Running spectral index from shooting-star moduli

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Abstract: We construct an inflationary model that is consistent with both large non-Gaussianity and a running spectral index. The scenario of modulated inflation suggests that modulated perturbation can induce the curvature perturbation with a large non-Gaussianity, even if the inflaton perturbation is negligible. Using this idea, we consider a multi-field extension of the modulated inflation scenario and examine the specific situation where different moduli are responsible for the perturbation at different scales. We suppose that the additional moduli (shooting-star moduli) is responsible for the curvature perturbation at the earlier inflationary epoch and it generates the fluctuation with $n > 1$ spectral index at this scale. After a while, another moduli (or inflaton) takes the place and generates the perturbation with $n < 1$. At the transition point the two fluctuations are comparable with each other. We show how the spectral index is affected by the transition induced by the shooting-star moduli.

Contents

1. Shooting-star moduli

String theory and supersymmetric models generically predict many flat directions and moduli that determine the coupling constants in the effective action. Assuming that at least a few of these fields are light during inflation, the vacuum fluctuations of the light scalar fields $\mathcal{M}_i$ are unstable and appear as classical random Gaussian inhomogeneities with an almost scale-free spectrum of amplitude $\delta\mathcal{M}_i \simeq H_I/2\pi$, where H_I is the Hubble parameter during inflation. Then the wavelength of the fluctuations is stretched during inflation over the Hubble horizon after inflation. This is the reason why we believe in this paper that the "modulated fluctuations" $\delta\mathcal{M}_i$ can be related in many different ways to the cosmological curvature perturbation in the present Universe. Let us first review the basic idea of modulated inflation that has been discussed by us in ref. [1]. Our starting point is the conventional equation for the number of e-foldings elapsed during inflation;

$$N = \frac{1}{M_p^2} \int_{\phi_e}^{\phi_N} \frac{V}{V_\phi} d\phi, \tag{1.1}$$

where ϕ_N is the value of inflaton field ϕ corresponding to N e-foldings, and ϕ_e denotes the end-point of inflation where the slow-roll condition is violated. Using δN-formula we can see that the fluctuation of a common spectrum $\delta\phi_N = H_I/2\pi$ induces the spectrum of the density perturbation given by

$$\delta_H^2 = \frac{4}{25}(\delta N)^2 = \frac{4}{25}\left(\frac{V}{M_p^2 V_\phi}\frac{H_I}{2\pi}\right)^2, \tag{1.2}$$

where we followed the notations given in the textbook [2]. Of course, in more generic situation one may expect several scalar fields (moduli or flat directions) that may play a similar role during inflation. The first specific example in this direction has been given by Bernardeau et al. [3] for modulated couplings in hybrid-type inflation, assuming that

ϕ_e depends on such a light field. Note that the word "modulated fluctuations" was introduced by Kofman in ref. [4]. Then Lyth [5] considered a multi-inflaton model of hybrid inflation and encounters another realization of "generating the curvature perturbation at the end of inflation". And more recently, we considered trapping inflation combined with inhomogeneous preheating[1] and found a different mechanism for generating the curvature perturbation at the end of inflation [6]. The multi-inflaton models [5, 6] are very useful for brane inflation, since there can be several directions for the fluctuation of the moving brane, as well as of the target brane. See ref. [7] for more details of the fluctuation related to the target brane. In fact, the multi-inflaton model has been applied to brane inflation to solve the serious η-problem in string theory [7]. Note that in string theory it is very hard to find a light field that is perfectly suitable for the conventional single-field inflation, especially when the potential of moduli fields are determined by some calculable mechanism of moduli stabilization. It is therefore very helpful if a light field other than the inflaton can contribute to the curvature perturbation. In fact, there are many alternatives for the conventional scenario, in which the inflaton fluctuation $\delta\phi \neq 0$ plays no role in generating the cosmological fluctuation. In those "alternatives", light fields other than the inflaton play crucial roles in generating the cosmological perturbation. For example, cosmological perturbation can be generated (1) long after inflation (curvatons) [8 – 10], (2) during preheating (inhomogeneous preheating) [11], or (3) during reheating (inhomogeneous reheating) [12], and also by combining (1) and (2) one can generate the initial perturbation of the curvaton from inhomogeneous preheating [13]. Note that large non-Gaussianity can be generated during inhomogeneous preheating, and moreover, even if the non-Gaussianity is not generated by the inhomogeneous preheating, small ratio $r \equiv \rho_\chi / \rho_{\text{total}} \ll 1$ at the decay can lead to a large non-Gaussianity $f_{nl} \propto r^{-1}$. This mechanism is similar to the one that has been discussed for curvatons [14].[2] Here ρ_χ denotes the energy density of the preheat field. As a result, f_{nl} in inhomogeneous preheating scenarios can be large and can take either (positive or negative) sign. One of the reasons that we consider such "alternatives" is that a large non-Gaussianity of the spectrum may be confirmed by the observation [16].

The idea of modulated inflation in ref. [1] is very simple. Let us look at the equation (1.1). Besides the inflation fluctuations related to $\delta\phi_N$ and $\delta\phi_e$, fluctuations induced by other components may generate curvature perturbation if these components are modulated during inflation. Based on this simple idea, we considered an alternative mechanism for generating the curvature perturbation [1], which relies neither on $\delta\phi_N$ nor $\delta\phi_e$. This distinguishes modulated inflation from the previous scenario of modulated fluctuation [3].

Besides the large non-Gaussianity that may exclude conventional single-field inflation, there is another problem related to the running of the spectral index. The Wilkinson Microwave Anisotropy Prove(WMAP) data favor primordial cosmological fluctuation with a spectral index $n > 1$ at large scale and $n < 1$ at smaller scale. One way to generate the fluctuation with the required running spectrum is to consider different forms of inflationary potential at different scales, and then merge them at the scale where n passes through

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[1]Note that thermal inflation is induced by "thermal trapping", while trapping inflation is induced by "trapping by the preheat field".

[2]See also ref. [15].

unity. This possibility of running spectral index has been discussed by many authors [17] for conventional inflationary scenario. However, these models may be excluded by a large non-Gaussianity parameter [16], since conventional inflationary scenario typically generates Gaussian perturbation.

Therefore, our motivation in this paper is to construct a first concrete example that is consistent with both large non-Gaussianity and a running spectral index. In this paper, we consider hybrid inflation with a simple moduli-dependent inflaton mass

$$m^2(\mathcal{M}_i) \equiv m_0^2 \left(1 + \beta_1 \frac{\mathcal{M}_1^2}{M_*^2} + \beta_2 \frac{\mathcal{M}_2^2}{M_*^2} \right), \tag{1.3}$$

which induces fluctuation related to δV_ϕ.[3] For simplicity, we consider a specific case in which the inflaton fluctuation is negligible.[4] In this specific example, $\mathcal{M}_2$ is the "shooting-star" moduli that has the positive η-parameter $\eta_2 > 0$ and is responsible for the running of the spectral index at a larger scale. We assume that the potential of the moduli fields are dominated by simple quadratic term

$$V(\mathcal{M}_i) = \frac{\eta_i H_I^2 \mathcal{M}_i^2}{2}. \tag{1.4}$$

Then, from the equation of motion we find that during inflation the value of the field $\mathcal{M}_2$ decreases as

$$\mathcal{M}_2 \propto e^{-\eta_2 \Delta N}, \tag{1.5}$$

where ΔN is the number of e-foldings elapsed during the evolution. We consider a parameter space where the effective mass that may appear from the interaction with the inflaton is not important.[5] At the earlier stage of inflaton, where the perturbation at the larger scale is generated, the fluctuation of the shooting-star moduli (i.e., $\delta \mathcal{M}_2$) generates the dominant part of the cosmological fluctuation which has the spectral index $n \simeq 2\eta_2 > 1$. Note that the derivative of N with respect to $\mathcal{M}_2$ is given by

$$N_2 \simeq 2N\beta_2 \left(\frac{\mathcal{M}_2}{M_*^2} \right), \tag{1.6}$$

which *decreases* with time. On the other hand, we suppose that $\mathcal{M}_1$ has a η-parameter $\eta_1 < 0$ and *increases* slowly during inflation. As a result, the fluctuation induced by the moduli $\mathcal{M}_1$ has the spectral index $n \simeq 2\eta_1 < 1$. The derivative of N with respect to $\mathcal{M}_1$ is given by

$$N_1 \simeq 2N\beta_1 \left(\frac{\mathcal{M}_1}{M_*^2} \right), \tag{1.7}$$

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[3]Note that these moduli fields are not the inflaton in hybrid-type inflation, since they cannot lead to the waterfall. In this respect, we are not considering a multi-field extension of the hybrid-type inflation model. Moreover, the inflaton fluctuation is not important in the modulated inflation scenario. Modulated inflation can be discriminated from the multi-inflaton model by these characteristics.

[4]Of course, the inflaton fluctuation can collaborate with "shooting-star" moduli. We will consider this possibility in appendix A.

[5]See appendix B for more details.

which *increases* with time. Here we introduce dimensionless parameters

$$r_1 \equiv \frac{N_1^2}{N_1^2 + N_2^2}$$

$$r_2 \equiv \frac{N_2^2}{N_1^2 + N_2^2}, \tag{1.8}$$

and consider the spectral index [2]

$$n - 1 = -\left(\frac{M_p V_a}{V}\right)^2 - \frac{2}{M_p^2 N_a^2} + 2\frac{M_p^2 N_a N_b V_{ab}}{V N_d N_d}$$

$$\simeq 2\eta_1 r_1 + 2\eta_2 r_2, \tag{1.9}$$

where the subscript of the potential means the derivative with respect to the corresponding field. Terms related to the ϵ-parameter is discarded because they are small in this case. Looking at eq. (1.9), we find that at the transition from the $\mathcal{M}_2$-dominated perturbation to the $\mathcal{M}_1$-dominated one, there is a "jump" in the spectral index. Note that the transition is a natural consequence of our set-up, and the time of the transition depends on the initial condition. The running of the spectral index is given by

$$\frac{dn}{d\ln k} \simeq -4\eta_2^2 r_2 \tag{1.10}$$

for $|\eta_2| \gg |\eta_1|$ and $r_1 \sim r_2$, which can be applied to the data at the scale $k = 0.002 Mpc^{-1}$.

Let us apply our results to the data. Since we are considering a model in which the perturbation at the smaller scale is generated by the $\mathcal{M}_1$-perturbation, we find $\eta_1 < 1$ and $r_2 \ll 1$ at that smaller scale. Here we can use the WMAP3 data [18] at the scale $k = 0.05 Mpc^{-1}$;

$$n_{0.05} = 0.948^{+0.014}_{-0.018} \; , \; \frac{dn}{d\ln k} \sim 0. \tag{1.11}$$

On the other hand, the value of the spectral index and its running at the larger scale $k = 0.002 Mpc^{-1}$ is given by

$$n = 1.21^{+0.13}_{-0.16} \; , \; \frac{dn}{d\ln k} = -0.102^{+0.050}_{-0.043}, \tag{1.12}$$

which leads to the condition

$$\eta_2 \sim 0.25 \tag{1.13}$$

and $r_2(k) \sim 0.4$ at $k = 0.002 Mpc^{-1}$. Of course, there are several ambiguities in this naive calculation. In addition to the ambiguities in the above data for the value of the spectral index and the running, the ambiguity may also arise in the value of the scale parameter k. In any case, we may conclude that the spectral index and the running at the scale $k = 0.002 Mpc^{-1}$ can be generated by the shooting-star moduli, with the cost

of tuning parameters and the initial condition.[6] Note also that the jump in the spectral index may occur several times during inflation, if there are many shooting-star moduli(or flat directions) in the theory.

2. Conclusions and discussions

We have studied a new class of modulated inflation that generates the running of the spectral index at a larger scale. We have shown a concrete example of modulated inflation in which the "shooting-star" moduli generates the running of the spectral index at a larger scale. As far as we know, the present model is the first and simple concrete example of the inflation scenario that is consistent with both the large non-Gaussianity and the running spectral index. Perhaps one can construct a model in which a similar transition occurs for curvatons, inhomogeneous preheating and inhomogeneous reheating scenarios. In fact, in these alternative scenarios the spectral index can be related to the η-parameter of the light field [10]. An obvious deficit of the modulated scenario may be the famous moduli problem. Late-time entropy production such as thermal inflation [2] may solve this problem, but thermal inflation may not work if the energy scale of the primordial inflation is very low. On the other hand, if the cosmological perturbation in modulated inflation is due to a flat direction of a supersymmetric gauge theory, the flat direction (i.e, $\mathcal{M}_i$) can decay fast through preheating. In this case, the moduli problem may not occur. Note that the multi-field models such as ref. [5, 6, 11] are free from the moduli problem because the light direction gets large mass soon after the inflation. Of course, it is always very hard to construct inflation model that works with a low inflationary scale [9, 10, 19] despite the fact that low-scale inflation may become important if the gravitational effect is observed at the Large Hadron Collider(LHC).

Acknowledgments

A. Shooting-star moduli that helps conventional inflation

The shooting-star moduli may induce a transition from the moduli-dominated perturbation to the inflaton-dominated one, -and vice versa. Therefore, the idea of the shooting-star moduli may be useful in explaining the running of the spectral index in conventional inflation model.

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[6]Although the δN formula that relates the final curvature perturbation on comoving slices to the inflaton perturbation on flat slices after horizon crossing is a very powerful tool for our computation, there are at least two possibilities that must be examined carefully. One is the inhomogeneous reheating [12] that may arise due to the modulated decay rate ($\delta\Gamma$) of the inflaton field, and the other is the possibility of generating the curvature perturbation at the end of inflation. Of course, the latter is a part of the δN formula, however the effect may not be obvious in a naive calculation. We added appendix B and C to discuss more precise conditions for our results.

For example, let us consider a case in which the inflaton perturbation is responsible for the curvature perturbation at the scale smaller than $k = 0.05 Mpc^{-1}$. Then we can find the condition for the inflaton potential as usual [2], using the data (1.11) at that scale. Note that unlike the conventional inflationary scenario, one does not have to worry about the running of the spectral index at a larger scale, since the shooting-star moduli is responsible for the running. The shooting-star moduli disappears from the spectrum soon after the transition and is not observed at the smaller scale. As a concrete example, we consider chaotic inflation with a quartic potential

$$V(\phi) = \frac{\lambda}{4}\phi^4 \tag{A.1}$$

and the moduli-dependent Planck mass

$$M_p(\mathcal{M}) = M_p \left(1 + \beta \frac{\mathcal{M}^2}{M_*^2}\right). \tag{A.2}$$

The δN-parameter related to the inflaton is

$$\delta N_\phi = \frac{\phi}{4M_p^2}\delta\phi, \tag{A.3}$$

and the one related to the moduli is [1]

$$\delta N_\mathcal{M} = -4N\beta \left(\frac{\mathcal{M}}{M_*^2}\right)\delta\mathcal{M}. \tag{A.4}$$

At the smaller scale we need the spectral index $n < 1$, which is realized by δN_ϕ that dominates the perturbation at that scale. On the other hand, at a larger scale the moduli fluctuation dominates the perturbation and generates the spectral index $n > 1$. Therefore, these two perturbations are comparable at the transition. The condition $\delta N_\phi \simeq \delta N_\mathcal{M}$ at that scale leads to

$$|\mathcal{M}| \simeq \frac{\phi M_*^2}{16N\beta M_p^2}\frac{\delta\phi}{\delta\mathcal{M}} \simeq M_p \times \frac{\alpha_*^2 \alpha_\delta}{4\sqrt{2N}\beta}, \tag{A.5}$$

where the definition of the dimensionless parameters are $\alpha_* \equiv M_*/M_p$ and $\alpha_\delta \equiv \frac{\delta\phi}{\delta\mathcal{M}}$. If a large non-gaussianity is generated by the moduli perturbation, we find

$$f_{nl} \sim -\frac{1}{4N\beta}\frac{M_*^2}{\mathcal{M}^2} \simeq -\frac{\beta}{2\alpha_*^2 \alpha_\delta^2}. \tag{A.6}$$

As we have explained in this paper, the running of the spectral index can be generated if the shooting-star moduli has large[7] and positive η-parameter. The running of the non-Gaussianity is significant in this specific example.

One may suspect that the modulated Planck mass may lead to the generation of the curvature perturbation at the end of inflation. In fact, ϕ_e is defined by the slow-roll parameter $\epsilon(\phi_e) \simeq 1$, which leads to $\phi_e \simeq 4M_p$. Therefore, M_p in this equation is

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[7]$\eta_\mathcal{M}$ is large conpared with η_ϕ, but it is smaller than unity.

determined by the value of the moduli $\mathcal{M}_e$ at the end of inflation. However, as far as we are considering the shooting-star moduli that rolls down toward the origin during inflation, the value of the moduli and its fluctuation at the end of inflation is significantly smaller than the one that appeared in the above calculation. We thus conclude that the perturbation generated at the end of inflation is negligible in this specific example.

B. Other conditions

In this appendix, we consider other conditions that are needed for realizing large non-Gaussianity and the running spectral index for the hybrid-inflation model. These conditions are highly model-dependent, but we hope they are helpful for the analysis in this direction.

First, we consider the condition for the primordial curvature perturbation generated by the modulated inflation;

$$
\begin{aligned}
\delta N &\simeq N_1 \delta \mathcal{M}_1 \\
&\simeq 2N \beta_1 \frac{\mathcal{M}_1}{M_*^2} \frac{H_I}{2\pi} \simeq 5 \times 10^{-5}.
\end{aligned}
\tag{B.1}
$$

If a large non-Gaussianity is generated by the $\mathcal{M}_1$ moduli, there is a condition

$$
\begin{aligned}
-\frac{3}{5} f_{nl} &\simeq \frac{1}{2} \frac{\partial^2 N / \partial \mathcal{M}_1^2}{(\partial N / \partial \mathcal{M}_1)^2} \\
&\simeq \frac{M_*^2}{4N \beta_1 \mathcal{M}_1^2}.
\end{aligned}
\tag{B.2}
$$

From eq. (B.1) and (B.2), we find

$$
\mathcal{M}_1 \simeq 10^4 \frac{H_I}{f_{nl}}.
\tag{B.3}
$$

The effective mass that is generated by the interaction between the moduli and the inflaton field must be small. Here we put the condition

$$
|\beta_i| \frac{m_0^2 \phi^2}{M_*^2} \leq |\eta_i| H_I^2,
\tag{B.4}
$$

which leads to the bound

$$
|\phi| \leq \frac{M_*}{\sqrt{|\beta_i|}}.
\tag{B.5}
$$

Our assumption in this paper is that the perturbation generated by the conventional inflaton fluctuation does not dominate the cosmological perturbation. We thus need the condition $N_\phi < N_1$, which leads to

$$
\frac{1}{|\eta_{\phi\phi}|} < 2N |\beta_1| \frac{\mathcal{M}_1}{M_*^2}.
\tag{B.6}
$$

Note that this condition gives the lower bound for the inflaton;

$$
|\phi| > \frac{M_*^2}{2N |\beta_1 \eta_\phi| \mathcal{M}_1}.
\tag{B.7}
$$

Combining eq. (B.5) and (B.7), we find

$$\mathcal{M}_1 > \frac{M_*}{|\eta_\phi| N \sqrt{|\beta_1|}}. \tag{B.8}$$

Since $\mathcal{M}_1 < M_*$ is a natural condition in this model, we find

$$|\eta_\phi| N \sqrt{|\beta_1|} > 1 \tag{B.9}$$

We find that fast-roll inflation is favored in this specific example.[8] Note that fast-roll inflaton field with the η-parameter larger than unity does not generate the primordial perturbation. Therefore, the condition (B.7) does not appear if $\eta_\phi \geq 1$. Finally, from eq. (B.3) and (B.8), we find the lower bound for the inflation scale;

$$H_I > \frac{f_{nl} M_*}{10^4 |\eta_\phi| N \sqrt{|\beta_1|}}. \tag{B.10}$$

One may also think that the modulated couplings may induce the generation of the cosmological perturbation at the end of inflation. However, at least in the present example, the fluctuations of the moduli fields do not induce significant fluctuation in $\delta\phi_e$, since the moduli fields do not appear in the equation that determines ϕ_e. In this respect, modulated inflation can be discriminated from multi-inflaton model in which the curvature perturbation generated (converted) near the end of inflation is crucial.

C. Inhomogeneous reheating

One may suspect that the modulated couplings that have been used in this paper may lead to inhomogeneous (modulated) reheating after inflation. If so, a significant perturbation may be generated at the reheating, which may ruin the model.

Let us first take a look at the hybrid inflation model. The reheating temperature of a hybrid inflation model is determined by the effective mass near the true minimum. Therefore, at least in the hybrid inflation model that has been discussed in this paper, the model is free from such problem, since there is no modulated fluctuation in the inflaton decay rate that remains until reheating.

On the other hand, in the chaotic inflation model that we considered in appendix A, the fluctuation of the Planck mass may induce inhomogeneous reheating after inflation. If this effect is larger than the preceding perturbation, the running of the spectral index and a larger non-Gaussianity may be erased at the reheating. This can be a serious problem in our scenario. We thus need to explain the conditions that are needed to avoid the problem in the chaotic inflation model. Since the problem may arise when inflaton decays through gravity-mediated interaction, we consider a decay rate that is proportional to M_p^{-n}, which leads to the fluctuation

$$\frac{\delta\Gamma}{\Gamma} \simeq -n \frac{\partial M_p / \partial \mathcal{M}}{M_p} \delta\mathcal{M} \simeq -2n\beta \frac{\mathcal{M}}{M_*^2} \delta\mathcal{M}, \tag{C.1}$$

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[8] Fast-roll hybrid inflation is discussed by Dimopoulos et.al [20].

where the values of the fields are evaluated at the reheating. Since we are considering a shooting-star moduli, $\mathcal{M}$ decreases rapidly during inflation. Therefore, the expectation value of the moduli $\mathcal{M}$ is much smaller than the one that has been used for the calculation of the running spectral index. Our conclusion is that at least in the specific example that was considered in appendix A, inhomogeneous reheating does not lead to the generation of a significant perturbation after inflation.

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