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Aligned natural inflation with modulations

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ABSTRACT

The weak gravity conjecture applied for the aligned natural inflation indicates that generically there can be a modulation of the inflaton potential, with a period determined by sub-Planckian axion scale. We study the oscillations in the primordial power spectrum induced by such modulation, and discuss the resulting observational constraints on the model.

1. Introduction

Inflation in the early universe explains the flatness, horizon, and entropy problems in the standard big bang cosmology, while providing a seed of the large scale structure and the anisotropy in cosmic microwave background (CMB) radiation observed today. If the energy scale of inflation is high enough, the de Sitter quantum fluctuation of spacetime metric can give rise to a primordial tensor perturbation which might be large enough to be detectable in the near future. On the other hand, such high scale inflation demands a super-Planckian excursion of the inflaton [1], so a scalar potential which is flat over a super-Planckian range of the inflaton field. In view of the UV sensitivity of scalar potential, this is a nontrivial condition required for the underlying theory of inflation.

As is well known, a pseudo-Nambu–Goldstone boson ϕ can have a naturally flat potential over a field range comparable to its decay constant f. The low energy potential is protected from unknown UV physics under the simple assumption that UV physics respects an approximate global symmetry which is non-linearly realized in the low energy limit as $\phi/f \to \phi/f + c$, where c is a real constant. In the natural inflation scenario [2,3], inflaton is assumed to be a pseudo-Nambu–Goldstone boson having a sinusoidal potential generated by non-perturbative dynamics. Then the inflationary slow-roll parameters have a size of $\mathcal{O}(M_{\rm Pl}^2/f^2)$, and therefore the model requires $f \gg M_{\rm Pl}$, where $M_{\rm Pl} \simeq 2.4\times 10^{18}$ GeV is the reduced Planck scale. Although it appears to be technically natural within the framework of effective field theory, there has been a concern that the required super-Planckian decay constant may not have a UV completion consistent with quantum gravity [4]. Also, previous studies on the axion decay constants in string theory suggest that generically $f < M_{\rm Pl}$, at least in the perturbative regime [5–7].

Nevertheless, one can engineer the model to get a super-Planckian axion decay constant within the framework of effective field theory [8–11], or even in string theory [12–14]. An interesting approach along this direction is the aligned natural inflation [8, 15–24]. In this scheme, initially one starts with multiple axions, all having a sub-Planckian decay constant. Provided that the axion couplings are aligned to get a specific form of axion potential [8], a helical flat direction with multiple windings is formed in the multi-dimensional field space with sub-Planckian volume. If the number of windings is large enough, this flat direction can have a super-Planckian length, so result in an inflaton with super-Planckian effective decay constant.

Recently there has been a renewed interest in the implication of the weak gravity conjecture (WGC) [25–29] for the aligned natural inflation. The WGC was proposed initially for $U(1)$ gauge interaction [4], implying that there should exist a charged particle with mass m and charge q satisfying $q/m \geq 1/M_{\rm Pl}$, so the gravity should be weaker than the $U(1)$ gauge force.[1] When translated to axions, the WGC suggests that there should exist an instanton which couples to the corresponding axion with a strength stronger than the gravity. This leads to an upper bound on the decay constant of individual axion, which is given by $f \leq M_{\rm Pl}/S_{\rm ins}$, where $S_{\rm ins}$ is the Euclidean action of the instanton [4].

[1] There are two different versions of the WGC, the strong and the mild. The strong WGC requires that the mass and charge of the lightest charged particle satisfy $q/m \geq 1/M_{\rm Pl}$, while in the mild version the required particle with $q/m \geq 1/M_{\rm Pl}$ does not have to be the lightest charged particle. Here we are mostly concerned with the mild version generalized to the case of multiple axions.

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It has been noticed [30] that for models with multiple $U(1)$ gauge interactions, the WGC often leads to a stronger constraint on the charge-to-mass ratios than the one obtained by considering the individual $U(1)$ separately. The reason is that the WGC applies for all directions in the multi-dimensional charge space, not just for the charge vectors of the individual particles. For the case of multiple axions, one similarly obtains a stronger constraint on the axion couplings [27]. One then finds [25–27,29] that the alignment mechanism *cannot* be compatible with the constraint from the WGC *if* the axion–instanton couplings required by the WGC coincide with the couplings generating the axion potential that implements the alignment mechanism.

A simple solution to this problem is that some of the instantons required by the WGC do not participate in implementing the alignment mechanism [25]. Since some part of the axion potential for the alignment mechanism could be induced by either perturbative effects such as flux or other forms of nonperturbative effects such as hidden gaugino condensation, this appears to be a rather plausible possibility. Indeed, known string theoretic construction of the aligned natural inflation involves an instanton which is not relevant for the alignment mechanism [31–35,54]. Yet, such instanton can generate an additional axion potential which does not affect the alignment mechanism as it corresponds to a subleading correction, but may give rise to an observable consequence in the precision CMB data. As we will see, in the presence of such instanton, the low energy inflaton potential is generically given by[2]

$$V_{\rm eff}(\phi) = \Lambda_{\rm eff}^4\left[1-\cos\left(\frac{\phi}{f_{\rm eff}}\right)\right] + \Lambda_{\rm mod}^4\left[1-\cos\left(\frac{\phi}{f_{\rm mod}}+\delta\right)\right], \quad (1)$$

where the first term with $f_{\rm eff} \gg M_{\rm Pl}$ corresponds to the dominant inflaton potential generated by a dynamics implementing the alignment mechanism, while the second term with $f_{\rm mod} \ll M_{\rm Pl}$ and $\Lambda_{\rm mod}^4 \ll \Lambda_{\rm eff}^4$ is a subleading modulation generated by an instanton which is required by the WGC, but does not participate in implementing the alignment mechanism.

In this paper, we first provide an argument implying that the presence of subleading modulation in the inflaton potential is a generic feature of the aligned natural inflation consistent with the WGC. We then study the observable consequences of such modulation, while focusing on the parameter region favored by theoretical or phenomenological considerations. Specifically we consider the region $f_{\rm eff} \gtrsim 5M_{\rm Pl}$ to avoid a fine tuning of the initial condition, while being consistent with the CMB data [36], and $f_{\rm mod} \lesssim \frac{M_{\rm Pl}}{2\pi}$ which is suggested by the WGC. Observable consequences of modulation in the axion monodromy inflation were studied extensively in [37–41], where it was noticed that modulation can lead to an oscillatory behavior of the power spectrum of the primordial curvature perturbation. We examine the constraint from CMB on modulations for the case of aligned natural inflation, and find that the CMB data restrict the amplitude of modulation as $\Lambda_{\rm mod}^4/\Lambda_{\rm eff}^4 \lesssim \mathcal{O}(10^{-4}\text{–}10^{-6})$, depending upon the value of $f_{\rm mod}$.

It has been pointed out that modulation may significantly change the predicted value of the tensor-to-scalar ratio r in natural inflation scenario [31,54]. We find that the change of the predicted value of r due to modulation is minor, e.g. at most of $\mathcal{O}(10)\%$, if the amplitude of modulation is within the range compatible with the observed CMB data.[3] On the other hand, including an oscillatory part of the curvature power spectrum in data-fitting analysis, we find that a larger parameter region in the (n_s, r) plane can be compatible with the CMB data compared to the case without an oscillatory piece, where n_s denotes the spectral index of the curvature power spectrum. This makes it possible that the potential tension between the CMB data and the natural inflation scenario is ameliorated under the assumption that there exists a modulation of the inflaton potential yielding a proper size of oscillatory piece in the curvature power spectrum.

This paper is organized as follows. In section 2, we revisit the weak gravity conjecture applied for models with multiple axions, as well as the Kim–Nilles–Peloso (KNP) alignment mechanism. We argue that a small modulation of the inflaton potential is a generic feature of the aligned natural inflation compatible with the WGC. In section 3, we study the oscillations in the curvature power spectrum induced by modulation, and discuss the constraints on the model from the CMB data. Section 4 is the conclusion.

2. Weak gravity conjecture and the KNP alignment

In this section, we revisit the weak gravity conjecture applied for the aligned natural inflation, as well as the alignment mechanism. As we will see, the WGC implies that generically there can be a small modulation of the inflation potential, with a period determined by sub-Planckian axion scale.

Let us begin with the constraint on the axion couplings for models with multiple axions, which is referred to the *convex hull condition* (CHC) [27,30]. It requires first that in the presence of N axions,

$$\vec{\phi} = (\phi_1, \phi_2, \ldots, \phi_N),$$

there exist corresponding (at least) N instantons generating axion-dependent physical amplitudes as

$$\mathcal{A}_I \propto \exp\left(-S_I + i\vec{q}_I \cdot \vec{\phi}\right) \quad (I = 1, 2, \ldots, N), \quad (2)$$

where S_I denotes the Euclidean action of the I-th instanton, and the axion–instanton couplings $\vec{q}_I$ are linearly independent from each other. It is always possible to parametrize the axion–instanton couplings as

$$\vec{q}_I = \left(\frac{n_{I1}}{f_1}, \frac{n_{I2}}{f_2}, \ldots, \frac{n_{IN}}{f_N}\right), \quad (3)$$

where f_i $(i = 1, 2, \ldots, N)$ can be identified as the decay constant of the i-th axion, and n_{Ii} are integer-valued model parameters, so the instanton amplitudes are periodic under the axion shift:

$$\phi_i \to \phi_i + 2\pi f_i. \quad (4)$$

In the following, we will assume for simplicity that all instanton actions have a common value bigger than the unity,[4] e.g.

$$S_I = S_{\rm ins} > 1.$$

By taking an analogy to the case of multiple $U(1)$ gauge fields, it has been argued that the axion–instanton couplings should be stronger than the gravity in *all* directions in the N-dimensional coupling space. Specifically, one finds that the convex hull spanned by

[2] The so-called multi-natural inflation scenario [42,43] assumes the same form of inflaton potential, but with $f_{\rm mod} \gtrsim M_{\rm Pl}/2\pi$ and $\Lambda_{\rm eff} \gtrsim \Lambda_{\rm mod}$, whose observational consequences are different from our case with $f_{\rm mod} < M_{\rm Pl}/2\pi$ and $\Lambda_{\rm eff} \gg \Lambda_{\rm mod}$.

[3] For an alternative scenario which can give rise to a significantly smaller r within the (aligned) natural inflation, see [44–46].

[4] Usually $S_I \propto 1/g^2$ for a certain coupling constant g, and then a strong–weak coupling duality on g may provide a firm basis on our assumption that $S_{\rm ins} > 1$.