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From hybrid to quadratic inflation with high-scale supersymmetry breaking

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ABSTRACT

Motivated by the reported discovery of inflationary gravity waves by the Bicep2 experiment, we propose an inflationary scenario in supergravity, based on the standard superpotential used in hybrid inflation. The new model yields a tensor-to-scalar ratio $r \simeq 0.14$ and scalar spectral index $n_s \simeq 0.964$, corresponding to quadratic (chaotic) inflation. The important new ingredients are the high-scale, $(1.6\text{–}10) \cdot 10^{13}$ GeV, soft supersymmetry breaking mass for the gauge singlet inflaton field and a shift symmetry imposed on the Kähler potential. The end of inflation is accompanied, as in the earlier hybrid inflation models, by the breaking of a gauge symmetry at $(1.2\text{–}7.1) \cdot 10^{16}$ GeV, comparable to the grand-unification scale.

1. Introduction

The discovery of B-modes in the polarization of the cosmic microwave background radiation at large angular scales by the Bicep2 experiment [1] has created much excitement among inflationary model builders, since this effect can be caused by an early inflationary era with a large tensor-to-scalar ratio $r = 0.16^{+0.06}_{-0.05}$ – after substraction of a dust foreground. Although other interpretations [2,3] of this result are possible, it motivates us to explore how realistic *supersymmetric* (SUSY) inflation models can accommodate such large r values.

The textbook quadratic inflationary model [4] predicting $r = 0.13 - 0.16$, and a (scalar) spectral index $n_s = 0.96 - 0.967$, seems to be in good agreement with Bicep2 (r) and the WMAP [5] and Planck [6] measurements (n_s). Quadratic inflation can be accompanied by a *Grand Unified Theory* (GUT) phase transition in non-supersymmetric inflation models, based either on the Coleman–Weinberg or Higgs [7] potential, which yield predictions for n_s that more or less overlap with the prediction of the quadratic model [8,9]. However, significant differences appear between the predictions of r in these models which can be settled through precision measurements. The consistent supersymmetrization of these models is a highly non-trivial task due to the trans-Planckian values of the inflaton field which aggravate the well-known η-problem within *supergravity* (SUGRA).

One of the more elegant SUSY models which nicely combines inflation with a GUT phase transition is the model of *F-term hybrid inflation* [10,11] – referred to as FHI. It is based on a unique renormalizable superpotential, dictated by a $U(1)$ R-symmetry, employs sub-Planckian values for the inflaton field and can be naturally followed by the breaking of a GUT gauge symmetry, G, such as $G_{B-L} = G_{\rm SM} \times U(1)_{B-L}$ [12] – where $G_{\rm SM} = SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_Y$ is the gauge group of the *Standard Model* (SM) – $G_{\rm LR} = SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)_{B-L}$ [13], and flipped $SU(5)$ [14], with gauge symmetry $G_{5_X} = SU(5) \times U(1)_X$. The embedding of the simplest model of FHI within a GUT based on a higher gauge group may suffer from the production of disastrous cosmic defects which can be evaded, though, by using shifted [15] or smooth [16] FHI.

In the simplest realization of FHI the standard [10] superpotential is accompanied by a minimal (or canonical) Kähler potential. The resulting n_s is found to be in good agreement with the WMAP and Planck data after including in the inflationary potential *radiative corrections* (RCs) [10] and the *soft SUSY breaking* (SSB) linear term [12,18] – with a mass parameter in the TeV range – an SSB mass term for the inflaton in the same energy region can be ignored in this analysis. This scenario yields [12] r values which lie many orders of magnitude below the measurement reported [1] by Bicep2. A more elaborate extension of this standard FHI scenario exploits non-minimal, quasi-canonical Kähler potentials [19,21] or SSB mass of magnitude as large as 10^{10} GeV for the inflaton field [20]. Depending on the underlying assumptions, the predictions for r are considerably enhanced compared to the minimal scenario of Refs. [12,18]. Thus, r values as large as 0.01 to 0.03 have been reported [20,21]; this fact certainly puts r in the observable range, but it still remains an order of magnitude below the Bicep2 measurement – however, see Ref. [22] for models of FHI with Kähler potential not-respecting the R-symmetry.

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Motivated by this apparent discrepancy between the large r values reported by BICEP2 and the predictions of FHI models, we present here a modified scenario of F-term inflation in which a quadratic potential dictates the inflationary phase, thus replicating the predictions of quadratic inflation, employing the well-studied standard superpotential of FHI. The two key elements for successfully implementing this scenario include a judicious choice of the Kähler potential and a high-scale SUSY breaking. In particular, following earlier similar attempts [23] a shift symmetry is imposed on the Kähler potential to protect the inflationary potential from SUGRA corrections which are dangerous due to trans-Planckian inflaton field values. Moreover, we assume that SUSY is broken at an intermediate scale, $\widetilde{m} \sim 10^{13}$ GeV, which can be identified with the SSB mass of the inflaton. In the context of high-scale SUSY [24,25], such a large SSB scale can become consistent with the LHC results [26] on the mass, $m_h \simeq 126$ GeV, of the SM Higgs boson, h. The end of inflation can be accompanied by the breaking of some gauge symmetry such as $G_{\rm LR}$ or $G_{5_{\rm X}}$ with the gauge symmetry breaking scale M assuming values close to the SUSY GUT scale $M_{\rm GUT} \simeq 2.86 \cdot 10^{16}$ GeV.

Below, we describe in Section 2 the basic ingredients of our inflationary scenario. Employing a number of constraints presented in Section 3, we provide restrictions on the model parameters in Section 4. Our conclusions are summarized in Section 5. Henceforth we use units where the reduced Planck scale $m_{\rm P} = 2.44 \cdot 10^{18}$ GeV is taken equal to unity.

2. The inflationary scenario

2.1. The GUT symmetry breaking

In the standard FHI we adopt the superpotential

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

which is the most general renormalizable superpotential consistent with a continuous R-symmetry [10] under which

$$S \to e^{i\varphi} S, \qquad \bar\Phi\Phi \to \bar\Phi\Phi, \qquad W \to e^{i\varphi} W. \tag{2}$$

Here S is a G-singlet left-handed superfield, and the parameters κ and M are made positive by field redefinitions. In our approach $\bar\Phi$, Φ are identified with a pair of left-handed superfields conjugate under G which break G down to $G_{\rm SM}$. Indeed, along the D-flat direction $|\bar\Phi| = |\Phi|$ the SUSY potential, $V_{\rm SUSY}$, extracted – see e.g. Ref. [28] – from W in Eq. (1), reads

$$V_{\rm SUSY} = \kappa^2\Big(\big(|\Phi|^2 - M^2\big)^2 + 2|S|^2|\Phi|^2\Big). \tag{3}$$

From $V_{\rm SUSY}$ in Eq. (3) we find that the SUSY vacuum lies at

$$\big|\langle S\rangle\big| = 0 \quad \text{and} \quad \big|\langle\Phi\rangle\big| = \big|\langle\bar\Phi\rangle\big| = M, \tag{4}$$

where the vacuum expectation values of Φ and $\bar\Phi$ lie along their SM singlet components. As a consequence, W leads to the spontaneous breaking of G to $G_{\rm SM}$.

2.2. The inflationary set-up

It is well-known [10] that W also gives rise to FHI since, for values of $|S| \gg M$, there exist a flat direction

$$s \equiv \sqrt{2}\,{\rm Im}[S] = 0 \quad \text{and} \quad \bar\Phi = \Phi = 0, \tag{5}$$

which provides us with a constant potential energy $\kappa^2 M^4$ suitable for supporting FHI. The inclusion of SUGRA corrections with canonical (minimal) Kähler potential does not affect this result at the lowest order in the expansion of S – due to a miraculous cancellation occurring. The SUGRA corrections with quasi-canonical Kähler potential [19,21] can be kept under control by mildly tuning the relevant coefficients thanks to sub-Planckian S values required by FHI. The resulting $n_{\rm s}$ values can be fully compatible with the data [5,6] but the predicted r [20,21] remains well below the purported measurement reported by BICEP2.

In order to safely implement quadratic inflation, favored by BICEP2, within SUGRA and employing W in Eq. (1), we have to tame the η problem which is more challenging due to the trans-Planckian values needed for the inflaton superfield, S. To this end, we exploit a Kähler potential which respects the following symmetries:

$$S \to S + c \quad \text{and} \quad S \to -S, \tag{6}$$

where c is a real number – cf. Ref. [23]. Namely we take

$$\begin{aligned} K = &-\frac{1}{2}\big(S - S^*\big)^2 + |\Phi|^2 + |\bar\Phi|^2 \\ &+ \frac{(S - S^*)^2}{2\Lambda^2}\big(k_S\big(S - S^*\big)^2 + k_{S\Phi}|\Phi|^2 + k_{S\bar\Phi}|\bar\Phi|^2\big) \\ &+ \frac{1}{\Lambda^2}\big(k_\Phi|\Phi|^4 + k_{\bar\Phi}|\bar\Phi|^4\big) + \cdots. \end{aligned} \tag{7}$$

Here $k_S, k_\Phi, k_{\bar\Phi}, k_{S\Phi}$ and $k_{S\bar\Phi}$ are positive or negative constants of order unity – for simplicity we take $k_{S\Phi} = k_{S\bar\Phi}$ – and Λ is a cutoff scale determined below. Although K is not invariant under the R symmetry of Eq. (2), the fields $\Phi^\alpha = S, \Phi, \bar\Phi$ are canonically normalized, i.e., $K_{\alpha\bar\beta} = \delta_{\alpha\bar\beta}$ – note that the complex scalar components of the various superfields are denoted by the same symbol.

The F-term (tree level) SUGRA scalar potential, $V_{\rm I0}$, of our model is obtained from W in Eq. (1) and K in Eq. (7) by applying the standard formula:

$$V_{\rm I0} = e^K\big(K^{\alpha\bar\beta}{\rm F}_\alpha {\rm F}_{\bar\beta} - 3|W|^2\big), \tag{8}$$

with $K_{\alpha\bar\beta} = K_{,\Phi^\alpha\Phi^{*\bar\beta}}$, $K^{\bar\beta\alpha}K_{\alpha\bar\gamma} = \delta^{\bar\beta}_{\bar\gamma}$ and ${\rm F}_\alpha = W_{,\Phi^\alpha} + K_{,\Phi^\alpha}W$. We explicitly verify that the SUSY vacuum of Eq. (4) remains intact for the choice of K in Eq. (7). Along the field direction in Eq. (5) the only surviving terms of $V_{\rm I0}$ are

$$V_{\rm I0} = e^K\big(K^{SS^*}|W_{,S}|^2 - 3|W|^2\big) = \kappa^2 M^4\left(1 - \frac{3}{2}\sigma^2\right), \tag{9}$$

where the canonically normalized inflaton, σ, is defined by

$$S = (\sigma + is)/\sqrt{2}. \tag{10}$$

As shown from Eq. (9), $V_{\rm I0}$ is not suitable to drive inflation mainly due to the minus sign which renders $V_{\rm I0}$ unbounded from below for large σ's – cf. Ref. [17]. On the other hand, the symmetries in Eq. (6) ensure a complete disappearance of the exponential prefactor in Eq. (9), which could ruin any inflationary solution for large σ's.

A satisfactory solution can be achieved, if we consider an intermediate-scale SSB mass parameter $\widetilde{m}$, whose contribution can exceed the negative contribution to $V_{\rm I0}$ for conveniently selected κ and M. Such a heavy mass parameter is normally generated following the usual SUSY breaking procedures – see e.g. Ref. [27] – provided that the gravitino mass is of similar size and the Polonyi field has canonical Kähler potential. The contributions to the inflationary potential from the SSB effects [12,18] can be parameterized as follows:

$$V_{\rm IS} = \widetilde{m}^2\sum_\alpha\big|\Phi^\alpha\big|^2 - \big({\rm a}_S\kappa M^2 S - \kappa A_\kappa S\Phi\bar\Phi + {\rm c.c.}\big), \tag{11a}$$