Curvaton reheating in non-oscillatory inflationary models

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Abstract

In non-oscillatory (NO) inflationary models, the reheating mechanism was usually based on gravitational particle production or the mechanism of instant preheating. In this Letter we introduce the curvaton mechanism into NO models to reheat the universe and generate the curvature perturbations. Specifically we consider the Peebles–Vilenkin quintessential inflation model, where the reheating temperature can be extended from 1 MeV to $10^{13}$ GeV.

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The inflationary universe [1] has solved many problems of the standard hot big-bang theory, e.g., flatness problem, horizon problem, etc. In addition, it has provided a causal interpretation of the origin of the observed anisotropy of the cosmic microwave background (CMB) and the distribution of large scale structure (LSS). In the usual inflation models, the acceleration is driven by the potential of a scalar field $\phi$ (inflaton) and its quantum fluctuations in this epoch generate the density perturbations seeding the structure formations at late time. To date, the accumulating observational data, especially those from the CMB observation of WMAP satellite [2–4] indicate the power spectrum of the primordial density perturbations is nearly scale-invariant, adiabatic, and Gaussian—just as predicted by the single-field inflation in the context of “slow-roll”. Generally, after inflation the inflaton field will oscillate about the minimum of its potential and eventually decay to produce almost all elementary particles populating the universe. This process is called reheating.

However, there exist some inflationary models [5–8], named NO models by the authors of Ref. [9], in which the minimum of the inflaton potential exist in the infinity. In these models the inflaton field would not oscillate after inflation and the standard reheating mechanism could not work. Conventionally one turns to gravitational particle production [6]. However, the authors of Ref. [9] pointed out that this mechanism is very inefficient. For the resolution to this problem, they proposed to use “instant preheating” [10] by introducing an interaction $g^2 \phi^2 \chi^2$ of the inflaton field $\phi$ with another scalar field $\chi$.

Furthermore, in these models since the inflaton field cannot decay away efficiently, its energy density must decrease extremely quickly (e.g., $\rho_\phi \propto a^{-6}$) soon after the end of inflation so that it cannot dominate the universe again too early. Otherwise, the successful
achievements of big-bang nucleosynthesis (BBN), CMB and structure formations would be spoiled. This rapid diminishing phase was called “kination” in Ref. [8] or “deflation” in Ref. [5]. It requires a steep region in the potential connecting to the flat plateau for inflation. This often leads to the potential being strongly curved near the end of inflation and tend to result in a power spectrum too far from scale-invariance in some NO models. This problem is called $\eta$-problem in the literature [11,12], because in these models the predicted spectral indices $n_s = 1 + 2\eta - 6\epsilon$, are in conflict with current observational value $n_s = 0.93 \pm 0.03$ [2,3] mainly due to a large $|\eta|$. In Eq. (1) the slow-roll parameters are defined as

$$\epsilon = \frac{M_{pl}^2 V'}{16\pi^2 V}, \quad \eta = \frac{M_{pl}^2 V''}{8\pi^2 V},$$

(2)

where $M_{pl} = 1.22 \times 10^{19}$ GeV is the Planck mass and prime denotes the derivative with respect to $\phi$. In addition, in a concrete NO model, the so-called original “quintessential inflation” [7] (which will be quoted as the example in present Letter), the inflation epoch is the same as chaotic inflation with potential $V = \lambda \phi^4$. It predicts a large gravitational wave amplitude, disfavored by the WMAP data [4].

In this Letter we put forward another reheating mechanism for NO models by introducing the curvaton mechanism [13] which received many attentions recently in the literature [11,12,14–17,19], and the problems mentioned above can be ameliorated. In our scenario, the reheating mechanism is based on the oscillations and decays of another scalar field $\sigma$ (the curvaton field) which is sub-dominant during inflation and has no interactions with inflaton except the gravitational coupling. This process is as same as that of the standard reheating in the usual inflation models. We will show by an example that the reheating temperature in our case can be as high as $10^{13}$ GeV. In addition, in the curvaton mechanism the curvature (adiabatic) perturbations are not originated from the fluctuations of the inflaton field, but instead from those of curvaton [13]. This happens in two steps. First, the quantum fluctuations in the curvaton field during inflation are converted into classical perturbations, corresponding to isocurvature perturbations when cosmological scales leave the horizon. Then, after inflation when the energy density of the curvaton field becomes significant, the isocurvature perturbations in it are converted into sizable curvature ones [20]. The curvature perturbations become pure when the curvaton field or the radiation it decays into begins to dominate the universe. Because the curvaton is very light during inflation, the final spectrum of the curvature perturbations is nearly flat and naturally consistent with current observations. At the same time, in curvaton scenario the fluctuations in inflaton field is negligible, so the energy scale of inflation is relatively lower and the gravitational wave amplitude is very small. Existing observations have detected no gravitational waves, hence those inflation models which usually predicted unlikely large tensor perturbations based on the standard paradigm of inflaton-generating curvature perturbations, like $\lambda \phi^4$ (and the example NO model cited below) [4], would become viable in the curvaton scenario. The primordial density perturbations in curvaton scenario have been studied specifically in Ref. [16] and its effects on CMB analyzed by the authors of Refs. [17,18]. Also, the curvaton mechanism has been used to liberate some inflation models [11,15]. In addition, there were some motivations for the curvaton model from particle physics [13,19].

For a specific presentation, we consider the quintessential inflation model given by Peebles and Vilenkin [7]. In this model, the inflaton field will survive to now to drive the present accelerated expansion suggested by recent measurements of type Ia supernova [21]. So, it cannot decay to other particles. The potential of the inflaton field is:

$$V(\phi) = \begin{cases} \lambda (\phi^4 + M^4) & \text{for } \phi < 0, \\ \lambda \phi^4 \frac{M^4}{\phi^4 + M^4} & \text{for } \phi \geq 0. \end{cases}$$

(3)

The energy scale $M$ is assumed very small compared with the Planck mass, the requirement of $\phi$ driving the present accelerated expansion gives that $\phi_0 > M_{pl}$ and $M > 10^5$ GeV, the subscript 0 represents present value. The inflation which happened at $-\phi \gg M$ is chaotic type with $V = \lambda \phi^4$. The slow-roll parameters are

$$\epsilon = \frac{M_{pl}^2}{\pi \phi^2}, \quad \eta = \frac{3M_{pl}^2}{2\pi \phi^2}.$$  

(4)

Inflation ends when $\epsilon = 1$, this corresponds to $\phi_{end} \simeq -0.56 M_{pl}$. The e-folding number between the horizon-exit of the comoving mode and the termination of
inflation can be estimated by

\[ N \equiv \int_{t_N}^{t_{\text{end}}} H \, dt \simeq \frac{\pi \phi_N^2}{M_{\text{pl}}^2} - 1. \]  

(5)

Hence,

\[ \phi_N \simeq -\sqrt{\frac{N + 1}{\pi}} M_{\text{pl}}, \]  

(6)

and

\[ \epsilon(\phi_N) \simeq \frac{1}{N + 1}. \]  

(7)

The power spectra of generated curvature and tensor perturbations by inflaton are respectively \[22\],

\[ P_\zeta = \frac{8V}{3M_{\text{pl}}^4} \epsilon, \]  

(8)

\[ P_h = \frac{128V}{3M_{\text{pl}}^4}. \]  

We numerically studied the evolution of the energy densities in the inflaton field and in the curvaton field. As demonstrated in Fig. 1, in the era of inflation, the curvaton field slowly rolled towards the minimum along its potential and its energy density changed little.

The curvaton field held slow-rolling at the beginning of kination because of \[m \ll H\], and its energy density \[\rho_\sigma \] decreased very slowly. Then it began to oscillate about its minimum at \[a = a_{\text{osc}}\] when \[H\] decreased below \[m\]. To avoid another inflation stage driven by the curvaton field, the universe must still be dominated by \[\rho_\phi\] at this point, this requires

\[ \rho_\sigma \simeq \rho_\phi \leq \rho_{\phi_{\text{osc}}} = \frac{3H_{\text{osc}}^2 M_{\text{pl}}^2}{8\pi}. \]  

(11)

From

\[ H_{\text{osc}} \simeq m, \quad \rho_{\sigma_{\text{osc}}} \simeq m^2 \sigma_{\text{osc}}^2, \]  

we can estimate that

\[ \sigma_{\text{osc}} \simeq \frac{3M_{\text{pl}}^2}{8\pi}. \]  

(13)
The reheating temperature can be estimated from:

$$\rho_{\phi, rh} \lesssim \rho_{\sigma, rh}. \quad (14)$$

Since $\rho_{\phi} \propto a^{-6}$, $\rho_{\sigma} \propto a^{-3}$ and

$$\frac{H_{osc}}{H_{eq}} = \frac{(a_{eq})^3}{(a_{osc})^3}, \quad \frac{H_{eq}^2}{H_{rh}^2} = \frac{(a_{rh})^3}{(a_{eq})^3}, \quad (15)$$

we get

$$\frac{\Gamma^2}{m H_{eq}} \leq \frac{8\pi \sigma_{osc}^2}{3M_{pl}^2}. \quad (16)$$

In above we have used Eq. (12). From $\rho_{eq} = \rho_{\phi eq}$ we have

$$H_{eq} = \frac{8\pi m \sigma_{osc}^2}{3M_{pl}^2}. \quad (17)$$

so the constraint is (with Eq. (13))

$$\frac{\Gamma}{m} \leq \frac{8\pi \sigma_{osc}^2}{3M_{pl}^2} < 1. \quad (18)$$

The reheating temperature can be estimated from:

$$\rho_{\sigma, rh} = \frac{3M_{pl}^2}{8\pi} r^2 \simeq \rho_{rad} = \frac{\pi^2}{30} g_* T_{th}^4, \quad (19)$$

where $g_*$ counts the total number of degrees of freedom of the relativistic particles, $g_* = 10.75$ at temperature $T \sim 1 \text{ MeV}$, and for $T \gtrsim 100 \text{ GeV}$, $g_* \sim O(100)$. The reheating process must be completed before BBN, so in this case, the reheating temperature is approximately

$$T_{th} \simeq 0.78 g_*^{-1/4} M_{pl} \Gamma \leq \sqrt{\frac{m \sigma_{osc}^2}{M_{pl}}}. \quad (20)$$

Similarly, in the latter case, when the curvaton field decayed when it was still sub-dominant but later than oscillation ($a_{osc} \lesssim a_{rh} < a_{eq}$), we have (for general, we assume $\sigma_{osc} > 0$)

$$\frac{8\pi \sigma_{osc}^2}{3M_{pl}^2} \leq \frac{\Gamma}{m} < 1, \quad \sqrt{\frac{m \sigma_{osc}^2}{M_{pl}}} < T_{th} < 0.4 \sqrt{m \sigma_{osc}} \quad (21)$$

In this case, the radiation dominated era began with $T_{eq} \sim (m \sigma_{osc}^2)^{1/4}/(\Gamma^{1/4} M_{pl})$ which is in the range

$$\sqrt{\frac{m \sigma_{osc}^2}{M_{pl}}} < T_{eq} \lesssim 0.6 \sqrt{\frac{m \sigma_{osc}^2}{M_{pl}}}. \quad (22)$$

For evaluation of $T_{th}$, one has to consider the constraints on the mass of $\sigma$ field and its initial value when it began oscillating, $\sigma_{osc}$. Based on the curvaton mechanism [13], the resulted power spectrum of the final curvature perturbations and its index are given by

$$P_{\zeta}^{1/2} = \frac{H_{in}}{3\pi \sigma_{in}^2} \simeq 0.1 \frac{H_{in}}{\sigma_{in}}. \quad (23)$$

$$n_s \equiv 1 + \frac{d \ln P_{\zeta}}{d \ln k} = 1 - 2\epsilon + \frac{2m^2}{3H_{in}^2}. \quad (24)$$

One can see that the spectrum is nearly flat. The curvaton field rolled very slowly before oscillation, we can evaluate that $\sigma_{osc} \sim \sigma_{in}$. Combined these results with the COBE normalization and the limit $H_{in} < 10^{-6} M_{pl}$, one has

$$\sigma_{osc} < 10^{-3} M_{pl} \sim 10^{16} \text{ GeV}. \quad (25)$$

Substituting Eq. (25) into Eqs. (20) and (21), and considering $m \ll H_{in}$ (we choose $m \lesssim 10^{-7} M_{pl} \sim 10^{12} \text{ GeV}$ for an evaluation), in both cases we have approximately

$$T_{th} \lesssim 10^{13} \text{ GeV}. \quad (26)$$

To ensure above analytical estimations we have made a simple numerical calculation. We set $\lambda = 10^{-15}$, $M = 4.7 \times 10^{-14} M_{pl}$, $m_{\sigma} = 10^{-8} M_{pl}$ and $\sigma_{in} = 3.27 \times 10^{-3} M_{pl}$. For curvaton decays at $a = a_{eq}$, one gets $T_{th} \sim 1.8 \times 10^{12} \text{ GeV}$. Assuming that curvaton decays into two fermions $\sigma \rightarrow \bar{f} f$, the decay width takes the form $\Gamma = g^2 m_{\sigma}/8\pi$. We find for $\sigma$ de-
cays at \( a = a_{eq} \) one requires \( g \sim 0.05 \), which is quite reasonable. When the curvaton decays at \( a < a_{eq} \), \( g < 1 \) gives \( T_{rh} < 8 \times 10^{12} \) GeV. The BBN constraint that \( T_{rh} > 1 \) MeV can also be easily satisfied, as from Fig. 1.

In conclusion, we have introduced the curvaton mechanism into the non-oscillatory inflationary models as a possible reheating mechanism and did specific studies in the quintessential inflation model proposed by Peebles and Vilenkin. In our scenario, the reheating process is not attributed to the gravitational particle productions, but due to the late-decaying of the curvaton field. This mechanism, as same as the standard reheating mechanism which based on the oscillations and decays of the scalar field (inflaton) in the usual chaotic inflation models, can be efficient. Our calculations showed that the reheating temperature can be as high as \( 10^{13} \) GeV, it is high enough for the quintessential baryogenesis [23,24]. At the same time, in addition to reheat the universe, curvaton has been endowed the role of generating curvature perturbations as in the original Letter [13]. By introducing curvaton mechanism into the NO models, the predicted power spectra of curvature perturbations are nearly scale-invariance and the tensor perturbations are negligibly small, consistent with current observations. These properties can ameliorate other defects owned by some NO models. For example, in Peebles–Vilenkin model we quoted in this Letter, the inflationary period is as same as the chaotic inflation \( V = \lambda \phi^4 \), it predicts unlikely large gravitational waves according to the usual paradigm of inflaton-generating curvature perturbations [4]. For some other NO models, the density perturbations are far from scale-invariance [11,12], in conflict with observations if the cosmic inhomogeneities are only due to the fluctuations of the inflaton field. Our scenario provides a picture that the particle productions and the cosmic density perturbations are both due to the curvaton field, this made it different from the original curvaton scenario (in which only a part of the components of the universe come from curvaton) and other reheating mechanisms that had been brought forward for NO inflationary models. Our work has also provided a new way to the reheating problem of tachyon inflation [25].

While this work was in progress a related paper [11] appeared. In Ref. [11] the author mainly dealt with quintessential inflation model building and parameter restriction and our Letter is focusing on the curvaton reheating mechanism.

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