THE SIGNATURES OF PARTICLE DECAY IN 21 cm ABSORPTION FROM THE FIRST MINIHALOS

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ABSTRACT

The imprint of decaying dark matter (DM) particles on the characteristics of the “21 cm forest”—absorption at 21 cm from minihalos in the spectra of distant radio-loud sources—is considered within a one-dimensional, self-consistent hydrodynamic description of minihalos from their turnaround point to virialization. The most pronounced influence of decaying DM on the evolution of minihalos is found in the mass range \( M = 10^{6}–10^{10} M_{\odot}, \) for which unstable DM with a current upper limit on its ionization rate of \( \xi_{L} = 0.59 \times 10^{-25} \) s\(^{-1}\) reduces the 21 cm optical depth by an order of magnitude compared with the standard recombination scenario. Even a rather modest ionization, \( \xi \sim 0.3 \xi_{L}, \) practically erases absorption features and results in a considerable decrease (by factor of more than 2.5) of the number of strong (\( W_{I}^{\text{obs}} \gtrsim 0.3 \) kHz at \( z \sim 10 \)) absorptions. In such circumstances, broadband observations are more suitable for inferring the physical conditions of the absorbing gas. X-ray photons from stellar activity of the initial episodes of star formation can compete with the contribution from decaying DM only at \( z < 10. \) Therefore, observing the 21 cm signal will allow us to follow the evolution of decaying DM particles in the redshift range \( z = 10–15. \) On the other hand, a non-detection of the 21 cm signal in the frequency range \( \nu < 140 \) MHz can establish a lower limit on the ionization rate from decaying DM.

Key words: cosmology: theory – dark matter – diffuse radiation – early universe – line: formation – radio lines: general

1. INTRODUCTION

The standard 21 cm tomography of the universe through observations of emission or absorption from the neutral intergalactic medium (IGM) against the cosmic microwave background (CMB; Shaver et al. 1999; Sethi 2005) and statistical studies of the angular distribution of the 21 cm intensity (Tozzi et al. 2000; Iliev et al. 2002) are known to suffer limitations from the yet-insufficient angular resolution of existing and future radio telescopes, e.g., only few arcseconds in the frequency range of interest (\( \sim 150 \) MHz) on LOFAR.\(^1 \) This resolution allows us to distinguish only hundreds of comoving kiloparsecs. Therefore, only huge structures, such as, for example, \( \text{H} \text{II} \) regions formed by stellar clusters and quasars, and the large-scale domain structures can possibly be resolved. On the contrary, absorption measurements in the 21 cm line to distant quasars—the “21 cm forest” (Carilli et al. 2002; Furlanetto & Loeb 2002)—are thought to provide information on small-scale structures such as individual dark matter (DM) minihalos, low-mass galaxies, and even stellar \( \text{H} \text{II} \) regions in the early universe (Kumar et al. 1995; Bagla et al. 1997; Furlanetto & Loeb 2002; Furlanetto 2006; Yue et al. 2009; Mack & Wyithe 2012). If so, the 21 cm forest would serve as a promising tool for studying the very beginning of the reionization epoch, when \( \text{H} \text{II} \) regions from different star-forming minihalos have not yet overlapped.

Detailed studies of line profiles in the 21 cm forest have therefore recently attracted much attention. In particular, dynamical effects on the line profile from baryon accretion (Xu et al. 2011) and from the overall contraction during the formation of the minihalos (Meiksin 2011; Vasiliev & Shchekinov 2012) have been recently accounted for, contrary to a fully static model with fixed DM and baryonic profiles described initially in Furlanetto & Loeb (2002) and Furlanetto (2006). Moreover, the 21 cm forest signal seems to carry information about the spatial distribution of DM in minihalos, and thus can shed light on the ongoing discussion of whether DM profiles in minihalos are cuspy, as shown first in Navarro et al. (1997), or not, as inferred by (Burkert 1995) from observations of local dwarf galaxies. The discussion has been recently exacerbated, on one side, by the finding of a steepening of the inner-slope of DM profiles in higher mass ellipticals in clusters (Sommer-Larsen & Limousin 2010; Gnedin et al. 2011); on the other hand, a flattening of profiles in the first protogalaxies (Marshenko et al. 2006; Tonini et al. 2006; Mikheeva et al. 2007) has also been found. A detailed consideration of the characteristics of the 21 cm forest—is necessary to robustly probe DM profiles at early epochs—is therefore needed.

Considerable contamination can, however, come from stellar ultraviolet (UV) photons (Yue et al. 2009; Xu et al. 2011) that ionize and heat gas in minihalos. Similar effects are expected from ionizing photons produced by decaying DM particles (Sciama 1982; Scott et al. 1991; Bharadwaj & Sethi 1998; Chen & Kamionkowski 2004; Hansen & Haiman 2004; Kasuya & Kawasaki 2004; Kasuya et al. 2004; Pierpaoli 2004; Belikov & Hooper 2009), annihilation of DM (Chuzhoy 2008; Myers & Nusser 2008; Yuan et al. 2010; Cumberbatch et al. 2010), and ultra-high energy cosmic rays originating from decaying superheavy (\( M_{X} \gtrsim 10^{12} \) GeV) DM particles (Berezinsky et al. 1997; Birkel & Sarkar 1998; Kuzmin & Rubakov 1998; Doroshkevich & Naselsky 2002; Doroshkevich et al. 2003). The background radiation from these sources can change the thermal and ionization evolution of the IGM (Dodelson & Jusab 1994; Biermann & Kusenko 2006; Shchekinov & Vasiliev 2004; Vasiliev & Shchekinov 2006; Mapelli et al. 2006) and affect the 21 cm global signal and fluctuations (Furlanetto et al. 2006; Shchekinov & Vasiliev 2007; Chuzhoy 2008; Myers & Nusser 2008; Yuan et al. 2010; Cumberbatch et al. 2010; Natarajan & Schwarz 2009). More recently, these sources have been strongly constrained (Zhang et al. 2007; Cirelli et al. 2009; DeLope Amigo et al. 2009; Peter et al. 2010; Zhang et al. 2010; Galli et al. 2011; Hütsi et al. 2011), although not fully excluded. In this paper, we focus therefore on whether or not the imprints from these sources can be recognized in the 21 cm forest absorptions.

\(^1\) http://www.lofar.org/index.htm
We assume a ΛCDM cosmology with the parameters \((\Omega_0, \Omega_X, \Omega_m, \Omega_b, h) = (1.0, 0.76, 0.24, 0.041, 0.73)\) (Spergel et al. 2007); for minihalos, we assume a flat DM profile.

2. MODEL DESCRIPTION

2.1. Evolution

DM profiles are described as suggested by Ripamonti (2007): the DM of \(M_{DM} = \Omega_{DM}M_{halo}/\Omega_{X}\) is a truncated isothermal sphere with a truncation radius \(R_0\) evolving as in Tegmark et al. (1997), and a flat core of radius \(R_{core}\); the ratio \(\eta = R_{core}/R_{vir}\) is assumed to be 0.1 throughout the simulations, as commonly used to mimic the evolution of a simple top-hat fluctuation (e.g., Padmanabhan 1993). The dynamics of the baryons is described by a one-dimensional Lagrangian scheme similar to that proposed by Thoul & Weinberg (1995); a reasonable convergence is found at a resolution of 1000 zones over the computational domain.

The chemical and ionization composition includes a standard set of species: H, H\(^+\), H\(_2\), He, He \(^+\), He \(^{+\ast}\), H\(_2\), H\(_2\)\(^+\), D, D\(_2\), \(D^+\), \(HD\), HD\(_+\), and \(e^+\), with the corresponding reaction rates from Galli & Palla (1998) and Stancil et al. (1998). The energy equation includes radiative losses typical of a primordial plasma: Compton cooling, recombination and bremsstrahlung radiation, and collisional excitation of H\(_1\) (Cen 1992), H\(_2\) (Galli & Palla 1998), and HD (Flower 2000; Lipovka et al. 2005).

Calculations start at a redshift of \(z = 100\). The initial parameters (gas temperature, chemical composition, and other quantities) are taken from simple one-zone calculations beginning at \(z = 1000\) with typical values taken at the end of recombination: \(T_{gas} = T_{CMB}\), \(x[H] = 0.9328\), \(x[H^\ast] = 0.0672\), \(x[\text{D}] = 2.3 \times 10^{-3}\), and \(x[\text{D}^+] = 1.68 \times 10^{-8}\) (see references and details in Ripamonti 2007, Table 2).

2.2. Ionization and Heating

Decaying DM contributes to the ionization and heating of baryons (see the recent discussion in Bertone 2010). The nature of decaying DM particles as well as the decay products is still under debate. Several candidates have been proposed: superheavy particles (Bertone et al. 2005), axions (Boehm & Fayet 2004; Boehm et al. 2004), sterile neutrinos (Dodelson & Widrow 1994; Hansen & Haiman 2004), and weakly interacting massive particles (e.g., Jungman et al. 1996). The expected mass range may range from the very light (a few keV; sterile neutrinos) to the relatively light (a few GeV; e.g., Chen & Kamionkowski 2004) to the very heavy (several TeV, as recently discussed by Valdés et al. 2012). Depending on the nature of the decaying particle, the decay products may include \(\gamma\) photons, electrons, positrons, and other more exotic particles. For example, detection of positrons of tens of GeV by PAMELA (Adriani et al. 2009) can be explained by the injection from annihilation and/or the decay of DM (He 2009; Nardi et al. 2009). It is clear, however, that through the formation of particle showers, the decays end when weakly interacting stable particles escape, while the other particles couple to baryons via electromagnetic interactions, ionize them, and deposit energy.

The most generic form of the ionization rate from decaying DM particles is proposed by Chen & Kamionkowski (2004):

\[
I_e(z) = \chi_i f_i \Gamma_X \frac{m_p c^2}{h v_i},
\]

where \(\chi_i\) is the energy fraction deposited into ionization (Shull & van Steenberg 1985), \(m_p\) is the proton mass, \(f_i = \Omega_X(z)/\Omega_b(z)\), \(\Omega_b(z)\) is the baryon density parameter, \(\Omega_X(z)\) is the fractional abundance of decaying particles, \(\Gamma_X\) is the decay rate, and \(h v_i\) is the energy of Lyman continuum photons. It is obvious that the contribution from decaying DM is determined by the product \(\xi_i = \chi_i f_i \Gamma_X\), which masks the nature of DM particles.

The corresponding heating rate can be written in the form (Chen & Kamionkowski 2004)

\[
K = \xi_h m_p c^2,
\]

where \(\xi_h = \chi_h f_i \Gamma_X\) and \(\chi_h\) is the energy fraction deposited into heating. Based on an order of magnitude approximation, \(\chi_i \sim \chi_h \sim 1/3\) for the conditions we are interested in (Shull & van Steenberg 1985).

Using CMB datasets, Zhang et al. (2007) have constrained the ionization rate associated with radiatively decaying DM to be \(\xi \lesssim 1.7 \times 10^{-25}\) s\(^{-1}\). An extended analysis of the data of Type Ia Supernovae, the Ly\(_\alpha\) forest, large-scale structure, and weak lensing observations have lead DeLope Amigo et al. (2009) to provide a stronger constraint: \(\xi \lesssim \xi_L = 0.59 \times 10^{-25}\) s\(^{-1}\). It is worth noting that all datasets favor long-living decaying DM particles with a lifetime \(\Gamma^{-1} \gtrsim 10^9\) Gyr (DeLope Amigo et al. 2009). Further improvement is expected from the Planck satellite. In this paper, we consider models with an ionization rate within this limitation \(\xi \leq \xi_L\). As will be seen below, such a constraint does not affect our understanding of what happens outside the limit \(\xi > \xi_L\).

Equations (1) and (2) were written under the assumption of a uniform production of ionizing photons by decaying DM with a density \(\Omega_X\), without accounting for its concentration in minihalos. Virialized minihalos are transparent for sufficiently energetic photons for which \(\tau(E) = n_e r_{vir} \sigma(E) < 1\), where \(r_{vir}\) and \(n_e\) are the radius and the mean density of a virialized halo, and \(\sigma(E)\) is the photoionization cross section. The corresponding lower energy of escaping photons is thus

\[
E_i \gtrsim 300\text{ eV} \left(\frac{M}{10^9 M_{\odot}}\right)^{1/9} \left(\frac{1 + z}{10}\right)^{2/3}.
\]

In this sense, our estimates correspond to a lower limit of the ionization and heating rates.

The upper energy limit for the photons being able to heat and ionize the IGM is determined by the assumption that they are absorbed in the IGM within a Hubble time; this limit can be readily estimated as \(E_a \lesssim 30\) keV (for a detailed description of the “transparency window,” see Chen & Kamionkowski 2004). In the energy range \(E_i < E_a\), photons are supposed to fill the IGM homogeneously except for relatively small circumgalactic regions. Note in this connection that even though each minihalo is a source of ionizing photons, their influence on the circumhalo baryons is obviously negligible because of a very low optical depth \(\tau(E)\) at the energies of interest.

Contrary to decaying DM, stellar and quasi-stellar sources of ionizing radiation emerge only at redshifts \(z < 20\). In addition, they heat nearby surrounding gas, which then emits at 21 cm with a patchy, spot-like distribution on the sky; the imprints from non-stellar and stellar sources can therefore be discriminated (see discussion below in Section 4).

2.3. 21 cm: Optical Depth and Equivalent Width

The spin temperature of the H\(_1\) 21 cm line is determined by atomic collisions and the scattering of UV photons (Field 1958; Wouthuysen 1952). In our calculations, we used collisional coefficients from Kuhlen et al. (2006) and Liszt (2001). In general,
collapsing minihalos in the standard recombination model can be found in Vasiliev & Shchekinov (2012). It is clearly seen that the IGM temperature under DDM heating can approach or even exceed the virial temperature of minihalos: DDM with \( \xi \gtrsim 0.1\xi_L \) heats the IGM up to \( T \simeq 250 \) K, which is only half of the virial temperature of a \( M = 10^5 M_\odot \) halo, while \( \xi \gtrsim 0.3\xi_L \) elevates the IGM temperature close to the virial temperature of \( M = 10^6 M_\odot \) minihalos. DDM heating results in a weakening of baryon accretion. Thus, the most obvious and important difference between evolving minihalos in the standard recombination regime and the presence of DDM is the absence of an accretion shock wave in minihalos with \( M \lesssim 10^6 M_\odot \), as obviously seen on the lower panels of Figure 1.

The radial density, temperature, and velocity profiles in low-mass (\( M \lesssim 10^6 M_\odot \)) minihalos in the presence of DDM heating look similar. The profiles\(^2\) in massive halos (\( M = 10^7 M_\odot \)) resemble to those in the standard recombination scenario (see the dashed lines in Figure 1), in spite of strong DDM heating. Thus, contrary to the halos of lower mass where gravitation is too weak to overcome additional heating, massive halos, \( M \gtrsim 10^7 M_\odot \), instead remain able to support the accretion rate on a practically unchanged level. It is obvious that within the limit \( \xi \lesssim \xi_L \), minihalos with \( M = 10^5 M_\odot \) represent the least massive halos sensitive to an additional heating from DDM. However, as readily seen, further increasing \( \xi \) results in a practically proportional growth of the IGM temperature with \( \xi \), \( T \propto \xi \), and consequently suppresses the accretion rate approximately as \( T^{\nu/2} \), which in turn increases the lower limit of halo mass insensitive to DDM heating.

Ionization from the DDM is considerable: it is seen from Figure 1 that in the low-mass range (\( M \lesssim 10^6 M_\odot \)), the fractional ionization within minihalos and outside them is nearly invariant in models with \( \xi \gtrsim 0.3\xi_L \). The ionization rate of \( \sim 10\xi_L \) can affect the evolution of minihalos with masses of classical dwarf galaxies (\( M \sim 10^9 M_\odot \)).

### 3. RESULTS

#### 3.1. Dynamics of Minihalos

We consider here only evolving minihalos with masses in the range \( M = 10^5 - 10^7 M_\odot \) virialized at \( z_v = 10 \). At lower redshifts, reionization by stellar and quasi-stellar sources comes in to play and contaminates the effects from the decaying DM. On the other hand, at higher redshifts, the number of bright background radio sources decreases. The choice of the halo mass range is motivated by the fact that halos with \( M = 10^5 M_\odot \) lie below the limit where the baryons can efficiently cool and form stars. Only inside minihalos with \( M \lesssim 2 \times 10^6 M_\odot \) can star formation potentially occur in the sense that these objects collapse at \( z_v = 10 \), i.e., the gas density in the inner-most shell reaches the critical value \( 10^8 \text{ cm}^{-3} \) when three-body reactions turn on to form H\(_2\) (Ripamonti 2007). On the other hand, minihalos of \( M = 10^7 M_\odot \) do eventually collapse and form stars and thus represent the opposite dynamical regime. The results we present here illustrate therefore the typical features of 21 cm absorptions produced by non-star-forming (\( M = 10^2 M_\odot \)), marginally star-forming (\( M = 10^5 M_\odot \)), and star-forming (\( M = 10^7 M_\odot \)) minihalos.

Heating from decaying DM (DDM) weakens the accretion rate of baryons onto minihalos. Therefore, in comparison with the evolution of minihalos in the standard scenario, one can expect smaller baryon masses and higher temperatures within the virial radius of a minihalo. The influence of decaying particles depends on the minihalo mass and the rate of the decay energy deposited in the gas, \( \xi \).

Figure 1 shows radial profiles of density (upper panels), temperature (upper middle panels), velocity (lower middle panels), and the ionized hydrogen fraction (lower panels) in minihalos of \( M = 10^5, 10^6, \) and \( 10^7 M_\odot \), virialized at \( z_v = 10 \) (from left to right); 21 cm absorption profiles from collapsing minihalos in the standard recombination model can

\[ \rho = \frac{3h_\nu c^3 A_{10}}{2\pi k T_0} \int_0^\infty \frac{n_M(t)}{\sqrt{\pi b^2(r)T_0(r)}} \times \exp \left[ \frac{-(v(r) - v_L(r))^2}{b^2(r)} \right], \]

where \( b^2 = (\alpha r_v)^2 + x^2 \), \( r_v = r_L/r_{\text{vir}} \) is the dimensionless impact parameter, \( v_L(r) = c(v_v - v_0)/v_0 \) is the infall velocity projected on the line of sight, and \( b^2 = 2k T_0(r)/m_p \) is the Doppler parameter.

The observed line equivalent width is determined by \( W_{\nu}^{\text{obs}} = W_{\nu} = W_{\nu}^{\text{obs}} = W_{\nu}/(1 + z) \), where the intrinsic equivalent width is

\[ W_{\nu} = \int_0^\infty \int_0^\infty (1 - e^{-\tau}) d\nu - \int_0^\infty \int_0^\infty (1 - e^{-\tau}) d\nu, \]

where \( \tau_{\text{IGM}} \) is the optical depth of the background neutral IGM.
it can be met when $\xi \gtrsim 0.3\xi_L$. Thus, DDM with $\xi \gtrsim 0.3\xi_L$ practically erases 21 cm absorption features from low-mass minihalos.

Massive minihalos, $M = 10^7 M_\odot$, demonstrate a more complex frequency dependence on optical depth: it does not peak in the center of line; the maximum is instead at $\nu - \nu_0 \sim 45$–50 kHz. Such a horn-like dependence originates from a strong accretion in massive halos (Xu et al. 2011; Vasiliev & Shchekinov 2012). In the presence of DDM, the range of impact factors with a horn-like profile decreases strongly even for $\xi \sim 0.1\xi_L$. The center of line optical depth ($\nu - \nu_0 \lesssim 30$ kHz) at small $\alpha \lesssim 0.1$ becomes flat and insensitive to $\xi$: it stays at a level $\sim 0.05$ even for $\sim \xi_L$. At higher $\alpha$, the optical depth merges with the background value.

It is clear that both the heating and the ionization from the DDM contribute to the decrease of optical depth. In order to evaluate their relative contributions, we performed calculations of two sets of models: in the first set, we turned off the ionization from the DDM $I_e = 0$, leaving the heating unchanged, while in the second set, the ionization remains unchanged, while the heating is turned off $K = 0$. The results are shown in Table 1, where the first column shows the line center optical depths $\tau_0$ in the standard ionization scenario, and $\tau_0$ is shown in the second column for the model with the DDM particles treated self-consistently. The second and the third columns correspond to the models with $I_e = 0$ and $K$ unchanged and $I_e$ unchanged and $K = 0$, respectively. An obvious trend of increased $\tau_0$ in the shortened models with either $I_e = 0$ or $K = 0$ is caused by a reduction in the DDM to the total contribution. It is also clearly seen that the influence of the ionization $I_e$ is not mainly due to a decrease in the fraction of H I in virialized halos, which is negligibly small: $\Delta x(\text{H I}) = -\chi(\text{H II}) \sim -10^{-3}$. The influence of the ionization stems predominantly from an enhanced Compton heating beginning from the turnaround point. Therefore, both the ionization and the heating decrease the optical depth via the additional heating. Separate contributions from these processes depend on minihalo mass: for instance, for $10^5 M_\odot$ halos, the contributions are approximately 1/3 for the ionization and 2/3 for the heating, although their contributions are not independent and their combined influence is not simply a sum of the two

![Figure 1](https://example.com/figure1.png)

**Table 1**

| $M$, $M_\odot$ | $\xi/\xi_L = 0$ | $\xi/\xi_L = 0.1$ | $\xi/\xi_L = 0.1$, $I_e = 0$ | $\xi/\xi_L = 0.1$, $K = 0$ |
|----------------|----------------|----------------|-----------------------------|-----------------------------|
| $10^7$         | 0.15           | 0.074          | 0.09                        | 0.12                        |
| $10^6$         | 0.37           | 0.074          | 0.083                       | 0.33                        |
| $10^7$         | 0.068          | 0.1            | 0.081                       | 0.078                       |
separate components; the additional heating from these sources changes the temperature, density, and velocity profiles that are involved in the optical depth (Equation (4)) nonlinearly.

### 3.3. Equivalent Width

Figure 3 shows the evolution of the radial profiles of the equivalent widths measured in the observer’s restframe. As expected, the equivalent widths decrease significantly with $\xi$ except for halos with $M = 10^5 M_\odot$; for instance, low-mass halos ($M = 10^5 M_\odot$) at $z = 10$ (solid lines) show a decrease in $W_{\nu,\text{obs}}^{\text{abs}}$ from $\sim 0.2$ kHz for the standard recombination to a negligible value $\lesssim 0.02$ kHz for $\xi \gtrsim 0.3 \xi_L$ within $r_\perp / r_{\text{vir}} \lesssim 0.5$. At $z = 15.5$ and 12 (dashed and dot-dashed lines), $W_{\nu,\text{obs}}^{\text{abs}}$ can hardly be resolved on future telescopes and may only contribute to the total signal in broadband observations (Xu et al. 2011).

More massive halos ($M \gtrsim 10^6 M_\odot$) show strong equivalent widths $W_{\nu,\text{obs}}^{\text{abs}} \gtrsim 0.2$ kHz near virialization ($z = 10$) even at a relatively high ionization $\xi \lesssim 0.3 \xi_L$ within the entire halo $\alpha \lesssim 1$. At $\alpha \lesssim 0.5$, $W_{\nu,\text{obs}}^{\text{abs}}$ can reach even $\sim 0.5$–0.9 kHz. At a higher redshift range, $z = 15.5$ and 12, $M \gtrsim 10^6 M_\odot$ halos can produce such strong equivalent widths only in the standard recombination scenario. More massive halos, $M = 10^7 M_\odot$, show strong absorption ($W_{\nu,\text{obs}}^{\text{abs}} \gtrsim 0.5$ kHz) even for high ionization rates $\xi \sim \xi_L$, although only in a narrow range of impact factors $\alpha \lesssim 0.1$. As a consequence, the DDM leads to a considerable decrease in the number of strong absorption lines: for $\xi \gtrsim 0.3 \xi_L$, sufficiently strong lines form only in high-mass ($M \gtrsim 10^7 M_\odot$) halos nearly along the diameter with a small probability of contributing absorption. A similar effect stems from the action of the stellar X-ray background at lower redshifts (Furlanetto & Loeb 2002; Xu et al. 2011); see also Section 4.

The sensitivity of future telescopes is at least an order of magnitude lower than the flux limit needed to separate spectral lines from individual halos, i.e., to observe with a spectral resolution of $\Delta \nu \sim 1$ kHz. Therefore, Xu et al. (2011) have proposed broadband observations with lower resolution. In this case, the measured quantity is the average signal from different halos lying along a line of sight. Accordingly, we introduce a radially averaged equivalent width

$$
\langle W_{\nu,\text{obs}}^{\text{abs}} \rangle = \frac{2}{9} \int_0^{3r_{\text{vir}}} \frac{W_{\nu,\text{obs}}^{\text{abs}}(r_\perp) r_\perp dr_\perp}{r_{\text{vir}}^2}.
$$

Figure 2. Dependence of the 21cm optical depth on frequency and impact parameter $\alpha = r_\perp / r_{\text{vir}}$ for halos $M = 10^5 M_\odot$, $10^6 M_\odot$, and $10^7 M_\odot$ (top to bottom), virialized at $z_{\text{vir}} = 10$, in the standard recombination model (left panels) and in the presence of DDM with $\xi / \xi_L = 0.1$ (right panels).
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Figure 3. Equivalent width vs. impact parameter $\alpha$ in the observer’s restframe for minihalos with masses $M = 10^5$, $10^6$, and $10^7 M_\odot$ (top to bottom) at redshifts $z = 15.5$, 12, and $z = z_{\text{vir}} = 10$ (dot-dashed, dashed, and solid lines, respectively) in the standard recombination model and in the presence of DDM with $\xi/\xi_L = 0.1$, 0.3, and 1 (left to right). Note that the $y$-axes are different between the panels.

Figure 4 shows the dependence of $\langle W^\text{obs} \rangle$ on $\xi/\xi_L$. The increase of $\langle W^\text{obs} \rangle$ for $M = 10^5 M_\odot$ at $z = 10$ and $\xi/\xi_L \leq 0.1$ is explained by a widening of $W^\text{obs}$ in the peripheric region $r_{\perp}/r_{\text{vir}} \lesssim 2$ (top panels in Figure 3). For higher masses and redshifts, the radially averaged $W^\text{obs}$ decreases with $\xi/\xi_L$ by factor of $\lesssim 2$ and apparently remains sufficient to distinguish effects from the ionization caused by DDM particles.

In previous studies, the theoretical spectrum of the 21 cm forest was simulated under the assumption of steady-state minihalos with fixed profiles corresponding to virialization (Furlanetto & Loeb 2002; Xu et al. 2011). When dynamics is taken into account, minihalos lying on a given line of sight are, in general, at different evolutionary stages and have different density, velocity, and temperature profiles. Moreover, a Press–Schechter formalism cannot be used anymore for a description of their mass function as soon as the minihalos stray too far from virialization. It is therefore problematic to describe correctly the number density of minihalos at each evolutionary stage. An additional complication stems from continuous structure formation. While major mergers involving merging minihalos with $M \gtrsim 0.5 M_\odot$ occur on times twice as long as a Hubble time at $z = 10$, less destructive mergers with $M \lesssim 0.25 M_\odot$ proceed within $\lesssim 0.7$ of a Hubble time (Lacey & Cole 1993). This time is shorter than the free-fall time in halos with $M \sim 2 \times 10^5 M_\odot$, thus making estimates based on the assumption of the virial equilibrium inapplicable to less massive halos. The possible formation of stars in massive evolved minihalos also introduces additional complications. Overall, the analysis of a theoretical spectrum within a statistical simulation becomes exceedingly cumbersome. A more relevant picture can be obtained from high-resolution cosmological gas dynamic simulations, although the current resolution with $\Delta M \sim 10^6 M_\odot$ does not seem to be sufficient.

However, with upcoming low-frequency interferometers (LOFAR and SKA), such modeling is apparently excessive. Indeed, the absorption line profiles and the spectral features from separate minihalos located at $z = 10$ are of $1–5$ kHz in width—close to the spectral resolution limit $1$ kHz. As discussed in Xu et al. (2011), the corresponding sensitivity requires enormously bright background sources. In order to resolve spectral lines of $\Delta \nu \sim 1$ kHz with a typical for the SKA telescope ratio of the aperture-to-system temperature $A_{\text{eff}}/T_{\text{sys}} = 5000$ m$^2$ K$^{-1}$ and a signal-to-noise ratio $S/N = 5$, an integration time of $30$ days and a minimum flux density of about $500 \mu$Jy are needed (Xu et al. 2011). This flux density is four times lower than the flux density of an object similar to the bright radio-loud galaxy Cygnus A (Carilli et al. 2002), but an order of magnitude higher than typical gamma-ray burst (GRB) afterglow fluxes (Xu et al. 2011). Note, in addition, that there are no confirmed quasi-stellar objects at $z > 7.5$; moreover, the mass of a black hole in the Cygnus A galaxy is about $2.5 \times 10^9 M_\odot$ (Tadhunter et al. 2003), which should apparently be a very rare object at $z \gtrsim 10$. GRB afterglows seem to be more promising background sources for 21 cm absorption studies. In this case, the integration time is restricted by the duration of the bright phase of the afterglow, $\sim 100$ days (Frail 2003). Thus, low resolution or broadband observations may be a better alternative.

In broadband observations, suppression of optical depth at $21$ cm caused by decaying particles manifests itself as a factor of $2–4$ decrease in the absorption in the frequency range $\nu < 140$ MHz, where the contribution from low-mass minihalos at $z \gtrsim 10$ dominates. Indeed, the number of halos in the low-mass
range 10⁵–10⁷ M☉ at z = 10 scales as n(M, z) ∼ M⁻¹. The probability of minihalos intersecting a line of sight is proportional to n(M, z) × (arₑ𝑞(M))^2, resulting in a decrease in the number of strong absorption lines with W⁰ < 0.3 kHz by a factor of at least 2.5 for ξ/ξ𝐿 = 0.3 and more than 4.5 for ξ/ξ𝐿 = 1. Such a decrease inevitably nullifies the average 21 cm forest signal from low-mass halos. This decrease also results in a several times decrease in the mean flux decrement D₅, and correspondingly the detectability limit in broadband observations. A strong suppression of the optical depth at ξ/ξ𝐿 < 0.3 would require time integration scales longer than the duration of the bright phase of GRB afterglows. Low-mass (M ∼ 10⁵ M☉) minihalos produce weak absorptions, W⁰ < 0.2 kHz, even for the standard ionization scenario.

Thus, as far as the characteristic scales corresponding to such broadband observations are of the order of hundreds of kiloparsecs, an immediate consequence is that the advantages expected initially from the 21 cm forest observations are not that obvious. However, once observations have been made covering a wide range of frequencies corresponding to redshifts 10 to 15, these data would in principle provide information about how the influence from DDM varies with redshift. More explicitly, a non-detection of absorption from 21 cm in the frequency range ν < 140 MHz can in principle serve to bound the ionization rate from DDM from below: ξ/ξ𝐿 > 0.3, unless contributions from stellar sources compete to ionize low-mass halos.

4. RELATIVE CONTRIBUTION FROM PARTICLE DECAY AND THE STELLAR X-RAY BACKGROUND

As discussed above, the contribution of X-ray photons from decaying particles to the ionization and heating of the IGM can compete with that from X-rays produced by early populations of binaries and/or black holes. Let us estimate here comparatively these two contributions. For this purpose, we assume the X-ray (>0.2 keV) luminosity of high-z galaxies to be comparable to that inferred for nearby starburst galaxies (Gilfanov et al. 2004):

\[ L_X = 3.4 \times 10^{40} f_X \left( \frac{\text{SFR}}{1 M☉ yr^{-1}} \right) \text{erg s}^{-1}, \] (7)

where SFR is the star formation rate and f_X is a correction factor accounting for the unknown properties of X-ray emitting sources in the early universe. A rather weak constraint on f_X inferred from the Wilkinson Microwave Anisotropy Probe (CMB optical depth ≲10⁻³; Pritchard & Loeb 2008) is much higher than found in the nearby universe, f_X ≈ 3–1 (Gilfanov et al. 2004; Mineo et al. 2012). From the signal in stacked Chandra images at the position of z ∼ 6 galaxies (Treister et al. 2011, the soft X-ray background is thought to limit the f_X factor to ≳2–5 at z > 1–2, although it allows f_X to increase sharply up to ∼100 at z > 5 (Dijkstra et al. 2012). However, further rigorous analysis did not confirm such a high f_X (Willott 2011; Fiore et al. 2012). In fact, analysis showed that this quantity remained invariant at least over z = 0–4 (Cowie et al. 2012). Thus, no reasons are seen to assume that f_X is much higher than what is observed in the local universe.

Assuming that the SFR is proportional to the rate at which matter collapses into galaxies (Furlanetto 2006), the total normalized X-ray emissivity ϵ_X can be written as

\[ \frac{2 f_X}{3 k n H(z)} = 5 \times 10^4 f_X \left( \frac{f_x}{0.1} \right) \left( \frac{d f_c / d z}{0.01} \right) \left( \frac{1+z}{10} \right), \] (8)

where df_c / dz is the fraction of baryons collapsed to form a protogalaxy per unit redshift and f_x is the fraction of baryons converted into stars in a single star formation event; normalization numbers are given in Furlanetto (2006). The corresponding heating rate can be found as Kₜ = χ_h ϵ_X, which can now be compared with the heating rate associated with decaying particles

\[ \frac{2 K}{3 k H(z)} = 8.9 \times 10^4 (\xi/ξ_L) \left( \frac{1+z}{10} \right)^{-2/3}. \] (9)

The condition that these two sources heat the IGM equally is therefore

\[ 0.54 f_X \chi_h \left[ f_x d f_c / d z \left( \frac{1+z}{10} \right)^{5/3} \right] = (\xi/ξ_L). \] (10)

Thus, in order for the heating from stellar X-ray background to be equal to the heating from decaying particles, one requires...
an X-ray correction factor $f_X \simeq 5.4(\xi/\xi_L)$ for $1 + z = 10$ and typical parameters for the star formation. At $\xi/\xi_L > 0.1$, such a value seems to be exceedingly higher than what follows from observations of starburst galaxies in the local universe with $f_X \simeq 0.3$ (Gilfanov et al. 2004). Moreover, the linear approximation (Equation (7)) is valid only for sufficiently massive systems with $\text{SFR} \gtrsim 10^6 \text{M}_\odot \text{yr}^{-1}$, while at the low end of SFRs, the correction factor can be one to two orders of magnitude lower. At the redshifts of interest, $z \sim 10$, only halos with masses $M_h \lesssim 10^7 \text{M}_\odot$ can be star forming (Loeb 2010), for which the SFR is at most $\sim 10^3 \text{M}_\odot \text{yr}^{-1}$ for typical numbers characterizing the formation of stars in the early universe: $f_e = 0.1, d\delta_{\text{coll}}/dz \sim 0.01$. Such a low SFR corresponds, however, to more than a factor of 10 weaker proportion between the SFR and the X-ray luminosity, i.e., $f_X \ll 0.1$ (see Figure 1 in Gilfanov et al. 2004). One may conclude therefore that at redshifts $z \gtrsim 10$, heating of atomic hydrogen in virializing minihalos can stem only from decaying particles, unless the star formation efficiency $f_e$ and the amount of a collapsed baryons $d\delta_{\text{coll}}/dz$ grow toward higher $z$ unprecedently. Without overwhelming assumptions, the conclusion about the dominance of decaying particles in heating looks the most plausible.

As discussed above, a higher $f_X$ can in principle be satisfied at $z \sim 10$ (Dijkstra et al. 2012), in which case the contribution from decaying particles decreases at $z \lesssim 10$, although at higher redshifts these decaying particles can still dominate due to an obvious sharp drop in star formation. The different redshift dependence of the stellar X-ray and the decaying particle heating rates (Equation (9)) may be used to discriminate between them. In general, though, both higher $\xi$ and $f_X$ values lead to a smaller number of absorption lines. As a consequence, the decrement $D_\chi$ decreases and the integration time increases such that even GRB afterglows cannot be used to observe the 21 cm forest.

It is obvious that strong stellar X-ray sources such as, e.g., supernova remnants or massive X-ray binaries, ionize and heat the IGM locally, even though the X-ray background from them can be weaker than from decaying particles. Indeed, the mean free path of photons with $\nu < 0.3 \text{ keV}$ at $z \sim 10$ is about $1 \text{ Mpc}/(1 + \delta)$, where $\delta$ is the density perturbation. The heating rate at a distance $D$ from a source with X-ray luminosity $L$ [erg s$^{-1}$] is

$$\Gamma \sim 6 \times 10^{-28} \left(\frac{L}{10^{45}}\right) \left(\frac{10 \text{ kpc}}{D}\right)^2 \chi_h \times \left(\frac{E/E_H}{20}\right)^{-3} \exp(-\tau) \text{ erg s}^{-1}$$

and the corresponding ionization rate is

$$I \sim 2 \times 10^{-17} \left(\frac{L}{10^{46}}\right) \left(\frac{10 \text{ kpc}}{D}\right)^2 \times \left(\frac{E/E_H}{20}\right)^{-3} \chi_i \exp(-\tau) \text{ s}^{-1}.\tag{12}$$

It is readily seen that in the presence of heating from decaying particles, the zone of influence of a star-forming dwarf galaxy lies within the radius

$$D \lesssim 10 \left(\frac{\text{SFR}}{1 \text{M}_\odot \text{yr}^{-1}}\right)^{1/2} (\xi/\xi_L)^{-1/2} \text{ kpc}.\tag{13}$$

Since a typical distance between minihalos is $d \sim 30(1 + z/20)$ kpc, only in the beginning of the reionization epoch can dwarf galaxies dominate the heating and ionization of hydrogen in neighbor minihalos. This process furthermore only happens when the ionization from the background X-ray photons from decaying particles is relatively weak, $(\xi/\xi_L) < 0.1$.

5. CONCLUSIONS

In this paper, we have considered the influence of DDM particles on the 21 cm absorption features from low-mass minihalos: $M = 10^5, 10^6 M_\odot$, and $10^7 M_\odot$, virialized at $z_{\text{vir}} = 10$. We used a one-dimensional, self-consistent hydrodynamic approach to study the evolution of minihalos, and followed the absorption characteristics from the turnaround to the virialization of the minihalos. We found the following.

1. Due to additional heating from decaying particles, the thermal and dynamical evolution of minihalos shows pronounced differences from those in a model without particle decay (i.e., the standard recombination scenario). These differences can be distinguished in the signal formed at redshifts $z > 10$.

2. The additional heating and ionization strongly suppresses the optical depth in the 21 cm line; these processes practically erase the 21 cm absorptions from minihalos with $M = 10^5–10^6 M_\odot$ even at a relatively modest ($\xi \gtrsim 0.3\xi_L$) ionization rate; the horn-like dependence of the optical depth found for minihalos with $M \sim 10^6–10^7 M_\odot$ in the standard recombination scenario (Xu et al. 2011) almost disappears even at a lower ionization rate $\xi \gtrsim 0.1\xi_L$. In total, approximately 1/3 of this suppression stems from ionization, while the remaining 2/3 is due to heating. The contribution from the ionization is caused by enhanced Compton heating on the additional electrons, rather than by a decreased fraction of H$^\text{1}$.

3. The suppression of the magnitude of 21 cm absorption by ionization from DDM particles and the widening of the lines by dynamical effects—baryon accretion and DM contraction—necessitate broadband observations, in which case the advantages of the 21 cm forest probing reionization on small scales become less obvious compared with the traditional 21 cm global signal and 21 cm angular distribution.

4. The stellar contribution at such redshifts, $z \gtrsim 10$, is negligibly small, so that a weakening of the 21 cm forest, if observed, can be only due to DDM particles.

5. The equivalent width of the 21 cm absorption line decreases significantly when $\xi$ increases and the number of strong absorption lines $W_{\text{abs}} \gtrsim 0.3 \text{ kHz}$ at $z = 10$ drops by more than a factor of 2.5–4.5 depending on $\xi$; such a decrease will inevitably erase the averaged 21 cm forest signal from low-mass halos ($M \sim 10^5–10^6 M_\odot$, i.e., the frequency range $\nu < 140 \text{ MHz}$) in future broadband observations. Under the conservative assumption that $f_X$ does not grow enormously and that its value at higher redshifts ($z \gtrsim 10$) remains comparable with its value in the local universe, such a decrease in equivalent width can be attributed only to the DDM. As far as it occurs at $\xi > 0.3\xi_L$, the deficiency of 21 cm forest absorptions at these frequencies can serve to put a lower limit on the ionization rate from unstable DM.

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