EDGES signal in presence of magnetic-fields

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(Dated: January 22, 2020)

We study the 21-cm differential brightness temperature in the presence of primordial helical magnetic fields for redshift $z = 10 - 30$. It is shown that the gas temperature can be lowered to 3.2 degree Kelvin at $z = 17$ by the alpha-effect due to the twisting of magnetic field lines by eddies generated due to the turbulence generated at earlier times. Using the EDGES results, we find the upper and lower limits on the primordial magnetic field to be $6 \times 10^{-3}$ nG & $5 \times 10^{-4}$ nG respectively. We also discuss the effect of Lyα background on the bounds. Our results do not require any new physics in terms of dark-matter.

Keywords: EDGES observation, Magnetic fields, 21-cm signal

Recently, the observations from the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) has created enormous interest in 21-cm cosmology with a hope to provide an insight into the period when the first stars and galaxies were formed [1, 2]. The EDGES collaboration has reported nearly two times more absorption for the 21-cm line than the prediction made by the standard cosmological scenario to explain the observations indicates a scenario based on the $\Lambda$CDM framework in the redshift range $15 \lesssim z \lesssim 20$ [1]. Analysis of the results shows that the absorption profile is in a symmetric “U” shaped form centered at $78\pm 1$ MHz. Minimum of the absorption profile reported being at $0.5_{-0.3}^{+0.5}$ K in the above-mentioned redshift range. Inability of the standard scenario to explain the observations indicates a possibility of new physics. Any possible explanation may require that either the gas temperature, $T_{\text{gas}}$, should be less than 3.2 K for the standard cosmic microwave background radiation temperature ($T_{\text{CMB}}$) or $T_{\text{CMB}}$ should be greater than 104 K in the absence of any non-standard mechanism for the evolution of the $T_{\text{gas}}$ at the centre of the “U” profile [1].

First, it ought to be noted that in the standard cosmological scenario, during the cosmic dawn, $T_{\text{gas}}$ and $T_{\text{CMB}}$ varies adiabatically with the redshift as $T_{\text{gas}} \propto (1+z)^2$ and $T_{\text{CMB}} \propto (1+z)$. At redshift $z = 17$, temperatures of both the components found to be $T_{\text{gas}} \sim 6.8$ K & $T_{\text{CMB}} \sim 48.6$ K, for example see Ref [3]. As explained above, one of the alternatives to explain the EDGES signal is by cooling the gas. In Ref. [4, 5], a Coulomb-like interactions between the dark-matter and baryon was considered for transferring energy from gas to dark-matter. This approach as argued in Ref. [6], can violate constraints on local dark-matter density. At the required redshift ionization fraction, $x_e = n_e/n_H \sim 10^{-4}$. Therefore, the dominating part is neutral hydrogen and it possesses only dipole interactions instead of Coulomb-like interactions [7, 8]. In addition, the non-standard Coulombic interaction between dark-matter and baryons is strongly constrained by observations and laboratory experiments. In the light of these constraints it is doubtful that one can produce 21-cm absorption signal using the Coulombic interaction [9–13]. A new approach was recently adopted in Refs. [14, 15] for the excess cooling of gas by introducing a new parametric model. This model allows the cooling to occur more rapidly at earlier times. However, origin of the new cooling term remain uncertain. The excessive cooling of the gas can also be obtained by allowing thermal contact between baryons and cold dark matter-axions [16].

Another alternative to explain EDGES results requires extra radiation at the time of cosmic down. This possibility has been investigated by several authors. In Ref. [7], the authors consider extra radiation field in the required frequency range by light dark-matter decay into soft photons. In presence of the intergalactic magnetic fields, axion-like particles can be converted into photons under some resonant condition to generate the extra radiation [17]. Similarly, resonant conversion of mirror neutrinos into visible photons can explain the EDGES observations [18]. Production of the visible photons from the dissipative dark-matter can explain EDGES result [19]. In Ref. [20], it was suggested that black-holes growing at certain rates can also produce a radio background at the required redshift. However, this type of scenario of the first-stars and black-holes producing enough background radiation was questioned in Refs. [14, 21].

In this work, we explore a novel possibility of cooling the gas by invoking the so-called alpha effect [22, 23]. In turbulence the twisting of magnetic field lines by eddies in absence of mirror symmetry can enhance the magnetic field. This would give rise to the alpha effect [22, 23] and the magnetic field enhances at the cost of gas energy. Here we note that alpha effect may not require any new physics in terms of dark-matter. However, the presence of a helical magnetic field is required. Indeed, the primordial magnetic fields (PMFs) generated in the early Universe due to some high energy process may have helical behavior and violation of parity [24–26]. These fields can survive in later times [26, 27]. We believe that this effect can contribute positively to explain the EDGES observations. Additionally, this 21-cm absorption signal can be used as a probe for PMFs strength at present time in the Universe. In the previous studies, upper bound on the strength of the magnetic fields is constrained for the various cosmological scenarios (for a detailed review see Refs. [28–37]). In the context of EDGES signal, constraint on the magnetic fields (MFs) with upper bound of $\lesssim 10^{-10}$ G has been studied by authors of the Ref. [38]. By invoking baryon dark-matter in-
teration this upper bound modifies to $\lesssim 10^{-6} \text{ G}$ [39]. Also, the lower bound on the magnetic field strength found in Refs. [40–42].

To compute the 21-cm differential brightness temperature, $T_{21}$, we use 21cmFAST code. We modify this code by adding ‘decay’ rates related with turbulence and ambipolar effects associated with the magnetic field together with the alpha effect. Following definition of $T_{21}$ given in Refs. [43–45], we write

$$T_{21} = 27 x_{\text{HI}} \frac{1}{1 + \delta_{v_f}/H} \left[ \frac{\Omega_{\text{HI}} h^2}{0.15} \right]^{1/2} \left( \frac{\Omega_{\text{b}} h^2}{0.023} \right) \times \left( 1 + z \right)^{1/2} \left( 1 - \frac{T_{\text{CMB}}}{T_{s}} \right) \text{ mK},$$

(1)

where, $x_{\text{HI}}$ is the neutral hydrogen fraction, $\delta_{v_f}$ is the comoving derivative of LOS component of the comoving velocity, $H \equiv H(z)$ is the Hubble expansion rate and $\delta_{av} \equiv \delta_{av}(x, z)$ is the density contrast. We take the following values for the cosmological parameters: $\Omega_{M} = 0.31, \Omega_{b} = 0.048, h = 0.68, \sigma_{8} = 0.82, n_{s} = 0.97$ and $T_{\text{CMB}}|_{z=0} = 2.726 \text{ K}$ [46, 47]. The spin temperature $T_{s}$ is defined via hydrogen number densities in 1S triplet ($n_{1}$) and singlet ($n_{0}$) hyperfine levels: $n_{1}/n_{0} = g_{1}/g_{0} \times \exp(-2 \pi \nu_{l}(z)/T_{s})$, here, $g_{1}$ and $g_{0}$ are spin degeneracy in triplet and singlet states respectively and $\nu_{l}$ is corresponding frequency for hyperfine transition. We write $T_{s}$ [2, 43],

$$T_{s}^{-1} = T_{\text{CMB}}^{-1} + x_{\alpha} T_{\alpha}^{-1} + x_{e} T_{\text{gas}}^{-1} \frac{1}{1 + x_{\alpha} + x_{e}},$$

(2)

Here, $T_{\alpha} \approx T_{\text{gas}}$ is the color temperature [48, 49]. $x_{\alpha}$ and $x_{e}$ are Wouthuysen-Field (WF) and collisional coupling coefficients respectively [45, 48–50]. We consider that first stars were formed at redshift $z \sim 30$. Later, their Ly$\alpha$ background cause the hyperfine transition and X-ray produced by these sources starts to heat the gas [14, 15, 43, 45, 51–53]. For this work we take the fiducial model as defined in the Ref. [45]. Following above References, we switch on the effect of Lyman $\alpha$ background and structure formation on $T_{\text{gas}}$ after $z = 30$. It is important to note here that in Ref. [54], the authors have claimed that $T_{\text{gas}}$ values can be even higher, without X-ray heating, if one incorporates indirect energy transfer from radio photons to the random motions of the gas.

In the presence of magnetic fields thermal evolution of the gas can modify. We follow the Refs. [31, 55–58], and write the temperature evolution of the gas in presence of PMFs as,

$$\frac{dT_{\text{gas}}}{dz} = 2 \frac{T_{\text{gas}}}{1 + z} + \frac{\Gamma_{c}}{(1 + z) H} \left( T_{\text{gas}} - T_{\text{CMB}} \right)$$

$$- 2 \left( \Gamma_{\text{turb}} + \Gamma_{\text{ambi}} + \Gamma_{\text{alph}} \right) \frac{N_{\text{tot}}}{3 N_{\text{HI}}(1 + z) H},$$

(3)

where $N_{\text{tot}}$ is the total number density of the gas i.e. $N_{\text{HI}}(1 + f_{\text{He}} + X_{e})$, $N_{\text{HI}}$ is the neutral hydrogen number density, $f_{\text{He}} \approx \frac{Y_{\text{He}}}{4(1 - Y_{\text{e}})}$. Helium mass fraction $Y_{\text{He}} = 0.24$, $X_{e} = N_{e}/N_{\text{HI}}$ is the free streaming electron fraction in the gas, $\Gamma_{c}$ is the Compton scattering rate [57, 58]. To get free electron fraction, $X_{e}$, we follow [3, 59] and correction suggested by [60–62]. In equation (3), $\Gamma_{\text{turb}}, \Gamma_{\text{ambi}}$, and $\Gamma_{\text{alph}}$ are heating or cooling rate per unit volume due to the turbulence, ambipolar and alpha effect respectively. $\Gamma_{\text{ambi}}$ and $\Gamma_{\text{turb}}$ are [31, 58],

$$\Gamma_{\text{ambi}} \approx \frac{(1 - X_{e})}{\gamma X_{e} (M_{H} N_{\text{HI}})} \frac{E_{B} f_{I}(n_{B} + 3)}{L^{2}},$$

(4)

$$\Gamma_{\text{turb}} = \frac{1.5 m}{[\ln(1 + t_{1}/t_{d})]^{m}} \left( \frac{1.5 \ln((1 + z))(1 + z)}{[\ln(1 + t_{1}/t_{d})]^{m+1}} \right) H E_{B},$$

(5)

here, the coupling coefficient $\gamma = 1.9 \times 10^{14} (T_{\text{gas}} / K)^{0.375} \text{ cm}^{3} / \text{g/s}, M_{H}$ is mass of Hydrogen atom, $N_{B}$ is baryon number density, $n_{B} = -2.9$ is magnetic spectral index, $f_{I}(x) = 0.8313 (1 - 1.020 \times 10^{-2} x) x^{1.1055}$, $t_{I} / t_{d} \approx 14.8 (1 + z) (n_{G} / B_{0}) (L / \text{Mpc})$, $m = 2(n_{B} + 3) / (n_{B} + 5) \& z_{i} = 1088$ is the initial redshift when heating starts. The magnetic field energy, $E_{B} = B^{2} / (8 \pi)$, in presence of the alpha-effect,

$$\frac{dE_{B}}{dz} = 4 \frac{E_{B}}{1 + z} + \frac{1}{(1 + z)^{3}} H \left[ \Gamma_{\text{turb}} + \Gamma_{\text{ambi}} \right] - \frac{\alpha}{4 \pi} | \mathbf{B} \cdot (\nabla \times \mathbf{B}) |.$$  

(6)

Following Refs. [22, 23, 63], if the magnetic Reynolds number is large enough, $\alpha = (1 / 3) \eta_{\text{magn}}$. Here we use Equipartition theorem- $u_{\text{rms}}^{2} = 3 T_{\text{gas}} / M_{H}$. Following Ref. [57], we approximate last term in equation (6) as

$$| \mathbf{B} \cdot (\nabla \times \mathbf{B}) | \approx \frac{B^{2}}{L}.$$  

(7)

$L$ is the coherence length scale of the magnetic field. It is constrained by Alfvén wave damping length scale, $k_{d} = 1 / (L(1 + z))$. Below this length-scale tangled magnetic fields are strongly damped by radiative-viscosity [31, 58, 64, 65],

$$k_{d} \approx 286.91 \left( \frac{n G}{B_{0}} \right) \text{ Mpc}^{-1}.$$  

(8)

where, $B_{0}$ is the present day magnetic field strength. Thus,

$$\Gamma_{\text{alph}} \approx -2 \left( \frac{T_{\text{gas}}}{3 M_{H}} \right)^{1/2} E_{B} / L.$$  

(9)

Ignoring logarithmic dependency of turbulent decay, it evolves as $\Gamma_{\text{turb}} \propto (1 + z)^{5/2}$, ambipolar diffusion $\Gamma_{\text{ambi}} \propto (1 + z)^{3/2}(1 - X_{e}) / X_{e}$ at early time since $T_{\text{gas}} \propto (1 + z)$ and after $z \lesssim 100$ it evolves as $\propto (1 + z)^{3/2} / X_{e}$ because of $T_{\text{gas}} \propto (1 + z)^{2}$ and $X_{e} \propto 1$ at late time. Magnetic energy rate due to the alpha-effect, $\Gamma_{\text{alph}}$, is $\propto (1 + z)^{3} / 2$ for $z \lesssim 100$ otherwise it’s $\propto (1 + z)^{3}$. Therefore, we expect cooling due to the alpha-effect is more effective than heating due to the turbulent decay. After that, at late time ($z < 100$) the ambipolar diffusion is more effective (also depends on PMFs strength). Thus, gas temperature will start increasing. As shown in Ref. [38, 58] in presence of a helical magnetic field $\Gamma_{\text{turb}}$ dominates over $\Gamma_{\text{ambi}}$ for $z > 100$. Presence of the alpha effect can also be
felt very strongly for this range of the redshift. One can write
\[
\frac{\Gamma_{\text{gas}}}{\Gamma_{\text{gas, fiducial}}} = 1.48 \left( \frac{T_{\text{gas}}}{\text{Kelvin}} \right)^{0.875} \frac{v_s}{v_{\text{c}}^0} (1 + z) \left( \frac{n_0}{B_0} \right).
\]

To study the magnetic heating (cooling) of the gas we use the code recfast++ [58]. In figure (1a), plots of gas temperatures for different values of \( B_0 \) are shown as function of \( z \). The dot-dashed line represent the standard recombination history. The figure shows that as values of \( B_0 \) approaches \( 10^{-5} \) nG, \( T_{\text{gas}} \) recovers the standard thermal evolution. By increasing magnetic field from \( 10^{-5} \) nG, \( T_{\text{gas}} \) decreases. For \( B_0 \approx 10^{-3} \), one gets \( T_{\text{gas}} < 3.2 \) Kelvin for \( z = 17 \). Further we note that by increasing \( B_0 \) the minimum of gas temperature shifts towards higher values of the redshift. Figure (1b) shows that by increasing of \( B_0 \) from \( 5 \times 10^{-3} \) nG, \( T_{\text{gas}} \) rises. However, gas temperature around \( z = 17 \) exceeds 3.2 Kelvin for \( B_0 > 6 \times 10^{-3} \) nG. Therefore, desired value of magnetic field should be in the range of \( 5 \times 10^{-4} \) nG \( \leq B_0 \leq 6 \times 10^{-3} \) nG. These upper and lower bounds on \( B_0 \) are also consistent with constraints found in Refs. [28–42].

Further in figure (2), we have included the X-ray heating due to first stars after the redshift \( z = 30 \) together with the adiabatic heating/cooling as a result of structure formation. The blue dot-dashed line indicates the \( T_{\text{gas}} \) evolution for the standard cosmological scenario and double-dot dashed line shows \( T_{\text{CMB}} \) evolution. The black and red solid line plots represent the case when only magnetic heating/cooling terms are included. The black and red dot-dashed line shows the cases when all these effects are present. In this case, gas temperature rises quickly in comparison with the only magnetic heating/cooling cases. Therefore, in the presence of X-ray heating our previously mentioned upper and lower bounds on magnetic field strength can modify.

In figure (3), we plot \( T_{21} \) as a function of redshift for different magnetic field strengths. We have considered two particular cases involving with (dot-dashed lines) and without (solid lines) X-ray heating. For the X-ray heating we consider the fiducial model [45]. In all cases, we incorporate adiabatic heating/cooling from structure formations [45]. Spin tempera-
ture coupling has two main contribution, one from X-ray excitation of neutral hydrogen and other from photons emitted between Lyman to Lyα limit from the first stars. For dot-dashed line we include both coupling and for solid lines we take only second coupling. The figure shows that without including X-ray heating one can obtain −1000 mK ≤ T_{21} ≤ −300 mK. For the dot-dashed lines, the minimum of T_{21} profile first decreases while increasing B_0 values from ~ 9 × 10^{-4} nG and after a certain value of B_0, minimum of T_{21} starts increasing: For B_0 = 3 × 10^{-3} nG and 9 × 10^{-4} nG we get T_{21} = −310 mK and −323 mK at z = 17 respectively. This gives allowed range for B_0 to be in the range (using EDGES upper bound on T_{21}) 9 × 10^{-4} nG ≤ B_0 ≤ 3 × 10^{-3} nG after inclusion of X-ray heating.

In conclusion, we have studied 21-cm differential brightness temperature in presence of helical primordial magnetic field. We have shown that the presence of the alpha effect can reduce gas temperature to 3.2 Kelvin, at the center of “U” shaped profile, when present day strength of the magnetic field is in the range 5 × 10^{-3} nG ≤ B_0 ≤ 6 × 10^{-3} nG without X-ray heating. For the case when X-ray heating is included we get 9 × 10^{-4} nG ≤ B_0 ≤ 3 × 10^{-3} nG. Here we note that our analysis does not require any new physics in terms of dark-matter.

All the computations were performed on the Vikram-100 HPC cluster at PRL, Ahmedabad.