial simulation, while for the mock adiabatic case, we have $\log_{10} \alpha = 2.33$ and $\beta = 0.165$. The heating effects result in a weaker dependence of the maximal signal on the local overdensity. We also fit a redshift dependence of the parameters, i.e., $\log_{10} \alpha = 2.66 - 0.31 \log_{10}(1 + z)$, and $\beta = -1.540 + 1.299 \log_{10}(1 + z)$, for redshifts from 25 to 15. This fitted relation could be used in semi-numerical simulations with large box sizes but low resolutions, which would not be able to capture the shock-heating and nonlinear density fluctuations. Note, however, that
Figure 7. The gas temperature profiles around a \( \sim 10^6 \, M_\odot \) halo (top panels) and a \( \sim 10^7 \, M_\odot \) halo (bottom panels) at redshift 17. In each row, the left panels show the profiles of the median gas temperature, and the right panels show the upper boundaries of the 90% probability in the temperature distribution. The red, green, and blue curves correspond to the fiducial case, the case without shock-heating, and the case with both shock-heating and Compton-heating removed, respectively. Dashed lines represent the mock adiabatic temperature of the infall model, and the thin solid lines show the CMB temperature.

Figure 8. The 21 cm global spectrum, for the simulated gas temperature (thick solid line), mock adiabatic temperature (thick dashed line), and the homogeneous IGM (thin solid line).

Figure 9. The mean 21 cm brightness temperature of sub-boxes with different mean local densities at redshift \( z = 17 \). The black dots are the \( \delta T_{21} \) of sub-boxes from the fiducial simulation, the red circles are from the simulation with no shock-heating, and the blue triangles are the \( \delta T_{21} \) of the sub-boxes assuming densities from the simulation but with mock adiabatic temperatures. The black line indicates the \( \delta T_{21} \) expected from the homogeneous IGM, and the cyan line represents the \( \delta T_{21} \propto \rho^{1/3} \) scaling.
this fitted relation applies only to the 1 Mpc \( h^{-1} \) cells. A different smoothing scale would have a different scaling, and that would require a separate simulation with a relevant box size and resolution.

### 3.3. Shock-heating and Compton-heating

To distinguish the effect of shock-heating and Compton-heating, we also compare with a simulation in which only the shock-heating is turned off, the results at \( z = 17 \) are plotted as the red circle symbol in Figure 9. The mean 21 cm brightness temperature averaged over the whole simulation box is \(-200 \text{ mK}\), which is about 10% decrement in the absolute value w.r.t. the homogeneous IGM case. Comparing the various cases, we see the shock-heating and the Compton-heating have comparable effects in decreasing the 21 cm absorption signal, and this is consistent with the previous study by McQuinn & O'Leary (2012). In the absence of radiation sources, the shock-heating dominates the heating effects in over-dense regions, while the Compton-heating dominates the heating effect in under-dense regions.

Figure 10 shows the probability distribution of the fractional difference of the 21 cm brightness temperature between the pixels in the default simulation and the corresponding pixels in the simulation without shock-heating. For most pixels, the shock-heating results in a suppression of the 21 cm signal by a few percent, but there is a small fraction of pixels that are shock-heated significantly, resulting in a long tail in the probability distribution.

### 3.4. Halo Clustering

The large-scale clustering generated during the structure formation may also affect the global 21 cm signal. We investigate the effect of clustering by comparing two mock simulations; one uses the halo catalog with both mass and position information from the hydrodynamic simulation (“Mock-clustering” simulation), and the other uses only the halo mass catalog with random halo positions (“Mock-random” simulation). Both use the infall model with appropriate normalization to predict the gas density distribution in the IGM, and the mock adiabatic temperature is adopted. The mean 21 cm brightness temperatures of the 64 sub-boxes are plotted in the left panel for the “Mock-clustering” simulation and in the right panel for the “Mock-random” simulation, respectively, in Figure 11. Note the range of density fluctuations \( \delta_{\text{local}} \) are much smaller for the “Mock-random” case. With the clustered positions of halos, the averaged 21 cm brightness temperature is \(-208 \text{ mK}\) (the green star in the plot), which is about 7% decrement in the absolute value with respect to the homogeneous IGM case, while if the halos are randomly distributed, then \( \delta T_{21} \sim -213 \text{ mK} \), which is only about 5% decrement in the signal level. Therefore, the clustering effect also reduces the absorption level of the 21 cm signal, by introducing a higher level of density fluctuations, but the effect is only moderate.

### 4. Conclusions and Discussions

In this work, we investigate the maximum signal level of the global 21 cm spectrum from cosmic dawn that could be achieved in the standard cosmology, and discuss various theoretical effects that could have impacts on the absorption level. By running a set of high-resolution hydrodynamic simulations, we find that the nonlinear structure formation affects the IGM density and temperature distribution significantly. The shock-heating and Compton-heating, the nonlinear density fluctuations, and the halo clustering, all have nonnegligible effects reducing the 21 cm absorption signal. Under the assumption of saturated coupling between the spin temperature of hydrogen and the gas temperature, the maximum absorption level that is achievable in the standard framework is reduce by about 15% at redshift 17, as compare to the homogeneous IGM case.

Among the various effects considered here, the shock-heating during the nonlinear structure formation and the Compton-heating play a dominant role in reducing the maximum absorption level. The nonlinear density fluctuations with adiabatic heating can also reduce the contribution from over-dense regions, but the effect is moderate. The clustering of halos, on the other hand, also enhances the density fluctuations and reduces the 21 cm signal mildly. By comparing the density profiles in the simulated IGM and those predicted by the infall model, we find that the infall model provides a fairly reasonable prediction for the density distribution around density peaks in the IGM.

We note that the heating effect of structure formation shocks during the cosmic dawn is still somewhat uncertain. The early work by Gnedin & Shaver (2004) shows that the shock-heating has a dramatic effect, dominating over Ly-\( \alpha \) heating and X-ray heating at high redshifts, and reduces the 21 cm global absorption substantially. Nevertheless, latter works (Furlanetto & Loeb 2004; Furlanetto et al. 2006; McQuinn & O’Leary 2012) show that the structure formation shocks have only a modest effect in heating the gas, being subdominant to X-rays, though the relative importance depends on the timing of the X-ray heating. Even if we disregard the uncertainties in the X-ray production, there are still significant theoretical uncertainties on the structure formation shocks. To capture shocks, the SPH algorithm, which is adopted in the GADGET-2 used here, introduces an artificial viscosity to provide the entropy generated by the microphysics process. This introduces unphysical extra heating and broadens the shock front (Monaghan 1992; Springel 2005). It may lead to the overcooling problem (Creasey et al. 2011; Nelson et al. 2013), and produce artificial cold blobs near the star-forming regions (Hobbs et al. 2013). O’Shea et al. (2005) did find that the gas properties in the SPH and the adaptive mesh refinement (AMR)
based simulations generally agree with each other. In particular, McQuinn & O’Leary (2012) found that for the same resolution, the GADGET-2 and the AMR-based Enzo code give a quite similar evolution of the mean gas temperature. Our results are all based on the GADGET-2 simulations, and they provide reasonable predictions for the scales we are interested in. Nevertheless, Jia et al. (2020) noted that there is still significant divergence in the number and strength of structure formation shocks among different numerical schemes, such uncertainties could affect the results obtained here.

Throughout our calculation, we have assumed that the IGM is totally neutral during the cosmic dawn, in order to estimate the maximum absorption level. However, we note that the first star formation has to occur in massive halos at rare density peaks, so as to provide the necessary Ly-α photons for spin temperature coupling. In order to assess the effect of ionization in the densest regions, we select all possibly star-forming halos with a virial temperature threshold of $10^4$ K, and 16 star-forming halos are identified at redshift 17 in our fiducial simulation. Then the evolution of the radii of ionized bubbles around these individual star-forming halos can be computed (see, e.g., Xu et al. 2011). We assume a Salpeter initial mass function (with a power-law slope of $\alpha = 2.35$) for the first stars and a mass range of $1500 M_\odot$, and a fixed metallicity of $Z = 10^{-3}$, then the emission rate of ionizing photons can be determined from the ionizing continua of high-redshift starburst galaxies (Schaerer 2002, 2003). Adopting a clumping factor of 35 as appropriate for high-redshift IGM (e.g., Kaurov & Gnedin 2014; Mao et al. 2020), a star formation efficiency of $\epsilon_s = 0.01$, an escape fraction of $f_{\text{esc}} = 0.07$; we obtain a global ionized fraction of about 1%. Eliminating all the 21 cm signals from these ionized regions results in mild suppression of the absorption signal, with $\delta T_{21} \sim -189 \text{ mK}$ at $z = 17$. Note that the parameters for the first star formation are quite uncertain, and regardless of these uncertain parameters, the maximum 21 cm absorption signal is achieved if, exactly, the emission regions are ionized around the star-forming halos, and this signal is found to be still about $-190 \text{ mK}$, very close to the maximum signal level if the IGM is totally neutral. Therefore, the emission signal from these very over-dense regions is almost negligible as expected.

In the present work, we have focused on the maximum absorption level, and include only the Compton-heating and shock-heating effects that are inevitable during the cosmic dawn, isolating them from any other astrophysical heating related to radiation sources. Note that as more and more galaxies form, various feedback effects including photoionization and X-ray heating would gradually dominate over the shock-heating and Compton-heating, the nonlinear density fluctuations, and the clustering effects, reducing the global 21 cm absorption more significantly. Our results provide a modified signal base for any other feedback processes to take on further effects, and indicate that one has to take into account the effects of nonlinear structure formation in order to accurately interpret upcoming observational data, and/or infer any requirement of new physics (e.g., Barkana 2018; Yang 2020).

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*Data are available at [http://cdsarc.u-strasbg.fr/cgi-bin/Cat?VI/109](http://cdsarc.u-strasbg.fr/cgi-bin/Cat?VI/109).*
