Constraints on Hybrid Inflation from Flat Directions in Supersymmetry

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We examine the constraints on F-term hybrid inflation by considering the flat directions in the Minimal Supersymmetric Standard Model (MSSM). We find that some coupling terms between the flat direction fields and the field which dominates the energy density during inflation are quite dangerous and can cause the no-exit of hybrid inflation even if their coupling strength is suppressed by Planck scale. Such couplings must be forbidden by imposing some symmetry for a successful F-term hybrid inflation. At the same time, we find that in the D-term inflation these couplings can be avoided naturally. Further, given the tachyonic preheating, we discuss the feasibility of Affleck-Dine baryogenesis after the F-term and D-term inflations.

Introduction: Hybrid inflation is now the standard paradigm of inflation and has proved very fruitful since it was introduced [1]. In the models of hybrid inflation, most of the energy density is provided by an auxiliary field σ instead of the slowly rolling inflaton field Φ. When σ falls below a critical value σ_c, the inflation ends, which gives a natural exit of inflation. But when a particle physics model is tried for hybrid inflation, e.g., F-term hybrid inflation, there always exist a mass term of inflaton which can be of the same order as the Hubble scale and destroy the slow-rolling condition (the so-called η problem). So far various approaches have been proposed to avoid this η problem [2].

The flat directions, abundant in the MSSM, have many distinctive features and may thus play an important role in the early universe. Such flat directions are protected from perturbative quantum corrections and only lifted by the soft breaking terms which are insignificant in the early universe. During the inflation these flat directions can get large vacuum expectation values (vev) which naturally make an initial condition for many phenomena. From the potential of a flat direction φ during inflation [11]

$$V(\varphi) = (m_0^2 + c_H H_I^2)|\varphi|^2 + \frac{A\lambda H_I \varphi^n e^{in\theta_\varphi} + h.c.}{nM^{n-3}} + \lambda^2 \frac{|\varphi|^{2(n-1)}}{M^{2(n-3)}}, \tag{1}$$

we get the large vevs

$$\varphi_0 \sim (H_I M^{n-3}/\lambda)^{1/n-2}. \tag{2}$$

Here n is an integer (≥ 4), H_I is the Hubble parameter during inflation, m_0 is the soft mass term, c_H (< 0) and A are constants of $\mathcal{O}(1)$, and M is usually the Planck scale [1]. Note that the large vevs of the flat directions can also cause some problems in various inflation models [3,4], especially they can kinematically block the resonance preheating in chaotic inflation due to the invalidation of the non-adiabaticity condition [5].

As noticed in [5], the large vevs of the flat directions can also cause no exit of hybrid inflation. In this work we will scrutinize this problem and find that such a problem can be caused by some coupling terms between the flat direction fields and the field which dominates the energy density during inflation. Such couplings must be forbidden by imposing some symmetry for a successful F-term hybrid inflation. Then we point out that in the D-term inflation these couplings can be avoided naturally and thus the problem of no-exit of hybrid inflation does not exist, and further the no-preheating problem can also be avoided.

We will also discuss the feasibility of Affleck-Dine baryogenesis for both F-term and D-term inflations, given the tachyonic preheating. It is well known that after chaotic inflation ends, the process of resonance preheating occur at once [6]. This preheating leads to the large oscillation of the fields which couples with inflaton, and can make the symmetries restored for a moment which can make the baryon number produced after chaotic inflation [7]. Noticing that similar processes may occur during tachyonic preheating [15] after hybrid inflation, we find that it is possible the baryon number produced in these phase is copious due to the large amplitude of inflaton.

Flat directions constraints in F-term hybrid inflation: So far in the literature the couplings of inflaton

[1] In fact if M is the GUT or smaller scale, the problem of no preheating in chaotic inflation (mentioned below) will be alleviated. The same thing will happen in hybrid inflation considered in our work below. But to be conservative, we consider the worst case where M is taken as the Planck scale.

to matter fields have not been intensively studied and only some toy models have been considered which have no relevance to SM particles [6,16]. In [17] the importance of gauge invariance was first highlighted and recently the strength of the couplings of inflaton to matter fields was studied [5]. In the following we will examine the couplings between the MSSM fields and the auxiliary field dominating the energy density where the gauge symmetry is also important.

In the simplest supersymmetric hybrid inflation model, the superpotential contains the terms

$$W \supset g\hat{\phi}(\hat{\sigma}^2 - \sigma_0^2), \tag{3}$$

where g is a coupling constant, $\hat{\phi}$ is the inflaton superfield and $\hat{\sigma}$ is the superfield containing the scalar field σ. Large vevs of flat directions can induce a mass $\lambda_1\varphi_0$ for the σ field if we assume the existence of the $\lambda_1^2|\varphi|^2|\sigma|^2$ interaction with λ_1 being a coupling constant (such a term is assumed to have the same sign as the interaction terms from the superpotential W). Then if

$$\lambda_1\varphi_0 > \sqrt{2}g\sigma_0, \tag{4}$$

the mass-square of σ will remain positive even for $\langle\phi\rangle < \phi_c$ (ϕ_c is the critical value at which the hybrid inflation naturally exits), which leads to $\langle\sigma\rangle = 0$ and no tachyonic preheating and no exit from hybrid inflation.

In fact, the above problem always exists in hybrid inflation if $\lambda_1 > \sqrt{2}g$, which can be seen clearly by replacing $H_I = \sqrt{V_0/3M_P^2}$ with $V_0 = g^2\sigma_0^4$ into Eq.(2). We find that if we ignore the coupling constants in Eq.(1), then we have $\varphi_0 \geq \sigma_0$, where σ_0 decides the dominant energy density in hybrid inflation even for $n = 4$.

Then a natural idea for solving this problem is to suppress the dangerous large coupling λ_1 to invalidate Eq.(4). But it is difficult to find out a way in generic hybrid inflation. For example, let us consider the matter fields contained in the MSSM flat directions besides the two scalar fields σ and ϕ in hybrid inflation. With the addition of σ field, the superpotential is obtained by multiplying the σ superfield with the following MSSM gauge invariant terms

$$H_uH_d \ , \ H_uL, \tag{5}$$

and

$$H_uQu \ , \ H_dLe \ , H_dLe \ , \ QLd \ , \ udd \ , \ LLe, \tag{6}$$

where H_u and H_d are the two Higgs doublets, L and Q denote respectively a doublet of lepton and quark, and e, u and d denote respectively a singlet of lepton, up-quark and down-quark. Here we drop out the higher order gauge-invariant terms, which are negligible, as shown in our following analysis. We will label a generic MSSM flat direction by φ. Examples of such flat directions are given by $LH_u \sim \varphi^2$ in terms of doublet components $L = (\varphi, 0)$ and $H_u = (0, \varphi)$, and by $Q_1L_1d_2 \sim \varphi^3$. Then we obtain interactions like

$$\lambda_1^2|\varphi|^2\sigma^2 + \lambda_2^2|\varphi|^4\sigma^2/M_P^2 \tag{7}$$

where $\lambda_i (i = 1, 2)$ are coupling constants.

Let us consider the renormalizable terms, i.e. σH_uH_d and σH_uL. It is natural to assume their coupling constants to be $\mathcal{O}(1)$. On the other hand, we know that these gauge invariant terms correspond to the D-flat directions of the MSSM [8]. These terms σH_uH_d and σH_uL can lead to $\lambda_{1,2} \sim \mathcal{O}(1)$. Since $\varphi_0 \geq \sigma_0$ even for $n = 4$ (D-flat H_uH_d and H_uL directions are lifted by $n = 4$ non-renormalizable terms), it is impossible to avoid Eq.(6) unless $g \gg \mathcal{O}(1)$.

Actually, the coupling terms in Eq.(7) with even a small λ_i cannot be neglected because the vevs of the flat directions which are lifted by a large n (n can be as large as 9 [8]) are much larger than σ_0. From some calculations we find that there are two other dangerous flat directions: LLe and udd, which are lifted up by $n = 6$ non-renormalizable terms.

Some global symmetry [2] like R-symmetry $U(1)_R$ [18] must be imposed to forbid the 4 dangerous terms H_uH_d, H_uL, LLe and udd in Eq.(6). If we use R-symmetry, we must make special assignment for the R-charges of involved superfields, e.g., the R-charge must be zero for σ field as can be seen from Eq.(3).

Now we discuss the feasibility of Affleck-Dine baryogenesis during tachyonic preheating after the F-term hybrid inflation. After the inflation the A-term in the potential in Eq.(1) becomes small as the Hubble parameter H decreases, and there will appear a CP-violating interaction [7]

$$c(\phi^2/M_P^{m-2})\varphi^m + h.c. \tag{8}$$

During tachyonic preheating, the large oscillation of inflaton ϕ can make the flat directions go to zero and

$$\phi^2 \sim \langle\phi^2\rangle e^{i2\theta_\phi}. \tag{9}$$

Through Affleck-Dine mechanism, this process will produce baryon number

$$n_B \sim 2|\varphi_0|^2\dot{\theta}_\varphi. \tag{10}$$

The initial value of θ_φ is determined by the H_I-dependent A-term in Eq.(1). Such baryon number will be released in the ensuing decay of φ. Because φ_0 is so large, this

[2] Note that unlike a discrete symmetry [20], such a global symmetry may have a potential problem since it may be violated by quantum gravity effects [19].

baryon number generated during the tachyonic preheating after hybird inflation cannot be neglected. This is quite similar to the case of resonance preheating after chaotic inflation considered in [7].

D-term inflation and its consequence: In the preceding section we have shown that it is not easy to obtain a negative mass-square term due to the large vevs of flat directions, which will lead to no elegant exit of hybrid inflation in the F-term inflation. Here we show that such a problem can be solved naturally in D-term inflation.

D-term inflation can preserve the flat directions of global supersymmetry and, in particular, keep the inflation potential flat provided that one of the contributions to the potential V_D contains a Fayet-Iliopoulos term as in Eq. (12). This was first pointed out in [10] and significantly improved in [9].

Consider a toy model of D-term inflation, whose field content includes a inflaton chiral superfield $\hat{\phi}$ and auxiliary superfields $\hat{\sigma}_\pm$ with charges ± 1 under an anomalous $U(1)_X$ symmetry. From the superpotential

$$W = c\hat{\phi}\hat{\sigma}_+\hat{\sigma}_-, \tag{11}$$

and the minimal Kahler potential, we obtain the tree-level scalar potential

$$\begin{aligned} V = &|c|^2(|\sigma_+\sigma_-|^2 + |\phi\sigma_+|^2 + |\phi\sigma_-|^2) \\ &+\frac{g^2}{2}(|\sigma_+|^2 - |\sigma_-|^2 + \xi^2)^2 \end{aligned} \tag{12}$$

Here c is a coupling constant and the Fayet-Iliopoulos term ξ^2 is assumed to be positive. The role of σ field in Eq. (3) is now replaced by the σ_- field in this model.

Now we argue that in the D-term inflation the no-exit problem happened in generic F-term inflation discussed in the preceding section does not exist. The magnitude of the vevs of the MSSM flat directions are primarily fixed by higher dimension operators in the Kahler potential that couple the flat direction to other fields like

$$\triangle\mathcal{L} = \int d^4\theta(c_1|\hat{\phi}|^2 + c_2|\hat{\sigma}_+|^2 + c_3|\hat{\sigma}_-|^2)\frac{\varphi^+\varphi}{M^2}, \tag{13}$$

where $c_i (i = 1, 2, 3)$ are coupling constants. These induced mass terms for flat direction φ always vanish because $\langle\sigma_-\rangle = 0$ and $\langle\sigma_+\rangle = 0$ during D-term inflation. Here the zero vev of $\sigma_\pm$ can be obtained by minimizing the potential of Eq. (12) when $\phi > \phi_c = g\xi/c$ with ϕ_c being the critical value at which inflation ends. Then the flat directions can only get vev after inflation where $U(1)_X$ is broken and we get

$$\langle\sigma_+\rangle = 0,\ \langle\sigma_-\rangle \sim \xi,\ \langle F_{\sigma_+}\rangle \sim \xi\phi. \tag{14}$$

After the quick tachyonic preheating, the inflaton ϕ fall down to its global minimum and equal to zero. So the $\langle F_{\sigma_+}\rangle \sim 0$, but there always exist the kinetic energies in Eq. (13) which will lead to the negative mass-square term of flat directions fields. Of course, such delayed appearance of the vevs of flat directions will not cause the problem of no-exit of inflation.

On the other hand, as pointed in [5], the large vev of flat directions will prohibit the tachyonic preheating in F-term inflation. However, we should point out that this problem does not happen in D-term inflation because the direct coupling terms between flat directions and $\sigma_\pm$ are forbidden by $U(1)_X$ gauge symmetry. Then the preheating will proceed despite of the large vevs of the flat directions. The ensuing Affleck-Dine baryogenesis can occur as indicated in [14] after tachyonic preheating, but the decays of inflaton and $\sigma_\pm$ must be quite different with those in no-preheating case.

Conclusion: We discussed the effects of large vevs of MSSM flat directions in hybrid inflation in detail. We have shown that some dangerous coupling terms between the flat direction fields and the field which dominate the energy density during inflation must be forbidden for a successful inflation even if their coupling constants are small. Such couplings must be forbidden by imposing some symmetry for a successful F-term hybrid inflation. At the same time, we found that in the D-term inflation these couplings can be avoided naturally. Further, given the tachyonic preheating, we discussed the feasibility of Affleck-Dine baryogenesis after the F-term and D-term inflations.

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