Inflection point inflation and dark energy in supergravity (postprint)

Authors: Tie-Jun Gao, Zong-Kuan Guo

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Full Text

Preamble

Inflection Point Inflation and Dark Energy in Supergravity

Tie-Jun Gao* and Zong-Kuan Guo†

State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

Abstract

We consider an inflection point inflationary model in supergravity with a single chiral superfield and show that the predicted values of the scalar spectral index and tensor-to-scalar ratio are consistent with the Planck 2015 results. In this model supersymmetry is strongly broken after inflation, which results in a non-SUSY de-Sitter vacuum responsible for the recent accelerated expansion of the Universe.

- gaotj@itp.ac.cn † guozk@itp.ac.cn

INTRODUCTION

Cosmological inflation is now becoming established by precise observational data from missions such as WMAP [1] and Planck [2]. The full-mission Planck observations of temperature and polarization anisotropies of the cosmic microwave background radiation constrain the spectral index of curvature perturbations and the tensor-to-scalar ratio to be $n_s = 0.9655 \pm 0.0062$ and $r_{0.002} < 0.10$ at 95% confidence level [2], respectively, which are consistent with the analysis from Planck 2013 [3]. However, the nature of inflation remains an open question in cosmology. An interesting framework for inflation model building is to embed inflationary models into a more fundamental theory of quantum gravity, and it is natural to consider supergravity. Some inflationary models have been constructed in supergravity [4-6], most of which however suffer from the so-called η problem [7]. The F-term of the potential is proportional to $e^{|K|}$, which gives a contribution to the slow-roll parameter η and breaks the slow-roll condition. Several methods have been proposed to solve this problem [8-11]. One way to overcome such obstacles is to add an extra chiral superfield S and to use a shift-symmetric Kähler potential $K(\Phi+\bar{\Phi}, S\bar{S})$ [12-14, 21, 22]. During inflation, the superfield S is stabilized at $S=0$. In these models there are two superfields, with four scalar degrees of freedom, but only one of them acts as the inflaton field while the others never participate in the cosmological evolution.

Recently, in Refs. [17, 18], Ketov and Terada proposed a new class of inflationary models with only one chiral superfield Φ. Generally, the superfield Φ is decomposed into a real part ϕ and an imaginary part χ, such that $\Phi = (\phi + i\chi)/\sqrt{2}$. Following [18], we consider the following logarithmic Kähler potential:

$$K = -\frac{1}{2}\ln\left[\frac{1}{2}(\Phi+\bar{\Phi})^2 + \zeta(\Phi+\bar{\Phi})^4\right]$$

Since it is invariant under the shift $\Phi \to \Phi + iC$ with a real parameter C, the imaginary component χ does not appear in the Kähler potential, which could play the role of the inflaton field. The quartic term serves to stabilize the field χ during the main part of inflation at $\phi = 0$. As shown in Appendix C of Ref. [18], although quadratic and cubic terms in the Kähler potential are allowed by the symmetries, the coefficients of such terms can be suppressed by tuning the coupling between the superfield Φ and other superfields. In this paper, we shall take $\zeta = 1$ for simplicity.

A complete cosmological model must include both the early acceleration and the later acceleration of the Universe. In the framework of supergravity with the Kähler potential (2), the authors of Ref. [19] considered a linear superpotential with a small constant and a quadratic superpotential with a linear correction, respectively. At the end of inflation, the field rolls to a non-SUSY AdS vacuum. By a small modification of the parameters in the theory, one can uplift the vacuum to a non-SUSY dS vacuum with a tiny cosmological constant $V_0 \sim 10^{-120}$, which does not violate the no-go theorem [20].

In the framework of MSSM, a successful inflection point inflation was first realized along the gauge invariant flat directions udd or LLe [21]. In such a model, the fine-tuning and reheating are discussed in detail in Ref. [22]. A solution to the fine-tuning problem was proposed in a minimal extension of MSSM in [23]. Due to an attractor behavior towards the inflection point, the initial condition for MSSM inflation can be naturally realized [24]. Recently it has been pointed out that inflection point inflation can yield large tensor-to-scalar ratios [25, 26]. The purpose of the present paper is to investigate a class of supergravity models motivated by superstring compactification and supersymmetric particle phenomenology beyond the Standard Model [17-19]. The inflaton may belong to a hidden sector and can decay into SM particles after inflation [27].

In this paper, we shall consider the possibility of constructing an inflection point inflationary model in supergravity with a single chiral superfield. We shall focus on a superpotential of the form $W = m(\Phi^3 + ae^{i\theta}\Phi + be^{i\rho})$. We study the inflaton dynamics and show that the predicted scalar spectral index and tensor-to-scalar ratio can lie within the 1σ confidence region allowed by the results of Planck 2015. After the end of inflation, the potential has a global non-SUSY minimum; as found in Ref. [19], one can uplift the potential to have the desirable dS vacuum with $V_0 \sim 10^{-120}$ by fine-tuning the model parameters.

The rest of this paper is organized as follows. In the next section, we set up the inflection point inflationary model in supergravity. In Section 3, we investigate the inflaton dynamics of the model. In Section 4 we study the vacuum structure of the model and explore the parameter space to give desirable inflation and dark energy. The last section is devoted to a summary.

II. SETUP OF THE INFLECTION POINT INFLATION

In supergravity theory with the Kähler potential (2), for an arbitrary choice of the superpotential, the kinetic term of the field Φ is given by [19]:

$$L_{\text{kin}} = \frac{1 + 24\sqrt{3}\zeta\phi^2 - 8\sqrt{2}\zeta\phi^3 + 32\zeta^2\phi^6}{(\sqrt{3} + \sqrt{2}\phi + 4\zeta\phi^4)^2}\partial_\mu\Phi\partial^\mu\bar{\Phi}$$

The coefficient of the kinetic term does not depend on χ and it is positive definite when $\phi \in (-0.159, 0.152)$ for $\zeta = 1$. So ϕ is confined to a narrow interval, and χ plays the role of the inflaton field.

The potential is determined by a given superpotential W as well as the Kähler potential, which is given by:

$$V = e^K D_i W (K^{-1})^{i\bar{j}} (D_{\bar{j}} W)^*$$

where $D_i W = \partial_i W + (\partial_i K)W$, and $(K^{-1})^{i\bar{j}}$ is the inverse of the Kähler metric $K_{i\bar{j}} = \partial_{\Phi_i}\partial_{\bar{\Phi}_{\bar{j}}}K$.

In order to achieve inflection point inflation as well as a tiny cosmological constant after inflation, we consider the superpotential of the form:

$$W = m(\Phi^3 + ae^{i\theta}\Phi + be^{i\rho})$$

where the coefficient m is real, a and b are positive without loss of generality, and θ and ρ are the phases of the coefficients. In order to study further inflation and vacuum structure after inflation in the parameter space, let us first consider the case of $\rho = 0$ for simplicity. Later we will show that the value of ρ cannot affect the inflationary predictions.

[Figure 1: see original paper]

Substituting the superpotential (7) and Kähler potential (2) into (4), one can obtain the potential. Because of the shift symmetry, there is no imaginary component χ in the Kähler potential, so the potential is considerably flat along the χ direction and thus χ becomes an inflaton candidate. As shown above, the real component ϕ is stabilized at zero during inflation. Therefore, we can set $\phi = 0$ and obtain the scalar potential of χ:

$$V(\chi) = m^2 \left(\sqrt{6}a\sin\theta\,\chi^3 + 3(\sqrt{3}b - a\cos\theta)\chi^2 + a^2 - 2\sqrt{3}ab\cos\theta\right)$$

The cubic term leads to a negative contribution when $a\sin\theta > 0$. The inflation potential is shown in Fig. 1.

If the parameters satisfy the relation $9\cos\theta + 2a\sin^2\theta = 0$, there are two minima at $\chi = 0$ and at $\chi = -4a\sin\theta/(3\sqrt{6})$, respectively, as shown in Fig. 1. As b increases, the minimum at $\chi = -4a\sin\theta/(3\sqrt{6})$ is uplifted. In this case, for a large initial value of χ, the inflaton field may be trapped in the false vacuum.

An interesting case occurs when the parameters satisfy the relation:

$$b = b_0 = \frac{4\cos\theta + a\sin^2\theta}{\sqrt{3}}$$

In this scenario, the minimum of the potential at $\chi = \chi_0 = a\sin\theta/\sqrt{6}$ becomes equal to the local maximum, and thus the false vacuum disappears. This point is the so-called inflection point. At this point, the inflation potential is:

$$V(\chi_0) = \frac{m^2}{4}\left(4\cos^2\theta - a\cos\theta\sin^2\theta + a^2\sin^4\theta\right)$$

Both the first and second derivatives of V vanish at χ_0. We will see shortly that since there is a flat plateau around the inflection point, the predicted spectral index of curvature perturbations as well as the tensor-to-scalar ratio can lie within the 1σ confidence region allowed by Planck 2015. When $a\sin\theta \to 0$ and consequently $\chi_0 \to 0$, the chaotic inflationary model is reproduced.

In addition, it is known that large Hubble-induced mass corrections to the inflation potential can ruin the flatness of the potential. However, such corrections may not be a serious issue in the context of inflection point inflation. The key point is that certain relations among the parameters need to be satisfied in order to find an inflection point in the potential. Adding such terms will modify these relations, but one may still be able to realize inflection point inflation as discussed in Ref. [28].

In this paper we focus on the inflation potential with an inflection point. Since the parameters satisfy the relation (10), there are only three free parameters: a, m, and θ. The inflation potential (8) becomes:

$$V(\chi) = \frac{m^2}{4}\left(4\sqrt{6}a\sin\theta\,\chi^3 + 3a^2\sin^2\theta\,\chi^2 - a\sin^2\theta\cos\theta + 2\cos^2\theta\right)$$

III. SLOW-ROLL INFLATION

The slow-roll parameters are defined as:

$$\epsilon = \frac{1}{2}\left(\frac{V'(\chi)}{V(\chi)}\right)^2, \quad \eta = \frac{V''(\chi)}{V(\chi)}$$

To first order in the slow-roll approximation, the scalar spectral index and tensor-to-scalar ratio are given by:

$$n_s = 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon$$

The e-folding number during inflation is given by:

$$N = \int_{\chi_f}^{\chi_i} \frac{V}{V'} d\chi$$

where the field value at the end of inflation χ_f is determined by $\max\{\epsilon(\chi_f), \eta(\chi_f)\} = 1$. The parameter m is constrained by the amplitude of curvature perturbations:

$$\Delta_R^2 = \frac{1}{24\pi^2}\frac{V}{\epsilon}$$

Using the maximum likelihood value $\Delta_R^2(k_0) = 2.19\times10^{-9}$ from the Planck 2015 data and setting $\theta = 1.55$ and $a = 96$, we can obtain $m \simeq 5.76\times10^{-5}$ in Planck units. In order to achieve an appropriate vacuum structure, the parameters are strongly restricted (see Fig. 4 [Figure 4: see original paper]), so only one parameter remains free. For example, if one sets $\theta = 1.55$, then one can obtain the desired dS vacuum only if $a \simeq 96$, which gives $n_s = 0.968$ and $r = 0.081$ for the e-folding number $N = 60$.

[Figure 2: see original paper]

Figure 2 shows the n_s-r region (pink region) predicted by the model with the e-folding number ranging from $N = 50$ (left boundary line) to $N = 60$ (right boundary line). The contours represent the marginalized joint 68% and 95% confidence level regions for n_s and r at the pivot scale $k = 0.002\,\mathrm{Mpc}^{-1}$ from the Planck 2015 TT+lowP data. It can be seen that the predictions are consistent with the Planck 2015 results.

IV. VACUUM STRUCTURE OF THE POTENTIAL

After inflation the field χ rolls towards $\chi = 0$. However, the global minimum of the potential is no longer at $\chi = 0$ and $\phi = 0$, but the location shifts slightly in the ϕ direction. Such a small deviation from $\phi = 0$ cannot affect the inflationary predictions. One can adjust the values of a and θ to uplift a non-SUSY AdS vacuum to a non-SUSY dS vacuum, which does not violate the no-go theorem. For example, for $a \simeq 96$ and $\theta = 1.55$, there is a global non-SUSY minimum at $\chi = 0$ and $\phi \simeq -0.15$. The desired dS vacuum with $V_0 \sim 10^{-120}$ can be uplifted by a minuscule change of the parameters a and θ. Although this requires fine-tuning, it is not a major problem in the landscape scenario of string theory.

[Figure 3: see original paper]

Figure 3 shows the value of the cosmological constant at the minimum as a function of the parameter a for $\theta = 1.55$ (left panel) and as a function of θ for $a = 96$ (right panel). We can see that as the parameter θ increases or a decreases, it can give rise to a transition between AdS and dS vacuum, passing through Minkowski vacuum. Therefore, in order to obtain an appropriate vacuum structure, we can fine-tune a for a given θ. The relation between θ and a that yields a non-SUSY Minkowski vacuum is shown in Fig. 4. Then the inflationary predictions of n_s and r depend only on the value of θ.

[Figure 4: see original paper]

In addition, supersymmetry is strongly broken at the minimum of the potential. For $\zeta = 1$, $\theta = 1.55$, the superpotential at the minimum is $W \sim 6.0 \times 10^{-5}$, and the gravitino mass is $m_{3/2} \sim 5.76 \times 10^{-5}$ in Planck units, i.e. $m_{3/2} \sim 10^{14}\,\mathrm{GeV}$, which is one order of magnitude higher than in Ref. [19]. Such a scale is much higher than the usual predictions of the supersymmetry breaking scale in supergravity phenomenology.

When the parameter ρ in the superpotential is changed, the desired dS vacuum can be obtained by adjusting a and θ. Moreover, we have checked that the inflationary predictions are independent of ρ. Figure 5 shows the value of the cosmological constant as a function of ρ for $\theta = 1.55$ and $a = 96$.

[Figure 5: see original paper]

V. SUMMARY

The complete cosmological model including both the early acceleration and the present acceleration of the Universe has been investigated in the framework of supergravity with a single chiral superfield. In this model, inflection point inflation in the χ direction has been successfully constructed using the logarithmic Kähler potential (2) and the cubic superpotential (7). The inflationary predictions of the model are consistent with the Planck 2015 results. Such predictions in the n_s-r plane do not overlap those of hilltop quartic inflation and have small overlap with those of natural inflation. Future measurements of temperature and polarization anisotropies of the cosmic microwave background radiation can test and distinguish them.

After inflation, the non-SUSY minimum of the potential can be uplifted to a non-SUSY dS vacuum with vanishingly small vacuum energy $V_0 \sim 10^{-120}$ without violating the no-go theorem by fine-tuning the model parameters. In this model, supersymmetry after inflation is strongly broken and the predicted value of the gravitino mass is much higher than the often assumed TeV mass range.

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