

Sensitivity of the redshifted 21 cm signal from the Dark Ages to parameters of primordial magnetic fields

B. Novosyadlyj^{1,*}, Yu. Kulinich¹, N. Fortuna¹, and A. Rudakovskiy^{2,3}

¹ Astronomical Observatory of Ivan Franko National University of Lviv, Kyryla i Methodia str., 8, Lviv 79005, Ukraine

² Bogolyubov Institute for Theoretical Physics of the NAS of Ukraine, Metrolohichna Str. 14-b, Kyiv 03143, Ukraine

³ Dipartimento di Fisica e Astronomia, Università di Bologna, Via Gobetti 93/2, 40122 Bologna, Italy

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ABSTRACT

We analyse the impact of the decaying magnetic turbulence of primordial magnetic fields (PMFs) and ambipolar diffusion on the ionisation and thermal history of the Dark Ages Universe ($30 \leq z \leq 300$), and its imprint on the spectral profile of the global signal in the redshifted 21 cm hydrogen line. The heating function caused by decaying magnetic turbulence monotonically decreases after cosmological recombination; its amplitude strongly depends on the strength of the PMFs' B_0 and weakly depends on the spectral index of the initial power spectrum of the PMFs' n_B . The heating function caused by ambipolar diffusion, in contrast, noticeably depends on the spectral index in the range $-3 \lesssim n_B \lesssim 4$ but is subdominant in the Dark Ages epoch for PMF models with $B_0 \lesssim 0.5$ nG. We computed the ionisation and thermal history of intergalactic gas from the cosmological recombination up to the end of the Dark Ages epoch for a range of PMF parameters, $0.05 \lesssim B_0 \lesssim 0.5$ nG, $-2.9 \lesssim n_B \lesssim 4$, and show the essentially distinguished thermal evolution from one in the Lambda cold dark matter (Λ CDM) model. We also show that the profile of the redshifted 21 cm hydrogen line is very sensitive to the PMF parameters from this range and can be used for their constraints in conjunction with other observational data.

Key words. cosmological parameters – cosmology: miscellaneous – early Universe – dark ages, reionization, first stars

1. Introduction

There is a broad range of observational evidence indicating the existence of magnetic fields in the Universe. Relatively strong fields residing in star systems and galaxies are believed to result from the amplification of seed fields with understood hypothetical magnetodynamoes. In contrast, magnetic fields in cosmic voids have no apparent connection to astrophysical sources and support the idea of their cosmological origin (see reviews by Durrer & Neronov 2013; Subramanian 2016). They are called primordial magnetic fields (PMFs), and the experimental evidence for their existence follows from the observations of blazar radiation in GeV and TeV energy ranges by advanced gamma-ray telescopes (Neronov & Vovk 2010; Dolag et al. 2011; Takahashi et al. 2013; Tiede et al. 2020; Acciari et al. 2023). They give a lower limit on the value of such fields on scales of several megaparsecs: $B_0 > 10^{-20}$ G. There are a few methods of studying the magnetic fields at cosmological space-time scales, including Faraday rotation measurements (O'Sullivan et al. 2020; Neronov et al. 2024), magnetic fields' impact on CMB (Paoletti et al. 2022), Ly- α forest method (Pavičević et al. 2025), dwarf galaxies studies (Sanati et al. 2024), studying high- z structures (Ralegankar et al. 2024), and line-intensity mapping (Adi et al. 2023). The upper limit follows from the study of the cosmic microwave background (CMB) anisotropy by the Planck Space Observatory (Planck Collaboration XIX 2016): $B_0 < 9 \cdot 10^{-10}$ G.

The signals from the Dark Ages, when physical processes in the baryonic component with primordial chemistry were simplest,

promise to unveil some puzzles of current cosmology related to primordial fields, the nature of dark matter particles, and others. Such signals are the 21 cm line of atomic hydrogen (see reviews Barkana & Loeb 2001; Fan et al. 2006; Furlanetto et al. 2006; Bromm & Yoshida 2011; Pritchard & Loeb 2012; Natarajan & Yoshida 2014; Shimabukuro et al. 2023; Minoda et al. 2023) and the ro-vibrational lines of the first molecules (Kamaya & Silk 2002; Ripamonti et al. 2002; Kamaya & Silk 2003; Omukai & Kitayama 2003; Mizusawa et al. 2004, 2005; Liu et al. 2019; Novosyadlyj et al. 2020, 2022; Maio et al. 2022). They manifest themselves as a weak distortion of the CMB spectrum. In this paper, we discuss the redshifted 21 cm signal in the decametre wavelength range.

The development of theoretical aspects regarding the dependence of the 21 cm signal from the early Universe on PMFs can be followed in papers (Sethi & Subramanian 2005; Tashiro & Sugiyama 2006; Schleicher et al. 2009; Kunze & Komatsu 2014; Chluba et al. 2015; Kunze 2019; Cruz et al. 2024; Bhaumik et al. 2025). They are mainly focused on the global signal at 50–100 MHz expected from the Cosmic Dawn epoch as the strongest one capable of being detected by current advanced antennas, such as EDGES (Bowman et al. 2018) and SARAS 3 (Singh et al. 2022), or power spectrum by array telescopes such as LOFAR¹, MWA², PAPER³, GMRT⁴ or HERA⁵.

¹ www.lofar.org

² <https://www.mwatelescope.org>

³ eor.berkeley.edu/

⁴ <http://www.gmrt.ncra.tifr.res.in/gmrt/gmrt.html>

⁵ <https://reionisation.org/>

* Corresponding author: bnovos@gmail.com

In this paper we study the impact of primordial magnetic fields on the predicted 21 cm hydrogen line signal from the Dark Ages redshifted to the decametre range of electromagnetic waves 10–50 MHz. Due to magnetic field decay, there is additional heating of intergalactic gas. The goal is to establish the sensitivity range of this signal to the large-scale averaged amplitude and power spectrum index of PMFs. In previous papers (Novosyadlyj et al. 2023, 2024), we analysed the sensitivity of the Dark Ages global signal to the strength of nearly scale-invariant PMFs ($n_B = -2.9$). In the paper by Konovalenko et al. (2024), it was shown that the sensitivities of ground-based Ukrainian array telescopes, UTR-2 and GURT, are enough to detect the redshifted 21 cm signal from the Dark Ages with integration time ~ 60 days. The most promising ground-based array telescope for investigating the metre-decametre wavelength sky with the highest sensitivity and angular resolution is Square Kilometre Array⁶ (SKA), which will start observations in the coming years. Moreover, a few projects of far-side lunar telescopes aiming to detect this line are under development (Burns et al. 2011; Shkuratov et al. 2019; Bentum et al. 2020; Burns 2021; Goel et al. 2022; Bale et al. 2023). The Chinese low-frequency radio spectrometer⁷ Chang'E-4 is already in operation and is taking measurements. So detailed investigations of the 21 cm line from the Dark Ages, its dependence on parameters of cosmological models, and the existence of degeneracies between them are important tasks of current cosmology.

The plan of the paper is as follows. In Sect. 2, we describe the state of the intergalactic medium during the Dark Ages, from cosmological recombination up to the beginning of intensive reionisation at $z = 10$, in the Λ CDM cosmological models with different values of amplitude and power spectrum index of PMFs. In Sect. 3, we analyse the dependence of the position and profile of the 21 cm absorption line in the Dark Ages on cosmological parameters in the standard Λ CDM model and additional heating of the baryonic component in models with PMFs. The comparison of our results with analogical ones of other authors, discussions of disagreements and degeneracies are presented in Sect. 4. The results are summarised in Sect. 5.

2. Thermal history of the intergalactic medium in the Dark Ages

For the calculation of distortion of the CMB thermal spectrum at the redshifted 21 cm line in the Dark Ages epoch, it is necessary to compute the ionisation and thermal history of the gas, as well as the populations of levels of the hyperfine structure of atomic hydrogen. They depend on the parameters of the cosmological model, the ionisation mechanisms, heating, and cooling of the baryonic gas. In this section, we consider the ionisation and thermal history of the gas in the model with primordial magnetic fields and in the standard Λ CDM model for comparison. In all computations, we assume the cosmological parameters following from Planck Collaboration VI (2020): $H_0 = 67.36 \pm 0.54$ km/s · Mpc (Hubble constant), $\Omega_b = 0.0493 \pm 0.00112$ (density parameter⁸ of baryonic matter), $\Omega_{dm} = 0.266 \pm 0.0084$ (density parameter of dark matter), $\Omega_r = 2.49 \cdot 10^{-5}$ (density parameter of relativistic component (CMB and neutrinos)),

$\Omega_\Lambda = 0.6847 \pm 0.0073$, and $\Omega_K = 0$ (dimensionless⁹ cosmological constant Λ and curvature of 3-space K , respectively). We assume the primordial chemical composition with the mass fraction of helium $Y_p = 0.2446$ (Peimbert et al. 2016), following from the cosmological nucleosynthesis of the standard Big Bang model.

After the epoch of cosmological recombination and before reionisation ($800 \lesssim z \lesssim 10$), more than 99% of hydrogen was in the neutral state. The residual ionisation of the Universe is a consequence of its expansion. The fraction of ionised hydrogen x_{HII} is less than 1% at these redshifts and depends on the density, the mechanisms of heating and cooling of the gas, and the expansion rate of the Universe. For a homogeneous expanding Universe, the gas temperature and ionisation of atoms are calculated by integrating a system of differential equations describing energy balance and ionisation-recombination kinetics of atoms¹⁰. In the standard Λ CDM model, the main mechanism of gas heating in this period is Compton scattering of CMB radiation on free electrons and adiabatic cooling caused by cosmological expansion. All other heating and cooling mechanisms that occur in astrophysical plasma under Dark Ages conditions are significantly weaker (see Fig. 4 in Novosyadlyj et al. 2023).

In our computations, during cosmological recombination and in the epoch of the Dark Ages, the temperature of the plasma and the ionisation of hydrogen and helium up to $z = 200$ are calculated using an effective three-level atomic model implemented in the publicly available code RecFast¹¹ (Seager et al. 1999, 2000). The calculation for $z < 200$ is by the numerical integration of the system of differential equations:

$$-\frac{3}{2}n_{\text{tot}}k_B(1+z)H\frac{dT_b}{dz} = \Gamma_{\text{CMB}} - \Lambda_{\text{ad}} - \Lambda_{\text{ff,phr,H}_2} + \Gamma_{\text{pmf}}, \quad (1)$$

$$-(1+z)H\frac{dx_{\text{HII}}}{dz} = R_{\text{HI}}x_{\text{HI}} + C_{\text{HI}}^i n_i x_{\text{HI}} - \alpha_{\text{HII}} x_{\text{HII}} x_e n_{\text{H}}, \quad (2)$$

$$-(1+z)H\frac{dx_{\text{HeII}}}{dz} = R_{\text{HeI}}x_{\text{HeI}} + C_{\text{HeI}}^i n_i x_{\text{HeI}} - \alpha_{\text{HeII}} x_{\text{HeII}} x_e n_{\text{H}}, \quad (3)$$

$$H = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda}, \quad (4)$$

where T_b is the temperature of the baryonic gas; $n_{\text{tot}} \equiv n_{\text{HI}} + n_{\text{HII}} + n_e + n_{\text{HeI}} + n_{\text{HeII}} + n_{\text{HeIII}}$ is the number density of particles of all types; $n_{\text{H}} \equiv n_{\text{HI}} + n_{\text{HII}}$ is the number density of hydrogen; $n_e \equiv n_{\text{HII}} + n_{\text{HeII}} + 2n_{\text{HeIII}}$ is the number density of electrons; $x_e \equiv n_e/n_{\text{H}}$, $x_{\text{HI}} \equiv n_{\text{HI}}/n_{\text{H}}$, $x_{\text{HII}} \equiv n_{\text{HII}}/n_{\text{H}}$, $x_{\text{HeI}} \equiv n_{\text{HeI}}/n_{\text{He}}$, $x_{\text{HeII}} \equiv n_{\text{HeII}}/n_{\text{He}}$, k_B is the Boltzmann constant; Γ_{CMB} is the heating function due to Compton scattering of CMB quanta on free electrons (Seager et al. 1999, 2000); Λ_{ad} is the adiabatic cooling function due to the expansion of the Universe (Seager et al. 1999); Λ_{ff} is the cooling function due to free-free transitions of electrons (Shapiro & Kang 1987); Λ_{phr} is the cooling function due to photorecombination (Anninos et al. 1997); Λ_{H_2} is the cooling function due to emission in rotational-vibrational transitions of the H_2 molecule (Seager et al. 1999); Γ_{pmf} is the heating function caused by PMFs decaying; R_{HI} , R_{HeI} are the photoionisation rates of hydrogen and helium atoms; C_{HI}^i , C_{HeI}^i are the collisional ionisation coefficients of the i -th type of particles; α_{HII} , α_{HeII} are the recombination coefficients of hydrogen and

⁶ <https://www.skao.int/>

⁷ https://www.nssdc.ac.cn/nssdc_en/html/task/change4.html

⁸ Density parameter is the mean density of the component in the current epoch in units of critical density: $\Omega_i \equiv \rho_i^0/\rho_{\text{cr}}^0$ where $\rho_{\text{cr}}^0 \equiv 3H_0^2/8\pi G$.

⁹ $\Omega_\Lambda \equiv c^2\Lambda/3H_0^2$, $\Omega_K \equiv -c^2K/H_0^2$.

¹⁰ The first molecules make up a small fraction of all particles (see Novosyadlyj et al. 2020, 2022) and are not discussed here in the context of ionisation history.

¹¹ <http://www.astro.ubc.ca/people/scott/recfast.html>

helium ions; and $\Omega_m = \Omega_b + \Omega_{dm}$, $H(z)$ is the expansion rate of the Universe. The reaction rates used here can be found in Appendix of Novosyadlyj et al. (2023).

We assume that the non-helical magnetic field in the Dark Ages is an isotropic and homogeneous random process, and the following equations by Mack et al. (2002), Sethi & Subramanian (2005), Kunze & Komatsu (2014), Chluba et al. (2015), Minoda et al. (2019) describe its statistical properties in terms of a power spectrum,

$$\langle \tilde{B}_i^*(\mathbf{k}) \tilde{B}_j(\mathbf{k}') \rangle = 4\pi^3 \delta_D(\mathbf{k} - \mathbf{k}') (\delta_{ij} - k_i k_j) P_B(k), \quad (5)$$

where $\tilde{B}_i(\mathbf{k})$ is a Fourier component of $B_i(\mathbf{x})$ with wave vector $\mathbf{k}$ and

$$P_B(k) = \frac{(2\pi)^{n_B+5}}{\Gamma(\frac{n_B+3}{2})} \langle B_\lambda^2 \rangle \frac{k^{n_B}}{k_\lambda^{n_B+3}}, \quad (6)$$

where n_B is the spectral index, $\tilde{B}_\lambda$ is the Fourier mode of the smoothed field B_λ over scale λ . Magnetohydrodynamics of the baryon-photon plasma before recombination predicts the decay of magnetic fields at small scales. The smallest scale that survives is defined by the field strength, the dimensionless Alfvén velocity, and the baryon-photon Silk damping scale (Subramanian & Barrow 1998). The damping scale at the recombination epoch is as follows:

$$k_D^{rec} = \left[7.32 \cdot 10^4 \left(\frac{k_\lambda}{\text{Mpc}^{-1}} \right)^{n_B+3} \left(\frac{\omega_m}{0.15} \right)^{\frac{1}{2}} \left(\frac{\omega_b}{0.02} \right) \times \left(\frac{x_e^{rec}}{0.1} \right) \left(\frac{1+z_{rec}}{1100} \right)^{\frac{5}{2}} \left(\frac{nG}{B_\lambda} \right)^2 \left(\frac{h}{0.7} \right)^2 \right]^{\frac{1}{n_B+5}} \text{Mpc}^{-1}, \quad (7)$$

where $\omega_i \equiv \Omega_i h^2$ and x_e^{rec} is the fraction of free electrons at the time of recombination z_{rec} . The justification for this expression is given in Appendix A. At any time after recombination, the evolution of the damping scale is presented as $k_D(z) = k_D^{rec} f_D(z)$, where we obtain $f_D(z)$ by integrating the energy conservation equation for PMFs:

$$-(1+z)H \frac{d\rho_{mf}}{dz} = -4H\rho_{mf} - \Gamma_{mf}, \quad (8)$$

simultaneously with Eqs. (1)–(4). In this equation, the first term on the right-hand side describes the adiabatic decay of the PMFs' energy density caused by expansion of the Universe ($\rho_{mf}^{ad} \propto (1+z)^4$), and where $\Gamma_{mf} = \Gamma_{mf}^{(dt)} + \Gamma_{mf}^{(amd)}$ is the dissipation rate of the PMFs' energy density in the post-recombination plasma due to the decaying magnetic turbulence and ambipolar diffusion. We set the initial condition for $f_D(z_{rec}) = 1$.

In such an approach, the magnetic field strength $B(z)$, smoothed at a scale λ at any redshift z , is given as follows (Minoda et al. 2019):

$$B_\lambda^2(z) = \frac{f_D^{n_B+3}(z) \cdot (1+z)^4}{2\pi^2} \int_0^\infty P_B(k) e^{-k^2 \lambda^2} k^2 dk. \quad (9)$$

We note $B_{\lambda_D}^{ad}(z) \equiv B_0 \cdot (1+z)^2$, where $\lambda_D = 2\pi/k_D$. Then the energy density of the PMFs at any z is

$$\rho_{mf}(z) = f_D^{n_B+3}(z) \cdot \rho_{mf}^{ad}(z) = 3.98 \cdot 10^{-20} \left(\frac{B_0}{\text{nG}} \right)^2 f_D^{n_B+3}(z) \cdot (1+z)^4 \frac{\text{erg}}{\text{cm}^3}. \quad (10)$$

So, the factor $f_D^{n_B+3}$ describes the over-adiabatic decay of PMFs caused by heating the slightly ionised plasma after recombination. The often-used strength of smoothed PMFs on the scale of $\lambda = 1 \text{ Mpc}$ is related to B_0 as $B_{1\text{Mpc}} = B_0 (2\pi/k_D)^{\frac{n_B+3}{2}}$. So, for $\lambda_D < 1 \text{ Mpc}$, $B_{1\text{Mpc}} < B_0$ and decreases with increasing n_B .

The decay of magnetic fields leads to the heating of baryonic matter, affecting the thermal and ionisation history of the Universe in the Dark Ages. Two mechanisms of heating of baryonic matter are considered: decaying magnetic turbulence and ambipolar diffusion. Taking into account the results in Mack et al. (2002), Sethi & Subramanian (2005), Chluba et al. (2015), Kunze & Komatsu (2014), Minoda et al. (2019), the dependence of the corresponding heating functions on redshift can be represented as follows:

$$\Gamma_{pmf}^{(dt)}(z \geq z_{rec}) = 1.5 \rho_{mf}^{ad} H(z) \frac{w_B}{a} [f_D(z)]^{n_B+3} \times \exp \left\{ -\frac{(z - z_{rec})^2}{5000} \right\} \left(\frac{1 + z_{rec}}{1 + z} \right)^4, \quad (11)$$

$$\Gamma_{pmf}^{(dt)}(z < z_{rec}) = 1.5 \rho_{mf}^{ad} H(z) [f_D(z)]^{n_B+3} \times \frac{w_B a^{w_B}}{(a + 1.5 \ln((1 + z_{rec})/(1 + z)))^{w_B+1}}, \quad (12)$$

$$\Gamma_{pmf}^{(amd)}(z) = \frac{1 - x_{\text{HII}}}{g(T_b) x_{\text{HII}}} [f_D(z)]^{2n_B+8} \times \left[\frac{(1+z) k_D^{rec}}{3.086 \cdot 10^{24}} \frac{\rho_{mf}^{ad}}{\rho_b} \right]^2 f_L, \quad (13)$$

where $[\Gamma] = \text{erg/cm}^3/\text{s}$, $z_{rec} = 1088$, and t_{rec} are the redshift and time of cosmological recombination accordingly; $a = \ln(1 + t_d/t_{rec})$, $w_B \equiv 2(n_B + 3)/(n_B + 5)$, $t_d/t_{rec} = 14.8/(B_0 k_D)$, and $\rho_b = \rho_{cr}^{(0)} \Omega_b (1+z)^3$ is the baryonic matter density; $g(T_b) = 1.95 \cdot 10^{14} T_b^{0.375} \text{ cm}^3/\text{s/g}$, and $f_L = 0.8313(n_B + 3)^{1.105} (1.0 - 0.0102(n_B + 3))$ is the analytic approximation of the Lorentz force integral (Chluba et al. 2015).

With regard to the value of the spectral index n_B , there are no strong theoretical constraints placed on it. In fact, the spectral index serves as the major discriminating factor among the generation mechanisms of primordial magnetic fields, given that different mechanisms inherently produce fields with different values of the spectral index. A variety of hypothetical generation mechanisms during the inflation epoch are considered in the literature; almost all of them introduce extra non-standard fields and/or interactions. Some of them include coupling of electromagnetic field to scalar fields, such as inflaton or dilaton (Subramanian 2010; Bamba & Yokoyama 2004; Durrer et al. 2023); coupling to space-time curvature (Kushwaha & Shankaranarayanan 2020); generation in Higgs-Starobinsky inflation (Durrer et al. 2022); coupling to axion-type fields (Adshead et al. 2015); introducing an extra-dimensional scale factor (Kunze 2005); and considering spatial anisotropy in the background metric (Pal et al. 2024). There is also a possibility of magnetic field generation during phase transitions of the Universe. Scientists have done a lot of work to study this scenario, while the results for generated magnetic fields and spectral indices are strongly model dependent (Vachaspati 2021). Finally, there are some models with primordial black holes that allow late field generation after primordial nucleosynthesis (Saga et al. 2020; Papanikolaou & Gourgoulatos 2023).

Nevertheless, we want to consider values of n_B that could be detectable with other observational methods. To be observable with current Planck constraints from CMB anisotropy, for example, the spectral index should not exceed the range $n_B \approx 1-2$

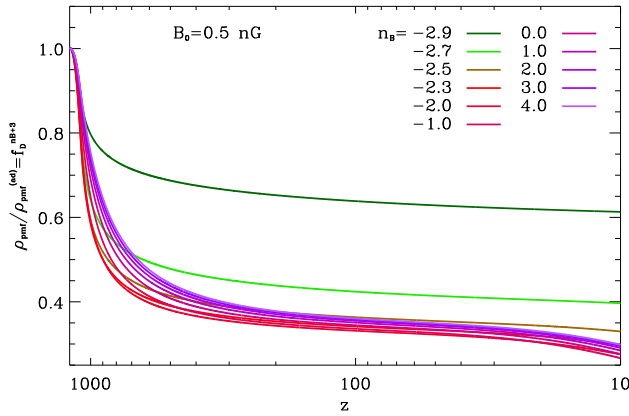


Fig. 1. Time evolution of PMFs' cut-off scale caused by decaying magnetic turbulence and ambipolar diffusion ($f_D^{n_B+3} = \rho_{\text{mf}}/\rho_{\text{mf}}^{\text{ad}}$) for different values of n_B (colour lines).

(Planck Collaboration XIX 2016). However, it should be noted that there is still a possibility that the true value of the spectral index is higher than this (Durrer & Caprini 2003). For this reason, we are interested in the range of $n_B \in [-2.9, +4]$ and $B_0 \in [0.05, 0.5]$ nG. The expression for the heating function via ambipolar diffusion (13) is correct in the range of spectral index $-3 \leq n_B \leq 5$ (Kunze & Komatsu 2014).

In Fig. 1, we present $f_D(z)$ in power $n_B + 3$ for different $n_B = -2.9, \dots, 4$. It depends on the amplitude of the magnetic field very weakly, therefore, we show it only for $B_0 = 0.5$ nG. The curves also illustrate the decrease in the PMFs' energy density caused by decaying magnetic turbulence and ambipolar diffusion over and above the adiabatic losses due to the expansion of the Universe: $f_D(z)^{n_B+3} = \rho_{\text{mf}}(z)/\rho_{\text{mf}}^{\text{ad}}(z)$. They decrease when n_B increases to ~ -1 , then slightly increase to some approximant curve as the spectral index continues to grow. We explain this by the fact that the power spectrum $\propto k^{n_B}$ with damping scale k_D becomes similar to the delta-function when $n_B \rightarrow +\infty$.

In Fig. 2, we show the dependencies of heating functions caused by decaying magnetic turbulence and ambipolar diffusion on redshift in models with different values of B_0 and n_B . Both increase with increasing B_0 . But the first one weakly depends on the value of n_B , while the heating function caused by ambipolar diffusion quickly increases with increasing n_B . Nevertheless, ambipolar diffusion at $z > 100$ makes a negligible contribution to baryonic gas heating compared to the decay of field turbulence $\Gamma_{\text{pmf}}^{(\text{dt})}$, but it is comparable and large at lower z . In the inset of the right panel of Fig. 2, the ratios $\Gamma_{\text{pmf}}^{(\text{dt})}(z, B_0, n_B)/\Gamma_{\text{pmf}}^{(\text{dt})}(z, B_0, n_B = -2.9)$ are presented to illustrate the change in the dependencies of $\Gamma_{\text{pmf}}^{(\text{dt})}$ on n_B in the redshift range $300 \leq z \leq 50$, and the existence of an approximant curve for $\Gamma_{\text{pmf}}^{(\text{dt})}$ for $n_B > 0$. We also note that an approximant curve exists for $\Gamma_{\text{pmf}}^{(\text{amd})}$ as well (right panel). The apparent convergence of the curves in the left panel is illusory, due to the logarithmic scale.

In Fig. 3, we show the dependencies of the ionised fraction of hydrogen on redshift during the Dark Ages for PMF models with different values of B_0 in the range 0.05–0.5 nG and $n_B = -2.9$. They differ only slightly from $x_{\text{HI}}(z)$ in the standard Λ CDM since the heating of the gas in the PMF models with $B_0 = 0.5$ and $n_B = -2.9$ does not exceed $1.3T_{\text{CMB}}$ (see Figs. below). Helium remains completely neutral, so $x_e = x_{\text{HI}}$.

The results of integrations of the system of equations, (1)–(4) with (11)–(13), are presented in Fig. 4 for the models with different root mean square values of field strength $B_0 = 0.05$ –0.5 nG and $n_B = -2.9$ (left panel), and for different values of $n_B = -2.9 \dots 4$ and $B_0 = 0.5$ nG (right panel). One can see that PMFs with $B_0 \geq 0.05$ nG noticeably increase the temperature of baryonic matter at $z < 300$ in comparison with temperature in the null field model. If $B_0 \gtrsim 0.35$ –0.40 nG and $n_B = -2.9$, then the temperature T_b throughout the Dark Ages epoch is higher than the temperature of the CMB. Increasing n_B for the same values of B_0 and z causes a non-monotonic increase of the temperature amplitude that we see in the inset of the right panel of Fig. 4, where the ratios $T_b(z, B_0, n_B)/T_{\text{CMB}}(z)$ are shown. This behaviour is caused by the dependence of $\Gamma_{\text{pmf}}^{(\text{dt})}$ on z shown in the inset of Fig. 2. The baryon temperature is an integral of $\Gamma_{\text{pmf}}^{(\text{dt})}$ on z , which explains their different dependencies on z , but similar ones on n_B .

3. Global signal in 21 cm line: sensitivity to primordial magnetic field parameters

In this section, we analyse the dependence of the global signal in the 21 cm hydrogen line on PMF parameters. We have shown in previous papers (Novosyadlyj et al. 2023, 2024) that this line is noticeably sensitive to the heating of the intergalactic medium by PMFs when its amplitude is $\gtrsim 0.1$ nG and $n_B = -2.9$. For lower B_0 , the global signal is an absorption line with differential brightness temperature $\delta T_{\text{br}} \approx -41$ mK at frequency ≈ 16 MHz and the effective width of the line ≈ 25 MHz as in the standard Λ CDM model¹². With increasing B_0 , the depth of the absorption line decreases, disappears, and becomes an emission line at $B_0 \approx 0.3$ nG. In those papers, we supposed a nearly scale-invariant power spectrum of PMF with $n_B = -2.9$. Since there are no observable constraints for the spectral index, it is sound to analyse the dependence of the brightness temperature in the line δT_{br} on n_B too.

Thus, we computed the evolution of the baryonic gas temperature T_b and the fraction of neutral hydrogen x_{HI} according to the prescription of Sect. 2: the excitation or spin temperature T_s and the differential brightness temperature δT_{br} as the solutions of the kinetic equations of excitation – de-excitation of hyperfine structure levels and radiation transfer equations accordingly,

$$\delta T_{\text{br}}(z) = 0.144 x_{\text{HI}} \frac{\Omega_b h}{\Omega_m^{1/2}} (1+z)^{1/2} \left[1 - \frac{T_{\text{CMB}}}{T_s} \right] \text{ K}, \quad (14)$$

$$T_s^{-1} = \frac{T_{\text{CMB}}^{-1} + x_c T_b^{-1}}{1 + x_c}, \quad x_c \equiv \frac{C_{10}}{A_{10}} \frac{h_P \nu_{21}}{k_B T_{\text{CMB}}}, \quad (15)$$

where A_{10} is the Einstein spontaneous transition coefficient for the excited hyperfine structure level; C_{10} is its collisional deactivation rate by electrons, protons, and neutral hydrogen atoms; $\nu_{21} = 1420$ MHz is the rest frame frequency of the 21 cm line; h_P and k_B are Planck and Boltzmann constants accordingly. The total collisional deactivation rate C_{10} depends on the temperature of the gas, the number densities of neutral hydrogen, protons, and electrons. It is crucial in the computation of the collisional coupling coefficient x_c , which defines the spin temperature. The evolution of x_c in the Λ CDM model with PMFs is shown in Fig. 5. It explains the evolution of the spin temperature T_s shown in Fig. 4 by dotted lines. The relation between T_s

¹² In the papers Novosyadlyj et al. (2023, 2024), the amplitude of δT_{br} in the Λ CDM is cited as ≈ -35 mK by number 23 instead of 27 in the expression for δT_{br} .

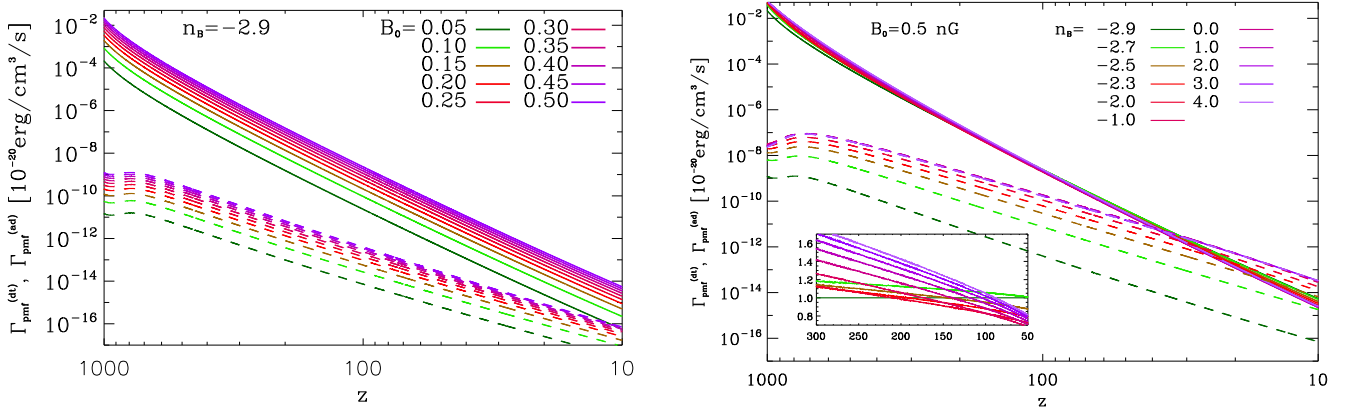


Fig. 2. Heating functions caused by decaying magnetic turbulence (solid lines) and ambipolar diffusion (dashed lines) in PMFs models with different B_0 (left) and n_B (right). The inset panel shows $\Gamma_{\text{pmf}}^{(\text{di})}(z, B_0, n_B)/\Gamma_{\text{pmf}}^{(\text{di})}(z, B_0, n_B = -2.9)$ for the purpose of distinguishing lines in the 21 cm line formation region.

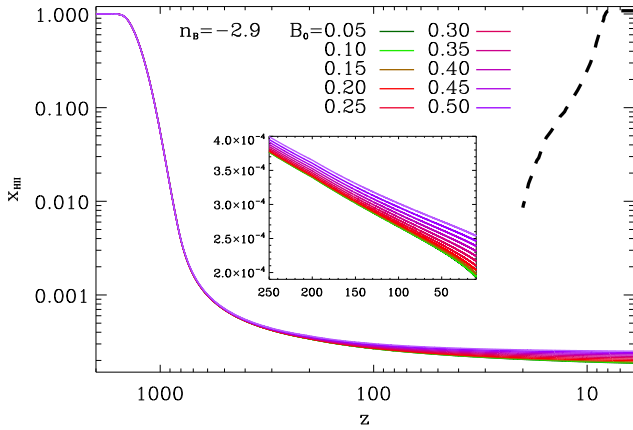


Fig. 3. Dependence of ionized hydrogen fraction on redshift in models with primordial stochastic magnetic fields with different values of B_0 , which increases for lines from bottom to top. The dashed line is the 2σ upper limit from the CMB radiation polarization data (Planck Collaboration VI 2020).

and T_{CMB} at any z defines the differential brightness temperature $\delta T_{\text{br}}(z)$, which follows from Eq. (14). When $T_s \rightarrow T_{\text{CMB}}$, then $\delta T_{\text{br}}(z) \rightarrow 0$. At $z > 400$, the coupling coefficients are $x_c \gg 1$ and $T_s \rightarrow T_b$. But there $T_b \approx T_{\text{CMB}}$, so $\delta T_{\text{br}}(z) \rightarrow 0$ again.

We computed the brightness temperature in the 21 cm hydrogen line using expressions (14)–(15) for the same values of cosmological parameters and PMFs as in the previous section. The results are presented in Fig. 6 for different values of field strength $B_0 = 0.05 \dots 0.5$ nG, and in Fig. 7 for different values of spectral index $n_B = -2.9 \dots 4.0$.

The results presented in Fig. 6 illustrate the dependence of the line profile on field strength, the transition from the absorption line to the emission line with increasing B_0 . Fig. 7 shows that the global signal in the 21 cm hydrogen line is also sensitive to the value of the spectral index n_B . In Fig. 8 we show the dependence of the amplitude of 21 cm line, $|\delta T_{\text{br}}^{\text{max}}|$, on n_B for models with $B_0 = 0.1$ and 0.5 nG. We note some non-monotonic dependence of spectral feature amplitude on n_B in the range $-2.9 \leq n_B \leq -2$ for models with $B_0 = 0.5$ nG.

In the paper Okamatsu et al. (2024), the authors propose using the high-frequency wing of the Dark Ages 21 cm line, especially the relation between two ratios

$$R_{20/30} \equiv \frac{\delta T_{\text{br}}(\nu = 20 \text{ MHz})}{\delta T_{\text{br}}(\nu = 30 \text{ MHz})} \quad \text{and} \quad R_{40/30} \equiv \frac{\delta T_{\text{br}}(\nu = 40 \text{ MHz})}{\delta T_{\text{br}}(\nu = 30 \text{ MHz})},$$

as a measure of the deviations of the cosmological models from the standard Λ CDM one and the possible distinction of them. In Fig. 9 we present the relation $|R_{20/30}| - |R_{40/30}|$ for all profiles in Figs. 6–7. One can see that all Λ CDM+PMF models deviate from the Λ CDM one mainly along the diagonal $|R_{40/30}|^{\text{max}} - R_{20/30}|^{\text{max}}$, similar to other models in Okamatsu et al. (2024) (Fig. 4), but the spreads for the models analysed here are wider.

4. Comparison and discussions

Let us compare our results with similar ones recently published by other authors, in particular Minoda et al. (2019), Okamatsu et al. (2024), Mohapatra et al. (2024). First, we note that the evolution of baryonic gas temperature and the 21 cm signal during the Dark Ages in the Λ CDM model with close parameters is practically the same as in these and other papers cited here. Comparison of results for PMFs models is not so unambiguous due to the authors' use of different approximations in calculations of decaying turbulence and ambipolar diffusion, the cut-off scale of the magnetic field at the time of recombination, taking into account its changes over time during the Dark Ages, and so on. In this paper, we completely describe the PMFs model and all the parameters and approximations used in the calculations. We even provide in Appendix A the derivation of the dependence of k_D on the cosmological parameters, since it is different from paper to paper.

In PMF models with $n_B = -2.9$ and $B_0 = 0.1, 0.2, 0.5$ nG, Minoda et al. (2019) obtained baryonic temperature T_b at $z = 10$, approximately 4, 10, and 50 K (see Fig. 1 in Minoda et al. 2019). Our values in the left panel of Fig. 4 are 4, 8, 37 K accordingly. The small differences are caused by the small differences in the parameters of the fiducial cosmological models and k_D^{rec} . Mohapatra et al. (2024) obtained T_b with the same k_D^{rec} at $z = 10 \sim 4, 10$, and 30 K for PMF models with $n_B = -2.99$ and $B_0 = 0.1, 0.3, 0.55$ nG respectively (see Fig. 3a in Mohapatra et al. 2024).

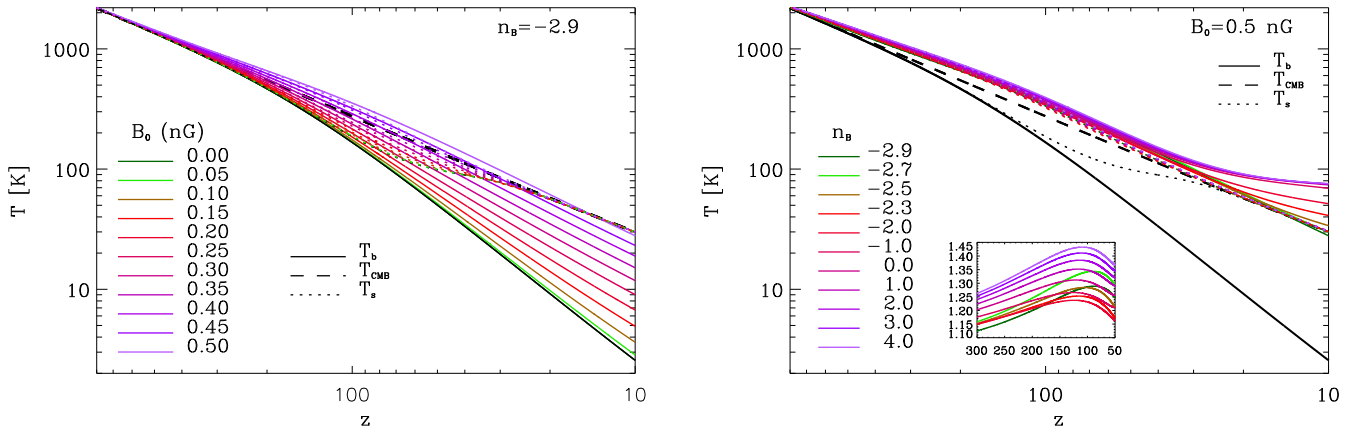


Fig. 4. Evolution of baryonic matter temperature T_b (solid lines) and spin temperature T_s (dotted lines) from cosmological recombination up to $z = 10$ in Λ CDM model with PMF with different B_0 (left panel) and with different values of spectral indices n_B (right panel). The dashed line in both panels shows the temperature of CMB. The inset in the right panel shows $T_b(z, B_0, n_B)/T_b(z, B_0, n_B = -2.9)$ for the purpose of distinguishing lines in the 21 cm line formation region.

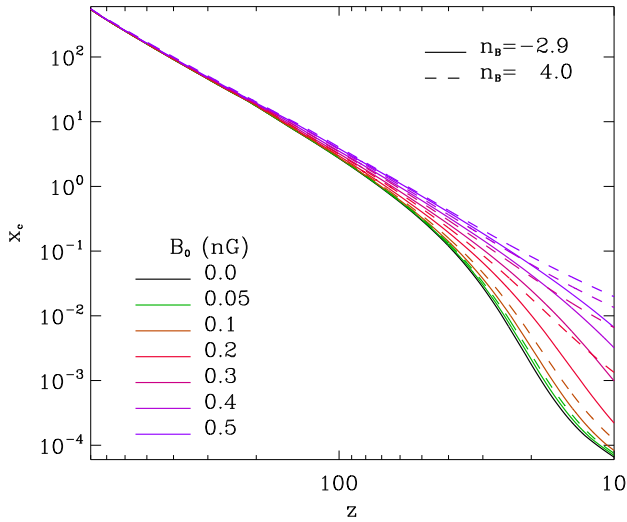


Fig. 5. Dependencies of collisional coupling x_c on redshift in the models Λ CDM+PMF with different values of B_0 and n_B .

So, we can conclude that for an almost scale-invariant spectrum, the results are close.

But if we compare our results for $n_B = -2.5$ and $B_0 = 0.1, 0.3$ nG with those corresponding to Mohapatra et al. (2024) (Fig. 3a), then we see a strong disagreement despite the same expressions for $\Gamma_{\text{pmf}}^{(\text{dt})}$ and $\Gamma_{\text{pmf}}^{(\text{amd})}$. Their results show a steep increase in T_b with a small increase in n_B , while our results show a slow increase in T_b (and δT_{br} , Fig. 8) with n_B . The authors in Mohapatra et al. (2024) did not explain such behaviour. This may be the case if the heating due to ambipolar diffusion is overestimated by several orders of magnitude, as can be assumed on the basis of Fig. 2.

Comparing the profiles of the redshifted 21 cm line from the Dark Ages in the PMF models (Fig. 6) with profiles in the models with self-annihilating and decaying dark matter particles (see Fig. 12 in Novosyadlyj et al. 2024), one can see the similarities between them. It means that other signals from the Dark Ages must be used, together with the 21 cm hydrogen line redshifted to decametre wavelengths, to constrain the parameters of PMFs and decaying dark matter.

These can be signals in the ro-vibrational lines of the first molecules (Novosyadlyj et al. 2025; Kulinich & Novosyadlyj 2025), the Cosmic Dawn 21 cm line redshifted to metre wavelengths (Sethi & Subramanian 2005; Tashiro & Sugiyama 2006; Schleicher et al. 2009; Kunze & Komatsu 2014; Chluba et al. 2015; Kunze 2019; Cruz et al. 2024; Bhaumik et al. 2025), Faraday rotation measurements (O’Sullivan et al. 2020), magnetic fields’ impact on CMB (Paoletti et al. 2022), Ly- α forest method (Pavičević et al. 2025) and so on.

Last but not least, the question is about the possibility of detecting the impact of PMFs on the 21 cm signal formed in the Dark Ages. It was mentioned in the Introduction that detection of the 21 cm signal from the Dark Ages needs about 1500 hours of integration time by ground-based Ukrainian radio telescope UTR-2 (Konovalev et al. 2024). Nevertheless, observations in the ~ 10 –50 MHz band are particularly challenging, as the 21 cm signal from the Dark Ages is strongly contaminated by several sources of foreground.

First, artificial, human-made sources, such as short-wave broadcasting, aviation communication, and amateur radio, produce radio frequency interferences that are many orders of magnitude stronger than the cosmological signal. Second, the ionosphere contributes a strong, time-dependent foreground that varies with the time of day. Third, our Galaxy emits synchrotron and bremsstrahlung radiation at these wavelengths, which constitutes a foreground with temperatures in order of 10^3 – 10^4 K.

Recently proposed missions, such as DAPPER (Burns et al. 2011) and FARSIDE (Burns et al. 2021), designed to operate from the far side of the Moon, will be largely shielded from the first two sources of contamination. In contrast, the Galactic synchrotron foreground, unlike the cosmological 21 cm signal, is polarised and exhibits a distinctive spatial structure, allowing for its effective removal through foreground subtraction techniques. Moreover, the spectral density of the galactic foreground is well described by the power-law frequency dependence (see, e.g., Furlanetto et al. 2006).

Interestingly, the non-detection of the 21 cm absorption line from the Dark Ages at $z \approx 100$ may allow us to put an upper limit on the strength and spectral index of PMFs, if we overcome the degeneracy with alternative non-standard heating sources, for example, decaying or self-annihilating dark matter. We estimated that ~ 3600 hours of FARSIDE integration time would be sufficient to place an upper limit 0.1 nG on the magnetic field strength

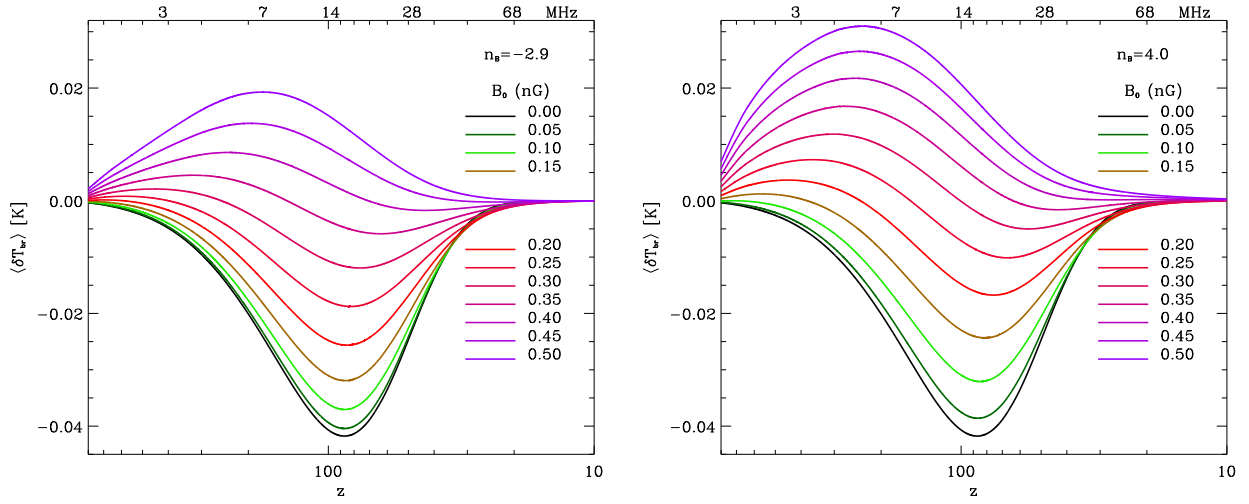


Fig. 6. Global signal in hydrogen 21 cm line for PMF models with $n_B = -2.9$ (left panel) and $n_B = 4$ (right panel), with different values of B_0 (coloured lines).

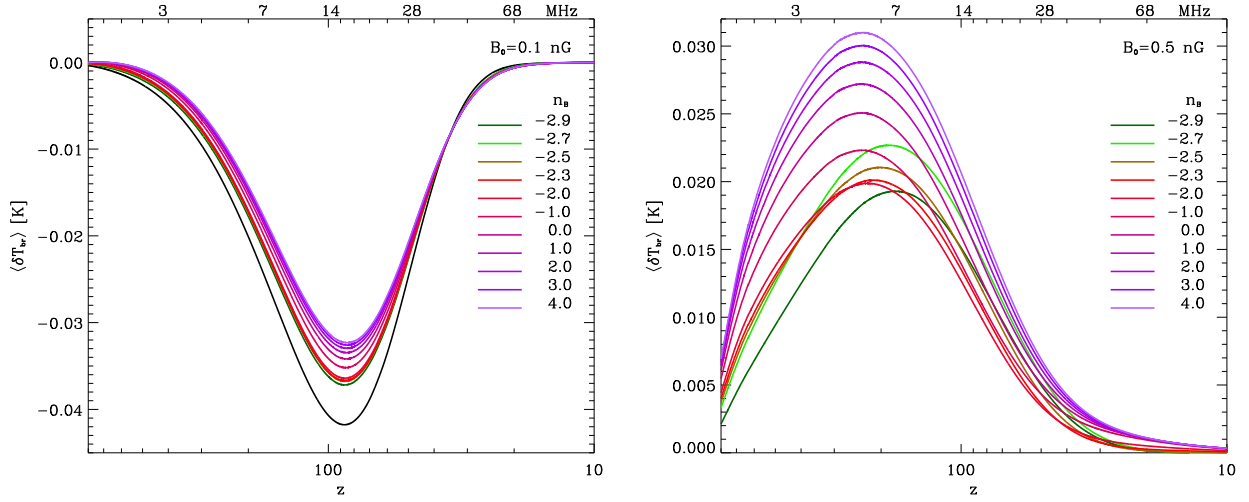


Fig. 7. Global signal in hydrogen 21 cm line for PMF models with $B_0 = 0.1$ nG (left panel) and $B_0 = 0.5$ nG (right panel), with different values of n_B (coloured lines).

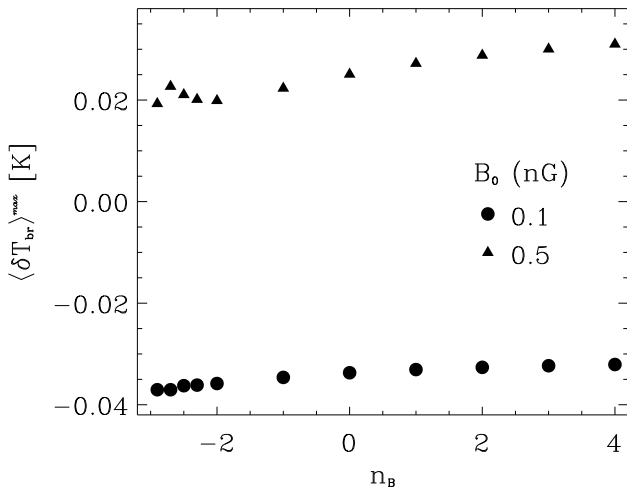


Fig. 8. Dependence of amplitude of 21 cm line $\delta T_{br}^{\text{max}}(n_B)$ on spectral index of PMF power spectrum for $B_0 = 0.1$ and 0.5 nG.

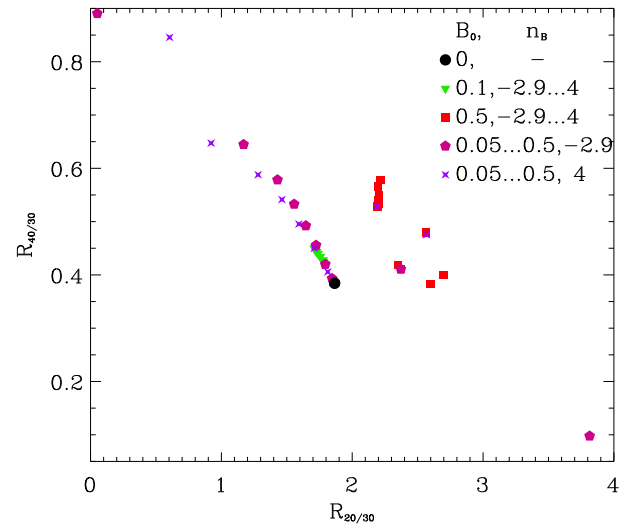


Fig. 9. Profiles of 21 cm lines in different (B_0, n_B) models of PMFs in the space $R_{20/30} - R_{40/30}$.

for $n_B = -2.9$ or $n_B = 4.0$ (see Appendix B for details). With 10 000 hours of integration time, we will be able to detect even the 21 cm absorption signal in the scenarios with $B_0 \approx 0.2$ nG. Moreover, within such an integration time it is possible to find signatures of the 21 cm emission for frequencies near 10 MHz ($z \approx 100$) in the scenarios with $B_0 = 0.5$ nG and $n_B = 4.0$.

5. Conclusions

We analysed the impact of primordial magnetic fields on the thermal history of the Universe in the Dark Ages due to the decaying magnetic turbulence and ambipolar diffusion in low-ionised plasma, and showed that fields with $B_0 \geq 0.05$ nG reduce the depth of the 21 cm absorption line of the standard Λ CDM model, in which the brightness temperature in line is $\delta T_{\text{br}} \approx -40$ mK at frequency ≈ 16 MHz and the effective width ≈ 25 MHz. At $B_0 \sim 0.25$ – 0.3 nG, the absorption line becomes the emission line in the low-frequency wing of the absorption line. In models with $n_B = -2.9$ and $0.05 \leq B_0 \leq 0.5$ nG, the amplitude of the absorption/emission line ranges from -40 to $+20$ mK in the frequency range of 16 – 8 MHz, the width at half-maximum 25 – 20 MHz. Thus, the global signal in the 21 cm line from the Dark Ages is sensitive to PMFs with a nearly scale-invariant power spectrum $n_B = -2.9$ when $B_0 \gtrsim 0.05$ nG.

We found a sensitivity of the amplitude and profile shape of the 21 cm hydrogen spectral line formed during the Dark Ages to the value of the spectral index n_B at fixed values of the field strength B_0 . As n_B increases from -2.9 to 4.0 in the case of PMFs with $B_0 = 0.1$ nG, the absorption line becomes shallower from -35 to -32 mK at the same frequency ~ 16 MHz. In the case of PMFs with $B_0 = 0.5$ nG, the amplitude of the emission line increases from ~ 20 to ~ 30 mK. Comparisons with other gas-heating mechanisms in models outside the standard Λ CDM model revealed similarities in profiles with the decaying dark matter model, indicating the need to use other signals from the early Universe to resolve this degeneracy.

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Appendix A: Damping scale of PMFs at the recombination epoch

The damping scale of PMFs at the recombination epoch is defined in [Subramanian & Barrow \(1998\)](#) as

$$\lambda_D = \sqrt{\frac{3}{5}} \frac{V_A}{c} \lambda_D^\gamma, \quad (\text{A.1})$$

where the magnetohydrodynamic Alfvén velocity in units of light velocity at this epoch, according to [Kunze & Komatsu \(2014\)](#), equals

$$\frac{V_A}{c} = 3.24 \cdot 10^{-4} \left(\frac{B_\lambda}{1 \text{ nG}} \right) \left(\frac{k_D}{k_\lambda} \right)^{\frac{n_B+3}{2}} h^{-1}, \quad (\text{A.2})$$

and baryon-photon Silk damping scale ([Silk 1968](#); [Peebles & Yu 1970](#); [Kaiser 1983](#)):

$$\lambda_D^\gamma = 5.7 \omega_m^{-\frac{1}{4}} \omega_b^{-\frac{1}{2}} \left(\frac{x_e^{\text{rec}}}{0.1} \right)^{-\frac{1}{2}} \left(\frac{1+z_{\text{rec}}}{1100} \right)^{-\frac{5}{4}} \text{ Mpc}. \quad (\text{A.3})$$

This approximation agrees well with the approximation proposed in [Hu & White \(1997\)](#). So,

$$\begin{aligned} \frac{1}{k_D} \equiv \frac{\lambda_D}{2\pi} &= 3.25 \cdot 10^{-4} \omega_m^{-\frac{1}{4}} \omega_b^{-\frac{1}{2}} \left(\frac{x_e^{\text{rec}}}{0.1} \right)^{-\frac{1}{2}} \\ &\times \left(\frac{1+z_{\text{rec}}}{1100} \right)^{-\frac{5}{4}} \left(\frac{B_\lambda}{\text{nG}} \right) \left(\frac{k_D}{k_\lambda} \right)^{\frac{n_B+3}{2}} \frac{0.7}{h} \text{ Mpc}. \end{aligned} \quad (\text{A.4})$$

From this equation, we obtain the damping scale of PMFs (7) at the epoch of cosmological recombination.

Appendix B: Sensitivity of lunar radio-telescopes to the impact of PMFs on 21 cm signal

We consider the FARSIDE mission ([Burns et al. 2021](#)), proposed to operate for frequencies $\nu \leq 40$ MHz, as a case study to evaluate the potential of constraining primordial magnetic field (PMF) parameters through observations of the 21 cm signal from the Dark Ages. The thermal noise of an ideal radiometer at frequency ν is given by ([Condon & Ransom 2016](#)):

$$\sigma_{\text{rms}}(\nu) = \frac{T_{\text{sys}}(\nu)}{\sqrt{N \Delta \nu t}}, \quad (\text{B.1})$$

where $T_{\text{sys}}(\nu)$ is the system temperature, approximately equal to the foreground temperature T_{fg} , N is the number of antennas operating in autocorrelation mode, $\Delta \nu$ is the bandwidth, and t is the integration time. The foreground emission can be modelled as a power law:

$$T_{\text{fg}} = 5000 \text{ K} \left(\frac{\nu}{50 \text{ MHz}} \right)^{-2.5},$$

following [Burns et al. \(2021\)](#); see also ([Furlanetto et al. 2006](#)). The FARSIDE mission concept includes 128 antennas with a bandwidth of $\Delta \nu = 0.5$ MHz.

Detecting a $\sim 10^{-2}$ K signal against a foreground with $T_{\text{fg}} \sim 10^3$ – 10^4 K is extremely challenging. A pragmatic strategy is to focus on identifying the extrema of the global absorption or emission profile (private communication with Y. Vasylyukivskyi, Institute of Radio Astronomy, NAS of Ukraine). Assuming a signal-to-noise ratio of $\text{SNR} \geq 10$, we estimate that detecting the

21 cm Dark Age signal in the absence of PMFs requires at least 1800 hr of integration. With 5000 hr integration time, FARSIDE could potentially detect the absorption signal predicted in a cosmological scenario with $n_B = -2.9$ ($n_B = 4.0$) and $B = 0.2$ nG ($B_0 = 0.15$ nG). By contrast, detecting the 21 cm emission from $z \simeq 200$ at $\nu \simeq 6$ MHz in the case of a non-helical magnetic field with $B_0 = 0.5$ nG and $n_B = -2.0$ (see Fig. 7-8) would require roughly 55 000 hr, corresponding to more than six years of continuous observations.

In addition, for scenarios with $n_B = 4.0$ and $B_0 = 0.3$ nG, where the signal exhibits two regimes, emission at $z \sim 200$, and absorption at $z \lesssim 100$, the FARSIDE array can detect the absorption signal with an integration time of 10 000 hr and a signal-to-noise ratio of $\text{SNR} = 10$. Notably, within the same observational strategy, this instrument can also detect emission at $z \lesssim 90$ for the scenario with $B_0 = 0.5$ nG and $n_B = 4.0$.