Early reionization by decaying particles in the light of three-year WMAP data

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Received 11 December 2006
Accepted 17 January 2007
Published 7 February 2007

Online at stacks.iop.org/JCAP/2007/i=02/a=010
doi:10.1088/1475-7516/2007/02/010

Abstract. We study reionization histories where ionizing UV photons are emitted from decaying particles, in addition to the usual contributions from stars and quasars, taking account of the fact that the universe is not fully ionized until $z \sim 6$, as observed by the Sloan Digital Sky Survey. Likelihood analysis of the three-year data from the WMAP (Wilkinson Microwave Anisotropy Probe) severely constrains the decaying particle scenario. In particular, a decaying particle with relatively short lifetime is not favoured by the polarization data.

Keywords: CMBR theory, dark matter, high energy photons, physics of the early universe
1. Introduction

The ionization history after recombination was not known for many years, until recent developments of observations. The Sloan Digital Sky Survey (SDSS) obtained the first evidence of the reionization epoch [1]. The Gunn–Peterson test for the observed spectra of quasars revealed that neutral hydrogen existed at the redshift $z \sim 6$, which implies that the completion of the reionization of the universe was seen at $z \sim 6$, although the amount of neutral hydrogen at $z \gtrsim 6$ may not be large enough to explain the observed Gunn–Peterson trough.

On the other hand, the Wilkinson Microwave Anisotropy Probe (WMAP) observation found the reionization earlier than $z \sim 6$ in terms of the large optical depth [2,3]. The first-year data favoured a very large optical depth $\tau_{op} = 0.17 \pm 0.04$ [2]. The conventional reionization by UV photons emitted from usual early formed stars and quasars could only reach to the optical depth of $\sim 0.05$ [4,5] if it is consistent with the SDSS data. Of course, using a non-standard initial mass function and an unrealistic UV fraction escaping from galaxies, one could achieve a large optical depth [6]. However, the UV fluxes from stars and quasars increase with time and full reionization takes place before $z \sim 6$. Thus, one has to consider a more complex ionization history which may be realized, for example, by the use of different photon emission processes between Population II and III stars [7].

An alternative line is to consider another source of UV photons. It could be decaying particles [8–10]. In [8,9], we considered decaying particles in addition to conventional stars and quasars and found that the decaying particle scenario is consistent with the first-year WMAP data for large parameter space.

Recently, WMAP team released three-year data, in which the value of the optical depth is lowered: $\tau_{op} = 0.09 \pm 0.03$ [3]. It has changed towards the conventional value of $\sim 0.05$, but some extra UV photons are still necessary. It would be possible to have such a small amount of extra UV photons before $z \sim 6$ using less unrealistic assumptions for stars and quasars. In this paper, however, we stick to the decaying particle scenario to assess its capability.

The structure of the paper is as follows. In the next section, we explain how we follow the evolution of the ionization history including the decaying particles. In section 3, we evaluate the $\chi^2$ for each model parameters, and construct likelihood contours for the
parameters of the decaying particle scenario. At the same time, the details of the power spectra of temperature and polarization anisotropies in the cosmic microwave background (CMB) radiation are shown, and we discuss how it discriminates between the preferred model parameters in the same section. The final section is devoted to our conclusions.

2. Reionization history

We consider that ionizing UV photons are emitted from decaying particles as well as from usual stars (and quasars). The latter are indeed responsible for full ionization at \( z \sim 6 \). On the other hand, UV photons from particle decays keep a non-zero but small amount of the ionization fraction before \( z \sim 6 \).

We follow the thermal history from \( z > 10^3 \) including the recombination epoch, calculating the ionization fraction of hydrogen and helium, and the electron temperature, on the basis of the hierarchical clustering scheme of the cold dark matter scenario used in Fukugita and Kawasaki [11].

In addition, we include the contribution of UV photons from decaying particles [8,9]. We assume that the particle \( \phi \) emits two photons with monochromatic energy of half the mass of that particle, i.e., \( E_\gamma = m_\phi/2 \). The number density of \( \phi \) particle is given by

\[
n_\phi = n_\phi(0)(1 + z)^3 e^{-t/\tau_\phi},
\]

where \( \tau_\phi \) is the lifetime of the \( \phi \) particle. Hydrogen atoms can be ionized if the emitted photons have energy with \( E_\gamma > 13.6 \) eV. Then the source term for the decaying particle can be written as

\[
\left( \frac{dn_\gamma}{dt} \right)_d = \frac{n_\phi}{\tau_\phi}.
\]

The amount of emitted photons is determined once the mass, \( m_\phi \), lifetime, \( \tau_\phi \), and abundance, \( \Omega_\phi \), of the particle are fixed. We calculate the ionization histories for \( E_\gamma = 15–1000 \) eV and \( \tau_\phi = 10^{14}–10^{18} \) s, adjusting the abundance, \( \Omega_\phi \), to get the optical depth in the range of \( \tau_{opt} = 0.075–0.2 \), which is defined by

\[
\tau_{opt} = \int_0^\infty dz \sigma_T \left( \frac{dt}{dz} \right) [n_e - n_e^{(sr)}],
\]

where \( \sigma_T \) is the Thomson cross section and \( n_e^{(sr)} \) is the electron number density for standard recombination. We subtract this term to estimate only the effect of reionization.

3. Cosmic microwave background radiation

As is well known, the temperature and polarization anisotropies of the CMB radiation could inform us of what happened during the dark age after recombination. We now look at whether ionization histories in the decaying particle scenario are consistent with CMB observation in the three-year WMAP data.

We obtain the power spectra by the code modified from CMBFAST [12] so as to equip us with the capability of using the evolution obtained for the ionization fraction and matter temperature, and evaluate \( \chi^2 \) using the code provided by WMAP [3]. We seek for the range \( E_\gamma = 15–1000 \) eV, \( \tau_\phi = 10^{14}–10^{18} \) s (with nine bins), and \( \tau_{opt} = 0.075–0.2 \) (with six bins). For fixed mass, lifetime, and optical depth, \( \chi^2 \) is calculated adjusting \( \Omega_b \).
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\( \Omega_m, H_0, n_s \), and the amplitude of the spectrum. We construct the contour of likelihood with grid based analysis, using \( \Delta \chi^2 = \chi^2 - \chi^2_{\text{best}} \), where \( \chi^2_{\text{best}} \) is the six-parameter \( \chi^2 \) minimum for \( \Lambda \text{CDM} \) with WMAP only.

Before going into the analyses with hybrid UV sources of stars and decaying particles, let us ask a question: Is it possible that the decaying particles alone could provide an ionization history consistent with SDSS and three-year WMAP? It is indeed possible to have an ionization history such that the ionization fraction rises rapidly at \( z \sim 6 \), which is consistent with SDSS observation. For example, this is realized with \( \tau_\phi = 9.5 \times 10^{17} \) s, \( \Omega_\phi = 1.2 \times 10^{-5} \), and \( m_\phi = 80 \) eV. However, the \( \chi^2 \) is about 4\( \sigma \) larger than that of the best-fit \( \Lambda \text{CDM} \) model. Of course, the optical depth has a very large value, such as 0.23. Thus, we can exclude this possibility.

We next consider another limiting case, that the ionization fraction becomes unity at \( z \sim 6 \) due to UV photons emitted from stars and quasars only, and there is no contribution from decaying particles, which leads to the optical depth \( \tau_{\text{op}} \approx 0.05 \). In this case, the \( \chi^2 \) is just outside the 1\( \sigma \) region. One may hope that the \( \chi^2 \) will be reduced once an extra contribution of UV photons from decaying particles is included. As we shall see below, however, this is not the case.

We show the likelihood contours for \( E_\gamma = 15, 100, \) and 1000 eV, in the top left, top right, and bottom panels, respectively, in figure 1. They look very similar to each other. Contrary to our expectation, there is no 1\( \sigma \) region. We can see that there is a weak dependence on the lifetime, and that the larger optical depth is not favoured.

It is wise to compare these with the contours for which only the temperature power spectrum is used for estimating the likelihood. We can then see that the \( \chi^2 \) does not depend on the lifetime \( \tau_\phi \) at all, as can be seen in figure 2 for \( E_\gamma = 100 \) eV. Moreover, there is a 1\( \sigma \) region: \( \tau_{\text{op}} \lesssim 0.13 \) (0.17) is allowed for the 68\% (90\%) confidence level. This is easy to understand, because the temperature power spectrum is dependent on only the value of the optical depth, and does not ‘see’ the actual ionization history. On the other hand, the polarization anisotropy in the CMB radiation discriminates among the different ionization histories. This is why we can see the dependence on the lifetime in figure 1, and the longer lifetime seems to be preferable.

Notice that lifetime longer than \( 10^{16} \) s for \( E_\gamma = 1 \) keV is excluded. This is because the flux of the photons exceeds the observed diffuse x-ray background [8], although the ionization history respects the Gunn–Peterson trough observed by SDSS.

We can thus obtain the allowed region for the decaying particle scenario in the parameter space \( (\tau_\phi, \Omega_\phi) \). We show each line with a 99\% confidence level in figure 3. For \( E_\gamma \lesssim 100 \) eV, longer lifetime is also allowed, until the abundance reaches the whole amount of the dark matter, since it is the ratio of \( n_\phi/\tau_\phi \) that determines the amount of emitted photons from the decaying particles for lifetime longer than the age of the universe. Among the decaying particles, saxion, the scalar partner of the axion, in the gauge-mediated supersymmetry breaking scenario, may be the best candidate. Its lifetime is about \( 10^{17} \) s for the saxion mass \( m_s \sim 100 \) eV and the axion decay constant \( F_{\text{PK}} \sim 10^{12} \) GeV. Since the saxion decays into photons through a one-loop diagram with branching ratio of order \( \sim 10^{-7} - 10^{-6} \), it matches the allowed region of the parameter space very well. Notice that these constraints apply to most kinds of decaying particles which emit photons with branching ratio \( B_\gamma \), provided that one regards the effective abundance as \( B_\gamma \Omega_\phi \).
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Figure 1. Likelihood contours of the decaying particle scenario with $E_\gamma = 15$ eV (top left), 100 eV (top right), and 1 keV (bottom). We show 90, 95, and 99% CL lines. Lifetime longer than $\sim 10^{16}$ s (shaded region) is excluded by diffuse x-ray background observation in the bottom panel.

Now let us move on to the detailed power spectra of temperature and polarization anisotropies in CMB. Temperature ($TT$), temperature–polarization ($TE$), and polarization ($EE$) power spectra are shown for optical depth in the range of $\tau_{op} = 0.075$–0.2 with fixed lifetime $\tau_\phi = 10^{17}$ s in figure 4. For the limiting case of the decaying particle scenario, we also plot the spectra without any contributions from decaying particles ($\tau_{op} \approx 0.05$). In addition, the one-step instantaneous reionization case ($\tau_{op} \approx 0.09$) is shown.

Since it is not easy to obtain some information only from the figures of the spectra, we give the breakdown of the $\chi^2$ in these cases in upper half of table 1. Here, we tabulate the difference of $\chi^2$ from the minimum case, $\Delta \chi^2$, defined above. Larger optical depth is disfavoured by all the components, which may be seen in all the spectra in figure 4. The case with $\tau_{op} \approx 0.01$ seems to be slightly favoured by the polarization data, which almost mimic the instantaneous reionization case in $TE$ spectra. However, the significance is not so great, and $TT$ data do not favour this case. Anyway, the total $\chi^2$ slightly favours smaller optical depth.

On the other hand, one can look for the dependence on the lifetime with fixed optical depth in figure 5 and the lower half of table 1. In this case, $TT$ data do not favour any
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Figure 2. Likelihood contours of the decaying particle scenario with $E_\gamma = 100$ eV, using only temperature anisotropy data. We show 68% and 90% CL lines.

Figure 3. Allowed region of the parameter space of the decaying particle scenario. The lines are drawn for the 99% CL contours in figure 1, which are thus the upper limits for the amount of the decaying particles, $\Omega_\phi$, for fixed lifetime $\tau_\phi$.

Table 1. $\Delta \chi^2$ for various optical depths for $\tau_\phi = 10^{17}$ s (upper), and for various lifetimes for $\tau_{\text{op}} \approx 0.1$ (lower). In the upper half, the last line represents for the case without contributions from decaying particles. $TT$, low $TT$, $TE$, and low pol. stand for the $TT$ power spectrum, pixel based $TT$ for low $\ell$, $TE$ power spectrum, and pixel based polarization for low $\ell$, respectively.

| $\tau_\phi$ | $\tau_{\text{op}}$ | $TT$ | Low $TT$ | $TE$ | Low pol. | Total |
|-------------|------------------|------|----------|------|----------|-------|
| $10^{17}$   | 0.199            | 3.34 | 1.48     | 1.68 | 6.62     | 13.13 |
| $10^{17}$   | 0.150            | 1.81 | 0.78     | 0.94 | 2.83     | 6.37  |
| $10^{17}$   | 0.100            | 1.06 | 0.10     | 0.33 | 1.60     | 3.10  |
| $10^{17}$   | 0.074            | −0.07| 0.03     | 0.76 | 1.93     | 2.66  |
| −           | 0.050            | −0.24| −0.23    | 0.44 | 2.44     | 2.42  |
| $10^{18}$   | 0.100            | 1.05 | 0.10     | 0.32 | 1.56     | 3.04  |
| $10^{17}$   | 0.100            | 1.06 | 0.10     | 0.33 | 1.60     | 3.10  |
| $10^{16}$   | 0.100            | 1.24 | 0.10     | 0.36 | 1.93     | 3.58  |
| $10^{15}$   | 0.101            | 1.16 | 0.01     | 1.42 | 2.65     | 5.25  |
| $10^{14}$   | 0.100            | 1.21 | −0.23    | 4.04 | 2.79     | 7.82  |
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Figure 4. TT (top left), TE (top right), and EE (bottom) power spectra of the CMB for $\tau_\phi = 10^{17}$ s with various optical depths. We also show the spectra for the limiting case of no decaying particle contribution, and the (one-step) instantaneous reionization. The three-year WMAP data are plotted as well.

lifetime, since the $TT$ power spectra are almost only sensitive to the value of the optical depth, not to the history of actual ionization. Short lifetime is severely disfavoured since it has large $\chi^2$ from the polarization data. This is not so apparent from the figures for either $TE$ or $EE$ power spectra, but it seems that larger power is needed in the low $\ell$ regions in order to fit the polarization data much better.

4. Conclusions

We have considered the ionizing UV photons emitted from decaying particles, in addition to the usual contributions of stars and quasars. The stars and quasars are responsible for the quick rise of the ionization fraction at $z \sim 6$ observed by SDSS as the Gunn–Peterson trough. On the other hand, the decaying particles cause partial ionization at $z > 6$.

The decaying particle scenario could explain the large optical depth, and was consistent with the first-year WMAP data. However, the three-year WMAP data do not favour the decaying particle scenario so much. Notice that our results apply to most kinds of decaying particles which emit photons with branching ratio $B_\gamma$, provided that one regards the effective abundance as $B_\gamma \Omega_\phi$. 
Figure 5. Power spectra of $TT$ (top left), $TE$ (top right), and $EE$ (bottom) of CMB for $\tau_{\text{op}} = 0.1$ with various lifetimes. Also shown are the spectra for the (one-step) instantaneous reionization, and the three-year WMAP data.

The ionization by the decaying particles with $\tau_{\text{op}} \lesssim 0.17$ does indeed seem to be consistent within 2$\sigma$ with the $TT$ power spectrum. The peculiar aspect of the three-year WMAP data is in the polarization; in particular, the polarization data do not allow the earlier reionization which is a distinct feature of the ionization history from the UV emission from particle decays, and hence the longer lifetime is favoured. Since more power at low $\ell$ is favoured by the polarization anisotropy, one may ambitiously claim that a better fit may be obtained for the decaying particle scenario with increasing decay rate.

Acknowledgments

SK is grateful to Kazuhide Ichikawa for useful discussions. The work of SK is supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture of Japan, No 17740156.

References

[1] Fan X et al, 2002 Astron. J. 123 1247 [SPIRES]
[2] Kogut A et al, 2003 Astrophys. J. Suppl. 148 161
Spergel D N et al, 2003 Astrophys. J. Suppl. 148 175
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[3] Spergel D N et al, 2006 Preprint astro-ph/0603449
Page L et al, 2006 Preprint astro-ph/0603450
Hinshaw G et al, 2006 Preprint astro-ph/0603451
Jarosik N et al, 2006 Preprint astro-ph/0603452

[4] Loeb A and Barkana R, 2001 Ann. Rev. Astron. Astrophys. 39 19 [SPIRES]

[5] Chiu W A, Fan X and Ostriker J P, 2003 Astrophys. J. 599 759 [SPIRES]
Onken C A and Miralda-Escudé J, 2004 Astrophys. J. 610 1 [SPIRES]

[6] Fukugita M and Kawasaki M, 2003 Mon. Not. R. Astron. Soc. 343 L25
Ciardi B, Ferrara A and White S D M, 2003 Mon. Not. R. Astron. Soc. 344 L7
Chen X L, Cooray A, Yoshida N and Sugiyama N, 2003 Mon. Not. R. Astron. Soc. 346 L31

[7] Cen R, 2003 Astrophys. J. 591 12 [SPIRES]
Hui L and Haiman Z, 2003 Astrophys. J. 596 9 [SPIRES]
Sokasian A, Abel T, Hernquist L and Springel V, 2003 Mon. Not. R. Astron. Soc. 344 607
Sokasian A, Yoshida N, Abel T, Hernquist L and Springel V, 2004 Mon. Not. R. Astron. Soc. 350 47
Benson A J, Sugiyama N, Nusser A and Lacey C G, 2005 Preprint astro-ph/0512364

[8] Kasuya S, Kawasaki M and Sugiyama N, 2004 Phys. Rev. D 69 023512 [SPIRES]

[9] Kasuya S and Kawasaki M, 2004 Phys. Rev. D 70 103519 [SPIRES]

[10] Hansen S H and Haiman Z, 2004 Astrophys. J. 600 26 [SPIRES]
Chen X L and Kamionkowski M, 2004 Phys. Rev. D 70 043502 [SPIRES]
Avelino P P and Barbosa D, 2004 Phys. Rev. D 70 067302 [SPIRES]
Biermann P L and Kusenko A, 2006 Phys. Rev. Lett. 96 091301 [SPIRES]
Mapelli M, Ferrara A and Pierpaoli E, 2006 Mon. Not. R. Astron. Soc. 369 1719
Zhang L, Chen X L, Lei Y A and Si Z G, 2006 Preprint astro-ph/0603425
Shechkinov Y A and Vasiliev E O, 2006 Preprint astro-ph/0604231

[11] Fukugita M and Kawasaki M, 1994 Mon. Not. R. Astron. Soc. 269 563

[12] Seljak U and Zaldarriaga M, 1996 Astrophys. J. 469 437 [SPIRES]