**H I ABSORPTION FROM THE EPOCH OF REIONIZATION AND PRIMORDIAL MAGNETIC FIELDS**

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Received 2014 February 10; accepted 2014 March 21; published 2014 April 25

**ABSTRACT**

We study the impact of primordial magnetic fields on the H I absorption from the epoch of reionization. The presence of these fields results in two distinct effects: (1) the heating of the halos from the decay of the magnetic fields owing to ambipolar diffusion, and (2) an increase in the number of halos owing to additional matter fluctuations induced by magnetic fields. We analyze both of these effects and show that the latter is potentially observable because the number of halos along of line of sight can increase by many orders of magnitude. While this effect is not strongly dependent on the magnetic field strength in the range 0.3–0.6 μG, it is extremely sensitive to the magnetic field power spectral index for the near scale-free models. Therefore, the detection of such absorption features could be a sensitive probe of the primordial magnetic field and its power spectrum. We discuss the detectability of these features with the ongoing and future radio interferometers. In particular, we show that LOFAR might be able to detect these absorption features at \( \zeta \approx 10 \) in less than 10 hr of integration if the flux of the background source is 400 mJy.

**Key words:** cosmology: theory – early universe – line: formation – magnetic fields – radio lines: general

**Online-only material:** color figure

1. **INTRODUCTION**

Future observations of the 21 cm line from neutral hydrogen from the redshift range 10–50 will be an important source of information about, first, the study of the global 21 cm signal after the recombination, which depends on the evolution of the thermal state of the universe (e.g., Pritchard & Loeb 2010; Furlanetto et al. 2006a; Sethi 2005; Gnedin & Shaver 2004; Shaver et al. 1999), and, second, the formation of the first stellar objects and reionization topology through the statistical properties of the 21 cm signal (e.g., Tozzi et al. 2000; Iliev et al. 2002). These observations can also help to put constraints on the relics of the inflation, such as super-heavy dark matter particles, which can produce ultra-high energy cosmic rays (Shchekinov & Vasiliev 2004; Vasiliev & Shchekinov 2006; Shchekinov & Vasiliev 2007), annihilation and decays of dark matter particles (Furlanetto et al. 2006b; Shchekinov & Vasiliev 2007; Chuzhoy 2008; Myers & Nusser 2008; Yuan et al. 2010; Cumberbatch et al. 2010; Natarajan & Schwarz 2009), and primordial magnetic fields (Sethi & Subramanian 2005; Tashiro & Sugiyama 2006; Sethi & Subramanian 2009).

The first two relics lead to extra ionization and heating of the gas both in the background (e.g., Shchekinov & Vasiliev 2007; Chuzhoy 2008; Myers & Nusser 2008) and in minihalos (Vasiliev & Shchekinov 2013). The impact of the primordial magnetic fields is more complicated. The decay of these fields in the post-recombination era alters the thermal and ionization evolution of the gas which influences the properties of the 21 cm global signal (Sethi 2005; Sethi & Subramanian 2005; Tashiro & Sugiyama 2006; Schleicher et al. 2009a). Also, additional ionization and heating stimulate the growth of the molecular hydrogen fraction (Sethi et al. 2008), which can influence the formation of first luminous objects.

A more significant effect caused by the primordial magnetic fields originates from the additional density fluctuations induced by these fields (Wasserman 1978; Kim et al. 1996; Subramanian et al. 1998; Gopal & Sethi 2003). These effects act to both cut the number of halos below the magnetic Jeans' scale and increase the number of halos at larger scales owing to additional density perturbations (e.g., Sethi & Subramanian 2005).

Unlike super-heavy dark particles and decaying dark matter, which have no observational counterparts in the local universe, the primordial magnetic field of nano-Gauss strength may be the progenitor of the large-scale magnetic fields observed in galaxies and clusters of galaxies with the coherence lengths up to \( \approx 10–100 \) kpc (for details of observations and theoretical models, see, e.g., Beck 2012; Widrow 2002). Even though these fields play an important role in various astrophysical processes, little is known about the origin of large-scale cosmic magnetic fields and their role in the evolutionary history of the universe. These fields could have originated from dynamo amplification of very small seed magnetic fields \( \approx 10^{-20} \) G (e.g., Parker 1979; Zeldovich et al. 1983; Brandenburg & Subramanian 2005; Schober et al. 2013; Sur et al. 2012). It is also possible that much larger primordial magnetic fields \( \approx 10^{-9} \) G were generated during the inflationary phase (Turner & Widrow 1988; Ratra 1992; Widrow 2002; Ryu et al. 2012) and the large-scale magnetic field presently observed is a relic of these fields. In this paper, we investigate one possible implication of such primordial magnetic fields.

The strength of the primordial magnetic field can be constrained by using a host of cosmological observables: the cosmic microwave background measurements, early reionization of the universe and H I signal from the era, cosmological gravitational lensing, and the study of Lyman-α clouds, etc. From the combination of Wilkinson Microwave Anisotropy Probe and other CMBR data, an upper limit \( B_0 < \) a few nG is obtained (Paoletti & Finelli 2013; Yamazaki et al. 2010; Trivedi et al. 2012). CMBR observations are sensitive to large-scale fields. For a single power law model, significantly tighter constraints are possible from the impact of these fields on smaller scales, which is also of direct relevance to this paper. From a host of constraints from the epoch of reionization, cosmological weak lensing, and the Lyα data, one can obtain an upper limit on...
magnetic field strength in the range \( \leq 0.4-1 \) nG (Pandey & Sethi 2013, 2012; Shaw & Lewis 2012; Kahliaishvili et al. 2010, 2013). Such fields can significantly modify the mass spectrum of the halos, which results in potentially observable changes in the H I emission signal from the epoch of reionization (Kahliaishvili et al. 2013; Sethi & Subramanian 2009). In this paper, we study the influence of primordial magnetic fields (in the range 0.3–0.6 nG) on the statistical properties of the 21 cm absorption from the epoch of reionization. In principle, the primordial magnetic fields can also be directly probed by the polarization of the 21 cm background through Zeeman splitting (Cooray & Furlanetto 2005).

We assume a ΛCDM cosmology with the parameters \( (\Omega_0, \Omega_{\Lambda}, \Omega_m, \Omega_{\nu}) = (1.0, 0.76, 0.24, 0.041, 0.73) \) (Planck Collaboration et al. 2013; Spergel et al. 2007).

2. THE EFFECTS OF THE PRIMORDIAL TANGLED MAGNETIC FIELDS

We assume the primordial magnetic field to be statistically homogeneous, isotropic, and Gaussian. The two-point function of the tangled fields (in comoving wave number) can be written as:

\[
\langle \mathbf{B}(\mathbf{q}) \mathbf{B}(\mathbf{k}) \rangle = \delta^2(k) \left( \mathbf{q} - \mathbf{k} \right) (\delta_{ij} - k_i k_j / k^2) M(k). \tag{1}
\]

Here \( M(k) \) is the magnetic field power spectrum and \( n = |\mathbf{k}| \) is the comoving wavenumber. Here we assume: \( M(k) = A \Lambda^3 \) and \( n \) is the magnetic field spectral index; we use \( n \approx -3 \) throughout this paper (for justification of this range of spectral indices, see, e.g., Pandey & Sethi 2013 and references therein). The power law is cut off at \( k_{\text{max}} \approx 200 \) (1 nG/\( B_0 \)), which is determined by the dissipation of magnetic fields in the pre-recombination era (for details, see Sethi & Subramanian 2005 and references therein). Here we refer to magnetic field strength \( B_0 \) as the rms \((\mathbf{B}^2(\mathbf{x}))^{1/2}\) filtered at \( k = 1 \) Mpc.

The presence of the magnetic field results in two distinct effects. The magnetic field dissipates in the collapsing halo owing to ambipolar diffusion which heats the halo. The spatial part of the heating rate by ambipolar diffusion can be computed (for details, see Sethi & Subramanian 2005):

\[
\left\langle (\nabla \times \mathbf{B}) \times \mathbf{B} \right\rangle^2 = \frac{2}{3} \int dk_1 \int dk_2 M(k_1)M(k_2) k_1^4 k_2^4. \tag{2}
\]

The presence of the primordial magnetic fields also result in additional matter perturbations at small scales. The magnetic-field-induced matter power spectrum \( P(k) \propto k^{3n+7} \) for \( n \approx -1.5 \) and it is sharply cut off at the magnetic Jeans’ scale \( k_{\text{J}} \approx 15 (1 \) nG/\( B_0 \)) (Kim et al. 1996; Gopal & Sethi 2003). This additional power at small scales changes the number of halos at masses of interest \( 10^9 M_6 \leq M \leq 10^8 M_6 \). If the halos in this mass range fail to form stars, then they would be observable in H I absorption.

In this paper, we take into account the following effects. (1) Additional heating due to ambipolar diffusion. (2) The impact of magnetic-field-induced small-scale power on matter power spectrum.

3. THE MODEL OF COLLAPSING HALO, H I OPTICAL DEPTH, AND THE NUMBER OF HALOS

3.1. Dark Matter, Gas Dynamics, and Magnetic Fields

To model the evolution of the dark matter, we follow the prescription given by Ripamonti (2007). The dark matter mass, \( M_{\text{DM}} = \Omega_{\text{DM}} M_{\text{halo}} / \Omega_{\text{M}} \), is assumed to be enclosed within a certain truncation radius \( R_{\text{tr}} \), inside which the dark matter profile is a truncated isothermal sphere with a flat core of radius \( R_{\text{vir}} \). The parameter \( \xi = R_{\text{vir}} / R_{\text{tr}} \) is taken to be 0.1 for all simulations. Such a description is used to mimic the evolution of a simple top-hat fluctuation (e.g., Padmanabhan 1993). The resulting dark matter profile has a flattened form (Burkert 1995).

The dynamics of baryons is described by a one-dimensional (1D) 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. Chemical and ionization composition includes a standard set of species: H, H+, H++, He, He++, He++, H2, H+2, D, D+, D++, HD, HD++, and e, with the corresponding reaction rates (Galli & Palla 1998; Stancil et al. 1998). The energy equation includes heating owing to ambipolar diffusion and different radiative losses in the primordial plasma: Compton cooling, recombination and bremsstrahlung radiation, collisional excitation of H I (Cen 1992), H2 (Galli & Palla 1998) and HD (Flower 2000; Lipovka et al. 2005). Our computation starts at redshift \( z = 100 \). The initial parameters—gas temperature, chemical composition, and other quantities—are taken from one-zone calculations that begin at \( z = 1000 \) with values at the end of recombination: \( T_{\text{gas}} = T_{\text{EMB}}, x[H] = 0.9328, x[H^+] = 0.0672, x[D] = 2.3 \times 10^{-3}, x[D^+] = 1.68 \times 10^{-6} \) (see references and details in Ripamonti 2007, Table 2).

In the early evolution of the halo, when it is still in the expansion phase and the overdensity is very small, the magnetic field strength scales as \( (1+z)^2 \). The initial condition is set during this phase. During the collapse phase of the halo, we assume the magnetic field strength to scale as its flux-frozen evolution with the gas density \( \rho : B_0 \propto \rho^{2/3} \) (e.g., Sethi et al. 2008; Schleicher et al. 2009b; Sethi et al. 2010). It should be noted that in both the expansion and the collapse phases, magnetic field scales as \( \rho^{2/3} \) with the gas density.

The heating rate due to the ambipolar diffusion is computed from Equation (2); during the expansion phase, this rate can be written as (Schleicher et al. 2008):

\[
L_A = \frac{B^4}{L_a} \frac{\lambda_{\text{HI}}}{16\pi^2\gamma_{\text{HI}} \rho^2} \tag{3}
\]

where \( B = B_0(1+z)^2 \), \( \gamma = 3 \times 10^{-9} / (2m_p) \), and

\[
L_a = 1.32 \times 10^{22} \frac{B_0}{10^{-9}} \frac{A}{1+z}.
\]

A depends on the cosmological parameters \( \Omega_m, h, \Omega_0 \) and the magnetic field power spectrum \( M(k) \). Equation (3) can be extended to the collapse phase using the flux-frozen condition discussed above.

Using the method and initial conditions described above we follow the evolution of minihalos with masses in the range \( M = 10^8-10^9 M_6 \); the virialization redshift of these halos is in the redshift range \( z = 10-15 \). In Figure 1 we show the density, temperature, velocity, and molecular hydrogen profiles for two halos, including the effects of the magnetic fields. We present the radial profiles of halos with \( M = 10^9, 10^8 M_6 \) virialized at \( z_{\text{vir}} = 10 \) for standard recombination \( (B = 0) \) and several values of initial magnetic strength: \( B = 0.1, 0.3, 0.6 \) and 1 nG. The most notable feature with a direct impact on the results presented in this paper is the change in the temperature profile. As seen in the figure, the presence of the magnetic fields results
in an increase in temperature across the halo, which has a direct bearing on the strength of the observed H\textsc{i} profile.

3.2. 21 cm Optical Depth and Equivalent Width

The spin temperature of the HI 21 cm line is determined by atomic collisions and the scattering of ultraviolet (UV) photons (Field 1958; Wouthuysen 1952). In our calculations, we used collisional coefficients from Kuhlen et al. (2006) and Liszt (2001). Magnetic fields provide the extra heating source. We do not include Ly\textalpha\ pumping in our study. We note that the inclusion of Ly\alpha\ scattering serves to couple the matter temperature with the spin temperature and plays a crucial role in the observability of intergalactic medium (IGM) H\textsc{i} in emission from the epoch of reionization (e.g., Sethi 2005; Gnedin & Shaver 2004). However, we consider only absorption from collapsing halos in the redshift range 10 < z < 15 against bright radio sources. In such halos, the spin temperature is coupled to the matter temperature through collisions and Ly\alpha\ does not play an important role.

The optical depth along a line of sight at a frequency $\nu$ is:

$$\tau\nu = \frac{3hpc^3A_{10}}{32\pi k v_0^2} \int_{-\infty}^{\infty} dx \frac{n_{\text{HI}}(r)}{\sqrt{\pi b^2(r)T_s(r)}} \exp \left[ -\frac{[v(\nu) - v_l(r)]^2}{b^2(r)} \right]$$

where $r^2 = \langle (ar_{\text{vir}})^2 + x^2 \rangle$, $\alpha = r_{\perp}/r_{\text{vir}}$ is the dimensionless impact parameter, $v(\nu) = c(v - v_0)/v_0$, $v_l(r)$ is the infall velocity projected along the line of sight, and $b^2 = 2kT_s(r)/m_p$ is the Doppler parameter.

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

$$W_{\nu} = \int_{v_0}^{\infty} (1 - e^{-\tau\nu})d\nu - \int_{v_0}^{\infty} (1 - e^{-\tau_{\text{IGM}}})d\nu$$

where $\tau_{\text{IGM}}$ is the optical depth of the background neutral IGM. Throughout this paper, we assume $\tau_{\text{IGM}} = 0$.

In Figure 2, we show the expected absorption profiles in the presence of magnetic fields. Additional heating owing to
Figure 2. Optical depth at the impact parameters 0.1, 0.3, 1, 1.5, 3 r_vir (solid, dashed, dotted, short-dashed, and dot-dash lines, correspondingly) for a halo $M = 10^7 M_\odot$ virialized at $z_{vir} = 10$ in the standard recombination model ($B = 0$) (Vasiliev & Shchekinov 2012) and in the presence of primordial magnetic fields with $B = 0.3$ nG. The $x$-axis denotes the frequency width of the signal in the rest frame of the halo.

Figure 3. Comoving mass function is shown for different models at $z = 10$: ΛCDM model (dot-dashed curve), solid and dotted lines ($B_0 = 0.3$ nG, $n = -2.9, -2.95$, respectively), dashed and dot-dot-dot-dashed lines ($B_0 = 0.6$ nG, $n = -2.9, -2.95$, respectively).

(A color version of this figure is available in the online journal.)

3.3. Number of Halos

We use the Press–Schechter formalism to compute the number of halos in a given mass range at a redshift. This allows us to compute the number of halos that intersect a given line of sight in a redshift range $z$ and $z + dz$:

$$N(z) = \int dM \left( \frac{dn}{dM} \right) \frac{\pi r_{\perp}^2}{\Omega^{1/2}} \frac{H_0^{-1} dz}{(1 + z)^{3/2}}.$$  \hspace{1cm} (6)

Here $r_{\perp}$ is the impact factor and for our computation we take the maximum impact factor $r_{\perp} = 3 r_{vir}$ for any mass; $dn/dM$ is the mass function of halos (in $Mpc^{-3} M_\odot^{-1}$).

The main impact of the primordial magnetic fields is on the number of halos in the mass range $10^6 M_\odot \leq M \leq 10^8 M_\odot$. Figure 3 shows the mass function of halos for the models with and without the primordial magnetic fields. The number of halos in the mass range of interest could be orders of magnitude larger than in the usual ΛCDM model. This is owing to the extra power at small scales induced by the primordial magnetic fields. This extra power increases the mass dispersion $\sigma(M, z)$ at mass scales comparable to the magnetic Jeans’ mass; in particular, such an increase might result in $1\sigma$ collapse of such halos while the ΛCDM model only allows nearly $3\sigma$ overdensities to collapse at $z = 10$ (e.g., Sethi & Subramanian 2005). In the Press–Schechter formulation, the mass function of halos is $dn/dM \propto \exp[-\delta_c^2/(2\sigma^2(M, z))]$ with $\delta_c = 1.68$; this results in a sharp increase in the number of halos at small scales. Two other notable features of the figure are as follows. (1) An increase in the strength of the magnetic field results in a decrease in the number of halos at small-mass scales and an increase for larger masses. This feature is caused by the increase of the magnetic Jeans’ length with the magnetic field strength. (2) The number of halos is seen to be extremely sensitive to the magnetic field spectral index. For $n \simeq -3$, the mass dispersion, $\sigma(M) \propto (n+3)$.

As the number of halos is exponentially sensitive to the value of mass dispersion, the number of halos sharply decreases as $n$ approaches $-3$.

For $\Delta z = 0.2$ (corresponding to a frequency width $\Delta \nu \simeq 2.4$ MHz at $z \simeq 10$) and the ΛCDM model, $N(z) \simeq 0.1$ or 1 out of 10 lines of sight is likely to intersect such a halo. For the magnetic strength of field $B_0 = 0.3$ nG and $n = \simeq -2.9$, we get $N(z) \simeq 18$.

To underline the impact of the primordial magnetic fields, we define an effective optical depth:

$$\tau_{eff}(z) = \int dr_{\perp} \int dM \left( \frac{dn}{dM} \right) (z)2\pi r_{\perp} \frac{H_0^{-1} dz}{\Omega^{1/2}(1 + z)^{3/2}} \times \tau(M, r_{\perp}, z).$$  \hspace{1cm} (7)

$\tau_{eff}(z)$ is weighted by $\tau(M, r_{\perp}, z)$ and scales as the number of halos so it captures both the decrease in optical depth owing to additional heating and the increase of the number of halos in the presence of the magnetic field.

4. RESULTS

To illustrate the difference between the ΛCDM model and the effects of the primordial magnetic fields, we simulate the absorption spectra in the redshifted H I line.

Equation (6) gives the number of halos in a redshift interval (or, equivalently, for a given frequency channel width).
For simulating the absorption spectrum, we choose the redshift bin $dz$ to be such that $N(z) \ll 1$. For each channel, a Poisson number is drawn with the average given by $N(z)$. Since $N(z) \ll 1$, this number is either 0 or 1. To determine the mass and impact factor of the intervening halo, random numbers are drawn from the mass function for the respective cases and probability density for the impact factor. Given the optical depth as a function of mass, impact factor, and the frequency, this procedure allows us to simulate synthetic spectra.

In Figure 4, we show the simulated spectra for two cases: $B_0 = 0.3 \text{ nG}$ and $B_0 = 0.6 \text{ nG}$ for $n = -2.9$ and $n = -2.95$ at $z = 10$. The channel width in the spectra is $\simeq 1 \text{ kHz}$ and the total frequency coverage is $\simeq 20 \text{ MHz}$.

As seen in the figure, the number of intersecting halos in the two cases are comparable, even though the number density of halos is larger in the former case (Figure 3). This is because the number of intersecting halos scales as $M^{1.6}dn/dm$ (Equation (6)), which puts higher weights on halos of larger mass as compared to the distribution shown in Figure 3. Also, this combination selects a maximum at certain mass scales: for $B_0 = 0.3, 0.6 \text{ nG}$, ($n = -2.90$) the mass scales are $7 \times 10^5 M_\odot$ and $6 \times 10^6 M_\odot$, respectively (for the $\Lambda$CDM model, the equivalent mass is $2 \times 10^6 M_\odot$). As the figure shows, the spectrum is not particularly sensitive to the strength of the magnetic field for a given value of the spectral $n$ in this range of magnetic field strengths.

However, the number of halos along a line of sight is very sensitive to the spectral index $n$. For $n = -2.95$, the number of such sources falls by more than an order of magnitude for both magnetic field strengths shown in the figure. This means that the observed spectra could be a strong discriminator of the magnetic field power spectral index.

In Figure 5, we show the simulated spectra at $z = 15$. The sharp fall in the number of absorption features is a result of the decrease in mass dispersion at higher redshifts.

As noted above, the $\Lambda$CDM model predicts roughly one intersecting halo for the frequency coverage displayed in Figure 4. Therefore, in principle, if deep absorption features seen in Figure 4 are detected toward a few lines of sight, it could be an indication of a process which produces extra matter fluctuations at small scales. In particular, the presence of a large number of sources along a line of sight (Figure 4) could be used to extract information about the magnetic field parameters.

4.1. Detectability of $\text{H}^\text{i}$ Absorption

As discussed above, the main impact of the inclusion of the magnetic field in our analysis is a sharp increase in the number of absorption lines (Figure 4). Each of the absorption features has a width of $\simeq 10 \text{ kHz}$ (in the observer frame for $z \simeq 10$; Figure 2).

This leads to at least three distinct possibilities for the detection of the signal.

1. Owing to a large number of absorption features, the probability of deep, narrow features that arise when the impact parameter is small increases (Figure 2). Figure 4 shows that many such features have optical depths in the excess of $\tau = 0.05$; such features are detectable at frequency resolutions $\simeq 1 \text{ kHz}$.

2. At the frequency resolution comparable to the line width we expect significant signal. Also, there is a reasonable probability of line blending owing to high density of such features.

3. At even lower frequency resolution, one can hope to detect the combined effect of many lines blending into a broad feature (Xu et al. 2011).

Ongoing experiments such as the Murchison Widefield Array (MWA) and the Low-Frequency Array (LOFAR) can, in principle, detect the absorption signal from the redshifted $\text{H}^\text{i}$ line. MWA can achieve channel widths $\simeq 40 \text{ kHz}$ and a total instantaneous bandwidth of $32 \text{ MHz}$ in the frequency range of interest (80–150 MHz). LOFAR can have a channel width of $\lesssim 1 \text{ kHz}$ with a total bandwidth of roughly 75 MHz. The LOFAR spectral resolution is comparable to the spectra shown in Figure 4.

Given the angular resolution of these experiments, one of the challenges in the detection of these absorption features
from the epoch of reionization is distinguishing high-redshift bright continuum sources from low-redshift sources. MWA has an angular resolution of nearly 4′ and a confusion noise \( \lesssim 10 \) mJy. On the other hand, LOFAR presents a better prospect with an angular resolution \( \approx 10′ \) which gives a confusion noise \( \approx 100 \) \( \mu \)Jy. LOFAR can reach a sensitivity of 200 \( \mu \)Jy in 8 hr of integration for a bandwidth of 3.66 MHz in the frequency range 100–200 MHz. This corresponds to a line sensitivity (for a channel width \( \Delta \nu \approx 1 \) kHz) of nearly 14 mJy. To detect a line feature with an optical depth \( \approx 0.05 \) (Figure 4) at a 5\( \sigma \) level, a source of a few Jansky flux density would be needed. A significantly longer integration time would be needed for fainter sources.

To investigate the possibility of detecting H I features at lower frequency resolution, we show equivalent widths, \( W_\nu \) (Equation (4)), for spectra at two different frequency resolutions in Figures 6 and 7. Even though the equivalent widths are clustered around \( W_\nu \leq 0.2 \) kHz in Figure 6, there are a number of features at higher equivalent widths, e.g., the lower left panel of Figure 6 has two features in the range \( W_\nu \approx 0.55–0.6 \) kHz, that arise from the blending of two lines. If the threshold of detection is \( \tau = 0.02 \), then these features can be detected with \( \Delta \nu \approx 30 \) kHz. Alternatively, at such spectral resolutions, one obtains a gain in the signal-to-noise of a factor of two over detecting a feature of \( \tau = 0.05 \) with \( \Delta \nu \approx 1 \) kHz.

In Figure 7, we display equivalent widths for spectra smoothed at \( \Delta \nu \approx 100 \) kHz. This allows us to assess the feasibility of detecting H I absorption features at low resolutions. The distribution of equivalent widths is seen to shift to larger values for the smoothed spectrum. This is a result of the blending of densely packed spectral lines as the resolution is decreased. The most notable feature of the figure is that many features are seen to have equivalent widths \( \approx 2 \) kHz, nearly three times the largest values for the high-resolution spectra. This means that the decline in the peak optical depth as the spectra are smoothed is compensated by the inclusion of more sources. In other words, if the threshold optical depth of detection is 0.02, it can be detected even with a resolution of \( \Delta \nu \approx 100 \) kHz. More specifically, using the parameters of LOFAR, such features are detectable by LOFAR at a 5\( \sigma \) level for a source flux density of \( \approx 400 \) mJy in 8 hr of integration.

As noted above, a few such sources might suffice to reveal the nature of magnetic-field-induced extra matter power. How likely are such bright radio sources at \( z \approx 10 \)? The radio source J0924-2201 has \( z \approx 5.2 \) with a flux \( F_\nu \approx 0.55 \) Jy at 230 MHz (Carilli et al. 2007). Such a steep spectrum source might be brighter at \( \nu \approx 130 \) MHz (redshifted H I frequency at \( z \approx 10 \)) with a flux comparable to its value at 235 MHz. Such rare radio sources might provide a suitable setting for understanding the nature of density perturbations during the epoch of reionization.

However, the expected radio flux distribution of sources from the epoch of reionization is highly uncertain and for fainter sources the integration time might become unrealistically large, e.g., for a 40 mJy source, 800 hr of integration time would be needed. The planned radio interferometer Square Kilometer Array will be ideal for detecting these features: its sensitivity is projected to reach 400 \( \mu \)Jy in 1 minute integration in the frequency range 70–300 MHz with subarcsec resolution, which will suppress the impact of confusion noise.5

In this paper, we only considered absorption from collapsed halos which are rarer but give rise to large optical depths. In addition, we could have mildly overdense regions (with density contrasts \( \delta \approx 1–10 \)) in the neutral gas (Mack & Wyithe 2012). These regions give rise to smaller optical depths but their effect might be detectable through statistical methods, based on the distribution of radio sources during the epoch of reionization (Mack & Wyithe 2012). Magnetic fields alter the density field at all scales and therefore would also change the statistical properties of such regions (e.g., Pandey & Sethi 2013). We hope to return to this issue in a later work.

In Table 1, we list \( t_{\text{eff}} \) for a range of models. As noted above, this measure captures the impact of both magnetic field heating and the change in the number of halos.

4.2. Comparison between Magnetic Heating, Dark Matter Decay, and X-Ray Heating

The evolution of the observed number and optical depths of absorption features is sensitive to the evolution of heating mechanisms of the IGM. Here we briefly compare the relative impact of X-ray heating, dark matter decay models, and the magnetic field heating.

5 https://www.skatelescope.org/
Using Equation (3) the heating rate due to ambipolar diffusion can be written as [K s\(^{-1}\)]:

\[
\frac{2L_A}{3knH(z)} \simeq 1.2 \times 10^4 \left( \frac{B_0}{10^{-9}} \right)^2 \left( \frac{1+z}{10} \right)^{-1/2} \left( \frac{10^{-4}}{x_r} \right). \tag{8}
\]

One can compare this rate to the heating rates due to X-ray and decaying dark matter. The total normalized X-ray emissivity \(\xi_X\) can be written as (Furlanetto 2006)

\[
\frac{2\xi_X}{3knH(z)} = 5 \times 10^4 f_X \left[ \frac{f_{\text{coll}}}{0.1} \frac{df_{\text{coll}}/dz}{0.01} \frac{1+z}{10} \right]. \tag{9}
\]

where \(df_{\text{coll}}/dz\) is the fraction of baryons collapsed to form a protogalaxy per unit redshift, \(f_X\), the fraction of baryons converted into stars in a single star formation event.

The corresponding heating rate due to Decaying Dark Matter can be found as \(K_e = \chi_0/\xi_L\) (Vasiliev & Shchekinov 2013)

\[
\frac{2K}{3kh(z)} = 8.9 \times 10^4 \left( \frac{\xi/\xi_L}{10} \right)^{-2/3}. \tag{10}
\]

The dependence of rates Equations (3), (9), and (10) on the redshift are not very different. Thus, from the global signal it would be difficult to separate between the decaying dark matter, X-ray heating, and magnetic fields.

In other words, the main discriminator between these models is the far larger number of halos produced owing to additional density perturbations in the presence of the primordial magnetic fields.

5. CONCLUSIONS

In this paper, we studied the impact of the primordial magnetic fields on H\(\alpha\) absorption from collapsed halos during the epoch of reionization. We considered halos in the mass range \(10^6 - 10^9 M_\odot\) and the absorption from these halos for \(r \leq 3 r_{\text{vir}}\). We consider magnetic field strength in the range \(B_0 = 0.3 - 0.6 \mu G\), comparable to the best upper bounds on these fields from cosmological observables (Pandey & Sethi 2013, 2012; Shaw & Lewis 2012; Kahnashvili et al. 2010, 2013).

The presence of the magnetic fields result in two separate effects. The decay of the magnetic fields in the collapsing halos owing to ambipolar diffusion heats the halo which lowers the optical depth of the absorption for intermediate masses (Figure 2). Primordial magnetic fields also generate additional density perturbations which result in a sharp increase in the number of halos (Figure 3). The latter effect dominates the observable signature (Figure 4).

If these halos become star-forming they could be responsible for early reionization and result in a distinct H\(\alpha\) fluctuation signature from the epoch of reionization. However, if these halos remain H\(\alpha\)-rich, then their presence will not significantly impact the H\(\alpha\) emission signal from the epoch of reionization as their temperatures are far larger than the CMBR temperature (Figure 1) and the H\(\alpha\) emission signal is nearly independent of the spin temperature (assuming \(T_e = T_B\) in this case. Therefore, the most promising way to observe them would be in absorption.

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