The variation of the baryon-to-photon ratio during different cosmological epochs due to decay and annihilation of dark matter

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Abstract. An influence of annihilation and decay of the dark matter particles on the baryon-to-photon ratio has been studied for different cosmological epochs. We consider the different parameter values of the dark matter particles such as mass, annihilation cross section, lifetime and so on. The obtained results are compared with the data which come from the Big Bang nucleosynthesis calculation and from the analysis of the anisotropy of the cosmic microwave background radiation. It has been shown that the modern value of the dark matter density $\Omega_{\rm CDM} = 0.26$ is enough to provide the variation of the baryon-to-photon ratio up to $\Delta\eta/\eta \sim 0.01 \div 1$ for decay of the dark matter particles, but it also leads to an excess of the diffuse gamma ray background. We use the observational data on the diffuse gamma ray background in order to determine our constraints on the model of the dark matter particle decay and on the corresponding variation of the baryon-to-photon ratio: $\Delta\eta/\eta \lesssim 10^{-5}$. It has been shown that the variation of the baryon-to-photon ratio caused by the annihilation of the dark matter particles is negligible during the cosmological epochs from Big Bang nucleosynthesis to the present epoch.

1. Introduction

Cosmology is an accurate science today. There are a lot of cosmological parameters which are determined with a high precision. One of them is a baryon-to-photon ratio $\eta \equiv n_{\rm b}/n_\gamma$, where $n_{\rm b}$ and n_γ are the numbers of the baryons and the photons in the Universe respectively. In the standard cosmological model it is considered that the modern value of η was formed a few second after the Big Bang and has not been changed till the present epoch.

Today there are several independent experiments to determine value of η for four cosmological epochs (z is the cosmological redshift of the corresponding epoch):

(i) Big Bang nucleosynthesis (BBN, $z \sim 10^9$, e.g., [1]),
(ii) primordial recombination (CMB, $z \simeq 1100$, e.g., [2]),
(iii) the period of time associated with the Lyα forest ($z \sim 2 \div 3$, e.g., [3]),
(iv) the present epoch ($z = 0$, e.g., [4]).

The analysis of the observation data for two first epochs gives the high accuracy of η parameter determination.

For the processes taking place at the BBN and the CMB epochs η is one of the most important parameters which determines physics of these processes. For these epochs the methods for determination of η are:

(i) a comparison of the observational data on the abundance of primordial chemical elements (such as D, ^{4}He, ^{7}Li) with predictions of the BBN theory,

(ii) an analysis of the anisotropy of the cosmic microwave background radiation.

These methods give us the most accurate values of η which coincide within the observational errors: $\eta_{\rm BBN} = (6.0 \pm 0.4) \cdot 10^{-10}$ [1] and $\eta_{\rm CMB} = (6.05 \pm 0.07) \cdot 10^{-10}$ [2]. It is an evidence of validity of the standard cosmological model. Determination of η for (iii) and (iv) epochs has lower accuracy and it is also strongly model-dependent. One can hope that future experiments and observational data will let us determine η with higher accuracy for different cosmological epochs. It, in its turn, can become a powerful tool for study of physics beyond the Standard Model where η can change.

In this work we study an opportunity of η variation due to decay and annihilation of dark matter (DM) particles during different cosmological epochs. There are many candidates for the DM particles including supersymmetric particles (see, e.g., [5, 6] and references therein). Such particles can annihilate and decay with emission of the Standard Model particles (such as baryons, leptons, photons and so on). It can lead to η variation. Since the number of baryons in the Universe is a billion times less than the number of photons this variation is more sensitive to variation of the baryon number density. An influence of the DM decay and annihilation processes on the photon component of our Universe has been studied in a large number of works (see, e.g, [7, 8, 9, 10, 11] and references therein). In this work we study an influence of the DM decay and annihilation processes: $\rm X \to \chi p\bar{p}$ and $\chi\bar{\chi} \to \rm p\bar{p}$, where χ and X are the lightest supersymmetric particle (LSP) and the next-to-lightest supersymmetric particle (NLSP), on the baryonic component of the Universe.

We consider different parameter values of the DM particles:

- WIMP's annihilation cross section $\langle \sigma v \rangle^{\rm ann}_{\chi\bar{\chi}} = 3 \cdot 10^{-26} \rm sm^3/s$ (see, e.g., [5]),
- lifetime $t_{\rm BBN} \ll \tau \lesssim t_0$, where $t_{\rm BBN} \simeq 3$ minutes and $t_0 \simeq 13.8$ billion years are the ages of the Universe at the end of the BBN epoch and today respectively,
- mass of the DM particles within the range $10\,\rm GeV \div 1\,TeV$.

Instead of the standard cosmological model which assumes no relic antimatter, we define η as follows:

$$\eta(z) = \frac{n_{\rm b}(z) + n_{\bar{\rm b}}(z)}{n_\gamma(z)} = \frac{n_{\rm b}^{\rm BBN}(z) + \Delta n_{\rm p}(z) + \Delta n_{\bar{\rm p}}(z)}{n_\gamma^{\rm BBN}(z)} = \eta_{\rm BBN} + \Delta\eta(z), \quad (1)$$

where $n_{\bar{\rm b}}$ is the number of antibaryons in the Universe; $n_{\rm b}^{\rm BBN}$ and $n_\gamma^{\rm BBN}$ are the numbers of baryons and photons, respectively, which are related with $\eta_{\rm BBN} = n_{\rm b}^{\rm BBN}/n_\gamma^{\rm BBN}$; $\Delta n_{\rm p}$ and $\Delta n_{\bar{\rm p}}$ are the numbers of the baryons and the antibaryons, respectively, which are the products of the decay and the annihilation of DM.

2. The variation of the baryon-to-photon ratio due to decay and annihilation of dark matter

The time evolution of the number densities $n_{\rm X}(t)$ of the NLSP, $n_\chi(t)$ the LSP, $n_{\rm p}(t)$ the protons and $n_{\bar{\rm p}}(t)$ the antiprotons is described by the system of Boltzmann equations:

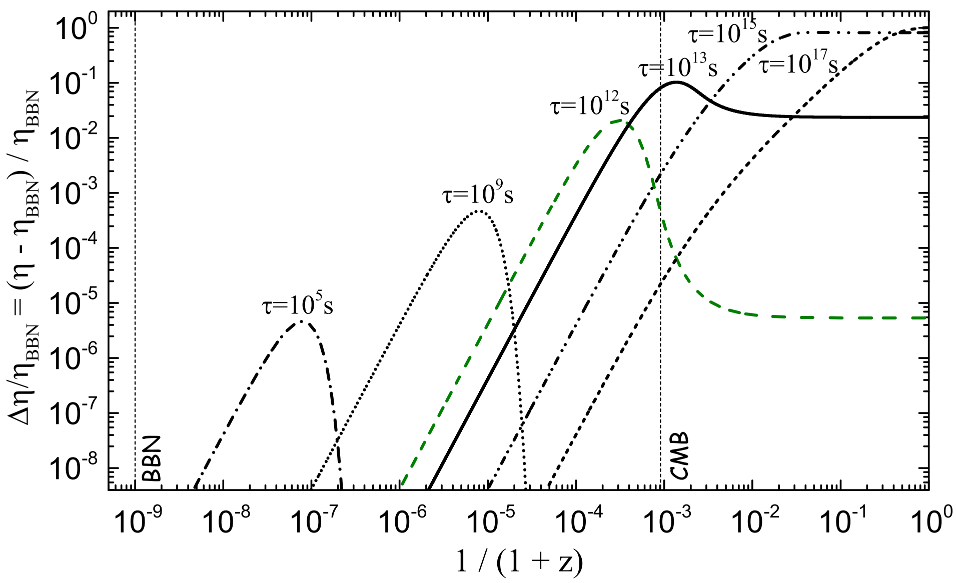

Figure 1. The variation of η due to decay of the dark matter particles with lifetimes $10^5\,\mathrm{s} \leq \tau \leq 10^{17}\,\mathrm{s}$ ($\alpha = 1$, $m_\chi = 10\,\mathrm{GeV}$). Vertical lines indicate the BBN and the CMB epochs.

$$\begin{aligned} \frac{dn_\mathrm{X}}{dt} + 3Hn_\mathrm{X} &= -\frac{1}{\tau}n_\mathrm{X}, \\ \frac{dn_\chi}{dt} + 3Hn_\chi &= \frac{1}{\tau}n_\mathrm{X}, \\ \frac{dn_{\mathrm{p},\bar{\mathrm{p}}}}{dt} + 3Hn_{\mathrm{p},\bar{\mathrm{p}}} &= -\langle\sigma v\rangle^{\mathrm{ann}}_{\mathrm{p}\bar{\mathrm{p}}} n_\mathrm{p} n_{\bar{\mathrm{p}}} + \frac{1}{\tau}n_\mathrm{X} + \frac{1}{2}\langle\sigma v\rangle^{\mathrm{ann}}_{\chi\bar{\chi}} n_\chi n_{\bar{\chi}}, \end{aligned} \tag{2}$$

where $H(t) = \dot{a}/a$ is the Hubble expansion rate, $a(t)$ is the scale factor of the Universe, $\langle\sigma v\rangle^{\mathrm{ann}}_{\chi\bar{\chi}} = 3{\cdot}10^{-26}\mathrm{cm}^3/\mathrm{s}$ [5] and $\langle\sigma v\rangle^{\mathrm{ann}}_{\mathrm{p}\bar{\mathrm{p}}} = 10^{-15}\mathrm{cm}^3/\mathrm{s}$ [12] are the thermally averaged total cross section for annihilation of $\chi\bar{\chi}$ and $\mathrm{p}\bar{\mathrm{p}}$, respectively, times relative velocity which are almost the constants in the wide energy range, 1/2 in the right side of the third equation is because of the annihilation of the Majorana particles ($\chi \equiv \bar{\chi}$). We use the values of cosmological parameters from [2].

We use the following initial conditions for the system (2):

$$z^0 = z_\mathrm{BBN} = 10^9, \quad t^0 = \frac{1}{2H(z_\mathrm{BBN})}, \quad n^0_\mathrm{p} = \eta_\mathrm{BBN} n_\gamma(z_\mathrm{BBN}),$$

$$n^0_{\bar{\mathrm{p}}} = 0, \quad n^0_\chi = (1-\alpha)\frac{\Omega_\mathrm{CDM}\rho_\mathrm{c}}{m_\chi c^2}, \quad n^0_\mathrm{X} = \alpha\frac{\Omega_\mathrm{CDM}\rho_\mathrm{c}}{m_\chi c^2},$$

where $0 \leq \alpha \leq 1$ is the fraction of NLSP to all DM number density at the BBN epoch, $\Omega_\mathrm{CDM} = 0.26$ is the cold DM density parameter, ρ_cr is the critical density of the Universe, m_χ is the mass of the LSP, c is the speed of light.

We found out that annihilation of the DM particles does not lead to significant change of the baryon-to-photon ratio during the cosmological epochs from the BBN to the present epoch. The variation of η due to the only annihilation of DM ($\chi\bar{\chi} \to \mathrm{p}\bar{\mathrm{p}}$) with masses

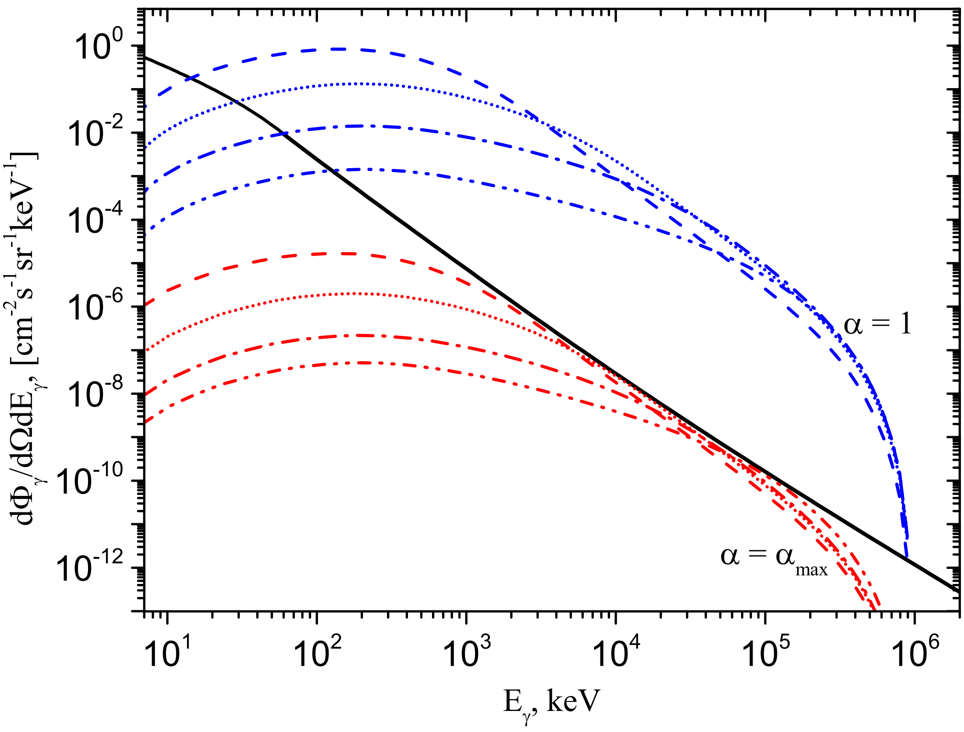

Figure 2. The diffuse gamma ray background due to annihilation of the protons and the antiprotons, the products of the decays of the DM particles with lifetimes $\tau = 10^{14}$ s (dashed curves), 10^{15} s (short-dotted curves), 10^{16} s (dash-dotted curves) and 10^{17} s (dash-dot-dotted curves), blue curves correspond to $\alpha = 1$, red curves correspond to $\alpha = \alpha_{\max}$, black solid curve corresponds to fitting the observational data from [13].

$m_\chi = 10\,\mathrm{GeV}\div 1\,\mathrm{TeV}$ even at the BBN epoch (where the rate of the annihilation is the highest) is negligible: $|\Delta\eta(z)/\eta_{\mathrm{BBN}}| < 10^{-11} \div 10^{-13}$.

The variation of η due to decay of the NLSP, in its turn, is sizeable. In Fig. 1 we present the results of calculations of η variation due to decay of the NLSP ($\mathrm{X} \to \chi \mathrm{p}\bar{\mathrm{p}}$) for the case $m_\chi = 10\,\mathrm{GeV}$ and $\alpha = 1$. One can see that the late decay of the DM ($\tau \gtrsim 10^{12}$) can lead to η variation up to $\Delta\eta(z)/\eta_{\mathrm{BBN}} \sim 0.01 \div 1$ (a particular value depends on τ) what is potentially observable.

The obtained results must not contradict observational data. We use the data [13] on the diffuse gamma ray background (DGRB) in order to make constraints on the DM decay model and on the maximum possible variation of η due to these NLSP decays.

3. The diffuse gamma ray background

Presence of antiprotons in the Universe would lead to emergence of the complementary DGRB due to annihilation of the protons and the antiprotons which can be observed today for the decays of the NLSP taking place in $z \lesssim 1000$ [8, 14] ($\tau > t_{\mathrm{CMB}} \simeq 400000$). The DGRB (the number of photons per unit area, time, solid angle and energy range) due to the annihilation of the protons and the antiprotons is given by

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \frac{c}{4\pi} \langle\sigma v\rangle^{\mathrm{ann}}_{\mathrm{p}\bar{\mathrm{p}}} \int\limits_0^{1000} dz \frac{n_{\mathrm{p}}(z) n_{\bar{\mathrm{p}}}(z)}{H(z)(1+z)^3} \frac{dN_\gamma}{dE_\gamma} \left[E_\gamma(1+z)\right], \qquad (3)$$

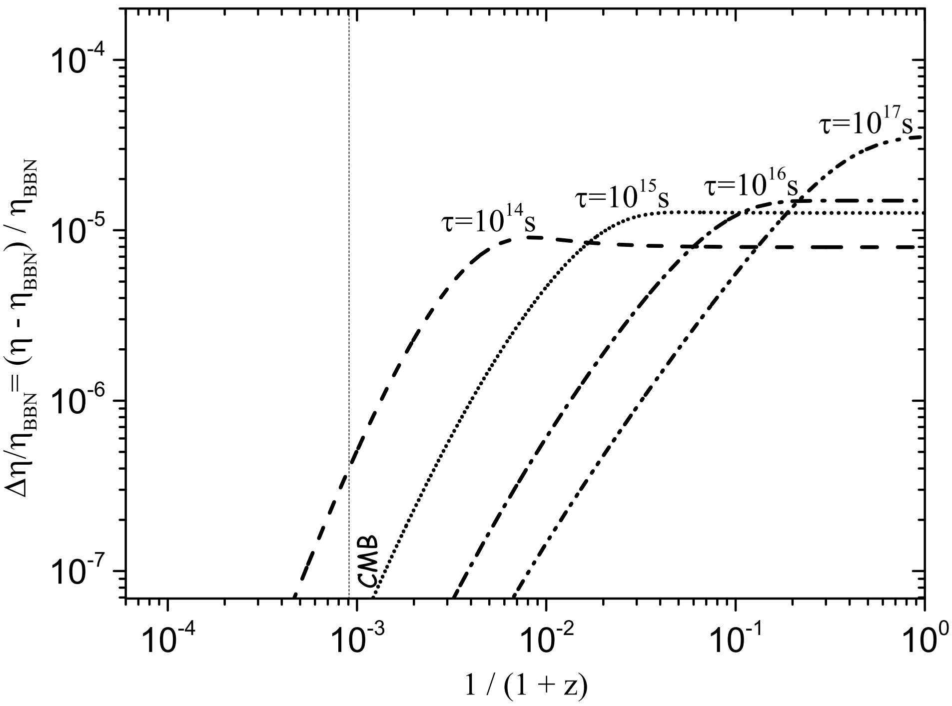

Figure 3. The variation of η due to decay of the dark matter particles with lifetimes $10^{14}\,\mathrm{s} \leq \tau \leq 10^{17}\,\mathrm{s}$ which are consistent with the observational data on the diffuse gamma ray background ($\alpha = \alpha_{\max}$, $m_\chi = 10\mathrm{GeV}$). Vertical line indicates the CMB epoch.

where dN_γ/dE_γ is the gamma spectrum (the average number of photons per energy range and per annihilation) from proton-antiproton annihilation [15]. In Fig. 2 we present this DGRB for the cases $m_\chi = 10\,\mathrm{GeV}$, $\alpha = 1$ and $\alpha = \alpha_{\max}$. The cases with $\alpha \lesssim \alpha_{\max}$ are allowed by the observational data [13]. For the DM mass $m_\chi = 10\,\mathrm{GeV}$ the values of $\alpha_{\max}$ are $2 \cdot 10^{-5}$ for $\tau = 10^{14}\,\mathrm{s}$, $1.5 \cdot 10^{-5}$ for $\tau = 10^{15}\,\mathrm{s}$, $1.5 \cdot 10^{-5}$ for $\tau = 10^{16}\,\mathrm{s}$ and $3.5 \cdot 10^{-5}$ for $\tau = 10^{17}\,\mathrm{s}$.

In Fig. 3 we present our final results on the variation of η for $m_\chi = 10\,\mathrm{GeV}$, $\alpha = \alpha_{\max}$ and $t_{\mathrm{CMB}} < \tau \lesssim t_0$ which are consistent with the observational data on the DGRB. One can see that the variation of baryon-to-photon ratio can be $\Delta\eta/\eta_{\mathrm{BBN}} \lesssim 10^{-5}$. Note that α and m_χ are included into the initial conditions of (2) as a ratio. Hence, the obtained results are the same for the cases of the heavier LSP with keeping the value of α/m_χ.

It should be noted that in this work an approximation of uniform density of the Universe has been used, while density inhomogeneities $\Delta\rho/\rho$ become significant at low redshifts ($z \lesssim 30$). However, given that in the present epoch most of baryons is contained in extragalactic gas where $\Delta\rho/\rho \lesssim 1 \div 10$ and that proton-antiproton annihilation virtually stops at the redshifts $z \sim 100$ (see Fig. 1), the results revealed in Fig. 1 (at $z \lesssim 30$) will not be affected noticeably by taking into account growth of inhomogeneities. At the same time, constraints stemming from the DGRB can be enhanced, especially in case of late X particle decays ($\tau \gtrsim 10^{16}\,\mathrm{s}$).

4. Conclusion

An influence of the annihilation and the decay processes of the dark matter particles:

$$\chi\,\bar{\chi} \longrightarrow \mathrm{p}\,\bar{\mathrm{p}}, \qquad \mathrm{X} \longrightarrow \chi\,\mathrm{p}\,\bar{\mathrm{p}},$$

on the baryon-to-photon ratio has been studied for different cosmological epochs.

We have shown that the annihilation of the dark matter particles with masses $m_\chi = 10\,\mathrm{GeV}\div 1\,\mathrm{TeV}$ and WIMP's annihilation cross section $\langle\sigma v\rangle^{\mathrm{ann}}_{\chi\bar{\chi}} = 3\cdot 10^{-26}\mathrm{sm}^3/\mathrm{s}$ does not lead to significant variation of the baryon-to-photon ratio during the cosmological epochs from Big Bang nucleosynthesis to the present epoch: $|\Delta\eta(z)/\eta_{\mathrm{BBN}}| < 10^{-11}\div 10^{-13}$.

It has been shown that the decay of the dark matter particles (in case of LSP masses $m_\chi = 10\,\mathrm{GeV}\div 1\,\mathrm{TeV}$) can lead to the variation of the baryon-to-photon ratio up to $\Delta\eta(z)/\eta \sim 0.01\div 1$, but it also leads to an excess of the gamma ray flux due to annihilation of the protons and the antiprotons.

We determined our constraints on the decay of the dark matter particles with lifetime $t_{\mathrm{CMB}} < \tau \lesssim t_0$: the fraction of such NLSP to all DM number density at the BBN epoch $\alpha \lesssim 10^{-5}\div 10^{-3}$ for the LSP masses $m_\chi = 10\,\mathrm{GeV}\div 1\,\mathrm{TeV}$, and on the corresponding variation of the baryon-to-photon ratio: $\Delta\eta(z)/\eta_{\mathrm{BBN}} \lesssim 10^{-5}$.

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