



Multi-natural inflation

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ABSTRACT

We propose a multi-natural inflation model in which the single-field inflaton potential consists of two or more sinusoidal potentials that are comparable in size but have different periodicity with a possible non-zero relative phase. The model is versatile enough to realize both large-field and small-field inflation. We show that, in a model with two sinusoidal potentials, the predicted values of the spectral index and tensor-to-scalar ratio lie within the 1σ region of the Planck data. In particular, there is no lower bound on the decay constants in contrast to the original natural inflation. We also show that, in a certain limit, multi-natural inflation can be approximated by a hilltop quartic inflation model.

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1. Introduction

The standard Λ CDM cosmology has been strongly confirmed by recent Planck observations [1]. In particular, the observed data is consistent with almost scale-invariant, adiabatic and Gaussian primordial density perturbations. This strongly suggests that our Universe experienced the inflationary expansion described by a simple (effectively) single-field inflation [2,3].

Among many inflation models so far, there is an interesting class of models called large-field inflation in which sizeable tensor perturbations are generated. One of the large-field inflation models is chaotic inflation [4], and by now there are many concrete realizations of the chaotic inflation in supergravity [5–11] and superstring theory [12,13] (see also e.g. Refs. [14–17] for the development after the Planck results).

The tensor-to-scalar ratio r as well as the spectral index n_s are tightly constrained by the Planck data combined with other CMB observations as [1]

$$n_s = 0.9600 \pm 0.0071, \quad (1)$$

$$r < 0.11 \quad (95\% \text{CL}). \quad (2)$$

While n_s is determined by the shape of the inflaton potential, r is determined by the inflation energy scale, as long as the slow-roll inflation is assumed. Then the inflation scale is related to r as

$$H_{\text{inf}} \simeq (8.5 \times 10^{13} \text{ GeV}) \left(\frac{r}{0.11} \right)^{\frac{1}{2}}, \quad (3)$$

where H_{inf} denotes the Hubble parameter during inflation, and the ongoing and planned CMB observations will be able to probe $r \gtrsim 10^{-3}$.

In a single-field inflation model with a canonical kinetic term, there is a relation between r and the field excursion of the inflaton [18]. In particular, the inflaton field excursion exceeds the Planck scale if $r \gtrsim 0.01$, which places a strict requirement on inflation model building to have good control over inflaton field values greater than the Planck scale. One possibility is to impose an approximate shift symmetry on the inflaton so as to keep the inflaton potential sufficiently flat at super-Planckian values. The simplest realization is natural inflation [19,20], in which the inflaton is a (pseudo) Nambu–Goldstone (NG) boson, and its potential takes the following form,

$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f)], \quad (4)$$

where the sinusoidal potential arises from some non-perturbative effects which explicitly break the shift symmetry. The predicted values of n_s and r are consistent with the Planck data for $f \gtrsim 5M_p$ [1], where $M_p \simeq 2.4 \times 10^{18} \text{ GeV}$ is the reduced Planck mass.

In this Letter we consider an extension of natural inflation by adding another sinusoidal potential which modifies the inflaton dynamics at large field values, leading to different predictions of n_s and r .¹ This is possible if there are multiple sources for the explicit breaking of the shift symmetry of the inflaton [21]. We shall

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¹ Increasing the number of parameters is not favored from the Bayesian point of view.

give concrete examples later.² Our model is versatile enough to realize both large-field and small-field inflation. We will show that the predicted values of n_s and r are consistent with the Planck data for a wide range of the decay constant. In particular, the sub-Planckian decay constant $f \ll M_p$ is allowed by the Planck data at 2σ ; the model is approximated by a hilltop quartic inflation model [3] in this limit.

Lastly let us briefly mention related works in the past. In the original natural inflation, the required decay constant $f \gtrsim 5M_p$ may be beyond the range of validity of an effective field theoretic description. One solution is to consider multiple axions (or NG bosons); in Ref. [24], it was pointed out that the effective large decay constant can be realized, leading to the (effectively) single-field natural inflation (4). See also Refs. [25,26] for other ways to relax the bound. Using pseudo NG bosons, multi-field inflation models such as hybrid inflation were proposed in Refs. [27]. In string theory, there are racetrack inflation [28], N -flation [29], and axion monodromy [12,13], in which the axions play the role of the inflaton; the first two models are multi-field inflation models, and the last one is equivalent to a linear-term chaotic inflation. Our model is a single-field inflation model based on multiple sinusoidal functions, and the inflaton potential as well as the predicted n_s and r are different from those of the natural inflation and the above models. Later we will briefly discuss a possible UV completion of our model.

2. Multi-natural inflation

2.1. Natural inflation

Here let us summarize the results of natural inflation. Natural inflation arises from a broken global symmetry in order to generate a very flat potential necessary for inflation [19,20]. The inflaton potential has the form

$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f)]. \quad (5)$$

In a standard slow roll analysis there are two sufficient conditions for inflation, given by

$$\varepsilon(\phi) \equiv \frac{M_p^2}{2} \left(\frac{V_\phi}{V} \right)^2 \ll 1, \quad \eta(\phi) \equiv M_p^2 \left(\frac{V_{\phi\phi}}{V} \right) \ll 1, \quad (6)$$

where subscripts of ϕ denote derivatives with respect to the scalar field.

For natural inflation, the parameters ε and η become

$$\varepsilon(\phi) = \frac{1}{2} \left(\frac{M_p}{f} \right)^2 \left[\frac{\sin(\phi/f)}{1 - \cos(\phi/f)} \right]^2 \quad (7)$$

and

$$\eta(\phi) = \left(\frac{M_p}{f} \right)^2 \left[\frac{\cos(\phi/f)}{1 - \cos(\phi/f)} \right]. \quad (8)$$

To first order, the spectral index n_s and the tensor-to-scalar ratio r can then be calculated using (see e.g. Ref. [36]),

$$n_s = 1 - 6\varepsilon + 2\eta \quad (9)$$

and

$$r = 16\varepsilon. \quad (10)$$

The predicted (n_s, r) for natural inflation is consistent with the Planck data for $f \gtrsim 5M_p$ [1].

² Although our model is a simple toy model at this stage, the implementation in string-inspired supergravity [22] as well as its implications for a large running spectral index [23] were studied after the submission of this paper.

2.2. Multi-natural inflation

In multi-natural inflation we consider an inflaton potential that consists of two or more sinusoidal functions. As a minimal extension, let us consider a potential with two sinusoidal terms. The potential takes the form³

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta), \quad (11)$$

where C is a constant that shifts the minimum of the potential to zero and θ is a non-zero relative phase. The last term shifts the potential minimum from the origin to $\phi = \phi_{\min}$, and also modifies the potential shape. This model is reduced to the original natural inflation in the limit of either $\Lambda_2 \rightarrow 0$ or $f_2 \rightarrow \infty$. As we shall see later, such two sinusoidal terms could be generated by two different non-perturbative sources. To simplify notation we set $f_1 = f$ and $\Lambda_1 = \Lambda$, and relate the parameters by,

$$f_2 = Af, \quad (12)$$

$$\Lambda_2^4 = B\Lambda^4, \quad (13)$$

where A and B are real and positive constants. Although in general Λ_2 , f_2 and θ are arbitrary parameters, we only investigate cases for which the second sinusoidal term gives relatively small perturbations, and the resulting potential is free of local minima so as to avoid the inflaton becoming trapped in a false vacuum. In general there are many other local minima and maxima at different values of ϕ . The stability of the vacuum at $\phi = \phi_{\min}$ is assumed in the following analysis.

We have solved the inflaton dynamics numerically. To be explicit, we have solved the inflaton equation of motion, $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$, with the inflaton potential given by (11), until the end of the accelerated expansion of the Universe. Then, we have identified the timing when the number of e-folds until the end of the inflation N is equal to 50 or 60, i.e., when the cosmological perturbations with the pivot scale, $k = 0.002 \text{ Mpc}^{-1}$, exited the horizon, and evaluated the slow-roll parameters at that time. We thus obtain the predicted values of (n_s, r) for a given inflaton potential. By repeating this procedure for different values of f , we obtain a line in the (n_s, r) -plane.

The resulting n_s and r predictions for varying values of Λ_2 and θ are shown in Figs. 1 and 2, respectively. Their corresponding potentials along with the positions on the potential for e-folding number $N = 60$ for various values of f/M_p are also shown.

In Fig. 1, we set $A = 0.50$ and $\theta = 2\pi/3$, varying $B = 0.30, 0.35$ and 0.40 . From the left panel, we can see that the predicted (n_s, r) approach those of the original natural inflation as f increases. This is because, in the limit of large f , both models are reduced to the quadratic chaotic inflation. Interestingly, for moderately large f , the predicted curves come closer to the center values of the Planck results, compared to the natural inflation. We also note that, for $f \gtrsim 5M_p$, the behavior of (n_s, r) is similar to that of the polynomial chaotic inflation [15]. This is not surprising because, if one expands the inflaton potential around the potential minimum, multi-natural inflation can be approximated by the polynomial chaotic inflation for some choice of the model parameters. In the right panel, we see that, for smaller values of f , the perturbation crosses the horizon scale further up the potential and, consequently, where V_ϕ/V is relatively small. Since $r = 16\varepsilon \propto (V_\phi/V)^2$, r decreases as f decreases. The behavior of n_s is more complicated since both the slope and curvature of the potential (through $\eta \propto V_{\phi\phi}/V$) play a role. As f becomes very large ($f \gtrsim 10M_p$), the potential at horizon

³ The potential of this form with f_1/f_2 being an irrational number was considered in Ref. [37] in a context of solving the cosmological constant problem.

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