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Inflation from Gaugino Condensation in Supergravity

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The mass parameter responsible for inflation in the simplest original F-term inflationary model can be generated if the gauginos in a hidden sector condense and the inflaton field linearly contributes to the relevant gauge kinetic function. We point out that the relevant local and/or global symmetries in the F-term inflationary models can be broken even during inflation if the inflaton field couples non-linearly to hidden sector gauginos and waterfall fields. Accordingly, the resultant topological objects are diluted away during inflation, so the monopole and/or the cosmic string problems in the simplest original F-term inflationary model can be resolved in this case.

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I. INTRODUCTION

The best idea to resolve the flatness and homogeneous problems arising in the standard big bang cosmology is believed to introduce the cosmological inflation [1,2]. As a big bonus, its introduction is known to provide also seeds of the large scale structure of the present universe as a result of its quantum phenomena [3–5]. However, it is highly non-trivial to realize the inflationary idea as a concrete model in the framework of the quantum field theory. It is basically because this scenario requires a light enough scalar field called "inflaton", which drives inflation. Although a light scalar mass compared to a given cutoff scale is known to be perturbatively unstable in quantum field theory [6], the inflaton mass should be much lighter than the Hubble scale during inflation era for successful cosmological inflation [7–9].

As in elementary particle physics, thus, introduction of supersymmetry (SUSY) in inflationary cosmology was expected to be helpful for resolving this problem. However, positive large vacuum energy density during inflation badly breaks SUSY, and so an inflaton mass of the Hubble scale during inflation can be induced even at tree level as a supergravity (SUGRA) effect ("η problem") [10, 11]. Nonetheless, the inflation has been attempted to be realized in the SUSY framework, maybe because such a problem associated with the quantum corrections on the inflaton mass would be expected to be resolved somehow in the SUSY framework [10,12].

In this paper, we will discuss one of the SUSY inflationary scenarios, "F-term inflation".

II. F-TERM INFLATION

The simplest F-term inflationary model is described with the following superpotential [10,13–16]:

$$W = \kappa S(\Phi\Phi^c - M^2), \tag{1}$$

where κ and M^2 are dimensionless and dimensionful parameters, respectively, and Φ, Φ^c, and S are superfields carrying local and/or global charges. Here we assume that M^2 is positive definite. It turns out that the size of M^2 should be around the scale of the SUSY grand unified theory (GUT), $M^2 \approx (10^{16}\,\text{GeV})^2$ [13] for explaining the cosmic microwave background anisotropy, $\delta T/T \sim 10^{-5}$ [17]. In fact, it was the main motivation to construct inflationary models in the framework of the SUSY GUT [14–16]. While Φ and Φ^c can carry various proper gauge charges, S carries only a (global) $\text{U}(1)_R$ charge. In this

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model, the scalar component of S plays the role of the inflaton.

From the above superpotential, the following scalar potential is derived:

$$\begin{aligned} V_F &= |F_s|^2 + (|F_{\phi^c}|^2 + |F_\phi|^2) \\ &= \left|\kappa(\phi\phi^c - M^2)\right|^2 + |\kappa\cdot s|^2\left(|\phi|^2 + |\phi^c|^2\right), \quad (2) \end{aligned}$$

where ϕ, ϕ^c, and s denote the scalar components of Φ, Φ^c, and S, respectively. When ϕ and ϕ^c ("waterfall fields") carry gauge charges, the corresponding D-term potential should also be considered. Since the F-term potential is assumed to dominate over the D-term potential in F-term inflationary scenario, throughout this paper we will take the D-flat direction, $\phi^* = \phi^c$, along which the D-term potential vanishes.

At the minimum of the the scalar potential, the waterfall fields ϕ and ϕ^c develop vacuum expectation values (VEVs), $\langle\phi\phi^c\rangle = \langle|\phi|^2\rangle = M^2$, while $\langle s\rangle = 0$. Consequently, the scalar potential V_F vanishes at the minimum, and so the Minkowski space can be achieved. Due to the non-zero VEVs of ϕ and ϕ^c, the gauge symmetry under which ϕ and ϕ^c are charged should be broken at the minimum of the scalar potential.

For inflation, let us suppose that $|s|^2 \gg M^2$ (but $|s|^2 \ll M_P^2$), which can be realized *e.g.*, by a thermal effect when the temperature of the universe is very high in the early hot universe. Since $\kappa\cdot s$ plays the role of the mass of ϕ and ϕ^c as seen in Eq. (2), ϕ and ϕ^c should stay at the origin in this case. Then we have a positive constant vacuum energy density, $V_F = |\kappa M^2|^2$, which gives rise to inflation.

Although we include the SUGRA correction to the constant potential $V_F = |\kappa M^2|^2$, it can be negligible in this model:

$$\begin{aligned} &V_{SUGRA} \\ &= e^{K/M_P^2}\left[\left|\frac{\partial W_{\rm eff}}{\partial s} + \frac{W_{\rm eff}}{M_P^2}\frac{\partial K}{\partial s}\right|^2 - \frac{3}{M_P^2}|W_{\rm eff}|^2\right] \\ &\approx \left(1 + \frac{|s|^2}{M_P^2} + \cdots\right)\left(\left|1 + \frac{|s|^2}{M_P^2}\right|^2 - 3\frac{|s|^2}{M_P^2}\right)\left|\kappa M^2\right|^2 \\ &\approx \left|\kappa M^2\right|^2\left[1 + \mathcal{O}(|s|^4/M_P^4)\right], \qquad (3) \end{aligned}$$

where M_P denotes the reduced Planck mass ($\approx 2.4\times 10^{18}$ GeV). Here we applied the effective superpotential during inflation, $W_{\rm eff} = -\kappa S M^2$ and assumed the minimal form for the Kahler potential, $K = |S|^2 + |\Phi|^2 + |\Phi^c|^2$. As seen in Eq. (3), the quadratic term yielding inflaton mass of the Hubble scale during inflation, $\sim |\kappa M^2|^2(|s|^2/M_P^2) = 3H^2|s|^2$ is canceled out in this model, avoiding the η problem [10].

Since ϕ and ϕ^c does not get a non-zero VEV, the gauge symmetry is not broken during inflation. On the other hand, $\mathrm{U}(1)_R$ is broken, because the potential of s is flat and so it can take a large VEV larger than M. Since SUSY is broken by the positive vacuum energy, however, quantum effects can radiatively modify the scalar potential as follows [13]:

$$V_{\rm inf} \approx |\kappa M^2|^2\left(1 + \alpha\ \log\frac{s}{\Lambda}\right), \qquad (4)$$

where Λ denotes a renormalization scale, and α is a loop factor $\alpha \equiv \kappa^2/8\pi^2$. By the logarithmic slope of s in the radiative correction of the scalar potential, s can slowly roll down to the origin: when $|s|^2 > M^2$ is violated, ϕ and ϕ^c also can return to the original minimum point with $\langle|\phi|^2\rangle = M^2$, breaking the gauge symmetry, and when $\langle s\rangle = 0$, inflation can eventually terminate, restoring the Minkowski space. In this scenario, thus, s drives inflation successfully.

We should note here that the gauge symmetry is broken at the end of inflation, while it is unbroken during inflation. As a result, unwanted topological objects such as monopoles, cosmic strings, *etc.* are created after inflation is over, if the gauge group is simple or U(1) symmetry is involved. Accordingly, they have no chance to be diluted away in the universe.

In order to address this issue, let us first discuss a dynamical generation mechanism of the mass parameter M.

III. THE MODEL

Unlike local SUSY, SUGRA adimts a gaugino's contribution to the F-term potential, if the gauge kinetic function is non-minimal ($\partial f_{ab}/\partial z_i \neq 0$, *i.e.*, not a constant kinetic function) [6]:

$$\begin{aligned} &V_F = \sum_i |F_i|^2 + \cdots \\ &\text{with}\quad F_i^* = \frac{1}{4}\sum_{a,b}\frac{\partial f_{ab}(z_i)}{\partial z_i}\lambda^a\lambda^b + \cdots, \qquad (5) \end{aligned}$$

where λ^a and λ^b are gauginos, *i.e.*, fermionic superpartners of the gauge fields in a non-Abelian gauge sector. $f_{ab}(z_i)$ stands for the gauge kinetic function, and z_i means scalar fields contributing to the gauge kinetic function. It defines the kinetic terms of the gauge fields, $e^{-1}\mathcal{L} \supset \frac{-1}{4}\text{Re}f_{ab}F^a_{\mu\nu}F^{b\mu\nu}$. Suppose that M^2 was absent in the bare superpotential and scalar potential, keeping only $\kappa S\Phi\Phi^c$ in the superpotential of Eq. (1). If the gaugino condenses by strong interaction in a hidden sector, *i.e.*, $\langle\lambda^a\lambda^b\rangle \neq 0$, and the inflaton s linearly contributes to the gauge kinetic function, *e.g.*, $f_{ab}(s) = \delta_{ab}(1+c\,s/M_P)$, one can readily see that the M^2 term in Eq. (2) can be reproduced, since F_s is modified as follows:

$$F_s^* = \kappa\phi\phi^c + c\sum_{a,b}\delta_{ab}\frac{\langle\lambda^a\lambda^b\rangle}{4M_P}, \tag{6}$$

where c is a constant and δ_{ab} means the Kroneker delta. Hence, M^2 in Eq. (2) is identified with $-(c/\kappa)\sum_a\frac{\langle\lambda^a\lambda^a\rangle}{4M_P}$.

Now let us extend our discussion to more general cases, where s couples non-linearly to $\phi\phi^c$ as well as a hidden gauge sector:

$$W_{\text{eff}} = -f(S)\ M^2 + g(S)\ \Phi\Phi^c, \tag{7}$$

where $f(S)$ and M^2 originate from the gauge kinetic function and hidden sector gaugino condensation. Then the resulting scalar potential is given by

$$V_{\text{eff}} = \left|g'(s)\ \phi\phi^c - f'(s)\ M^2\right|^2\ +\ |g(s)|^2\left(|\phi|^2 + |\phi^c|^2\right). \tag{8}$$

Comparing Eq. (8) with Eq. (2), we note that the original F-term inflation corresponds to the case that $f(s)$ and $g(s)$ are linear in s. Let us require $V_{\text{eff}} = 0$ with a breaking phase of the gauge symmetry at the *true* minimum for the (almost) flat spacetime after inflation over: $g'(s)|\phi|^2 - f'(s)M^2 = g(s) = 0$ with $\phi \neq 0$.

For the above potential, the (local) minimum conditions are as follows:

$$\frac{\partial V_{\text{eff}}}{\partial\phi^*} = \left[\left(g'\phi\phi^c - f'M^2\right)g'^* + |g|^2\right]\phi = 0, \tag{9}$$

$$\frac{\partial^2 V_{\text{eff}}}{\partial\phi\partial\phi^*} = \left[\left(g'\phi\phi^c - f'M^2\right)g'^* + |g|^2\right] + |g'|^2|\phi|^2 > 0, \tag{10}$$

where we applied the D-flat condition, $\phi^* = \phi^c$, along which the D-term potential associated with the gauge symmetry where ϕ and ϕ^c are involved vanishes. $\partial V_{\text{eff}}/\partial s^*$, $\partial^2 V_{\text{eff}}/\partial s\partial s^*$, $\partial^2 V_{\text{eff}}/\partial s\partial\phi^*$, *etc.* will be briefly considered later.

With the above expressions, let us first discuss the various cases the potential Eq. (8) admits for *inflation*. Since the minimal gauge kinetic function $f' = 0$ cannot induce the mass parameter M^2 from the gaugino condensation in a hidden sector, we will consider only the cases with $f \neq 0$ and $f' \neq 0$.

1. For the case, $g(s) = g'(s) = 0$

We have only a positive flat potential, $V_{\text{eff}} = |f'M^2|^2 > 0$, which breaks SUSY. ϕ and ϕ^c become moduli fields, which can take any field values. Hence, the gauge symmetry as well as SUSY are broken. f' should vanish eventually for the Minkowski space to be restored.

2. For $g(s) \neq 0$ while $g'(s) = 0$

V_{eff} still provides a positive constant term, $V_{\text{eff}} = |f'M^2|^2$. Since the waterfall fields ϕ and ϕ^c get masses of $g(s)$ as seen in Eq. (8), ϕ and ϕ^c should be stuck to the origin, $\phi = \phi^c = 0$ satisfying $\partial V_{\text{eff}}/\partial\phi^* = 0$ and $\partial^2 V_{\text{eff}}/\partial\phi\partial\phi^* > 0$. So the gauge symmetry remains unbroken, while SUSY is broken.

3. For $g'(s) \neq 0$ but $g(s) = 0$

Whether ϕ and ϕ^c $(= \phi^*)$ get VEVs or not depends on the sign of $f'\cdot g'$. If it is plus, $|\phi|^2$ get a VEV, $(f'/g')M^2$, making V_{eff} vanishing. So the gauge symmetry is broken, while SUSY is protected. On the other hand, if $f'\cdot g'$ is minus, they should be stuck to the origin with $\partial^2 V_{\text{eff}}/\partial\phi\partial\phi^* > 0$. As a result, the gauge symmetry is unbroken, while SUSY is broken by the positive vacuum energy density, $V_{\text{eff}}|_{\text{min.}} = |f'M^2|^2$.

4. For $g(s) \neq 0$ and $g'(s) \neq 0$ with $|g|^2 \geq f'g'^*M^2$

$\partial V_{\text{eff}}/\partial\phi^* = 0$ is satisfied only by $\phi = 0$ in Eq. (9) keeping the gauge symmetry, because $|g'|^2|\phi|^2 \geq 0$. $\partial^2 V_{\text{eff}}/\partial\phi\partial\phi^* > 0$ is definitely fulfilled. So we have $V_{\text{eff}}|_{\text{min.}} = |f'M^2|^2 > 0$, breaking SUSY.

5. For $g(s) \neq 0$ and $g'(s) \neq 0$ with $|g|^2 < f'g'^* M^2$

ϕ should develop a VEV, $\phi\phi^c = |\phi|^2 = (f'g'^* M^2 - |g|^2)/|g'|^2$ to satisfy Eq. (9). $\phi = 0$ cannot meet Eq. (10). At the minimum, we get positive vacuum energy density $V_{\rm eff}|_{\rm min.} = |g|^4/|g'|^2 + 2|g|^2|\phi|^2 > 0$. Consequently, both SUSY and the gauge symmetry are broken.

As discussed above, only Case 1 and 5 can break both SUSY and the gauge symmetry. However, Case 1 is a so trivial case: it does not provide a useful information for constructing an inflationary model. ϕ and ϕ^c cannot play any important role for successful inflation. We are more interested in Case 5.

Next let us discuss the slope of the inflaton s. For slow enough rolling down of the inflaton, the first and second derivatives of $V_{\rm eff}$ with respect to s should be suppressed enough:

$$\frac{\partial V_{\rm eff}}{\partial s^*} = \left(g'\phi\phi^c - f'M^2\right)\left(g''^*\phi^*\phi^{c*} - f''^* M^{2*}\right) + gg'^*\left(|\phi|^2 + |\phi^c|^2\right) \approx 0, \tag{11}$$

$$\frac{\partial^2 V_{\rm eff}}{\partial s \partial s^*} = \left|g''\phi\phi^c - f''M^2\right|^2 + \left|g'\right|^2\left(|\phi|^2 + |\phi^c|^2\right) \approx 0, \tag{12}$$

$$\frac{\partial^2 V_{\rm eff}}{\partial s \partial \phi^*} = \left[\left(g''\phi\phi^c - f''M^2\right)g'^* + g'g^*\right]\phi \approx 0. \tag{13}$$

Note that f'', g'', *etc.* are zero in the case that f and g are linear in s, namely, in the original F-term inflation. From Eq. (11), hence, $g \approx 0$ or $g' \approx 0$ or $\phi = \phi^{c*} \approx 0$ is required in such a case. With this condition, we cannot realize Case 5. We need to consider the case that f and g are non-linear in s. $\left(g'\phi\phi^c - f'M^2\right)\left(g''^*\phi^*\phi^{c*} - f''^* M^{2*}\right)$ would be helpful for realizing Case 5 by relaxing the constraint of Eq. (11). Then the monopole and/or cosmic string problems arising in the simplest original F-term inflation model can be resolved, because the gauge symmetry is broken even during inflation and the resultant unwanted topological objects are diluted away. To meet Eq. (12), however, $(g''\phi\phi^c - f''M^2)$ canonot be much large. Once Eq. (12) is somehow fulfilled, Eq. (13) would easily be satisfied.

In order to return to the (almost) flat spacetime from the inflationary phase, $|g(s)|$ needs to be made slowly decrease as in the original scenario: as $|g(s)|$ decreases, it fails to satisfy Eq. (10) at some point. Then, ϕ and ϕ^c start rolling down to their true minima, increasing their field values rapidly. So ϕ, ϕ^c and s could eventually meet $g'|\phi|^2 - f'M^2 = g = 0$ and $|g'|^2|\phi|^2 > 0$ together with $V_{\rm eff} = 0$. Since $F_s = 0$ at the minimum, thus, they restore SUSY.

In fact, the gaugino condensation or M^2 could be a SUSY breaking source in a hidden sector as seen in Eq. (5) [6]: in principle it can generate the soft SUSY breaking terms in the visible sector through gravity mediation effects. However, the effects of the gaugino condensation are compensated by ϕ, ϕ^c and s in this case so that $F_s^* = g'|\phi|^2 - f'M^2 = 0$. Accordingly, we need either another SUSY breaking source for explaining elementary particles' phenomena or an elaborate inflationary model with $V_{\rm eff} \neq 0$ at the absolute minimum, where the non-zero $V_{\rm eff}$ [$\approx (10^{10-11}\,{\rm GeV})^4$] should be compensated by the SUGRA correction for the flat universe with broken SUSY.

For slow roll of the inflaton, the SUGRA correction needs to be suppressed enough even during inflation as in the original scenario. Assuming $g|\phi|^2 \ll fM^2$ and $g'|\phi|^2 \ll f'M^2$ during inflation for simplicity, the SUGRA scalar potential approximately takes the following form:

$$V_{\rm SUGRA} \approx \left(1 + \frac{|s|^2}{M_P^2}\right) \times \left[\left|1 + \left(\frac{f}{f's}\right)\frac{|s|^2}{M_P^2}\right|^2 - 3\left|\frac{f}{f's}\right|^2 \frac{|s|^2}{M_P^2}\right]\left|f'M^2\right|^2, \tag{14}$$

where we took the minimal Kahler potential again. As discussed in Case 5 and Eq. (9), $|f'M^2|^2$ in Eq. (14) can be replaced by $|g|^4/|g'|^2$. The form of $f(s)$ should be constrained such that the mass term of s is suppressed enough.

Constructing a concrete model is beyond the scope of this paper. In this paper, we are satisfied with providing a foundation for a better scenario.

IV. CONCLUSION

In conclusion, we have seen that the simplest original F-term inflationary model can be reproduced, when the gauginos in a hidden sector condense and the relevant the gauge kinetic function linearly depends on the inflaton field. We pointed out that the monopole and/or cosmic string problems in the simplest original F-term inflationary model could be resolved, if the inflaton couples non-linearly to the waterfalls fields as well as the hidden sector gauginos.

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