Multi-brid DBI Inflation

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Abstract

We extend multi-brid idea to multi-field separable model with non-canonical kinetic term. Considering a specific surface of end of inflation and introducing new fields, we find explicit expression for number of e-folds in terms of this new fields. Using $\delta N$ formalism we get cosmological parameters for this general case. We use our general results for DBI model in speed limit, comparison to observation gives numerical estimation for the parameters of the model.
I. INTRODUCTION

Inflation theory provides an intelligent approach to basic problems of cosmology[1]. In this theory a rapid expansion era enlarges physical length up to about 60 times the original size, this rapid expansion solves old problems in cosmology, such as flatness, horizon and monopole problems. The fluctuations of inflaton, the field which drives inflation, seeds the fluctuations in energy density in such a way that the curvature power spectrum is almost scale invariant. There are several cosmological observations that support this theory. One of them is done by Planck satellite which observed Cosmic Microwave Background(CMB) anisotropy with small angular resolution, it results agree with inflation theory predictions[2] in general. Recently BICEP2, observed B-mode polarization of the CMB[4], they found the ratio of tensor to scalar perturbation of order 0.2 which is very large in comparison to Planck result. If these results are related to primordial gravitational waves produced at the early stage of inflation it would be another piece of evidence of inflation[5].

Although experimental tests support inflation, from the theoretical point of view there is no deep understanding of nature of what produce inflation. In the simplest model one field, the inflaton, which is minimally coupled to gravity, rolls in a very flat potential very slowly. The flatness of the potential is necessary to get enough inflation. One way to relax this condition is to change dynamics of the inflaton, when the kinetic term in the lagrangian of this field is non-canonic the slow-roll condition is not necessary anymore. For example when we have a DBI field we have a fast- roll inflation[6]. Brane-inflation is an example of this models in which the radial distance between a pair of D3-brane and anti D3-brane takes the role of the inflaton[7–19]. In general it is possible to get inflation from a general class of non-standard kinetic terms, which is called k-inflation, in this model inflation can exist even in the lack of potential[20, 21]. On the other hand, existence of more than one field can relax many limits on single field models. In multi-field models cooperation between fields can produce inflation even if each field is not able to drive inflation by itself, in such a way that e-folding number and curvature perturbation are proportional to the number of fields[22–27].

Regardless of model of inflation, this era must end at sometime $t_f$, for example a waterfall mechanism can cease inflation on a specific surface in field space which is called the surface of end of inflation. By using the equation of end of inflation surface, e-folding number can be written explicitly in terms of fields, this idea is known as multi-brid[30, 31]. We generalize this idea to separable multi-field models, assuming a general equation for this surface in terms of fields at $t_f$.

The rest of the paper is organized as follows. In section II we present our method for separable
models by introducing new fields and determining the end of inflation surface, we assume a general
equation for this surface. In the next section we use δN formalism to get observational parameter.
In section V we use our method for multi-speed DBI in speed limit. We summarizes our results
in section V.

II. THE MODEL

Consider a number of separate scalar fields with non-canonical kinetic terms, except for being
gravitationally coupled, there is no coupling between them, so the action can be written as a sum
on individual field actions [32–34],

\[
S = \frac{1}{2} \int d^4x \sqrt{-g} \left[ M_p^2 R + 2 \sum_I P_I (X_I, \phi_I) \right],
\]

where \(X_I\) is the kinetic term of \(\phi_I\), \(X_I = -\frac{1}{2} g^{\mu\nu} \nabla_\mu \phi_I \nabla_\nu \phi_I\). We consider a spatially flat FRW
metric, \(ds^2 = -dt^2 + a^2(t)d\vec{x}^2\), Friedmann and field equations are as follows :

\[
H^2 = \frac{1}{3M_{pl}^2} \sum_I (2X_I P_{I,X_I} - P_I),
\]

\[
3H^2 + 2\dot{H} = -\frac{1}{M_{pl}^2} \sum_I P_I,
\]

\[
\frac{d}{dt} (a^3 P_{I,X_I} \dot{\phi_I}) - a^3 P_{I,\phi_I} = 0.
\]

Since there is no direct interaction term between the fields, each field has its own equation of
motion. In addition there is a sound speed for each field, so we have a multi-speed model [32]. For
using multi-brid idea [30, 31] we need to rewrite these equations as ,

\[
\frac{1}{a^3 P_{I,\phi_I}} \frac{d}{dt} \left( a^3 P_{I,X_I} \dot{\phi_I} \right) = 1.
\]

in this form the right hand side is independent of fields [30, 31], allowing us to introduce new fields
as follows,

\[
\ln q_I \equiv \int -\frac{\dot{a}}{a^3 P_{I,\phi_I}} \frac{d}{dt} \left( a^3 P_{I,X_I} \dot{\phi_I} \right) dt.
\]

In terms of these new fields, the equation of motion can be written in a very simple form,

\[
\frac{d}{dt} \ln q_I = -H.
\]

For later convenience, change the time variable to the number of e-folds \(N\),

\[
dN = -H dt,
\]

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FIG. 1. In q’s space the motion is radial

the minus sign shows that the number of e-folds is backward in time (at the end of inflation, \( N_f = 0 \)). From (5), in terms of \( \mathcal{N} \) the equation of motion for \( \phi_I \) becomes

\[
\frac{d \ln q_I}{d \mathcal{N}} = 1, \tag{6}
\]

which can be solved as

\[
\mathcal{N} - N_f = \ln q_I - \ln q_{I,f}. \tag{7}
\]

It worth to mention that there is also another term contributing in \( \mathcal{N} \) which is neglected here, it comes from the fact that the end of inflation surface is not a constant energy density surface [30]. it is obvious that

\[
\frac{\ln q_I}{\ln q_J} = \frac{\ln q_{I,f}}{\ln q_{J,f}}, \tag{8}
\]

for each I and J. It means that in qIs space the motion is radial Fig[1] Suppose the surface of end of inflation is known, for example a water-fall mechanism terminate the inflation on a specific surface, this surface is determined by a relation between fields in q’s space at \( N_f = 0 \),f \((\ln q_{I,f}) = \mathcal{M}^2\). This condition can be rewritten as:

\[
\sum_I A_I \delta \ln q_{I,f} = 0, \tag{9}
\]

where \( A_I \)s are defined as follows,

\[
A_I \equiv \frac{\partial f}{\partial \ln q_{I,f}}. \tag{10}
\]

By using this relation and the radial motion in q’s space, it is possible to get variation of qI,f8s in term of qI,s variation.
The explicit expression of $N$ in terms of $q_I$ allows us to compute $\delta N$ in terms of fields variation. We assume slow variations at horizon exit to ignore $\dot{\phi}_I$. We use $\delta N$ formalism to calculate power spectrum, spectral index, non-Gaussianities and other observable parameters. To be more precise we restrict our problem to two fields in the rest of this paper.

III. $\delta N$ FORMALISM

1. First Order Variation

Using equation (7) and (9), we obtain $\delta_1 q_{1,f}$ and $\delta_1 q_{2,f}$ in terms of $\delta q_I$

$$\delta_1 \ln q_{1,f} = \frac{\delta \ln q_1 - \delta \ln q_2}{A_1 + A_2} A_2,$$

$$\delta_1 \ln q_{2,f} = \frac{\delta \ln q_2 - \delta \ln q_1}{A_1 + A_2} A_1,$$

where we have assumed that $\delta q_I$ are of linear order. Substituting in $\delta N$ gives,

$$\delta_1 N = \frac{A_1 \delta \ln q_1 + A_2 \delta \ln q_2}{(A_1 + A_2)},$$

(12)

2. Second Order Variation

Since the variation of $q_I$ are of linear order second order perturbation only comes from $q_{I,f}$ variations,

$$\delta_2 q_{I,f} = \frac{1}{2} \frac{A_1^2 A}{(A_1 + A_2)} \delta_1^2 \ln q_{I,f},$$

(13)

where $A \equiv \frac{2A_1 A_2}{A_1 A_2 - A_1^2 - A_2^2}$ and $A_{I,f} = \frac{\partial^2 A}{\partial \ln q_1 \ln q_f}$. The $ln q_I$ variation can be replaced by $\phi_I$ variation as $\delta \ln q_I = \dot{a} a^2 \delta \dot{\phi}_I / \dot{\phi}_I$. Using above relation, the second order variation of e-folding number is as follows,

$$\delta_2 N = -\frac{1}{2} H^2 \frac{A_1^2 A_2^2 A}{(A_1 + A_2)^3} \left( \frac{(\delta \phi_1)^2}{\phi_1^2} + \frac{(\delta \phi_2)^2}{\phi_2^2} - 2 \frac{\delta \phi_1 \delta \phi_2}{\phi_1 \phi_2} \right),$$

(14)
3. Cosmological Parameter

From (12) and (14) it is obvious that
\[
\frac{\partial N}{\partial \phi_1} = -\frac{H}{\dot{\phi}_1 A_1 + A_2},
\]
\[
\frac{\partial N}{\partial \phi_2} = \frac{H}{\dot{\phi}_2 A_1 + A_2},
\]
\[
\frac{\partial^2 N}{\partial \phi_1^2} = \frac{H^2}{4\pi^2} A_1^2 A_2^2 A_1^2 \delta_1^2 (A_1 + A_2)^3,
\]
\[
\frac{\partial^2 N}{\partial \phi_2^2} = \frac{H^2}{4\pi^2} A_1^2 A_2^2 A_2^2 \delta_2^2 (A_1 + A_2)^3
\]
\[
\frac{\partial^2 N}{\partial \phi_1 \phi_2} = \frac{H^2}{\dot{\phi}_1 \dot{\phi}_2 (A_1 + A_2)^3}
\]

Assume that the two point function of scalar field fluctuations at horizon exit is given by gaussian distribution,
\[
< \delta \phi_I \delta \phi_J >_k = \left(\frac{H}{2\pi}\right)^2 |t_k \delta_{IJ}
\]
where \(t_k\) is the horizon crossing time of the co-moving wave-number \(k\) such that \(k \hat{c}_s = Ha\). \(\hat{c}_s\) is the maximum of sound speeds which is characterize the final freezing scale. Using \(\delta N\) formalism the curvature power spectrum is given by
\[
\mathcal{P}_S = \sum_{I,J} N_{I,J}^2 \left(\frac{H}{2\pi}\right)^2 |t_k\n\]
\[
\mathcal{P}_S = \left(\frac{H^4}{4\pi^2} \frac{A_1^2 + A_2^2}{(A_1 + A_2)^2}\right) \delta_{IJ} t_k.
\]
where \(N_{IJ} = \partial N / \partial \phi_I\). \(\delta N\) formalism also gives spectral index as,
\[
n_s - 1 = \frac{d \log \mathcal{P}_S}{d \log k} = -2\epsilon_H + \frac{2}{H} \sum_{I,J} \frac{\dot{N}_{IJ} N_{IJ}}{N_{K,K}}
\]
\[
n_s - 1 = -2\epsilon_H + \frac{2 H^3 A_1^2 A_2^2 A_1^2}{(A_1 + A_2)^2} \left(\left(\frac{-A_1}{\phi_1} \frac{1}{\phi_1} \dot{\phi}_1\right) + \left(\frac{-A_2}{\phi_2} \frac{1}{\phi_2} \dot{\phi}_2\right) + \left(\frac{-A_1}{\phi_1} \frac{1}{\phi_2} \dot{\phi}_2\right) + \left(\frac{-A_2}{\phi_2} \frac{1}{\phi_1} \dot{\phi}_1\right)\right)
\]
\[
= -2\epsilon_H + \frac{H^2}{H^2 (A_1 + A_2)^2} \left(\frac{A_1}{\phi_1}\right)^2 + \left(\frac{A_2}{\phi_2}\right)^2
\]
where \(\epsilon\) is defined as usual \(\epsilon = -\frac{\dot{H}}{H^2}\). From the above expression, it is obvious that the second term vanishes regardless of the model. This surprising result comes from the fact that we have used the equation of the surface of end of inflation to replace derivative of e-folding number with respect to fields (it is consistent with results in [30, 31]), so we arrive at
\[
n_s - 1 = -2\epsilon_H = \frac{2 \dot{H}}{H^2}.
\]
Another cosmological parameter is local non-gaussianity which is given by,

$$f_{NL}^{\text{local}} = \frac{5}{6} \sum_{IJ} \mathcal{N}_I \mathcal{N}_J \mathcal{N}_{I,J}$$

where

$$\mathcal{N}_I = \frac{A_I^2 A_J^2}{6 A_1 + A_2} \left( \frac{\dot{A}_I}{\phi_1} - \frac{\dot{A}_J}{\phi_2} \right)^2$$

In addition there is equilateral type non-gaussianity or a mixed shape because of non-trivial kinetic term \cite{32, 34–36}, which we don’t calculate it explicitly here. We also compute one of the trispectrum parameter (up to second order) which is given by delta N formalism as follows \cite{37},

$$\tau_{NL} = \sum_{IJK} \mathcal{N}_I \mathcal{N}_J \mathcal{N}_{IJK} \mathcal{N}_{JK}$$

From (17,18,19,20) it seems that the observational parameters are not depend on the size of the end of inflation surface, it only depends on the surface equation, for example if the end of inflation surface is a circle the cosmological quantities does not depend on the radius of the circle.

IV. DBI IN SPEED LIMIT

Consider two stacks of branes inside a warped throat at different places, moving ultra relativistically towards the anti-branes which are located at the bottom of the throat, the distances between two stacks of branes and anti-branes play the role of inflaton, therefore this model is a two-field model \cite{38, 39}. We assume the background metric is flat FRW, the action is a follows

$$S = \frac{1}{2} \int d^4 x \sqrt{-g} \left( M_{pl}^2 R + 2 \sum_I [f_I^{-1} \left( 1 - \sqrt{1 - f_I \dot{\phi}_I^2} \right) - V(\phi_I)] \right)$$

We define Lorentz factor for each field as $$\gamma_I = \frac{1}{\sqrt{1 - f_I \dot{\phi}_I^2}}$$ and $$f_I = \frac{\lambda_I}{\phi_I}$$. In the speed limit $$\gamma_I \gg 1$$.

In this limit $$\dot{\phi}_I^2 \approx f_I^{-1}$$ and the equation of motion reduce to

$$\ddot{\phi}_I + \frac{3 f_I' \dot{\phi}_I^2}{2 f_I} - \frac{f_I'}{f_I} = 0,$$

it can be solved as

$$\phi_I(t) \approx \sqrt{\frac{\lambda_I}{t}}$$
Replacing in Friedmann equations gives Hubble constant as
\[ H = \frac{\Lambda}{t} \]  
(24)

where \( \Lambda = \sum I(\frac{\lambda^2 m^2}{2M_P^2}) \).

Integrating of H gives the number of e-fold as,
\[ \mathcal{N}(t) = -\Lambda \ln \frac{t}{t_f}, \]  
(25)
as before we have assumed \( \mathcal{N}_f = 0 \), \( t_f \) is the time of end of inflation. Eliminating \( t \) from (23) and (25) to write \( \mathcal{N} \) in terms of fields yields,
\[ \mathcal{N} = \Lambda \ln \phi_I - \Lambda \ln \phi_{I,f}. \]  
(26)

By comparing above relation with (7) we define new fields as,
\[ q_I = \left( \frac{\phi_I}{\phi_{I,f}} \right)^{\Lambda}. \]  
(27)

Up to first order in small parameter such as \( \epsilon \), the spectral index is obtained to be,
\[ n_s = 1 - \frac{2}{\Lambda}. \]  
(28)

According to Planck data \( n_s = 0.96 \) which gives \( \Lambda \sim 50 \). Also we have \( \mathcal{N}(t_i) \sim 60 \) \( (t_i \) is initial time) which implies \( t_f \sim 3.3 t_i \).

Assume that the surface of end of inflation is,
\[ g_1^2 \phi_{1,f}^2 + g_2^2 \phi_{2,f}^2 = \sigma^2, \]  
(29)
where \( \sigma \) is an arbitrary constant. Using (10) we have,
\[ A_1 = 2 \frac{g_1^2 \lambda_1}{\Lambda} \frac{1}{t_f^2}, \quad A_2 = 2 \frac{g_2^2 \lambda_2}{\Lambda} \frac{1}{t_f^2}. \]

where as before \( t_k \) is the time of horizon crossing corresponds to maximum of sound speed. The power spectrum, local non-Gaussianities and tri-spectrum parameter are as follows
\[ P_S = \frac{\Lambda^4}{4\pi^2} \frac{g_1^2 \lambda_1 + g_2^4 \lambda_2}{(g_1^2 \lambda_1 + g_2^4 \lambda_2)^2} \]  
(30)

\[ f_{NL}^{local} = \frac{5}{3} \frac{g_1^2 g_2^2 \Lambda^2 \lambda_1 \lambda_2}{\Lambda} \frac{(g_1^2 - g_2^2)^2}{(g_1^2 \lambda_1 + g_2^4 \lambda_2)^2} \]  
(31)

\[ \tau_{NL} = 4 g_1^4 g_2^4 \lambda_1 \lambda_2 \frac{(g_1^2 - g_2^2)^2}{(g_1^2 \lambda_1 + g_2^4 \lambda_2)^3} \]  
(32)

The smallness of observed local non-gaussianity \[ [3] \) implies that \( g_1 \) must be of order \( g_2 \). Define \( \delta \equiv g_1 - g_2 \) and \( g \equiv g_1 \simeq g_2 \), assume \( \lambda_1 \sim \lambda_2 \) and use \( \Lambda \sim 50 \) and COBE normalization for \( P_S \sim 2 \times 10^{-9} \) gives \( \lambda_1 \sim \lambda_2 \sim 10^{14} \).
V. SUMMARY AND DISCUSSIONS

In this paper we use multi-brid inflation idea to a general separable lagrangian. Introducing a new field which simplifies the equation of motion, lets us to write the e-fold number in terms of this new field explicitly. We assume the surface of end of inflation is known and the second order perturbations only comes from field variation on this surface, by equating the variations order by order we find the variation on the end of inflation surface in terms of variation of fields and replace in e-fold variation. Using $\delta N$ formalism gives observational parameters such as, scalar spectral index, its power spectrum, local non-guassianity and one of the tri-spectrum parameter, $\tau_{NL}$. We use this method for multi-speed DBI model in speed limit. By comparing to observation data we obtain numerical estimation for its parameters. This procedure is powerful in separable models in which each field has its own equation of motion regardless of dynamics and form of potential. The model in original paper of multi-brid [30] and separable model [35] are special cases of our results, using (17, 18, 19 and 20) arrive at their results.

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