

Cosmic Microwave Background from Late-Decaying Scalar Condensations*

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Abstract

We study the cosmic microwave background (CMB) anisotropy in the scenario with late-decaying scalar condensations which arise in many class of cosmological scenarios based on supersymmetric models. With such a scalar condensation ϕ , the CMB radiation we observe today originates to ϕ and hence the CMB anisotropy is affected if ϕ has a primordial fluctuation. In particular, if all the components in the universe (i.e., radiation, baryon, cold dark matter, and so on) are generated from the decay product of ϕ , the dominant source of the cosmic density perturbations can be the primordial fluctuation of ϕ , not the fluctuation of the inflaton field. In this case, the constraints on the inflation models can be drastically relaxed. In other case, the baryon or the CDM may not be from the decay product of ϕ and correlated mixture of the adiabatic and isocurvature fluctuations can be generated. If so, the CMB angular power spectrum may not be the same as the adiabatic result and the on-going MAP experiment may observe a deviation from the prediction of the standard inflationary scenario.

*Talk given by T. Moroi.

In supersymmetric models, it is known that there are various light scalar fields which play important roles in cosmology. In particular, in many class of scenarios, there exists a scalar field (other than the inflaton) which once dominates the universe and decays at a later stage of the evolution of the universe. Indeed, this is the case in, for example, Affleck-Dine baryogenesis [1] and sneutrino-induced leptogenesis [2]. In addition, if the modulus field acquires a large amplitude at the beginning of the universe, it is expected to decay after the big-bang nucleosynthesis (BBN) and spoils the success of the BBN if their masses are of $O(100 \text{ GeV} - 1 \text{ TeV})$ [3]. One solution to this cosmological difficulty is to push up the mass of the modulus field and make it decay before the BBN starts [4]. Although these scenarios have been attracted many attentions, it is very difficult to observe the consequence of the late-decaying scalar condensations.

One of the most important consequences of such scenarios is that the cosmic microwave background (CMB) radiation we observe today originates to the late-decaying scalar field (denoted as ϕ hereafter) rather than the inflaton field. Thus, if there exists a primordial fluctuation in the amplitude of ϕ , it becomes a new source of the cosmic density perturbations and affects the CMB anisotropy. In particular, recently the observation of the CMB power spectrum is being greatly improved and hence it may be possible to observe some signal in the CMB anisotropy from the late-decaying scalar condensations. Thus, it is very important to discuss the CMB anisotropy taking account of the effects of the late-decaying scalar condensations, which is the subject of the study here. We will see that, if the scalar condensation acquires a primordial fluctuation, it may significantly affect the CMB angular power spectrum. In particular, we will emphasize that the conventional constraints on the inflation models can be greatly relaxed if such a scalar field exists. In addition, in some case, correlated mixture of the adiabatic and isocurvature density fluctuations can be generated in such a scenario and the on-going MAP [5] experiment may observe the signal of the late-decaying scalar condensations.

Let us start our discussion with introducing the scenario we have in mind. Here, we consider the thermal history with a scalar field ϕ which decays and produces a large amount of entropy at a late stage of the evolution of the universe. In this study, we assume inflation to solve horizon, flatness, and other cosmological problems. Then, after the inflation, the universe is reheated and the radiation dominated universe is realized. We call this epoch as the RD1 epoch.

If the potential of ϕ is dominated by the parabolic term, ϕ changes its behavior depending on the relative size of H and m_ϕ , where m_ϕ is the mass of ϕ and H is the expansion rate of the universe. In the very early universe, the total energy density of the universe is extremely large and hence the relation $H \gg m_\phi$ holds. In this case, the slow-roll condition is satisfied and ϕ takes (almost) constant value. On the contrary, as the universe expands, H becomes smaller than m_ϕ at some point. Then, ϕ oscillates and the energy density of ϕ decrease as $\rho_\phi \propto a^{-3}$. Consequently, the energy density of the radiation decreases faster than ρ_ϕ if $H \lesssim m_\phi$. Thus, if the initial amplitude of the scalar field, denoted as ϕ_{init} , is large enough, the universe is once dominated by the scalar field ϕ after the RD1 epoch. (We call this epoch as ϕ D epoch.) In the following, we assume that ϕ_{init} is large enough so that the ϕ D epoch is realized. Then, ϕ decays when $H \sim \Gamma_\phi$ with Γ_ϕ being the decay rate of ϕ . After the decay of ϕ , the radiation-dominated universe is realized. We call this epoch as RD2 epoch.

In this framework, the CMB radiation we observe today originates to the scalar field ϕ , not to the inflaton field. Thus, if ϕ has an primordial fluctuation, it also affects the CMB anisotropy. Such a fluctuation is expected to be generated during the inflation; for the Fourier mode with comoving momentum k , the initial value of the fluctuation of ϕ is given by $\delta\phi(t, \vec{k}) = [H_{\text{inf}}/2\pi]_{k=aH_{\text{inf}}}$, where H_{inf} is the expansion rate of the universe during the inflation. (Here, we assumed $m_\phi \ll H_{\text{inf}}$.)

In this class of scenario, there are two independent sources of the cosmic density perturbations; one is the primordial fluctuation of the inflaton field χ and the other is the primordial fluctuation of the scalar field. Since we use the linear perturbation theory, their effects can be discussed separately. The effect of the inflaton-field fluctuation $\delta\chi$ is parameterized by the metric perturbation $\Psi^{(\delta\chi)}$ generated by the inflaton fluctuation. (The superscript $(\delta\chi)$ is for perturbations from the inflaton fluctuation.) It is well-known that inflaton fluctuation provides the adiabatic density fluctuations, i.e., no entropy perturbation is generated from $\delta\chi$. Thus, in the following, we study the effects of the primordial fluctuation of the scalar field ϕ .

Since we are interested in the CMB anisotropy, it is crucial to understand the relations among the density fluctuations of each components, like photon, CDM, baryon, and so on, after the decay of the scalar field ϕ . For this purpose, we define the perturbed line element (in the Newtonian gauge) as

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)\delta_{ij}dx^i dx^j. \quad (1)$$

In addition, from the density fluctuations of each components in the Newtonian gauge, we define

$$\delta_X = \delta\rho_X/\rho_X, \quad (2)$$

where $X = r, c$, and b , corresponding to radiation,^{#1} CDM, and baryon, respectively.

To parameterize the density fluctuations of each components after the decay of ϕ , it is convenient to consider the “entropy” between the ϕ field and the components generated from the decay product of the inflaton field before the decay of ϕ :

$$S_{\phi\chi}^{(\delta\phi)}(k) = \frac{\delta\rho_\phi(t, k)}{\rho_\phi(t)} - \delta_\chi(t) = \frac{2\delta\phi_{\text{init}}(k)}{\phi_{\text{init}}}, \quad (3)$$

where $\delta\phi_{\text{init}}$ is the initial fluctuation of ϕ and the superscript “ $(\delta\phi)$ ” is for perturbations generated from the primordial fluctuation of ϕ .

Density (and other) fluctuations in the RD2 epoch are generally parameterized by using $S_{\phi\chi}^{(\delta\phi)}$. If a component X is generated from the decay product of ϕ , then there is no entropy between the photon and X . On the contrary, if the component X has some source other than ϕ , the entropy between the photon and X is the same as $S_{\phi\chi}^{(\delta\phi)}$. Thus, if all the components in the universe are generated from ϕ , the density fluctuations become purely adiabatic and

$$\left[\delta_\gamma^{(\delta\phi)}\right]_{\text{RD2}} = \frac{4}{3} \left[\delta_b^{(\delta\phi)}\right]_{\text{RD2}} = \frac{4}{3} \left[\delta_c^{(\delta\phi)}\right]_{\text{RD2}} = -2\Psi_{\text{RD2}}^{(\delta\phi)}, \quad (4)$$

^{#1}We assume that there is no entropy between the photon and the neutrinos.

where the subscripts γ , b , and c are for the photon, baryon, and CDM, respectively. In this case, the isocurvature perturbation in the ϕ field is converted to the purely adiabatic density perturbation after the decay of ϕ [6, 7, 8]. On the contrary, if the baryon asymmetry does not originate to the decay product of ϕ , the entropy between the radiation and the baryon becomes $S_{\phi\chi}^{(\delta\phi)}$ and hence [6]

$$[\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} = \frac{4}{3} [\delta_c^{(\delta\phi)}]_{\text{RD2}} = -2\Psi_{\text{RD2}}^{(\delta\phi)}, \quad [\delta_b^{(\delta\phi)}]_{\text{RD2}} = \frac{3}{4} [\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} + \frac{9}{2}\Psi_{\text{RD2}}^{(\delta\phi)}, \quad (5)$$

and in the case where all the components other the CDM are generated from the decay product of ϕ ,

$$[\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} = \frac{4}{3} [\delta_b^{(\delta\phi)}]_{\text{RD2}} = -2\Psi_{\text{RD2}}^{(\delta\phi)}, \quad [\delta_c^{(\delta\phi)}]_{\text{RD2}} = \frac{3}{4} [\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} + \frac{9}{2}\Psi_{\text{RD2}}^{(\delta\phi)}. \quad (6)$$

In addition, if the baryon and the CDM are both generated from sources other than ϕ , we obtain

$$[\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} = -2\Psi_{\text{RD2}}^{(\delta\phi)}, \quad [\delta_b^{(\delta\phi)}]_{\text{RD2}} = [\delta_c^{(\delta\phi)}]_{\text{RD2}} = \frac{3}{4} [\delta_{\gamma}^{(\delta\phi)}]_{\text{RD2}} + \frac{9}{2}\Psi_{\text{RD2}}^{(\delta\phi)}. \quad (7)$$

It is important to notice that, for the cases given in Eqs. (5) – (7), the entropy perturbations are correlated with the adiabatic perturbation.^{#2}

Now, we are at the point to discuss the CMB anisotropy. The CMB anisotropy is characterized by the angular power spectrum C_l which is defined as

$$\langle \Delta T(\vec{x}, \vec{\gamma}) \Delta T(\vec{x}, \vec{\gamma}') \rangle_{\vec{x}} = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\vec{\gamma} \cdot \vec{\gamma}'), \quad (8)$$

with $\Delta T(\vec{x}, \vec{\gamma})$ being the temperature fluctuation of the CMB radiation pointing to the direction $\vec{\gamma}$ at the position \vec{x} and P_l is the Legendre polynomial. As we mentioned, there are two sources of the density perturbations; the primordial fluctuations of the scalar fields χ and ϕ . Since there is no correlation between these fields, the CMB anisotropies from these fluctuations are uncorrelated and the resultant CMB power spectrum is given in the form

$$C_l = C_l^{(\delta\chi)} + C_l^{(\delta\phi)}, \quad (9)$$

where $C_l^{(\delta\chi)}$ and $C_l^{(\delta\phi)}$ are contributions from the primordial fluctuations of the inflaton field χ and the ϕ field, respectively. The inflaton contribution $C_l^{(\delta\chi)}$ is known to be the adiabatic result.

The new contribution $C_l^{(\delta\phi)}$ depends on the properties of the density perturbations of each components. If all the components in the universe (i.e., the photon, baryon, CDM, neutrino, and so on) are dominantly generated from the decay product of ϕ , there is no entropy between any of two components. In this case, $C_l^{(\delta\phi)}$ is from adiabatic

^{#2}Here, we assumed that the baryon number asymmetry and/or the CDM is generated before the ϕ field starts to oscillate. In other case, the size of the correlated entropy perturbation may change. For details, see [6].

perturbations. This fact has an important implication. In general, the scale dependences of $\Psi^{(\delta\chi)}$ and $S_{\phi\chi}^{(\delta\phi)}$ are different. In the slow-roll inflation scenario, $\Psi^{(\delta\chi)}$ is given by [9]

$$\Psi_{\text{RD2}}^{(\delta\chi)} = \frac{4}{9} \left[\frac{H_{\text{inf}}}{2\pi} \frac{3H_{\text{inf}}^2}{V'_{\text{inf}}} \right]_{k=aH_{\text{inf}}}, \quad (10)$$

where $V'_{\text{inf}} \equiv \partial V_{\text{inf}}/\partial\chi$ with V_{inf} being the inflaton potential. On the contrary, $S_{\phi\chi}^{(\delta\phi)}$ is related to the fluctuation of the amplitude of ϕ , as seen in Eq. (3), and hence

$$S_{\phi\chi}^{(\delta\phi)} = \frac{2}{\phi_{\text{init}}} \left[\frac{H_{\text{inf}}}{2\pi} \right]_{k=aH_{\text{inf}}}. \quad (11)$$

In many models of slow-roll inflation, the expansion rate H_{inf} is almost constant during the inflation. On the contrary, the slope of the inflation potential V'_{inf} may significantly vary. As a result, $S_{\phi\chi}^{(\delta\phi)}$ becomes (almost) scale independent while $\Psi^{(\delta\chi)}$ may have significant scale dependence. Since the currently measured CMB power spectrum suggests (almost) scale invariant primordial density perturbation in the conventional scenario, inflation models are excluded if $\Psi^{(\delta\chi)}$ has too strong scale dependence [10].

If the ϕ field exists, however, the situation may change [6]. Since $S_{\phi\chi}^{(\delta\phi)}$ is expected to be (almost) scale invariant, we can relax the constraint on the inflation models if $C_l^{(\delta\phi)}$ becomes significantly large, which happens when $S_{\phi\chi}^{(\delta\phi)} \gtrsim \Psi^{(\delta\chi)}$. As shown in Eq. (3), $S_{\phi\chi}^{(\delta\phi)}$ is inversely proportional to ϕ_{init} . Thus, if the initial amplitude of ϕ is small, this may happen and the CMB power spectrum may become consistent with the observational data in a larger class of models of inflation.

Now, we study effects of the correlated entropy fluctuations. We first plot the angular power spectrum with the correlated mixture of the adiabatic and isocurvature perturbations in the baryonic and/or CDM sector, i.e., the cases with the relations given in Eqs. (5) – (7). For comparison, we also plot the angular power spectrum for the purely adiabatic and isocurvature cases. As one can see, the CMB angular power spectrum strongly depends on properties of the primordial density perturbations. If there exists correlated entropy between the baryon and other components with the relation (5), negative interference between the adiabatic and isocurvature perturbations suppresses C_l at lower multipole while the effect of the isocurvature perturbation becomes too small to affect the structure at high multipole. As a result, the angular power spectrum is enhanced at the high multipole rather than at the low multipole. If the effect of the entropy perturbation becomes more efficient, then $C_l^{(\delta\phi)}$ at high multipole is suppressed relative to that at low multipole like in the purely isocurvature case. This happens when the entropy perturbation is in the CDM component with the condition given in Eq. (6). In addition, with the relation given in Eq. (7), the correlated entropy becomes more effective than the case where only the CDM sector has the correlated entropy. Then, the acoustic peaks are more suppressed relative to the Sachs-Wolfe (SW) tail.

As mentioned before, the actual CMB angular power spectrum is given by the sum of the inflaton contribution $C_l^{(\delta\chi)}$ and the contribution from the primordial fluctuation of the late-decaying scalar field $C_l^{(\delta\phi)}$. (See Eq. (9).) To parameterize their relative size, we define

$$R_b \equiv S_{b\gamma}^{(\delta\phi)}/\Psi_{\text{RD2}}^{(\delta\chi)}, \quad R_c \equiv S_{c\gamma}^{(\delta\phi)}/\Psi_{\text{RD2}}^{(\delta\chi)}, \quad (12)$$

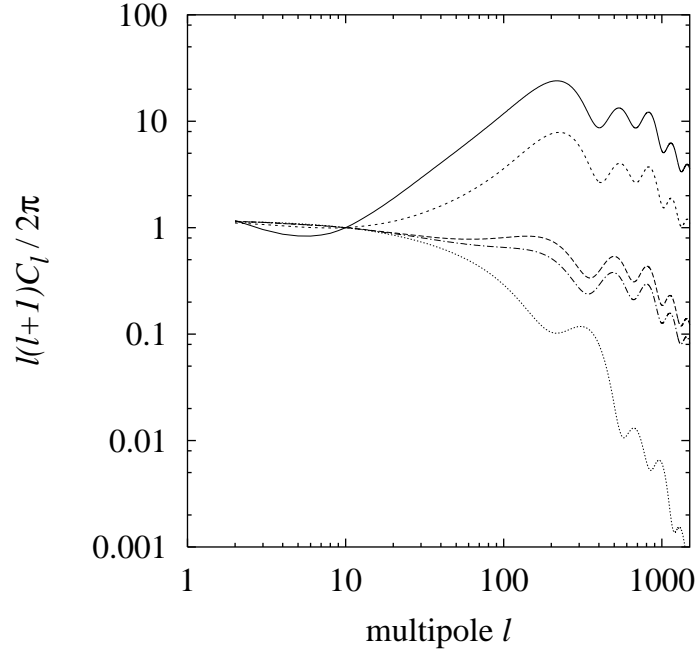


Figure 1: The angular power spectrum with correlated mixture of the adiabatic and isocurvature perturbations in the baryonic sector (solid line), in the CDM sector (long-dashed line), and in the baryonic and CDM sectors (dot-dashed line). (See Eqs. (5), (6), and (7), respectively.) We also show the CMB angular power spectrum in the purely adiabatic (short-dashed line) and isocurvature density perturbations (dotted line). We consider the flat universe with $\Omega_b h^2 = 0.019$, $\Omega_m = 0.3$, and $h = 0.65$, where Ω_b and Ω_c are the (present) density parameters for the baryon and the CDM, respectively, and h is the Hubble constant in units of 100 km/sec/Mpc. The overall normalizations are taken as $[l(l+1)C_l/2\pi]_{l=10} = 1$.

where $S_{b\gamma}^{(\delta\phi)}$ ($S_{c\gamma}^{(\delta\phi)}$) is the entropy between the baryon and the photon (between the CDM and the photon) generated from the primordial fluctuation of ϕ . (We adopt Eqs. (5) and (6), and hence $S_{b\gamma}^{(\delta\phi)}$ and $S_{c\gamma}^{(\delta\phi)}$ are equal to $\frac{9}{2}\Psi_{\text{RD2}}^{(\delta\phi)}$ if they are non-vanishing.) The shape of the CMB angular power spectrum depends on the values of these parameters.

Using Eqs. (10) and (11), the R -parameters are given as

$$R_{b,c} = \frac{3}{2} \left[\frac{V'_{\text{inf}}}{\phi_{\text{init}} H_{\text{inf}}^2} \right]_{k=aH_{\text{inf}}} . \quad (13)$$

Hence $R_{b,c}$ is model- and scenario-dependent; it depends on the scale of inflation, shape of the inflaton potential, and initial amplitude of ϕ . For example in the chaotic inflation model with the parabolic potential $V_{\text{inf}} = \frac{1}{2}m_\chi^2\chi^2$, the above expression becomes

$$[R_{b,c}]_{\text{chaotic}} = \left[\frac{9M_*^2}{\phi_{\text{init}}\chi} \right]_{k=aH_{\text{inf}}} . \quad (14)$$

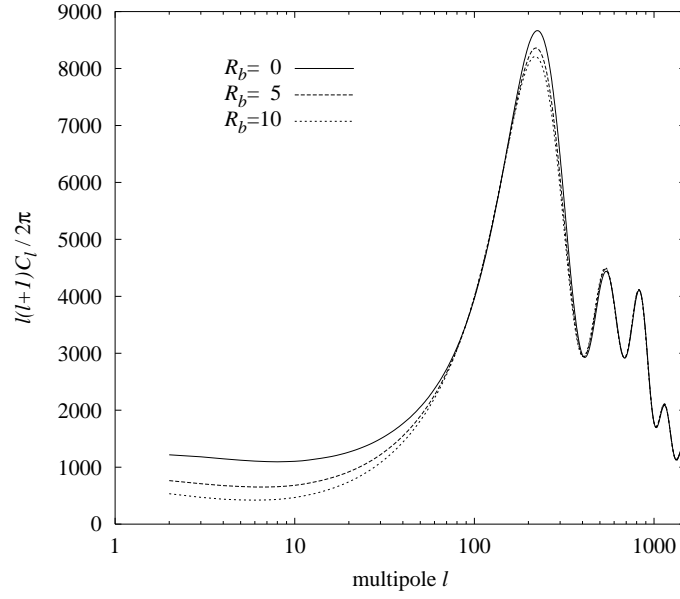


Figure 2: The CMB angular power spectrum for the case of $\alpha_b = 0$. Here we take $R_b = 0$ (solid line), 5 (long-dashed line) and 10 (short-dashed line). The cosmological parameters are the same as those in Fig. 1. The overall normalizations are arbitrary.

Using the fact that the inflaton amplitude at the time of the horizon crossing of the COBE scale is $\chi \simeq 15M_*$ in the chaotic inflation model, $[R_{b,c}]_{\text{chaotic}} \simeq 0.6M_*/\phi_{\text{init}}$. Of course, the values of R_b and R_c depend on the model of inflation, and they vary if we consider different class of inflation models.

In Fig. 2, we plot the resultant angular power spectrum with several values of R_b . As expected, C_l at the high multipole is more enhanced relative to that at low ones as the R_b -parameter increases. It is important to note that the effect of the uncorrelated entropy fluctuation always suppresses C_l at high multipole relative to that at low multipole. Thus, if the on-going experiments, like MAP [5], observes the enhancement of the C_l at high multipole, it can be regarded as a unique signal of the late-decaying scalar condensation. In fact, if the R_b -parameter is too large, the angular power spectrum at high multipole is too much enhanced, which becomes inconsistent with the currently available data. We checked that $R_b \geq 4.5$ is excluded at 95 % C.L. even adopting the most conservative constraint.

We also studied the effects the correlated entropy perturbation in the CDM. If R_c is non-vanishing, C_l at high multiple is suppressed compared to the SW tails. Thus, too large R_c is also excluded from the current data of the observations of the CMB power spectrum; R_c is constrained to be smaller than 2.0 for $R_b = 0$.

In summary, we have discussed the effects of the late-time entropy production due to the decay of the scalar-field condensations on the cosmic density perturbations. If the universe is reheated by the decay of the scalar field ϕ , many of the components in the present universe are generated from the decay products of the ϕ field. In such a case, cosmic density perturbations are affected by the primordial fluctuation of ϕ which may

be generated during the inflation.

If all the components in the universe originate to the decay product of ϕ , density perturbations generated from the primordial fluctuation of ϕ becomes adiabatic. In this case, the CMB angular power spectrum from the fluctuation of ϕ becomes the usual adiabatic ones with (almost) scale-invariant spectrum. If this becomes the dominant part of the cosmic density perturbations, then we have seen that the constraints on inflation models from observations of the CMB angular power spectrum are drastically relaxed [6].

If the baryon or the CDM is not generated from ϕ , on the contrary, correlated mixture of the adiabatic and isocurvature perturbations may arise. In this case, the CMB angular power spectrum may be significantly affected and the shape of the resultant power spectrum depends on which component has the correlated isocurvature perturbation. In particular, if the baryonic component has the correlated isocurvature perturbation, C_l at high multipole is more enhanced relative to that at low multipole, which may be observed by the MAP experiment and regarded as a unique signal of the late-time entropy production.

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