Explaining the Results of EDGES Observation of 21 cm Line with Dark Matter-Dark Energy and Dark Matter-Baryon Interactions

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Abstract

The EDGES experiment related to the observation of the brightness temperature T_{21} of the 21 cm line arising from the ground state of the neutral Hydrogen atom, has shown an excess absorption feature (-500^{+200}_{-500} mK) in the T_{21} spectrum corresponding to the era of the cosmic dawn ($z \simeq 17.2$). In order to explain the observed excess trough of T_{21}, we consider an Interacting Dark Energy scenario (interactions of Dark Matter and Dark Energy) along with the scattering of baryons with Dark Matter. Three different Interacting Dark Energy (IDE) models are used, and the viability of these models is tested in the context of the EDGES experimental results. It is found that Dark Matter-Dark Energy interactions modify the evolution process of the Universe and, hence, affect the brightness temperature. Dark Matter-baryon interactions also affect the T_{21} temperature since the baryon fluid would transfer heat to the colder Dark Matter fluid due to the Dark Matter-baryon collisions. In addition, we also give bounds on the model parameters of IDE models and Dark Matter model from the EDGES observational data. It is noted that Dark Matter-Dark Energy interactions enable exploring a larger range of Dark Matter mass regimes that would satisfy the EDGES result.

Keywords: dark energy, dark matter, 21 cm line of hydrogen atom
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1. INTRODUCTION

The 21 cm line (emission or absorption) arises due to the transition between the hyperfine splitting of the ground state energy level of the neutral Hydrogen (HI) atom. Since $\sim$ 75% of the known mass content of the Universe is Hydrogen, the 21 cm line is a very useful probe to map the Cosmos. In fact, this hyperfine transition line is a very crucial probe to understand the cosmic processes in the Cosmic dark ages or in the Cosmic Dawn during the epoch of reionization.

The 21 cm line is used to probe the cosmic processes in the line of sight of the Cosmic Microwave Background (CMB) or any other astronomical radio objects like pulsar, etc. [1]. In this work, CMB is assumed to be the background radiation, and the brightness temperature of the 21 cm line is provided by

$$T_{21} = \frac{T_s - T_\gamma}{1+z}(1 - e^{-\tau}) \simeq \frac{T_s - T_\gamma}{1+z}\tau, \tag{1}$$

where T_s, T_γ, and τ denote the spin temperature of the Hydrogen gas, the CMB temperature, and the optical depth of the Hydrogen gas, respectively. The spin temperature here represents the excitation temperature of the Hydrogen gas and is defined as the ratio of the number densities of the Hydrogen atoms in the hyperfine levels, $n_1/n_0 = g_1/g_0 \exp(-h\nu/kT_s)$, with $g_1(=3)$ and $g_0(=1)$ being the statistical weights of the hyperfine states.

The EDGES (Experiment to Detect the Global Epoch of Reionization Signature) experiment has reported an excess absorption feature of the 21 cm signal at the era of the cosmic dawn in the redshift range $14 < z < 20$. The EDGES has observed the 21 cm brightness temperature $T_{21} = -500^{+200}_{-500}$ mK in the sky averaged spectrum around $z \sim 17.2$ with a 99% confidence limit (CL) [2]. But according to the standard cosmological model (ΛCDM model), T_{21} should not be less than -200 mK at this redshift. This gives rise to the discrepancy between the EDGES observational data and the standard cosmological prediction. In order to address this discrepancy, one would require obtaining a smaller T_s or a larger T_γ or a larger optical depth (equation (1)). There are theoretical attempts in the literature to explain such excess absorption signals [3]-[8].

In [9], we address the problem by considering Dark Matter-Dark Energy (DM-DE) interactions along with Dark Matter-baryon (DM-baryon) scatterings. The DM-DE interactions modify the evolution of the Universe which in turn affect the evolution of the Hubble parameter $H(z)$ as well as the evolutions of DM and DE densities. Therefore, the modified evolutions have impacts on the optical depth of the gas, on the heating rate of baryon and DM, etc. Hence, all these interactions can alter the 21 cm brightness temperature T_{21} as is evident from equation (1).

Six coupled differential equations (evolution equations of DM temperature, baryon temperature, the drag term (arises due to the relative velocity between DM and baryon fluid), electron fraction, and DE and DM densities) are solved to obtain the T_{21} at $z \sim 17.2$ when all the interaction effects mentioned earlier are included. Three phenomenological models of IDE are considered in this work, and the results are computed for each of them. Constraints on the model parameters of such IDE models as well as on DM mass and DM-baryon scattering cross section are also explored by using the EDGES observational data. These constraints are further compared with the bounds provided from other cosmological experiments.

In the following sections, we describe DM-baryon and DM-DE interactions in detail and show the impacts of these interactions on the evolution of the brightness temperature. We then discuss our calculations and results. We conclude with a summary and discussions in the end.

2. INTERACTIONS BETWEEN BARYON FLUID AND DARK MATTER FLUID

The interactions between DM and baryon fluids of different temperatures lead to the flow of heat from the warmer baryon fluid to the colder DM fluid, thereby reducing the baryon temperature [10]. The heating rate in such scenario is proportional to the temperature difference of the fluids. But in [11], the authors showed that the velocity difference between the two fluids (DM and baryon) can also influence the temperature of the fluids. The tendency to damp the relative velocity between the fluids will heat up both of them. By taking into account these two effects, the heating rate of the baryons can be derived as [11]

$$\frac{dQ_b}{dt} = \frac{2m_b\rho_\chi\sigma_0 e^{-r^2/2}(T_\chi - T_b)}{(m_\chi + m_b)^2\sqrt{2\pi}u_{\rm th}^3} + \frac{\rho_\chi}{\rho_m}\frac{m_\chi m_b}{m_\chi + m_b}V_{\chi b}D(V_{\chi b})\,, \quad (2)$$

where $V_{\chi b}$ is the relative velocity while ρ_χ and ρ_m are the energy densities of DM and total matter, respectively, and T_b and T_χ denote the baryon temperature and the Dark Matter temperature, respectively. In the above, $r \equiv V_{\chi b}/u_{\rm th}$, $u_{\rm th}^2 \equiv \frac{T_b}{m_b} + \frac{T_\chi}{m_\chi}$ with m_b and m_χ as the masses of baryon and DM, respectively. The term $D(V_{\chi b})$ in equation (2) is the dragging term and is defined as

$$D(V_{\chi b}) \equiv -\frac{dV_{\chi b}}{dt} = \frac{\rho_m\sigma_0}{m_b + m_\chi}\frac{1}{V_{\chi b}^2}F(r)\,, \quad (3)$$

with $F(r) \equiv {\rm erf}(\frac{r}{\sqrt{2}}) - \sqrt{\frac{2}{\pi}}e^{-r^2/2}r$. Here, the DM-baryon scattering cross section is used in the parameterized form $\sigma = \sigma_0 v^{-4}$ [12]. The heating rate of DM $\dot{Q}_\chi$ can also be obtained in a similar way as $\dot{Q}_b$ is given in equation (2). It can be noted here that as $\dot{Q}_b$ and $\dot{Q}_\chi$ depend on ρ_χ, ρ_m, and $H(z)$, the heating rates are related to the process that can affect the evolution of the Universe.

3. INTERACTIONS BETWEEN DARK ENERGY AND DARK MATTER

The DM-DE interactions will also have impacts on the absorption signal of the 21 cm line. The presence of the DM-DE interactions modifies the evolution of the Universe, and hence, the evolutions of ρ_χ and $\rho_{\rm de}$ (energy density of DE) are no longer proportional to $(1+z)^3$ and $(1+z)^{3(1+\omega)}$, respectively. As a consequence, the expansion rate of the Universe would be modified, and the evolution of the Hubble parameter $H(z)$ would not be described by its usual form $H(z) = H_0\sqrt{\Omega_{b0}(1+z)^3 + \Omega_{\chi 0}(1+z)^3 + \Omega_{\rm de0}(1+z)^{3(1+\omega)}}$. Therefore, the optical depth τ and the spin temperature T_s of the Hydrogen gas will be affected due to the DM-DE interactions, and consequently, the T_{21} signal will be affected.

Assuming the possible interactions between DM and DE, the continuity equations of their energy densities are given by

$$(1+z)H(z)\frac{d\rho_\chi}{dz} - 3H(z)\rho_\chi = -Q\,, \quad (4)$$

$$(1+z)H(z)\frac{d\rho_{\rm de}}{dz} - 3H(z)(1+\omega)\rho_{de} = Q\,. \quad (5)$$

Model	ω	λ
$3\lambda H\rho_{\rm de}$	$-0.9191^{+0.0222}_{-0.0839}$	$-0.1107^{+0.085}_{-0.0506}$
$3\lambda H\rho_{\rm de}$	$-1.088^{+0.0651}_{-0.0448}$	$0.05219^{+0.0349}_{-0.0355}$
$3\lambda H\rho_\chi$	$-1.1041^{+0.0467}_{-0.0292}$	$0.0007127^{+0.000256}_{-0.000633}$
$3\lambda H(\rho_{\rm de}+\rho_\chi)$	$-1.105^{+0.0468}_{-0.0288}$	$0.000735^{+0.000254}_{-0.000679}$

TABLE 1: Constraints on the parameters of the IDE models from PLANCK, Supernova Ia (SNIa), baryon acoustic oscillation (BAO), and the Hubble constant results.

In the above, Q represents the energy transfer between DE and DM due to their interactions. Although in the literature there are various expressions of different interacting Dark Energy (IDE) models for Q [13]-[15], in this work, we adopt three simple and well studied phenomenological models of IDE [16, 17] for simplicity. According to these models, the energy transfer Q has the following forms:

$$\text{Model-I:} \quad Q = 3\lambda H(z)\rho_{\rm de}\,, \quad (6)$$

$$\text{Model-II:} \quad Q = 3\lambda H(z)\rho_\chi\,, \quad (7)$$

$$\text{Model-III:} \quad Q = 3\lambda H(z)(\rho_{\rm de} + \rho_\chi)\,, \quad (8)$$

where λ is the parameter representing the interaction strength of the DM-DE interactions. Moreover, these three IDE models are extensively studied and tightly constrained from cosmological observations like PLANCK, Supernova Ia (SNIa), baryon acoustic oscillation (BAO), and the Hubble constant. Constraints on the model parameters ω (equation of state of DE) and λ for the three IDE models are shown in Table 1 [18, 19].

In this work, we explore whether an IDE model which is well in agreement with other observational results could also be useful in explaining the EDGES observational limit of the 21 cm brightness temperature when DM-DE interaction effects are included for the evaluation of the T_{21}.

4. EFFECTS OF THE INTERACTIONS ON THE TEMPERATURE EVOLUTIONS

As mentioned earlier, we explore the evolutions of T_b (baryon temperature) and T_χ (DM temperature) with the additional effects of DM-baryon collisions and DM-DE interactions

$$\frac{dT_\chi}{dz} = \frac{2T_\chi}{1+z} - \frac{2\dot{Q}_\chi}{3(1+z)H(z)} - \frac{1}{n_\chi}\frac{2Q}{3(1+z)H(z)}\,, \quad (9)$$

$$\frac{dT_b}{dz} = \frac{2T_b}{1+z} + \frac{\Gamma_c}{(1+z)H(z)}(T_b - T_\gamma) - \frac{2\dot{Q}_b}{3(1+z)H(z)}\,. \quad (10)$$

On the right-hand side (r.h.s) of equation (9), the third term is added to include the effects of the DM-DE interactions on the DM temperature T_χ, while the first term on the r.h.s. represents the cooling of DM for the adiabatic expansion of the Universe and the additional heating of the DM fluid for the DM-baryon collisions is attributed to the second term on the r.h.s. Similarly, the first and third terms on the r.h.s. of equation (10) correspond to the adiabatic cooling of the Universe and DM-baryon interactions, respectively, but the second term is related to the Compton scattering of the Hydrogen gas. Here, the CMB temperature $T_\gamma = 2.725(1+z)$ K and $\Gamma_c = \frac{8\sigma_T a_r T_\gamma^4 x_e}{3(1+f_{\rm He}+x_e)m_e c}$ is the

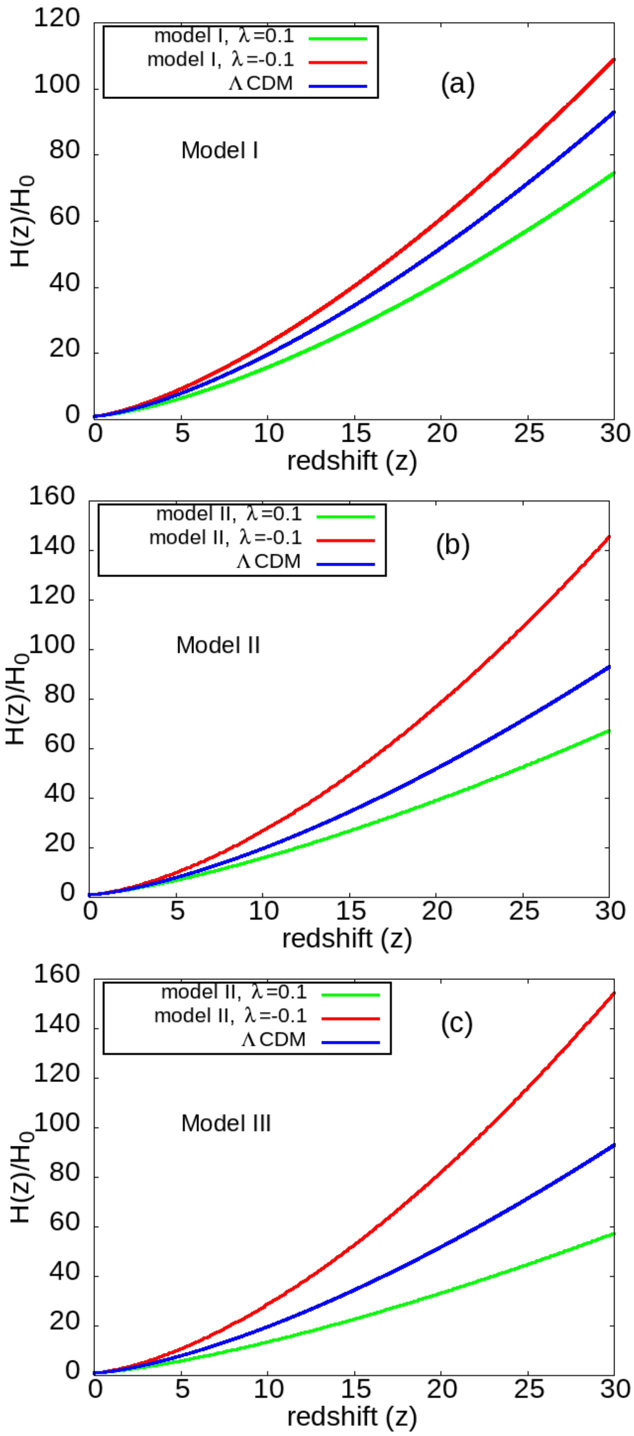

FIGURE 1: Evolutions of the Hubble parameter for different IDE models (Model-I in (a), Model-II in (b), and Model-III in (c)) with the values of $\lambda = -0.1, 0.1$.

Compton interaction rate. Here, σ_T is the Thomson scattering cross section, and a_r is the radiation constant while $x_e = n_e/n_H$ denotes the free electron abundance and $f_{\rm He}$ is the fractional abundance of He. The electron mass and speed of light are denoted as m_e and c, respectively. As the temperature evolutions depend on the free electron fraction, the evolution of x_e also needs to be computed and this evolution of x_e is expressed as

$$\frac{dx_e}{dz} = \frac{C_P}{(1+z)H(z)} \left(n_H A_B x_e^2 - 4(1-x_e) B_B e^{\frac{-3E_0}{4T_\gamma}} \right). \quad (11)$$

In the above equation, C_P is the Peebles C-factor and E_0 denotes the ground state energy of Hydrogen while A_B and B_B are the effective recombination coefficient and the effective photoionization rate, respectively.

The evolution of the DM-baryon relative velocity $V_{\chi b}$ also contributes to the evolution of the baryon temperature and the DM temperature and is given by

$$\frac{dV_{\chi b}}{dz} = \frac{V_{\chi b}}{1+z} + \frac{D(V_{\chi b})}{(1+z)H(z)}, \quad (12)$$

where the first term on the r.h.s is related to the expansion of the Universe while the second term arises due to the dragging force on $V_{\chi b}$.

By solving the six coupled differential equations described in equations (4)-(12) with proper initial conditions, we obtain the temperature evolutions of baryons and DM. Moreover, at $z \sim 17.2$, the spin temperature is tightly coupled to the gas temperature or the baryon temperature (i.e., at $z \sim 17.2$, $T_s = T_b$) due to the Wouthuysen-Field effect induced by the Lyα photons. The temperature T_b thus obtained is used to calculate T_s, and then T_{21} is computed by using the relation $T_{21} = \frac{T_s - T_\gamma}{1+z}(1 - \exp^{-\tau}) \approx \frac{T_s - T_\gamma}{1+z}\tau$, while the optical depth τ is calculated from $\tau = \frac{3}{32\pi}\frac{T_*}{T_s} n_{\rm HI} \lambda_{21}^3 \frac{A_{10}}{H(z)}$.

It can be mentioned here that as the optical depth of the intergalactic medium depends on $H(z)$, it will also be affected by the presence of the DM-DE interactions. In fact, smaller values of $H(z)$ lead to larger values of τ and thus a larger absorption signal of the 21 cm spectra.

5. CALCULATIONS AND RESULTS

In this section, we discuss the calculations and results in relation to the computation of T_{21} while considering the additional effects of the DM-DE interactions as well as the DM-baryon interactions. In doing this, we solve the set of equations mentioned and discussed in the previous sections.

Evolutions of Hubble parameter $H(z)$ with redshift z are plotted in Figure 1 for different IDE models adopted in this work and different values of the DM-DE interaction parameter λ ($\lambda = -0.1, 0.1$). In Figures 1(a), 1(b), and 1(c), the variations are shown for Model-I, Model-II, and Model-III (see Section 3), respectively. The results are also compared in all the cases with the $H(z)$ of the ΛCDM model (blue lines in Figure 1). It can be observed that for each of the three IDE models the value of $H(z)$ at $z \sim 17.2$ for $\lambda = 0.1$ is less than that in the ΛCDM case (for ΛCDM, $\lambda = 0$). Hence, the positive values of the DM-DE interaction parameter appear to indicate a larger optical depth and consequently a larger absorption feature of the T_{21}.

In Figure 2, the variations of ΔT_{21} with λ for different fixed values of the DM-baryon scattering cross section σ_{41} ($\sigma_{41} = \frac{\sigma_0}{10^{-41}\,{\rm cm}^2}$) and DM mass m_χ for Model-I of IDE are plotted. The chosen values of σ_{41} are $\sigma_{41} = 0, 0.1, 1, 10$ while the values of DM mass are $m_\chi = 0.1$ GeV, 1 GeV, 10 GeV. ΔT_{21} is defined as $\Delta T_{21} = T_{21}^x - T_{21}^0$, where T_{21}^0 is the calculated value of the brightness temperature T_{21} at $z \simeq 17.2$ for the ΛCDM model

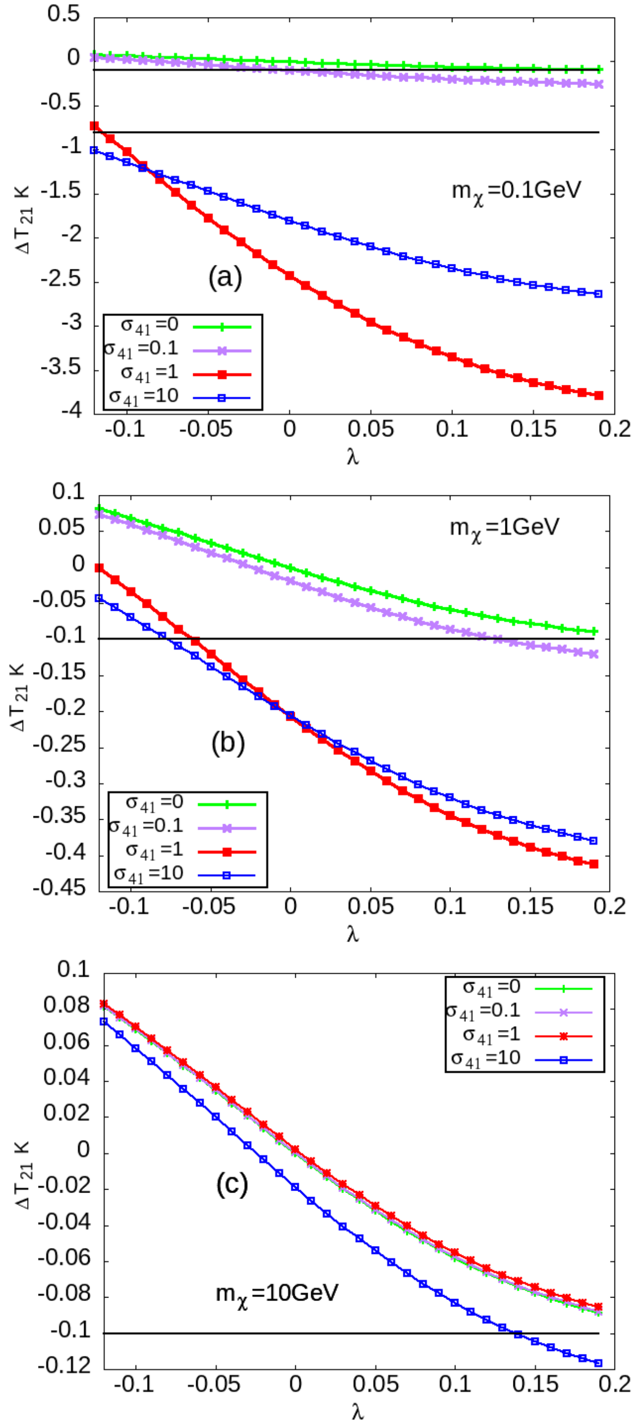

FIGURE 2: The variations of ΔT_{21} ($= T_{21}^x - T_{21}^0$) with the DM-DE interaction strength λ for Model-I. The plots are shown for different DM masses m_χ and different DM-baryon interaction cross sections σ_{41} (in units of 10^{-41} cm^2). The region between the two black lines in (a) and the regions below the black lines in (b) and (c) represent the allowed values of ΔT_{21} which can satisfy the EDGES results.

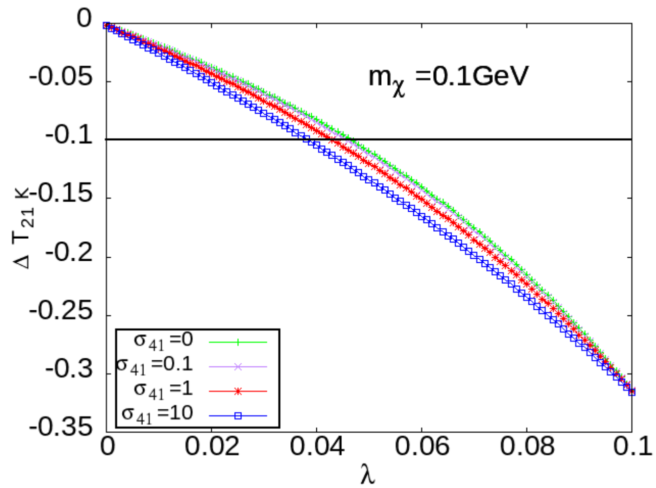

FIGURE 3: The variations of $\Delta T_{21} (= T_{21}^x - T_{21}^0)$ with the DM-DE interaction strength λ for Model-III.

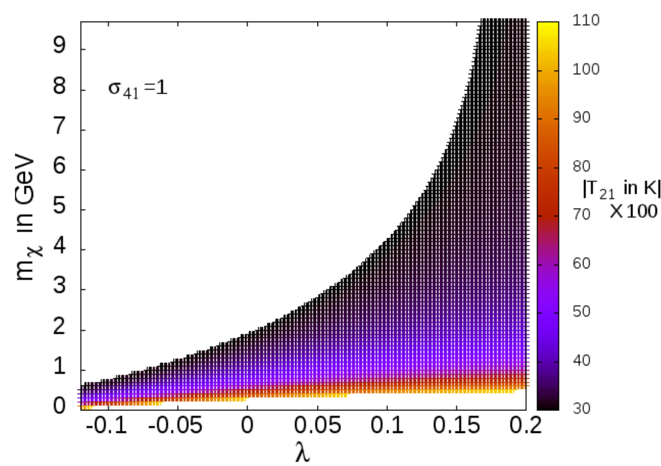

FIGURE 4: Allowed parameter space for the DM-DE interactions strength and DM mass to satisfy the EDGES observations

and $T_{21}^0 \simeq -0.22$ K while T_{21}^x corresponds to the same evaluation including DM-DE and DM-baryon interactions. From Figures 2(a), 2(b), and 2(c) (corresponding to the results with the chosen DM masses 0.1 GeV, 1 GeV, and 10 GeV, respectively), it can be observed that, for all the cases, ΔT_{21} tends to achieve more negative values (this in turn signifies a larger absorption signal of the 21 cm line) for a larger DM-DE interaction parameter λ and, therefore, the discrepancy between the observed value of T_{21} and theoretically predicted T_{21} reduces as λ increases. It can also be noted that, for every value of m_χ, the EDGES results can be addressed for the nonzero values of σ_{41}, but in the absence of the DM-baryon interactions ($\sigma_{41} = 0$) T_{21} cannot satisfy the EDGES limit (the region between the two black lines in Figure 2(a) and the regions below the black line in Figures 2(b) and 2(c) represent the allowed regions to satisfy the EDGES results). Hence, when DM baryon interactions are switched on, the larger absorption signal of the 21 cm line can be observed. It is also clear from Figure 2 that smaller DM masses produce larger values of T_{21}^x at $z \simeq 17.2$.

In Figure 3, similar plots are obtained as in Figure 2 but with Model-III of IDE. From Figure 3, it can be noted that the EDGES observations for T_{21} are satisfied for $\lambda \geq 0.04$ (region below the black horizontal line in the figure), but it is found from Table 1 that the upper bound of λ from other cosmological experiments is 0.000989. Hence, the values of λ required to satisfy the

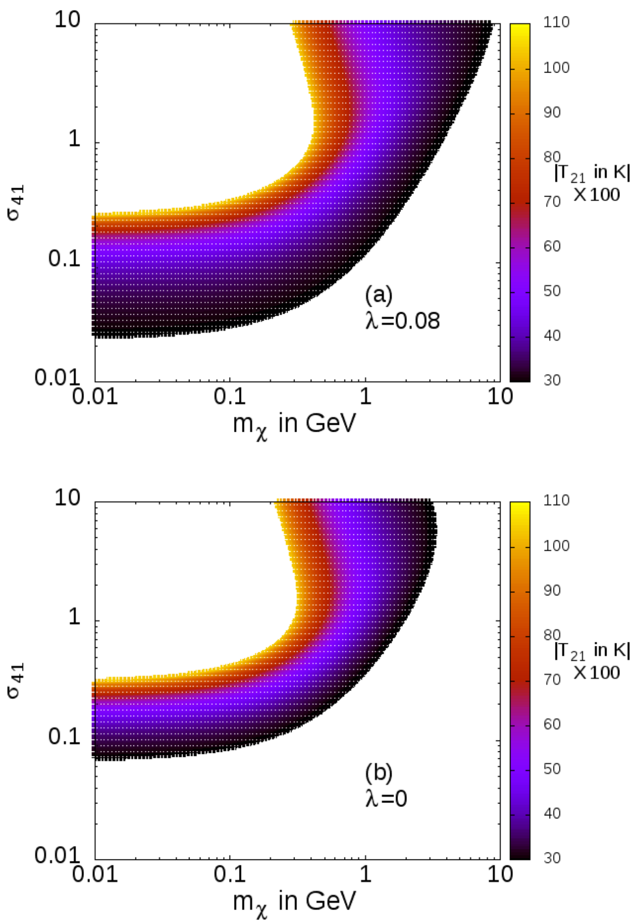

FIGURE 5: Allowed parameter space for the DM-baryon scattering cross section and DM mass to satisfy the EDGES observations.

EDGES limit do not corroborate with the bounds from other experimental results for Model-III of IDE. This is also the case when Model-II of IDE is adopted in the analysis.

In Figure 4, the allowed parameter range in $\lambda - m_\chi$ parameter space is plotted for which the EDGES results can be satisfied. It can be observed from Figure 4 that the smaller DM mass and the larger DM-DE interaction strength are favorable to satisfy the EDGES limit of the T_{21}. Here, the computations are performed with $\sigma_{41} = 1$, but it is also checked that $\sigma_{41} = 0.1$ or $\sigma_{41} = 10$ yield similar allowed regions.

We also explore in this work the allowed region of DM mass m_χ and the DM-baryon scattering cross section. To this end, in Figure 5, the allowed parameter regions in the $m_\chi - \sigma_{41}$ parameter space are plotted that can satisfy the results of the EDGES experiment ($-300\,\text{mK} \geq T_{21} \geq -1000\,\text{mK}$). These allowed regions are obtained by keeping the DM-DE interaction parameter fixed at $\lambda = 0.08$ (Figure 5(a)) and $\lambda = 0$ (Figure 5(b)). Thus, Figure 5 compares the allowed parameter spaces with and without DM-DE interactions. Comparing Figure 5(a) with Figure 5(b), it can be observed that the region of the allowed parameter space increases when the DM-DE interactions are turned on. Therefore, the presence of the DM-DE interactions not only lowers the gas temperature T_b but also allow us to probe a larger mass range of DM that could be responsible for the observed EDGES results for the T_{21} brightness temperature.

6. SUMMARY AND CONCLUSIONS

In this work, we study the effects of the DM-DE interactions as well as the scattering of baryons with DM to describe the excess of the 21 cm absorption temperature reported by the EDGES experiment. According to the EDGES result, $T_{21} = -500^{200}_{-500}$ mK at redshift $z \simeq 17.2$. But the ΛCDM model theoretically predicts that the 21 cm brightness temperature should not be below -200 mK at that era. The formalism in this work involves solving six coupled differential equations that include the evolutions of the energy density of DM (ρ_χ), the energy density of DE (ρ_{de}), DM temperature (T_χ), baryon temperature (T_b), free electron fraction (x_e), and DM-baryon relative velocity ($V_{\chi b}$). We observe that the DM-DE interactions modify the expansion rate $H(z)$ of the Universe. This modification of $H(z)$ would affect the optical depth and the spin temperature of the Hydrogen cloud and consequently modify the brightness temperature of the 21 cm line. Moreover, the scattering between DM and baryons would also have an impact on the baryon temperature and hence modify the T_{21} signal. By including these additional interactions, we show that the observed trough of the 21 cm brightness temperature by the EDGES experiment can be explained. We found that the larger the values of the DM-DE interaction parameter, the larger the scattering cross sections of baryon and DM and the smaller the DM masses in order to be more favorable in obtaining the brightness temperature within the EDGES limit $T_{21} = -500^{200}_{-500}$ mK.

For the DM-DE interactions, we consider three interacting Dark Energy (IDE) models (see Section 3), and constraints on these IDE models from the EDGES results are obtained. Moreover, we compare these constraints with the constraints obtained from other observations (Table 1) and find that the constraints obtained from EDGES observations are consistent with other experimental results for Model-I ($Q = 3\lambda H(z)\rho_{\text{de}}$) but it is not the case for Model-II ($3Q = \lambda H(z)\rho_\chi$) or Model-III ($Q = 3\lambda H(z)(\rho_{\text{de}} + \rho_\chi)$). The allowed parameter spaces in $\lambda - m_\chi$ and $m_\chi - \sigma_{41}$ planes for which the EDGES results are satisfied are explored. It can be noticed from the allowed regions of the plots in Figure 5 that DM-DE interactions enhance the possibility that higher ranges of DM mass and scattering cross section could give rise to the observed EDGES results for the T_{21} brightness temperature.

The direct detection experiments provide upper bounds on WIMP (Weakly Interacting Massive Particle)—nucleon cross sections with DM mass in the range of ~ 7 GeV to $\mathcal{O}(10^4)$ GeV. From Figure 5, it is seen that the allowed values of DM mass can go up to 8 GeV and not beyond (even for $\lambda = 0.08$). The comparison of these plots with the bounds given by the DM direct detection experiments is not very useful. But few experiments like SNOLAB can probe the DM mass below the order of ~ 8 GeV, and the upper limit of the cross sections is given to be around 10^{-40}-10^{-44} cm^2 [20]. This is in the same ballpark of the results in Figure 5.

It can be mentioned here that, in [21], the authors have shown that a fraction of charged DM can interact with baryon with a scattering cross section $\sigma = \sigma_0 v^{-4}$ and can influence the T_{21}. Our work can be extended in the future by considering such charged subcomponent of DM to observe the changes in the results we have obtained.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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