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Plateau inflation in SUGRA-MSSM

Girish Kumar Chakravarty [a,*], Gaveshna Gupta [a], Gaetano Lambiase [b,c], Subhendra Mohanty [a]

[a] Theoretical Physics Division, Physical Research Laboratory, Ahmedabad 380009, India
[b] Dipartimento di Fisica "E.R. Caianiello", Universitá di Salerno, I-84084 Fisciano (Sa), Italy
[c] INFN - Gruppo Collegato di Salerno, Italy

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ABSTRACT

We explored a Higgs inflationary scenario in the SUGRA embedding of the MSSM in Einstein frame where the inflaton is contained in the $SU(2)$ Higgs doublet. We include all higher order non-renormalizable terms to the MSSM superpotential and an appropriate Kähler potential which can provide slow-roll inflaton potential in the D-flat direction. In this model, a plateau-like inflation potential can be obtained if the imaginary part of the neutral Higgs acts as the inflaton. The inflationary predictions of this model are consistent with the latest CMB observations. The model represents a successful Higgs inflation scenario in the context of Supergravity and it is compatible with Minimal Supersymmetric extension of the Standard Model.

1. Introduction

Observations of super-horizon ansiotropies in the CMB (COBE, WMAP, Planck) have established that early universe underwent a period of cosmic inflation [1]. Such a period of rapid expansion can solve a number of cosmological problems, such as the horizon, flatness and monopole problems, and generate the initial conditions (homogeneity and isotropy) for the hot big bang evolution of the universe thereafter. It not only explains the scale-invariant and Gaussian spectrum of density fluctuations on superhorizon scales but also provides the seed for the large-scale structures formation in the universe. In particle physics, the issues like dark matter, hierarchy problem, baryogenesis and non-renormalizability of gravity etc. perpetuates and hints towards the existence of new physics beyond standard model. To date the most promising approach to address these key issues is local supersymmetry also known as supergravity (SUGRA).

In the framework of global supersymmetry (SUSY), there have been attempts to construct Higgs field driven inflation models in MSSM (minimal supersymmetric standard model) and NMSSM (next-to-minimal supersymmetric standard model) with or without non-minimal coupling to curvature [2–8]. Within the SUGRA framework, the non-minimal and minimal Higgs inflation models in MSSM and NMSSM are studied in [9–12]. Apart from these SUGRA-(N)MSSM models, there exist a number of inflation models in the framework of Einstein gravity and modified gravity [13,14]. In the standard slow-roll inflationary scenario if one tries to couple the standard model (SM) with Einstein gravity, one finds that the SM Higgs can not be identified as the inflaton because it has a very small self-coupling $\mathcal{O}(10^{-13})$ and light mass $\mathcal{O}(10^{13})$ GeV at Planck scale. Apart from this it predicts large amplitude of the gravity waves which is ruled out by the joint analysis of BICEP2/Keck Arrey and the Planck observations at 95%CL [15]. However, if a non-minimal interaction of the type $\xi H^\dagger H R$ between the inflaton and gravity is considered then for large values of the non-minimal coupling parameter $\xi \sim 10^4$, the inflaton can be identified with the SM Higgs [16,17]. The large ξ allows the self coupling to be $\mathcal{O}(1)$ and therefore Higgs mass ~ 125 GeV at Electroweak scale consistent with the LHC experiment [18,19]. Also this scenario predicts small gravity wave amplitude consistent with the observations. However, in this setting Higgs-graviton scattering suggests the cut off in the theory to be $\Lambda = Mp/\xi$ which is much smaller than the energy scale during inflation $\Lambda = Mp/\sqrt{\xi}$ due to large non-minimal coupling, and therefore this scenario suffers from unitarity violation problem. Various ways to solve this issue are proposed in [20–23]. However at present, this model (and the equivalent Starobinsky model of inflation) is one of the most favored models of inflation due to its small but observationally consistent prediction of tensor to scalar ratio $r \simeq 0.003$.

* Corresponding author.
E-mail addresses: girish20@prl.res.in (G.K. Chakravarty), gaveshna@prl.res.in (G. Gupta), lambiase@sa.infn.it (G. Lambiase), mohanty@prl.res.in (S. Mohanty).

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In the context of Jordan Frame SUGRA embedding of MSSM in presence of non-minimal interaction of Higgs, Einhorn and Jones demonstrated that, under certain assumptions, the slow-roll conditions are not met along β-direction (β being the ratio of two Higgs vevs) for non-zero D-term and therefore slow-roll inflation can not be achieved. On the other hand, in D-flat direction the inflaton potential is negative and therefore unsuitable for inflation. However they found that slow-roll inflation can be realized in NMSSM in which a gauge singlet S is added to existing two Higgs doublets (H_1, H_2) [9]. $\mathcal{N}=1$, $D=4$ Jordan frame supergravity in a superconformal approach [24] with arbitrary scalar-curvature coupling is formulated in [10,25]. The Einhorn and Jones NMSSM inflationary scenario appears as a special case of this formulation where they showed that a strong tachyonic instability ($m_{\bar{S}}^2 > H^2$) in the S-direction during inflation because the scalar potential in D-flat direction has a saddle point at $S=0$ and therefore inflaton has an unstable trajectory at $S=0$ [10]. Later on it was shown in [11], that a higher order correction of the type $-\gamma(S^\dagger S)^2$ to the frame function can cure the problem of tachyonic instability if, for $\gamma \gtrsim 0.003$, one chooses a very small cubic coupling $\sim \mathcal{O}(10^{-5})$ of the gauge singlet in the superpotential. Also the unitarity problem, which exists even in Supergravity generalization [9] of standard non-minimal Higgs inflation scenario [17], seems to be resolved here. The possibility of Higgs inflation in MSSM in context of supergravity with large Higgs field and fractional power potential has been explored in [12].

In the present work we study an inflation model in the SUGRA embedding of the MSSM in Einstein frame. As this will be a minimal SUGRA-MSSM model, so there will not arise issues like tachyonic instabilty and unitarity violation during slow-roll inflationary regime. Unlike the Einhorn and Jones MSSM-SUGRA inflationary scenario, in this model, a D-flat positive inflaton potential can be achieved by adding higher order non-renormalizable terms to the MSSM superpotential $\mu H_u \cdot H_d$. And to obtain the correct inflationary observables, the required flatness of the inflation potential can be achieved when the imaginary part of the neutral Higgs component in the Einstein frame acts as the inflaton.

The organization of the remainder of the paper is as follows. In Section 2, we introduce the model and calculate the F-term and D-term inflaton potential. Then to constrain the inflationary observables, we derive the effective potential in canonical inflaton field basis. In Section 3, we present the model predictions of inflationary observables: in particular spectral index n_s and its running α_s, tensor-to-scalar ratio r and constrain the couplings in the model from CMB normalization. Also we discuss the possibility of the slow-roll potential with respect to the field β. Finally, we present our conclusions in Section 4.

2. The model

In this model we consider the following Kähler potential $K(\phi_i, \phi_i^*)$

$$K = 3M_p^2 \ln\left[1 + \frac{1}{3M_p^2}\left(H_u^\dagger H_u + H_d^\dagger H_d\right)\right], \tag{1}$$

and superpotential $W(\phi_i)$ with higher order non-renormalizable terms

$$W = \mu(H_u \cdot H_d) + \lambda\frac{(H_u \cdot H_d)^2}{M_p}\exp\left(\frac{H_u \cdot H_d}{M_p^2}\right), \tag{2}$$

where H_u and H_d are $SU(2)$ Higgs doublets identified as up-type and down-type Higgs superfields, given by

$$H_u = \begin{pmatrix}\phi_u^+\\ \phi_u^0\end{pmatrix}, \qquad H_d = \begin{pmatrix}\phi_d^0\\ \phi_d^-\end{pmatrix}, \tag{3}$$

and the contraction $H_u \cdot H_d$ is the $SU(2)$ invariant $H_u \cdot H_d \equiv H_u^T i\sigma_2 H_d = \phi_u^+\phi_d^- - \phi_u^0\phi_d^0$. Considering only the neutral components of H_u and H_d to be non-vanishing, we obtain $H_u \cdot H_d = -\phi_u^0\phi_d^0$.[1] The first term $\mu(H_u \cdot H_d)$ in (2) is the MSSM superpotential contains a parameter μ of the order of electroweak scale $\sim O(100)$ GeV whereas Higgs fields are of the order of Planck scale during inflation. Therefore we will neglect the first term in W compared to the second term which includes all higher order terms in $H_u \cdot H_d$.

The scalar potential in SUGRA depends upon the Kähler function $G(\phi_i, \phi_i^*)$ given in terms of superpotential $W(\phi_i)$ and Kähler potential $K(\phi_i, \phi_i^*)$ as

$$G(\phi_i, \phi_i^*) \equiv K(\phi_i, \phi_i^*) + \ln W(\phi_i) + \ln W^*(\phi_i^*), \tag{4}$$

where ϕ_i are the chiral scalar superfields. The scalar potential in Einstein frame is given as $V = V_F + V_D$, where the F-term potential is given by

$$V_F = e^G\left[\frac{\partial G}{\partial \phi^i}K^i_{j*}\frac{\partial G}{\partial \phi_j^*} - 3\right] \tag{5}$$

and the D-term potential is given by

$$V_D = \frac{1}{2}\left[Ref_{ab}^{-1}(\phi_i)\right]D^a D^b, \tag{6}$$

where

$$D^a = -g\frac{\partial G}{\partial \phi_k}(\tau^a)^l_k\phi_l \tag{7}$$

and f_{ab} is related to the kinetic energy of the gauge field thus it must be a holomorphic function of ϕ_i. g is the gauge coupling constant corresponding to each gauge group and τ^a being the corresponding generator. For $SU(2)_L$ symmetry $\tau^a = \sigma^a/2$, where σ^a are Pauli matrices and for $U(1)_Y$ symmetry, τ^a are hypercharge of the fields, i.e. $Y_u = 1$ and $Y_d = -1$.

The kinetic term of the scalar fields is given by

$$\mathcal{L}_{KE} = K_i^{j*}\partial_\mu\phi^i\partial^\mu\phi_j^*, \tag{8}$$

here K^i_{j*} is the inverse of the Kähler metric

$$K_i^{j*} \equiv \frac{\partial^2 K}{\partial\phi^i\partial\phi_j^*}. \tag{9}$$

Using (3), the Kähler potential (1) and superpotential (2) reduce to

$$K = 3\ln\left[1 + \frac{\phi_u\phi_u^* + \phi_d\phi_d^*}{3}\right], \tag{10}$$

$$W = \lambda(-\phi_u\phi_d)^2\exp(-\phi_u\phi_d), \tag{11}$$

respectively. Considering the canonical form the gauge kinetic function $f_{ab} = \delta_{ab}$ for simplicity, the D-term potential becomes

$$V_D = \frac{(g_1^2 + g_2^2)}{8\left(1 + \frac{\phi_u^*\phi_u + \phi_d^*\phi_d}{3}\right)^2}\left[\phi_u^*\phi_u - \phi_d^*\phi_d\right]^2, \tag{12}$$

where g_1 and g_2 are gauge couplings of $U(1)_Y$ and $SU(2)_L$ symmetries, respectively. It is convenient to parametrize the complex fields ϕ_u and ϕ_d as $\phi_u = \phi\sin(\beta)$ and $\phi_d = \phi\cos(\beta)$. Here, we shall treat ϕ as a complex field and β to be real field. For the given parametrization, the D-term potential can be given as

[1] For simplicity, we shall omit the superscript '0' and work in $M_p = (8\pi G)^{-1/2} = 1$ unit from here onwards.