High Mass X-ray Binaries and the Cosmic 21-cm Signal: Impact of Host Galaxy Absorption

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ABSTRACT

By heating the intergalactic medium (IGM) before reionization, X-rays are expected to play a prominent role in the early Universe. The cosmic 21-cm signal from this “Epoch of Heating” (EoH) could serve as a clean probe of high-energy processes inside the first galaxies. Here we improve on prior estimates of this signal by using high-resolution hydrodynamic simulations to calculate the X-ray absorption due to the interstellar medium (ISM) of the host galaxy, typically residing in halos with mass \(10^{7.5-8.5} M_\odot\) at \(z \sim 8-15\). X-rays absorbed inside the host galaxy are unable to escape into the IGM and contribute to the EoH. We find that the X-ray opacity through these galaxies can be approximated by a metal-free ISM with a typical column density of \(\log[N_{\text{HI}}/\text{cm}^{-2}] = 21.4^{+0.4}_{-0.6}\), with the quoted limits enclosing 68% of the sightline-to-sightline scatter in the opacity. We compute the resulting 21-cm signal by combining these ISM opacities with public spectra of high-mass X-ray binaries (thought to be important X-ray sources in the early Universe). Our results support “standard scenarios” in which the X-ray heating of the IGM is inhomogeneous, and occurs before the bulk of reionization. The large-scale \(k \sim 0.1 \text{ Mpc}^{-1}\) 21-cm power reaches a peak of \(\approx 100 \text{ mK}^2\) at \(z \sim 10-15\), with the redshift depending on the cosmic star formation history. This is in contrast to some recent work, motivated by the much larger X-ray absorption towards local HMXBs inside the Milky Way. Our main results can be reproduced by approximating the X-ray emission from HMXBs with a power-law spectrum with energy index \(\alpha \approx 1\), truncated at energies below 0.5 keV.

Key words: cosmology: theory – dark ages, reionization, first stars – diffuse radiation – early Universe – galaxies: evolution – formation – high-redshift – intergalactic medium – X-rays: diffuse background – galaxies – binaries – ISM

1 INTRODUCTION

The cosmic 21-cm signal promises to be a remarkable probe of the early Universe. Since the signal is sensitive to the thermal and ionization state of the intergalactic medium (IGM), upcoming low frequency interferometers will allow us to study the unseen population of galaxies and black holes during the first billion years of our Universe, prior to the completion of cosmic reionization. First generation interferometers, such as the Low Frequency Array (LOFAR; van Haarlem et al. 2013)1, the Murchison Wide Field Array (MWA; Tingay et al. 2013)2 and the Precision Array for Probing the Epoch of Reionization (PAPER; Parsons et al. 2010)3 are currently taking data, hoping for a statistical detection of the epoch of reionization (EoR). Second generation instruments, the Hydrogen Epoch of Reionization Array (HERA; DeBoer et al. 2016)4, and eventually the Square Kilometre Array (SKA; Koopmans et al. 2015)5 will have the sensitivity and frequency coverage to probe the 21-cm signal out to the birth of the first galaxies at \(z \sim 30\).

Since the IGM is seen in contrast against the CMB, the detectability of the signal is strongly dependent on their relative temperatures. The 21-cm line is seen in absorption while the IGM is colder than the CMB; when the IGM is heated to temperatures above the CMB, the signal transitions to being seen in emission. Simple estimates based on the observed X-ray luminosity \(L_X\) to star-formation rate (SFR) in galaxies out to \(z \lesssim 4\) (e.g. Mineo et al. 2012a; Basu-Zych et al. 2013), suggest that X-rays from early

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star-forming galaxies were sufficient to heat the IGM to temperatures above the CMB prior to reionization (e.g. Furlanetto 2006; McQuinn & O’Leary 2012). The fact that this “Epoch of Heating” (EoH) likely precedes the EoR, simplifies the interpretation of the 21-cm signal. The pre-EoR signal, while the IGM is still seen in absorption against the CMB, could thus serve as a clean probe of the X-ray processes inside the first galaxies.

The dominant source of these early X-rays is usually assumed to be high-mass X-ray binaries (HMXBs), which should appear only a few Myr after the first stars (e.g. Fragos et al. 2013a). Alternatively, the interstellar medium (ISM), heated by supernovae (SNe) and cooling through Bremsstrahlung and metal line cooling, can play a prominent role (e.g. Pacucci et al. 2014), given that the hot ISM and HMXBs are observed to have comparable soft band luminosities in local star-forming galaxies (e.g. Strickland et al. 2000; Grimes et al. 2005; Owen & Warwick 2009; Mineo et al. 2012b; Li & Wang 2013).

Additionally, Xu et al. (2014) postulated that the top-heavy initial mass function expected for the first, metal-free (PopIII) stars might have boosted the X-ray production in excess of estimates based on local IMFs. Although PopIII stars likely only dominate the cosmic SFR in the very first stages of the Cosmic Dawn (e.g. Salvaterra et al. 2011; Pallottini et al. 2014; Koh & Wise 2016), their X-ray luminosity per unit star formation could be large if they have a high binary fraction and/or strong accretion onto the majority of their remnants (e.g. Turk et al. 2009; Stacy et al. 2010; Stacy & Bromm 2013). Larger black holes at high-z, if surrounded by enough gas to fuel accretion (e.g. so-called mini-QSOs) could also contribute to the EoH (e.g. Yue et al. 2013; Ghara et al. 2016). An even more exotic source of heating is through the annihilation of dark matter particles, which can dominate the IGM heating rates in certain particle models (e.g. Evoli et al. 2014; Lopez-Honorez et al. 2016).

The bolometric X-ray luminosity per unit star formation of the first galaxies can be calibrated to observations of local galaxies or modeled with stellar population synthesis. However, the 21-cm signal during the EoH depends also on the X-ray spectral energy distribution (SED). Since the photo-ionization cross-sections of hydrogen and helium are strong functions of photon energy, low energy X-rays are able to more efficiently heat the IGM, provided they manage to escape the host galaxy. The SED also impacts the inhomogeneity of the EoH, with soft SEDs boosting the temperature fluctuations as heating is confined to the relative proximity of galaxies (Pacucci et al. 2014).

The X-ray SED emerging from the host galaxies is determined by (i) the intrinsic X-ray emission of the sources mentioned above (i.e. HMXB, hot ISM, mini-QSO); and (ii) the absorption within the host galaxy. It is very challenging to disentangle these two effects using observations of local X-ray sources at low energies (e.g. 1 keV). Low-energy photons (most relevant for the EoH) can easily be absorbed inside both the host galaxy and the Milky Way, making it difficult to test theoretical models of the intrinsic emission.

To compute the X-ray spectrum emerging from the first galaxies, we populate a high-resolution cosmological simulation with HMXBs (in post-processing), drawing random sight-lines through the simulation to compute the corresponding opacities. Below we discuss the procedure in detail.

The emerging spectrum along a line of sight (LOS) to a star forming system can be written as:

\[ L(E) = L_0(E) e^{-\tau_E(E)} \]

where \( E \) is the photon energy, \( L_0(E) \) the intrinsic spectrum of HMXBs in the system, and \( \tau_E(E) \) the optical depth along the LOS. We present all spectra in common units of the specific luminosity per unit star formation rate\(^7\), i.e. \( \text{erg s}^{-1} \text{keV}^{-1} M_{\odot}^{-1} \text{yr} \).

### 2.1 The intrinsic HMXB spectrum from population synthesis

The intrinsic HMXB emission spectrum, \( L_0(E) \), is taken from the publicly-available models presented in Fragos et al. (2013b)\(^8\). Fragos et al. (2013a) performed suites of population synthesis models using StarTrack (Belczynski et al. 2002, 2008), calibrated to observations of Galactic neutron star and black hole X-ray binaries at different spectral states. They estimated the intrinsic SEDs by subtracting the assumed ISM absorption from the models used to match observations, and by assuming the intrinsic power-law components do not extend to energies below \( \sim 1 \) (0.2) keV in the high (low) state\(^9\). They then used star formation histories from the public HMXB models are very uncertain at energies below 1 keV (T. Fragos, private communication), which unfortunately are the ones relevant for heating the IGM.

\(^6\) Throughout, “soft band” will refer to X-ray energies below \( \sim 2 \) keV, motivated by the detectors on the Chandra X-ray telescope. Note that the mean free path through the neutral IGM can be expressed as (e.g. Furlanetto et al. 2006; McQuinn 2012): \( \lambda_X \sim 40 \left( E_X/0.5 \text{keV} \right)^{2/3} \left( 1 + z \right)/15 \) Mpc. Equating this to the Hubble length and solving for the photon energy, one obtains that only photons with energies less than \( E_{\text{threshold}} \sim 2 \left( 1 + z \right)/15 \) keV are likely to interact with the IGM. Therefore the EoH is only sensitive to the rest-frame SED in the soft band.

\(^7\) Note that since HMXBs correspond to young stellar populations, their combined luminosity output is expected to scale linearly with the galaxy’s SFR. This has been confirmed observationally, both in local star-forming galaxies (e.g. Mineo et al. 2012a) and in moderate redshift galaxies (e.g. Lehmer et al. 2016).

\(^8\) http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/ApJ/776/L31

\(^9\) Note that the intrinsic emission and the interstellar and local star system absorption are very degenerate at low energies; thus the Fragos et al. (2013a) models are very uncertain at energies below 1 keV (T. Fragos, private communication), which unfortunately are the ones relevant for heating the IGM.
The optical depth, \( \tau \), is the integral of the X-ray absorption along a given line of sight (LOS), which is a function of the LOS number density, \( n \), and the gas column density, \( \Sigma \), along the LOS:

\[
\tau(E) = \int_{b}^{R_{vir}} \frac{R_{vir} \sigma_{HI} + n_{He} \sigma_{HeI} + Z \sigma_{metal} \exp(-\frac{E}{\epsilon})}{\Sigma \sigma_{metal} \exp(-\frac{E}{\epsilon})} \, dR
\]

Here \( n_{He} \) is the helium number density, \( n_{HI} \) is the hydrogen number density, \( R_{vir} \) is the virial radius of the host halo, and \( \sigma_{HI} \), \( \sigma_{HeI} \), \( \sigma_{metal} \) are the photo-ionization cross-sections of HI, HeI, and metals, respectively. The metal cross-section is defined per hydrogen atom and is computed from \( \text{Morrison & McCammon} (1983) \) using solar abundance ratios.\(^{10}\) For simplicity we conservatively assume all elements heavier than hydrogen are neutral.\(^{11}\)

We take the hydrogen number density, \( n_{HI} \), neutral fraction, \( x_{HI} \), and metallicity, \( Z \), from the cosmological radiation hydrodynamics simulation of \( \text{Wise et al.} (2014) \), computed using the adaptive mesh refinement code \( \text{ENZO} (\text{Bryan et al.} 2014) \) and its radiation transport module \( \text{MORAY} (\text{Wise & Abel} 2011) \). This 1 Mpc on a side, “first galaxy” simulation follows the buildup of 32 galaxies, including the effects of radiative and supernova feedback from both massive, metal-free (Population III) and metal-enriched stars. For this work, we focus on the \( \sim 7 \) galaxies which are actively forming stars in any given snapshot, and are thus expected to host active HMXBs. Other relevant physical processes included in the simulation are radiative cooling from metals, direct radiation pressure from starlight, and a time-dependent Lyman-Werner (H\(_2\) dissociating) radiation background.

The simulation has a maximal spatial resolution of 1 comoving parsec, dark matter particle mass of \( 1840 \, M_{\odot} \), and is halted at \( z = 7.3 \). At this time, the most massive galaxy has a stellar mass of \( 3.7 \times 10^{10} M_{\odot} \) hosted in a halo of mass \( 6.8 \times 10^{10} M_{\odot} \).

For each galaxy, we randomly shoot sight-lines originating from those star particles which are younger than 20 Myr (and are thus expected to host HMXBs; \( \text{e.g. Fragos et al.} 2013a \)). We integrate eq. 2 out to the halo virial radius of each halo, \( R_{vir} \). We sample each galaxy with 30000 LOSs, resulting in at least 1000 LOSs per active star particle.

In the left panel of Fig. 2 we show the average HI column densities for star forming halos. The color bar represents the total star formation rate of the galaxy. The figure illustrates halos becoming more massive with higher star formation rates as time progresses. Star formation is dominated by halos with masses around \( 10^{9} M_{\odot} \), whose virial temperature is high enough for baryons to be able to efficiently cool through atomic hydrogen transitions. For these halos the average column density\(^{12}\) is around \( 10^{21.5-16} \, \text{cm}^{-2} \).

We note that our simulated column densities are somewhat lower than absorption seen in high-z gamma ray bursts (GRBs; \( \text{e.g. Totani et al.} 2006; \text{Campana et al.} 2012; \text{Salvaterra} 2015 \)) afterglow signals of X-ray absorption in the first galaxies 3

\[ 21\text{-cm signatures of X-ray absorption in the first galaxies} \]

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spectra. However, estimating the column densities from optical or X-ray GRB spectra is very challenging, as there is a degeneracy between the intrinsic GRB + ISM emission, the host ISM absorption, as well as the intervening absorption from the IGM and/or the Milky Way. Indeed, Campa et al. (2015) find that the high column densities inferred from X-ray GRB spectra at high-$z$ can be entirely explained with intervening systems.

In the right panel of Fig. 2, we show the average metallicity of the galaxies, weighted by the density along the LOS. In addition to the HI column densities shown in left panel, the metallicity sets the X-ray absorption of the host halo. Here we do see a marked difference from Milky Way-like absorption, typically assumed in the literature. Since these galaxies are relatively pristine, we expect the contribution of metals to the X-ray optical depth to be sub-dominant to that of hydrogen and helium. Indeed, all of the star-forming galaxies in our sample have density-weighted metallicity below $0.06\,Z_\odot$.

3 RESULTS

Following the procedure outlined above, we now present the resulting X-ray spectra emerging from our $z > 8$ galaxies in §3.1. Then in §3.2 we present the corresponding forecasts for the cosmic 21cm signal, adopting various SFR histories.

3.1 The emerging spectrum

In Fig. 3 we show the median opacity through our star-forming galaxies (black curve), and the 68% confidence limits (C.L.) (shaded region). Since the luminosity of the HMXB population scales linearly with the SFR (e.g. Fragos et al. 2013a; Mineo et al. 2012a), we weigh the opacity from each LOS with the SFR of the host galaxy.$^{13}$ We do not differentiate between redshift outputs, sampling all of the star-forming galaxies shown in the previous two figures. This allows us to increase the statistical sample, without any obvious biases (there are no clear redshift trends in Fig. 2 when comparing at a fixed halo mass). We also note that Xu et al. (2016) show that the simulations used here are indeed statistically representative of a larger sample.

Fig. 3 illustrates one of the main findings of this work: the X-ray opacity of the galaxies driving the epoch of cosmic heating can be approximated by a metal-free ISM with a typical column density of $\log[N_{\text{HI}}/\text{cm}^{-2}] = 21.4^{+0.40}_{-0.65}$. The quoted limits enclose 68% of the uncertainty in the opacity. Due to the relative dearth of metals, the ISM in high-$z$ galaxies is more transparent than in local galaxies. Thus photons with energies as low as 0.5 keV can escape into the IGM. Moreover, the resulting $\exp(-\tau_I)$ is a much steeper function of energy than if metals contribute significantly. Our findings therefore support relatively ad-hoc assumptions used in prior works (e.g. Furlanetto 2006; Pritchard & Furlanetto 2007; Mesinger et al. 2013) for a sharp cut-off in energy, roughly corresponding to these column densities in a metal poor environment.

In Fig. 4 we combine these opacities with the intrinsic HMXB emission, showing the X-ray spectrum emerging from the galaxies into the IGM (black curve). The interstellar absorption from our simulations results in only a few percent of $\sim 1$ keV photons being absorbed within the host galaxies. This is in stark contrast with the red curve showing the previously-used absorption model (motivated by local observations). This absorption results in a factor of $\sim 5$ fewer 1 keV photons escaping the galaxy.

Overall, the soft-band ($< 2$ keV) luminosity of HMXBs which is responsible for IGM heating is $1.8 \times 10^{40}$ erg s$^{-1} \, M_\odot \, yr^{-1}$ for our median opacity. This is over a factor of three larger than the soft-band luminosity corresponding to the red curve, $5.3 \times 10^{39}$ erg s$^{-1} \, M_\odot \, yr^{-1}$. This comparably low soft-band luminosity largely explains the inefficient X-ray heating suggested by Fialkov et al. (2014, who used the SED shown with the red curve), as we quantify further below.

$^{13}$ Note that in doing so, our opacity distributions are biased towards the actively star-forming galaxies, which in general will have higher column densities than the average galaxy. However our goal in this work is to predict the X-ray background from HMXB, whose luminosity scales with the SFR of the host galaxy; therefore weighing the opacity by the SFR is appropriate for our purposes.
we find that an opacity corresponding to our weighted distribution is shown with a black solid curve, while the 68% C.L. have the most efficient star formation. The median of the resulting SFR-SFR-weighted opacities from our simulations (shown in Fig. 3). As in the Intrinsic (absorbed) HMXB SEDs from Fragos et al. (2013b) are Figure 4.

Intrinsic SED (Fragos et al. 2013) Absorbed SED (Fragos et al. 2013)

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The angle-averaged specific X-ray intensity (in erg s$^{-1}$ keV$^{-1}$ cm$^{-2}$ sr$^{-1}$), which drives the EoH is computed by integrating along the light-cone (cf. Haardt & Madau 1996):

$$J(E, z) = \frac{(1 + z)^3}{4\pi} \int_{\Omega} \langle \int_{\gamma} \frac{d\Omega}{d\Omega} \rangle$$

with the comoving specific emissivity evaluated at the rest-frame energy $E_\gamma = E(1 + z')/(1 + z)$:

$$\epsilon_x(E_\gamma, z', z') = L(E_\gamma) \frac{\rho_{crit,0} f_{s,0} (1 + \delta_{crit})}{\Omega_{m,0}} \left(\frac{\partial f_{coll}}{\partial t}\right).$$

Here, $L(E_\gamma)$ is the X-ray spectrum emerging from galaxies (eq. 1), $\Omega_{m,0}$ is the comoving matter density, $f_{coll}$ is the fraction of matter inside halos, and $f_*$ is the fraction of the halo baryons in stars. The quantity in the brackets is the star formation rate density (SFRD) along the light-cone. Our models for the SFRD assume a constant $f_*$ $= 0.05$ for halos above some critical threshold virial temperature required for efficient star formation, $T_{vir}$. With this assumption, the SFRD shown in eq. 5 can be expressed as a function of the time derivative of the collapse fraction.
We note that our approach is not completely self-consistent: the hydrodynamics using two values for the limiting halo virial temperature: 

\[ T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \]

\[ T_{\text{vir}}^{\text{min}} = 5 \times 10^5 \text{K} \]

dominant population. Therefore here we compute the SFR histories using various values for the limiting magnitudes, \( M_{\text{min}}^{\text{UV}} \). For context, note that \( M_{\text{min}}^{\text{UV}} = -17 \) corresponds roughly to the observed limit using unlensed deep fields with the Hubble telescope. However, gravitational lensing magnification provided by the Frontier Fields clusters has yielded even fainter galaxies, with the faint end slope shown to extend down to at least \( M_{\text{min}}^{\text{UV}} = -15 \) to -13 at \( z \approx 6-7 \) (Atteg et al. 2015; Livermore et al. 2016; Bouwens et al. 2016). Although the uncertainties become large at high magnifications, these observations motivate our \( T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \) model (green curve) as being more realistic than the \( T_{\text{vir}}^{\text{min}} = 5 \times 10^5 \text{K} \) one (blue curve). Hence, below we shall refer to the \( T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \) model as “fiducial”.

In Fig. 6 we show the evolution of the volume-weighted mean temperature inside the predominately neutral IGM (i.e. outside of the cosmic ionized patches), corresponding to these two SFRD histories. The lines and shaded regions correspond to the median and 68% C.L. of our computed X-ray SEDs (cf. Fig. 4). We also show the 1-σ lower limit for this quantity from Greig et al. (2016), derived from a combination of observations: (i) the upper limit on the 21-cm power spectrum at \( z = 8.4 \) measured by PAPER-64 (Ali et al. 2015); (ii) the dark fraction in the Lyman forests of high-z QSO spectra (McGreer et al. 2015); (iii) the Thomson scattering optical depth to the CMB (Planck Collaboration et al. 2015).

It is evident from the figure that the uncertainty in the cosmic SFRD evolution is more important than the comparably minor scatter in the X-ray opacity of our simulated galaxies. The blue curve, corresponding to our extreme model with \( T_{\text{vir}}^{\text{min}} = 5 \times 10^5 \text{K} \), results in the predominantly neutral IGM being heated above the CMB relatively late at \( z \approx 9 \), when roughly half of the volume of the Universe is already ionized. This evolution is consistent with the result in Madau & Fragos (2016), whose fiducial model only accounts for star formation in galaxies down to \( M_{\text{min}}^{\text{UV}} \sim 16 \).

As discussed above, the green curve is likely more realistic as it accounts for star formation inside fainter galaxies, whose presence at \( z \approx 6 \) has already been detected using cluster lensing (Atteg et al. 2015; Livermore et al. 2016; Bouwens et al. 2016). In this model, the Universe is heated earlier, at \( z \approx 13 \). This result is consistent with most prior studies of the EoH, when accounting for the slightly lower star formation efficiencies and updated L_X/SFR relations used here (e.g. Furlanetto 2007; Pritchard & Furlanetto 2007; Mesinger et al. 2016).

We now present the complete 21-cm signal from our simulations (see eq. 3). In Fig. 7 we show slices through the 21-cm maps, corresponding to the epoch in which temperature fluctuations dominate the signal. The figure illustrates that our fiducial X-ray SFR results in a more inhomogeneous temperature field, compared with the Fragos et al. (2013b) absorption (which was motivated by local HMXBs). These spatial fluctuations in the gas temperature are driven by the soft X-ray photons, which are more abundant in our fiducial SED.

The cosmic SFR history is very uncertain at high redshifts, since we cannot detect the faintest galaxies which could be the dominant population. Therefore here we compute the SFR history using two values for the limiting halo virial temperature: \( T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \) and \( 5 \times 10^5 \text{K} \). The corresponding SFRDs

\[ f_{\text{coll}}(> T_{\text{vir}}^{\text{min}}, x, z') \]

are shown in Fig. 5. Also shown are the observational estimates from Bouwens et al. (2015), obtained by integrating down the faint end slope of the observed UV luminosity functions to various limiting magnitudes, \( M_{\text{min}}^{\text{UV}} \). For context, note that \( M_{\text{min}}^{\text{UV}} = -17 \) corresponds roughly to the observed limit using unlensed deep fields with the Hubble telescope. However, gravitational lensing magnification provided by the Frontier Fields clusters has yielded even fainter galaxies, with the faint end slope shown to extend down to at least \( M_{\text{min}}^{\text{UV}} = -15 \) to -13 at \( z \approx 6-7 \) (Atteg et al. 2015; Livermore et al. 2016; Bouwens et al. 2016). Although the uncertainties become large at high magnifications, these observations motivate our \( T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \) model (green curve) as being more realistic than the \( T_{\text{vir}}^{\text{min}} = 5 \times 10^5 \text{K} \) one (blue curve). Hence, below we shall refer to the \( T_{\text{vir}}^{\text{min}} = 5 \times 10^4 \text{K} \) model as “fiducial”.

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dynamic simulations used to compute the HMXB opacities are not also used to predict the SFRD and the corresponding halo-SFR relations. We keep the global SFR calculation independent so as to allow our forecasts to be more flexible. We note that the 21-cm signal is driven by fluctuations on scales of tens–hundreds of Mpc; the relevant fluctuations of the SFR and halo-SFR relations are unlikely to be well captured by a single 1 Mpc hydro simulation. Indeed as seen from Fig. 2, these simulations do not have any halos with mass \( M_{\text{halo}} > 10^{8.5} M_\odot \) at these redshifts.
Figure 7. Slices through the 21-cm brightness temperature fields. Slices are 500 Mpc on a side and 1.25 Mpc deep. Both assume our fiducial SFRD evolution (i.e., green curve in the previous two figures). The left panel was computed using the absorption from Fragos et al. (2013b, motivated by local HMXBs), while the right panel corresponds to our fiducial SED computed from our simulations. The slices are taken at $\tau_{\text{peak}} = 15.1$ (fiducial SED) and $\tau_{\text{peak}} = 13.7$ (absorbed SED from Fragos et al. 2013b), when the large-scale ($k = 0.1$ Mpc$^{-1}$) 21-cm power is at its peak, driven by spatial fluctuations in the gas temperature.

atons (see Pacucci et al. 2014). Assuming absorption typical of the Milky Way washes-out the fluctuations and makes heating less efficient (cf. Fialkov et al. 2014).

This is quantified in Fig. 8, which shows the redshift evolution of the 3D 21-cm power spectrum, corresponding to the three SEDs from Fig. 4. Focusing on results using the fiducial SED (black curves), we recover several previously-noted trends across the four panels: (i) the large-scale power exhibits a three-peaked evolution, driven by fluctuations in the WF coupling, gas temperature, and ionization (left to right); (ii) the middle peak, corresponding to the EoH, has the largest amplitude; (iii) rarer, more biased galaxies (denoted with a higher $T_{\text{vir}}^{\text{min}}$) result in this evolution being delayed and then occurring more rapidly; (iv) if the EoH extends into the EoR (as is the case with a high $T_{\text{vir}}^{\text{min}}$), the signal during the EoR is decreased owing to the $(1 - T_{\gamma}/T_b)$ factor in eq. 3 not saturating to unity until the end stages of the EoR.

The impact of the X-ray SED on these trends can be seen by comparing the different curves in each panel. Not including any absorption (green curves) results in a slightly earlier EoH compared to our fiducial model (black curves), due to the additional soft photons escaping the galaxy. However, this shift in the power spectrum is relatively minor, $\Delta z \sim 1$, given the modest X-ray opacities of our simulated galaxies.

In contrast, including the absorption in the Fragos et al. (2013a) model has a much more dramatic effect (red curves), as noted by Fialkov et al. (2014). This SED, calibrated to local HMXBs, results in most of the photons below $\lesssim 2$ keV being absorbed in the host galaxy (c.f. Fig. 4). The resulting dearth of soft photons results in a very uniform and inefficient heating of the IGM. This is evidenced by a factor of $\sim 3$ reduction in the amplitude of the EoH peak in large-scale power for the $T_{\text{vir}}^{\text{min}} = 5 \times 10^4$ K model. For the more extreme $T_{\text{vir}}^{\text{min}} = 5 \times 10^5$ K model, the inefficient heating means that the EoH and EoR power spectrum peaks merge, as the first half of the EoR occurs while the IGM is still colder than the CMB and thus seen in absorption (cf. Fig. 6). The resulting “cold reionization” (Mesinger et al. 2014) is evidenced with a single, high-amplitude peak in large-scale 21-cm power, driven by the large contrast between the cold, neutral IGM (with a $\delta T_b \sim -150$ mK), and the ionized IGM (with a $\delta T_b \sim 0$ mK).

Finally, in the upper left panel, we also include the power spectrum evolution corresponding to a simplified SED: a power-law with energy index $\alpha = -1$, truncated below $E < 0.5$ keV, whose amplitude is set by matching the soft-band luminosity to our fiducial SED. As expected from Fig. 4, a simple truncated power-law reproduces the results using our fiducial SED remarkably well (comparing the blue and black curves in the top left panel). A truncated power-law is the default X-ray SED in 21CMFAST, as it is computationally inexpensive to evaluate along the light-cone. Our results here support this commonly-used simplification.

4 CONCLUSIONS

Upcoming 21-cm interferometers will allow us to study the first billion years of our Universe in unprecedented detail. The strongest cosmic signal is expected to come from the Epoch of Heating, which is expected to precede cosmic reionization. X-rays, likely from HMXBs, heat the IGM to temperatures above the CMB, driving the signal from absorption to emission. In this work we improve on prior estimates of this process, quantifying the X-ray opacities in high-resolution simulations of the first galaxies. Those X-ray photons absorbed inside the ISM cannot escape into the IGM and thus contribute to the EoH. If this host galaxy absorption is strong, the heating of the IGM is inefficient and can dramatically impact the 21-cm signal.

We find that the typical X-ray opacity through our simulated galaxies can be approximated by a metal-free ISM with a typical column density of $N_{HI} = 10^{21.4}$ cm$^{-2}$. This absorption is modest compared to some previously-used values, based on local HMXBs.

Combining our simulated ISM opacities with public spectra of HMXBs, we compute the resulting 21-cm signal. Our results are consistent with “standard scenarios” in which the X-ray heating of the IGM is inhomogeneous, and occurs before the bulk of reionization. In our fiducial model, the large-scale ($k \sim 0.1$ Mpc$^{-1}$) 21-cm power reaches a peak of $\approx 100$ mK$^2$ at $z \sim 15$, well before the
Evolution of the spherically-averaged 21-cm power spectra, computed at Figure 8.

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