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D-term inflation and nonperturbative Kähler potential of dilaton

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Abstract: We study the D-term inflation scenario with a nonperturbative Kähler potential of the dilaton field. Although the FI term which leads an inflationary expansion is given by the derivative of the Kähler potential with respect to the dilaton in heterotic string models with anomalous U(1), the too large magnitude is problematic for a viable D-term inflation. In this paper, we point out that the Kähler potential with a nonperturbative term can reduce the magnitude of FI term to desired values while both the dilaton stabilization and D-term domination in the potential are realized by nonperturbative superpotential.

Keywords: Cosmology of Theories beyond the SM, Superstrings and Heterotic Strings.

Within the framework of supergravity theory, scalar fields, including an inflaton field, generally gain the Hubble-induced masses during inflation, if the potential energy is dominated by F-terms. Violation of the slow-roll condition by these mass terms is known as the η-problem. From this viewpoint, the D-term inflation is an attractive scenario, because the inflaton field does not gain such a large mass if the D-term is dominant during inflation [1]–[3]. The Fayet-Iliopoulos (FI) term plays a role as the potential energy in D-term inflation models.

The FI term is generated through anomalous U(1) symmetries in four-dimensional string models. Indeed, most of four-dimensional string models have anomalous U(1)'s for both heterotic string models [4, 5] and type I string models [6]. These anomalies can be cancelled by the Green-Schwarz (GS) mechanism [7], where certain fields transform nonlinearly under anomalous U(1) symmetries. In heterotic string models, the gauge kinetic function f is obtained by the dilaton field S as

$$f = S\,, \tag{1}$$

up to Kac-Moody levels, that is, the gauge coupling g is determined by the vacuum expectation value (VEV) of S as $1/g^2 = \langle \mathrm{Re}(S) \rangle$. Under the anomalous U(1) transformation, the dilaton field S transforms nonlinearly as $S \to S + i\delta_{GS}\theta(x)$, where $\theta(x)$ is a parameter of the anomalous U(1) transformation and the anomaly coefficient δ_{GS} is obtained as[1]

$$\delta_{GS} = \frac{1}{192\pi^2}\,\mathrm{Tr}(Q)\,, \tag{2}$$

with the summation of anomalous U(1) charges, $\mathrm{Tr}(Q)$. That generates the dilaton-dependent FI term

$$\xi = \delta_{GS} K_S\,, \tag{3}$$

in the unit of $M_P = 1$, where K_S is the first derivative of the Kälher potential K with respect to S and M_P denotes the reduced Planck scale. Hereafter we use the unit $M_P = 1$.

Thus, it seems possible to embed the D-term inflation scenario in string models. However, we have problems.[2] One of problems is due to the fact that the FI term ξ and anomalous U(1) gauge coupling g depend on S. The tree-level Kähler potential of S is obtained as

$$K_0(S+\bar{S}) = -\ln(S+\bar{S})\,. \tag{4}$$

With this form of the Kähler potential, the D-term scalar potential V_D during inflation behaves $V_D = g^2\xi^2/2 \sim (S+\bar{S})^{-3}$. Only with this term, the dilaton rolls down rapidly the potential to infinity, $\mathrm{Re}(S) \to \infty$, and the potential energy goes to zero, $V_D \to 0$. The slow roll condition or the D-term inflation can not be realized. Therefore, the first problem is how to stabilize the dilaton field during inflation. For example, the dilaton can be stabilized by adding the F-term scalar potential due to dilaton-dependent nonperturbative superpotential terms [9].[3]

[1] In type I models, twisted moduli fields transform nonlinearly under anomalous U(1) symmetries.

[2] See also for recent works ref. [8] and references therein.

[3] Similarly, in the D-term inflation of type I models, one can stabilize twisted moduli, which determine FI terms [10].

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The second problem is concerned about the magnitude of ξ. The GS coefficient δ_{GS} is model-dependent, and explicit models lead to $\delta_{GS} = O(10^{-1}) - O(10^{-4})$ [5]. On the other hand, the magnitude of the anisotropy of the cosmic microwave background (CMB) requires $\xi^{1/2} \leq O(10^{15} - 10^{16})$ GeV [3]. Thus, explicit heterotic string models seem to have much larger value of the FI term ξ. Until now, just a few models leading to effectively small ξ have been studied [11, 12], this seems still an open question. Another way out of this problem is to consider D-term inflation in type I string models [10, 13].

Another problem is the generation of cosmic strings in the true vacuum after inflation. Its string tension is estimated as the FI term ξ in the true vacuum. If $\xi^{1/2} = O(10^{15} - 10^{16})$ GeV in the true vacuum, cosmic strings besides inflaton lead to the density perturbation, which is not consistent with the CMB observation [3, 14, 15].

Here we will study these problems in models with nonperturbative Kähler potential of the dilaton field, in particular, the stabilization problem and how to reduce the magnitude of the FI term. In the true vacuum, the dilaton stabilization has been studied in models with its nonperturbative Kähler potential in refs. [17]–[22]. In particular, in ref. [22] it has been shown that one can stabilize S with nonperturbative Kähler potential in the true vacuum such that $\mathrm{Re}(S) = O(1)$ and K_S is suppressed. That corresponds to a suppressed value of ξ. Thus, here we investigate the possibility for stabilizing S such that K_S and ξ are suppressed during inflation. We will also comment on the cosmic strings.

First, let us review briefly on the D-term inflation [2, 3]. We consider a simple model with U(1) gauge symmetry and the non-vanishing FI term ξ. This model includes three matter fields, X and $\phi_\pm$, and $\phi_\pm$ have U(1) charges ± 1 and X has no U(1) charge. The U(1) D-term is written as

$$D = \xi + |\phi_+|^2 - |\phi_-|^2 \,. \tag{5}$$

Here we take the charge normalization such that $\xi > 0$. In addition, we assume the following superpotential,

$$W = \lambda X \phi_+ \phi_- \,. \tag{6}$$

Then, the scalar potential is written as

$$\begin{aligned} V &= \sum_i |\partial_i W|^2 + \frac{g^2}{2} D^2 \,, &(7)\\ &= \lambda^2 |X|^2 (|\phi_+|^2 + |\phi_-|^2) + \lambda^2 |\phi_+ \phi_-|^2 + \frac{g^2}{2} (\xi + |\phi_+|^2 - |\phi_-|^2)^2 \,. &(8) \end{aligned}$$

The true vacuum corresponds to

$$X = \phi_+ = 0 \,, \qquad |\phi_-|^2 = \xi \,. \tag{9}$$

In order to analyze the minimum of V for a value of X fixed, we define X_c,

$$X_c \equiv \frac{g}{\lambda} \sqrt{\xi} \,. \tag{10}$$

For $|X| < X_c$, the minimum corresponds to

$$|\phi_-|^2 = \xi - \frac{\lambda^2}{g^2} |X|^2 , \qquad \phi_+ = 0 \,. \tag{11}$$

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On the other hand, for $|X| > X_c$, the minimum corresponds to

$$\phi_\pm = 0\,. \tag{12}$$

In the latter case, the potential energy is obtained as

$$V = \frac{g^2}{2}\xi^2\,, \tag{13}$$

and drives the inflationary expansion of the Universe, where the radial part of X is identified with the inflaton. At the tree level, the inflaton X has the flat potential. The supersymmetry (SUSY) is broken during inflation because of the non-vanishing D-term and the scalar components of $\phi_\pm$ have masses squared,

$$m_\pm^2 = \lambda^2|X|^2 \pm g^2\xi\,. \tag{14}$$

Here the second term is the SUSY breaking mass squared by non-vanishing D-term, while the first term is the supersymmetric mass squared, which fermionic partners also have. These mass splitting generates the one-loop effective potential,

$$V_{1-\mathrm{loop}} = \frac{g^2}{2}\xi^2\left(1 + \frac{g^2}{16\pi^2}\ln\frac{\lambda^2|X|^2}{\Lambda^2}\right), \tag{15}$$

where Λ is the renormalization scale. Thus, the potential for X is slightly lifted, and the inflaton X slowly rolls down the potential. The inflation ends when X reaches at X_c or X_f,

$$|X_f|^2 \equiv \frac{g^2}{8\pi^2}M_p^2\,, \tag{16}$$

where the slow roll condition is violated.

Next, let us consider the D-term inflation scenario from the viewpoint of 4D effective theory of string theory. Here, we use the tree-level Kähler potential (4) and the gauge kinetic function (1). Since the FI term and the gauge coupling are replaced with S-dependent FI term (3) and $g^2 = 2/(S+\bar{S})$ respectively, the scalar potential during inflation (13) is rewritten as

$$\begin{aligned} V &= \frac{(\delta_{GS}K_S)^2}{S+\bar{S}} && (17)\\ &= \frac{\delta_{GS}^2}{(S+\bar{S})^3}\,. && (18)\end{aligned}$$

Now, two problems we mentioned above become clear. The first one is that only with this potential the dilaton rapidly runs away to infinity, $\mathrm{Re}(S) \to \infty$, and the inflation can not be realized. In ref. [9], the dilaton stabilization has been studied by adding the F-term scalar potential generated by gaugino condensation as well as non-vanishing flux of the antisymmetric tensor field $B_{\mu\nu}$. The second problem is that the scale of the potential energy is too high to produce the density perturbation with an appropriate magnitude as long as $\mathrm{Re}(S) = O(1)$ and $\delta_{GS} = O(10^{-1}) - O(10^{-4})$. These problems will be studied in our models with nonperturbative Kähler potential.

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In ref. [22], the possibility for suppressing K_S has been studied by taking account of nonperturbative effects on Kähler potential. Actually, if we have additional terms in the Kähler potential K other than the tree-level term K_0, the potential minimum of eq. (17) can correspond to the point[4] $K_S = 0$. However, that implies vanishing FI term and that is not good, because we can not realize the D-term inflation. We need another contribution to lead to a suppressed, but non-vanishing value of K_S. Hence we will consider models with nonperturbative corrections and study the dilaton stabilization in order to lead to a suppressed, but non-vanishing FI term.

The Kähler potential must also have the perturbative correction K_p. We expect [23]

$$K_p(S+\bar{S}) = \frac{a}{S+\bar{S}} + \cdots \,, \tag{19}$$

with $a = O(1/8\pi^2)$, because of $\langle K_p/K_0\rangle = O(g^2/16\pi^2)$. We consider the case with $\mathrm{Re}(S) = O(1)$. Hence, it is expected that the perturbative correction would be irrelevant. For the moment, we neglect K_p, but we will consider its effects after examining explicit models.

Nonperturbative effects in the Kähler potential are still unknown. Following refs. [16, 17], we use the following Ansatz for the nonperturbative term,

$$K_{np}(S+\bar{S}) = d(S+\bar{S})^{p/2}e^{-b(S+\bar{S})^{1/2}} \,, \tag{20}$$

where $p, b > 0$. We also include the over-all moduli field T. Then, the total Kähler potential is written as

$$K = K_0(S+\bar{S}) + K_{np}(S+\bar{S}) - 3\ln(T+\bar{T}) + K_{X\bar{X}}|X|^2 + \cdots \,, \tag{21}$$

where the fourth term in the right hand side is the Kähler potential of X. Only with this Kähler potential, the scalar potential during inflation is written as $V = (\delta_{GS}K_S)^2/(S+\bar{S})$. Its minimum corresponds to $K_S = 0$ other than the runaway vacuum, that is, we can not obtain a finite vacuum energy deriving the inflation. Hence, another contribution is necessary to realize the dilaton stabilization leading to a suppressed, but finite value of K_S.

As a such contribution, here we assume a nonperturbative superpotential. We consider two types of nonperturbative superpotentials. One is written as

$$W_1 = Be^{-24\pi^2 S/B} + h \,. \tag{22}$$

Here the first term is due to the gaugino condensation with the 1-loop beta-function coefficient B, and the second term is due to the non-vanishing flux.[5] The second type of superpotential is written as

$$W_2 = \alpha b_1 e^{-24\pi^2 S/b_1} + \beta b_2 e^{-24\pi^2 S/b_2} \,. \tag{23}$$

This superpotential is generated by double gaugino condensations with 1-loop beta-function coefficients b_1, b_2, that is, the so-called racetrack type [26]. For simplicity, we have assumed that either W_1 or W_2 does not include T. Then, the total scalar potential during inflation

[4] See also refs. [23, 24].

[5] See ref. [25] for dilaton stabilization in heterotic models with the non-vanishing flux.

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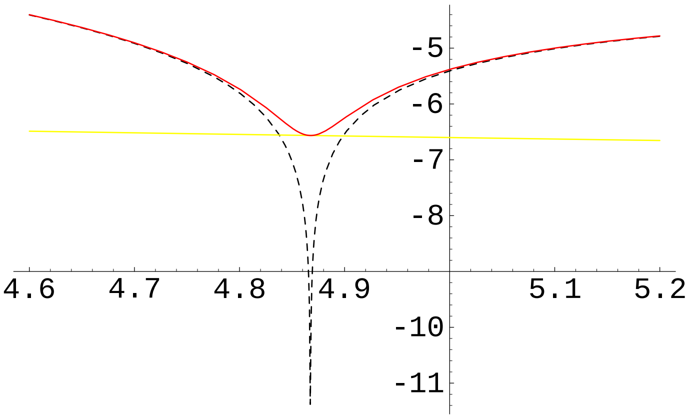

Figure 1: The potentials for W_1 with parameters, $p = 0, b = 1, d = 1, B = 54, h = -1/40$ and $\delta_{GS} = 0.005$. A horizontal axis represents s and a vertical axis represents potentials. When $s \simeq 4.9$, $V_T \simeq 2.7 \times 10^{-7}$. (light - V_D, dotted — V_F, bold — V_T).

is written as

$$V_T = V_F + V_D\,, \tag{24}$$

$$V_F = \frac{e^{K_{np}(s)+K_{X\bar{X}}|X|^2}}{s(T+\bar{T})^3 K_{S\bar{S}}}|K_S W + W_S|^2\,, \tag{25}$$

$$V_D = \frac{(\delta_{GS}K_S)^2}{s}\,, \tag{26}$$

where $s = (S + \bar{S})$.

In order to realize the D-term inflation, we have to stabilize S such that $V_D \gg V_F$. Note that V_D does not include T. Thus, if S is stabilized satisfying $V_D \gg V_F$, the potential for the moduli T would be insignificant and its dynamics also could be ignored. Furthermore, we are interested in the model leading to a suppressed value of V_D compared with δ_{GS}^2/s^3, which is the vacuum energy in the model only with the tree-level Kähler potential. Concerned about a stabilized value of Re(S), we are interested in models with $s = O(1)$, but we do not restrict ourselves to some specific values, e.g. $s = 4$. The stabilization we are discussing happens in the false vacuum, and in the true vacuum the dilaton potential and its stabilized value would be different from those of false vacuum.

Here we show examples of the dilaton stabilization with $V_D \gg V_F$. Note that the density perturbation generated by the inflaton is same as that in a simple model by the condition, $V_D \gg V_F$. For simplicity, we take $e^{K_{X\bar{X}}|X|^2}/(T+\bar{T})^3 = 1/2$ in the following analysis.

Figure 1 shows the case using the superpotential W_1 with the parameters, $p = 0$, $b = 1$, $d = 1$, $B = 54$, $h = -\frac{1}{40}$ and $\delta_{GS} = 0.005$. The almost flat light line corresponds to V_D, and the dotted one corresponds to V_F. The bold one corresponds to the total potential V_T. In this model, the dilaton is stabilized at $s = 4.9$, where we have $V_D \gg V_F$. Around this minimum, V_F is very steep, while V_D is very flat. Such situation plays a role in realizing $V_D \gg V_F$. The total potential value is obtained as $V_T = 2.7 \times 10^{-7}$, and that is comparable

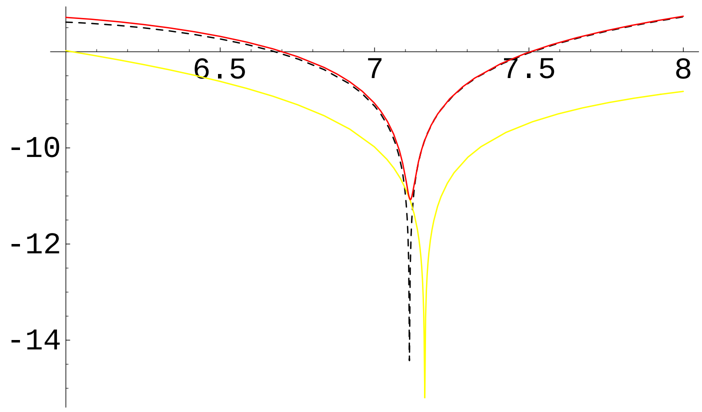

Figure 2: The potentials for W_1 with parameters, $p = 2, b = 1, d = -6, B = 54, h = -\frac{1}{40}$ and $\delta_{GS} = 0.005$. A horizontal axis represents s and a vertical axis represents potentials. When $s \simeq 7.1$, $V_T \simeq 1.3 \times 10^{-11}$. (light — V_D, dotted — V_F, bold - V_T).

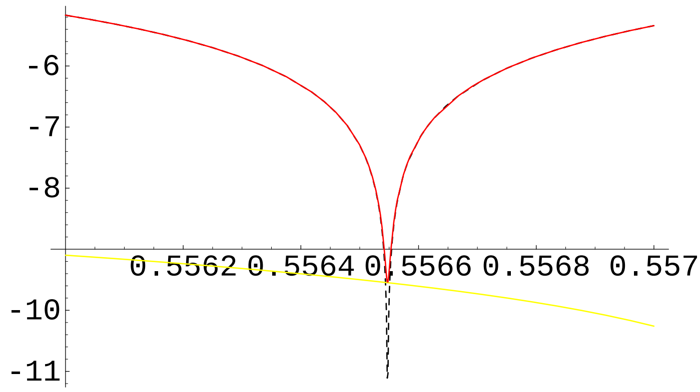

Figure 3: The potentials for W_2 with parameters, $p = 3, b = 1, d = 4.5, \alpha = 1, \beta = 3, b_1 = 15, b_2 = 12$ and $\delta_{GS} = 0.005$. A horizontal axis represents s and a vertical axis represents potentials. When $s \simeq 0.55$, $V_T \simeq 2.8 \times 10^{-10}$. (light — V_D, dotted — V_F, bold - V_T).

to δ_{GS}^2/s^3, which is the potential value derived only by the tree-level Kähler potential K_0. In this case, the non-perturbative Kähler potential does not contribute to suppress the FI term.

In order to obtain more suppressed FI term, we take another different set of parameters. Figure 2 shows the case using W_1 with the parameters $p = 2, b = 1, d = -6, B = 54, h = -\frac{1}{40}$ and $\delta_{GS} = 0.005$. The dilaton is stabilized at $s = 7.1$, where we have $V_D \gg V_F$. At this minimum, the total potential is obtained as $V_T = 1.3 \times 10^{-11}$. Now the potential value $V_T = 1.3 \times 10^{-11}$ is suppressed compared with δ_{GS}^2/s^3. In this case, the nonperturbative Kähler potential plays a role in suppressing the FI term. Thus, the non-perturbative Kähler potential is useful to lead to a suppressed FI term when we take proper parameters. The value of minimum potential depends linearly on δ_{GS}^2. When we take more suppressed value of δ_{GS}^2, we obtain much smaller potential value.

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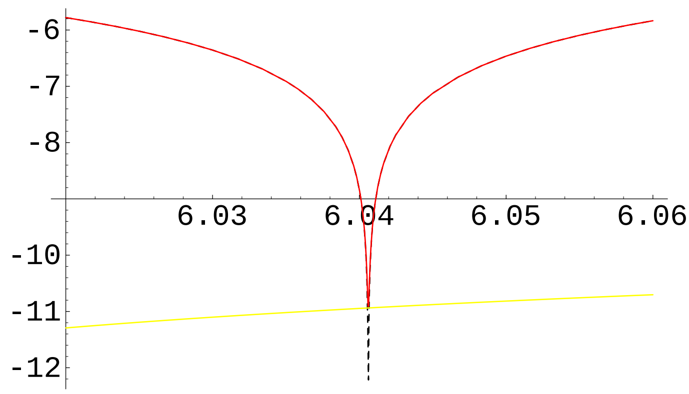

Figure 4: The potentials for W_1 with parameters, $p = 1, b = 1, d = -1.5, B = 54, h = -1$ and $\delta_{GS} = 0.02$. A horizontal axis represents s and a vertical axis represents potentials. When $s \simeq 6.0$, $V_T \simeq 1.1 \times 10^{-11}$. (light - V_D, dotted - V_F, bold - V_T).

Similarly, figure 3 shows the case using the superpotential W_2 with the parameters, $p = 3$, $b = 1$, $d = 4.5$, $\alpha = 1$, $\beta = 1$, $b_1 = 15$, $b_2 = 12$ and $\delta_{GS} = 0.005$. The dilaton is stabilized at $s = 0.55$, where we have $V_D \gg V_F$. At this minimum, the total potential is obtained as $V_T = 2.8 \times 10^{-10}$, which is very suppressed compared with δ_{GS}^2/s^3. The form of potential is steeper.

In the literature, another form of nonperturbative Kähler potential has been used like

$$K = \ln(e^{K_0} + e^{K_{np}})\,. \tag{27}$$

For this type, we can study similarly. For example, figure 4 shows the case using this Kähler potential and the superpotential W_1 with the parameters, $p = 1$, $b = 1$, $d = -1$, $B = 54$, $h = -1$ and $\delta_{GS} = 0.02$. The dilaton is stabilized at $s = 6.0$, where we have $V_D \gg V_F$. At this minimum, the total potential $V_T = 1.1 \times 10^{-11}$ is very much suppressed compared with δ_{GS}^2/s^3. Therefore, it is possible to stabilize the dilaton such that $\delta_{GS}^2/s^3 \gg V_D \gg V_F$ when we take suitable values of parameters. In this model, the potential value V_T depends linearly on δ_{GS}^2, again. When we take smaller values of δ_{GS}, we obtain more suppressed value of V_T.

We have neglected the perturbative Kähler term K_p. Here we investigate its effects on our results. We replace $K_0(S + \bar{S})$ as follows,

$$K_0(S + \bar{S}) \to K_0(S + \bar{S}) + \frac{a}{S + \bar{S}}\,, \tag{28}$$

in the above models. Then we repeat the above potential analysis. The results, the stabilized values of s and the potential values, are the same for $|a| < 0.1$ in all of the above models except the model shown in figure 3. In the model of figure 3, the stabilized value of s does not change, but the potential value changes, that is, the total potential value V_T at the minimum is obtained as $V_T \sim 10^{-7}$, e.g. for $a = 0.01$. This potential value $V_T \sim 10^{-7}$ is still suppressed compared with δ_{GS}^2/s^3. Thus, the nonperturbative

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Kähler potential contributes to suppress it. However, the perturbative term in the Kähler potential is important in this model. Its reason is that the stabilized value s is small, while the dilaton is stabilized at larger values in the other models. Hence, we have to take into account effects due to the perturbative Kähler term, in particular the models with a small value of s. Furthermore, there is a possibility that the perturbative Kähler term plays a role to lead to suppressed FI term by cancelling the contribution due to K_0 in models with little contribution due to K_{np}. In such case, the stabilized value of s would be quite small like $s \sim a$.

Finally, we give a brief comment on the cosmic string problem. After inflation, in the true vacuum the cosmic strings are generated,[6] and that leads to the density perturbation, which is inconsistent with the CMB observation for $\lambda \sim 1$ if the FI term ξ in the true vacuum is obtained as $\sqrt{\xi} = O(10^{15} - 10^{16})$ GeV. One way to avoid this problem is to take a suppressed value of λ like $\lambda = O(10^{-4} - 10^{-5})$ [15]. In string theory, the coupling λ also depends on the dilaton and other moduli fields. For example, in orbifold models, it is obtained as $\lambda \sim e^{-aT}$, where a is a constant factor [28]–[30]. That implies that a large value of T, e.g. $aT \sim 10$, leads to a small value of λ.[7] However, the inflaton must take a large expectation value of order M_p in a model with such a extremely small λ. In this sence, this option might not be a excellent solution.

The second possibility is that the FI term ξ is suppressed through the above mechanism both in the false vacuum during inflation and in the true vacuum like $\sqrt{\xi} < O(10^{15} - 10^{16})$ GeV. In this case, the density fluctuation generated by cosmic strings is suppressed sufficiently. However, at the same time, the density fluctuation due to the inflaton is also suppressed. We need another source of the density fluctuation to be consistent with the CMB observation, e.g. the curvaton.

We have another possibility, that is, the dilaton is stabilized through the above mechanism leading to $\sqrt{\xi} = O(10^{15} - 10^{16})$ GeV during inflation. After inflation, the superpotential can change, e.g. the VEV of ϕ_- in the true vacuum can make mass terms of hidden matter fields relevant to nonperturbative superpotential. In this case, the stabilized value of s in the true vacuum would be different from one in the false vacuum during inflation. The true vacuum can correspond to more suppressed values of K_S and ξ than those during inflation. Analysis of such possibility in explicit models is beyond our scope. It will be studied elsewhere. Here we would like to mention that the nonperturbative Kähler potential may solve not only the problem of the magnitude of the FI term but also the problem of cosmic string in D-term inflation.

To summarize, we have studied the possibility for suppressing the FI term in the D-term inflation scenario. That is possible when we consider the nonperturbative Kähler potential of the dilaton field. That is an interesting possibility. Thus, it would be important to study its implications in detail by investigating evolutions of dilaton and other moduli after inflation, a concrete model of gaugino condensation, and so on.

[6] Recently, the D-term inflation model without generating cosmic strings has been studied [27].

[7] Furthermore, the coupling λ also depends on continuous Wilson lines similarly [30]. Large value of continues Wilson lines lead to a suppressed value of λ.

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