Nontachyonic brane inflation

Tomohiro Matsuda*
Laboratory of Physics, Saitama Institute of Technology, Fusaiji, Okabe-machi, Saitama 369-0293, Japan
(Received 17 December 2002; published 29 April 2003)

We consider nontachyonic hybrid inflation in the context of the braneworld cosmology. When one considers models for brane inflation, hybrid inflation is a natural consequence of the tachyon condensation if it appears at the end of inflation. In this case, however, reheating is a difficult problem due to the peculiar properties of the tachyon. In this paper we show some models of brane inflation where a new type of hybrid inflation is realized due to the localized matter fields. The obvious advantage of our scenario is successful reheating, which is due to the potential that is localized on the brane. The serious problem of the loop correction is also avoided.

DOI: 10.1103/PhysRevD.67.083519 PACS number(s): 98.80.Cq, 04.50.+h, 11.25.Mj

I. INTRODUCTION

In spite of the great success of quantum field theory, there is still no consistent scenario in which quantum gravity is included. The most promising scenario in this direction is string theory. In the context of string theory, consistency is ensured by the requirement of additional dimensions. Originally, the size of extra dimensions had been assumed to be as small as M_P^{-1}. Then later observations showed that there is no reason to require such a tiny compactification radius [1]. In these models with large extra dimensions, the observed Planck mass is obtained by the relation $M_P^2 = M_*^{n+2} V_n$, where M_* and V_n denote the fundamental scale of gravity and the volume of the *n*-dimensional compact space. Assuming more than two extra dimensions, M_* may be close to the TeV scale without conflicting with any observable bound. The most natural embedding of this picture in the string theory context will be realized by the brane construction. Of course, the brane construction will be a viable candidate for the Universe even if the fundamental scale is not so low as the TeV scale. In the braneworld scenario, there is no obvious reason to believe that the fundamental scale is as high as the Planck scale.

Although this new idea inspired many physicists and led them to a new paradigm of phenomenology, a drastic modification is required for the conventional cosmological scenarios. Models of inflation and baryogenesis [2] are especially sensitive to such a low fundamental scale, i.e., $M_* \ll M_{GUT}$, where M_{GUT} denotes the standard (old) grand unified theory (GUT) scale. To avoid extreme fine-tuning, one should reconstruct the conventional scenarios of the standard cosmology. This requires inclusion of novel ideas that are quite different from the conventional one. For example, if one puts the inflaton field on the brane, the inflation masses are required to be unnaturally small [3]. On the other hand, in generic cases, the mass of the inflaton is bounded from below to achieve successful reheating. Thus it seems quite difficult to construct a model for inflation driven by a field on the brane. A way to avoid this difficulty was put forward by Arkani-Hamed *et al.* [4], where inflation is assumed to occur before the stabilization of the internal dimensions. In this case, however, late oscillation of the radion field is a serious problem, which may or may not be solved by a second weak inflation. One may find other ways to realize inflation in models with large extra dimensions. Because of some dynamical mechanisms, the extra dimensions may have been stabilized before the Universe exited from inflation. If the stabilization of the internal dimensions occurred before the end of inflation, it is rather difficult to construct a model for inflation by the field on the brane, since their energy densities are suppressed. In this case one may use the bulk field rather than a field on the brane [5,6]. In this direction, it was found in Ref. [7] that the phase transition of the hybrid inflation becomes fast because of the huge number of destabilized Kaluza-Klein modes at the end of inflation. Although the problem of the slow phase transition [6] seems to be solved, another problem appears because of the excited Kaluza-Klein modes. Overproduction of the excited Kaluza-Klein modes is a serious problem, because they efficiently emit Kaluza-Klein gravitons when they decay into lower excited modes [5]. Thus one should conclude that the models for bulk inflation with low M_* are not candidates for the last (including weak) inflation. There is another serious obstacle in constructing models for hybrid inflation via the bulk field. Although the scale of inflation is enhanced by the factor of $O(M_P^2/M_*^2)$ for the bulk field, it is still difficult to produce the required cosmic microwave background (CMB) anisotropy, because of the serious constraint from the loop correction [8]. In this respect, realizing successful hybrid inflation with the fundamental scale M_* as low as the TeV scale seems very difficult for both conventional and weak inflation.[1]

In the braneworld scenario, one may find another interesting possibility, "brane inflation" [10], in which the interbrane distance is used for the inflaton. In this case, a hybrid version of brane inflation is naturally obtained by the tachyon instability. In generic models for hybrid brane inflation, the system develops tachyon modes when the brane distance becomes small, which then leads to a natural end of inflation via an extra field as in the conventional hybrid models. This type of scenario has been discussed on various occasions [11,12]. On the other hand, however, there are

*Electronic address: matsuda@sit.ac.jp

[1] To avoid the most serious constraint from the CMB anisotropy, one may consider curvaton scenario as an alternative [9].

problems[2] related to the peculiar properties of the tachyon field. For example, reheating after inflation is not so easy as in the conventional hybrid inflation [14]. Moreover, the analysis of such a collapsing process requires more investigations of the quantum deformation of the branes with manifestations of the couplings to matter fields. According to the above viewpoints, it should be interesting if one can construct a model for hybrid brane inflation that does not depend on the physics related to the tachyon.

In this paper we will consider new types of hybrid brane inflation. The instability at the end of inflation is induced by the localized fields on the brane. During inflation their cross terms are suppressed by the brane distance. Then at the end of inflation, the cross terms become as large as $O(1)$. We focus our attention on the possible models where the brane distance drives hybrid inflation after the radion stabilization. In our model, unlike other models for hybrid inflation in the brane Universe, the tachyon is not required. Inflation ends because the localized fields on each brane begin to interact. Then the interaction destabilizes the potential on the brane. Unlike the tachyon, the field on the brane can reheat the Universe. The most attractive point in our model is that reheating is realized by the localized matter fields on the branes, which may have $O(1)$ couplings to the standard model matter fields, while the serious loop correction to the inflaton mass is well suppressed during inflation.

In Sec. II, we first make a brief review of hybrid inflation in the braneworld cosmology. There are two important possibilities in this direction; one is hybrid inflation due to the conventional field [6,7,15] and the other is brane inflation [11,12]. In this paper we consider the latter possibility, inflation due to the branes at a distance. Then we show explicit examples of our idea, nontachyonic hybrid inflation due to branes separated at a distance. The potential on one brane is destabilized by the interaction between fields on the other brane, which terminates the brane inflation. The destabilized field can immediately decay into fields in the standard model. The important point is that the field destabilized at the end of inflation is not a tachyon but a conventional field on the brane, which may have couplings to the fields in the standard model. In spite of the large interaction after inflation, the serious loop correction, which is discussed in Ref. [8] and puts a serious constraint on hybrid inflation, is exponentially suppressed and negligible during inflation.

II. HYBRID BRANE INFLATION

If the braneworld represents the present Universe, supersymmetry is required to be broken by soft supersymmetry breaking terms, unless the fundamental scale is as low as the electroweak scale. Flat directions, which become flat in the supersymmetric limit, may have been raised by small supersymmetry breaking terms. The brane distance, which will be parametrized by a massless moduli field in the supersymmetric limit, will also be raised.

[2]The properties of the tachyon may be *attractive* for people who want to explore a new paradigm of tachyon cosmology [13].

An intersecting braneworld with angles has been discussed by many authors as a candidate for supersymmetry breaking configurations that may realize the hybrid brane inflation [12]. Within the context of interesting brane models, it was shown that obtaining a successful inflationary period is possible from slightly nonsupersymmetric configurations consisting of D4-branes interescting at one angle on a six-dimensional compact space [12]. In these models for inflation, the inflaton field is the moduli field that represents the distance between branes, whose potential is raised by the supersymmetry breaking. Inflation is terminated by the tachyon condensation that destabilizes the brane configuration when two branes come close and collapse into lower dimensional branes.

Although these models are interesting and theoretically attractive, reheating and the collapsing process are not well investigated, which may cause serious difficulty. To clarify the purpose of this paper, we should first discuss why reheating is difficult in thess scenarios. The simplest version of brane inflation begins with a parallel brane and an antibrane at some separation. Although parallel branes preserve supersymmetry and there is no force between them, the brane-antibrane system can break supersymmetry so that a nonvanishing potential energy appears and induces an attractive force between them. This potential drives inflation. The form of the potential changes once the branes have reached a critical separation, where the branes become unstable to annihilation or collapse into lower dimensional branes. The instability of the brane-antibrane system is described by the condensation of a tachyonic mode [16]. Because of its peculiarity, the tachyon starts from the unstable maximum at $T=0$ and rolls down to $T\rightarrow\infty$. Here the crucial difference from conventional hybrid inflation is that the tachyon cannot oscillate to reheat the Universe in the usual way. Although there are papers in which reheating by varying the tachyon is discussed [14], it is still interesting to find a model for hybrid brane inflation that is *not* due to the tachyon condensation.

From the above viewpoint, in order to obtain successful reheating, we investigate models for hybrid brane inflation without the tachyon. In our model, the origin of the supersymmetry breaking is not the angle between branes. Here we assume that supersymmetry is broken on the brane. We expect that at the end of inflation, when two branes come close, the trans-bulk interaction between localized fields on different branes becomes $O(1)$ and destabilizes the potential. We show two examples in this direction. In one case the potential is destabilized by a tree-level interaction, and in the other case the destabilization occurs dynamically.

A. Models with tree-level interactions

Here we consider a brane configuration that does not invoke the tachyon at the end of brane inflation. If one considers domain walls instead of branes, walls should consist of independent field configurations that satisfy independent Bogomol'nyi-Prasad-Sommerfield (BPS) conditions at least the the tree level. Supersymmetry is expected to be broken by the fields on the branes.

Let us consider a potential on one brane,

$$V(\phi_a)_a = m^2\phi_a^2 + \lambda_a\phi_a^4, \tag{2.1}$$

where the field ϕ_a is localized on the brane. We also consider a potential on the other brane,

$$V(\phi_b)_b = \lambda_b[\phi_b^2 - \Lambda^2]^2, \tag{2.2}$$

where ϕ_b denotes the field that is localized on the brane. The interaction between ϕ_a and ϕ_b is exponentially suppressed by the brane distance,

$$V(\phi_a,\phi_b)_{int} = -\lambda_I e^{-(M_* r)^2}\phi_a^2\phi_b^2, \tag{2.3}$$

where r denotes the distance between branes.

In our model, the inflaton field is the moduli field that parametrizes the distance between branes, which we denote by $\sigma \equiv M_*^2 r$. The potential for the moduli field σ is flat if the BPS condition is satisfied, but will be raised when supersymmetry is broken by the fields on the branes. The four-dimensional effective potential is

$$V(\phi_a,\phi_b,\sigma) = m^2\phi_a^2 + \lambda_a\phi_a^4 + \lambda_b[\phi_b^2 - \Lambda^2]^2 - \lambda_I e^{-(\sigma/M_*)^2}\phi_a^2\phi_b^2 + m_\sigma^2\sigma^2. \tag{2.4}$$

Inflation starts when σ is large. Then the minimum of the potential on each brane is located at $\phi_a = 0$ and $\phi_b = \Lambda$. Here we assume that the cosmological constant is tuned so that it vanishes after inflation.

Then what happens at the end of inflation, when σ becomes smaller than M_*? When two branes come close, the transbulk interaction between fields (2.3) becomes strong; then it destabilizes the potential $V(\phi_a)_a$. The destabilization occurs when $m^2 < \lambda_I\Lambda^2$. In this model the localized field ϕ_a can couple to the field in the standard model through $O(1)$ interactions, which makes it easier to reheat the Universe after brane inflation.

Our model also presents a new kind of steep binding energy between branes or quasi-BPS domain walls. The localized potential is destabilized only when branes come close, which appears as a short-range attraction between branes. The attractive force is induced by the field that breaks supersymmetry on the brane.

B. Models with dynamical destabilization

We consider a familiar mechanism for the radiative symmetry breaking in the minimal supersymmetric standard model (MSSM) as the most naive realization of our idea. In the MSSM, after supersymmetry breaking, the Higgs potential is destabilized due to the loop correction from the top quark, because of its large Yukawa coupling. On the other hand, in models of the braneworld, one can find many models for the fermion mass hierarchy that utilize the localization of the matter fields along extra dimensions [17]. Here we consider a model in which the top quark and the Higgs boson are localized on different branes, and the supersymmetry breaking is induced by the tree level soft mass $\sim O(M_*)$ $\sim O(\mathrm{TeV})$. In the true vacuum, these two branes must coincide to give the large Yukawa coupling for the top quark. However, in the early Universe, these branes may be placed at a distance along extra dimensions, which means that the Higgs potential is not destabilized at this time. Weak brane inflation can take place within the above settings, if the effective mass for the brane-distance moduli is well suppressed [8]. Reheating is successful in this model, because the field that decays after inflation is the conventional Higgs field on the brane. The potential near the origin becomes steep for the inflaton field, because of its exponential dependence on the distance between branes.

In general, an inflation model with a higher energy scale is more realistic. To construct such models, we should include additional components so that their typical scale becomes higher than in the above simplest example. In ordinary models for inflation, a light inflaton is a problem since it cannot reheat the Universe up to the MeV scale. However, in the above example, the field that decays and reheats the Universe at the end of inflation may have $O(\mathrm{TeV})$ mass and $O(1)$ interaction with the fields on the brane. The mass of the inflaton after inflation becomes much larger than it was during inflation, because the potential becomes steep near the origin.

C. Cosmological constraints

When one considers inflation, one of the most obvious expectations will be that it explains the origin of the cosmic microwave background anisotropy of the present Universe. On the other hand, sometimes, the requirement from the CMB anisotropy imposes a serious constraint on the models for inflation. Although the constraint from the Cosmic Background Explorer (COBE) measurement disappears when one considers alternative mechanisms, such as cosmic strings [18] or the curvaton hypothesis [9], it is still very important to ask whether the inflation itself can produce the required CMB anisotropy.

For the model that we have discussed above, it is easy to see that no fine-tuning is required if it is liberated from the COBE constraint. As we mentioned above, reheating is successful in our model. Thus our models for hybrid inflation is safely used at least for weak inflation.

According to the above arguments, here we consider the question of whether our model can produce the required CMB anisotropy during inflation without peculiar fine-tunings.

For the standard models for hybrid inflation, the requirement from the COBE measurement puts severe bounds on their scales and couplings, because of the large loop correction. For example, here we consider the original hybrid inflation model [19] with the potential

$$V(\phi,\sigma) = V_0 + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}g\phi^2\sigma^2 + \frac{1}{4}\lambda\phi^4 - \frac{1}{2}m_\phi^2\phi^2. \tag{2.5}$$

Let us consider the loop correction, which comes from the ϕ field. If there is supersymmetry, the result is simplified and only the logarithmic part of the following form is relevant:

$$\Delta V_{\text{one loop}}(\sigma)\,\frac{1}{64\pi^2}\left(m^4(\sigma)\ln\frac{m^2(\sigma)}{\Lambda^2}\right), \tag{2.6}$$

where the effective mass of the ϕ field is given by

$$m^2(\sigma)=(g^2\sigma^2-m_\phi^2) \tag{2.7}$$

and Λ is the renormalization scale. The flatness conditions require [8]

$$g\leqslant\frac{\langle\phi\rangle}{M_p} \tag{2.8}$$

and the COBE normalization requirement gives an additional constraint:

$$\langle\phi\rangle^4\sigma_{COBE}\geqslant(10^9\ \text{GeV})^5\frac{V_0 1}{2}(1\ \text{MeV})^2, \tag{2.9}$$

where σ_{COBE} denotes the expectation value of σ when the COBE scales leave the horizon. Considering these conditions, one must conclude that hybrid inflation is not viable at the TeV scale. In this model, the lower bound for the energy scale is about 10^9 GeV [9].[3]

Here we consider the potential (2.4) and examine the loop correction from ϕ_a and ϕ_b. In our model, the relevant coupling is given by Eq. (2.3). During inflation, when r is much larger than M_*^{-1}, the loop correction from the field ϕ_b does not depend on σ because the σ-dependent part of $m(\sigma)_{\phi_b}$ is actually zero during inflation. On the other hand, although the loop correction from the field ϕ_a does not vanish, the σ-dependent part of $m(\sigma)_{\phi_a}$ is suppressed by the exponential factor in Eq. (2.3), which makes the loop correction irrelevant to the inflaton potential.

Although the serious constraint from the loop correction is removed in our model, another problem still remains. Assuming that the inflaton fluctuation is the origin of the structure of the Universe, one will find the constraint

$$M_P^{-3}\frac{V_0^{3/2}}{V'}=5.3\times10^{-4}. \tag{2.10}$$

This implies that

$$\sigma_{COBE}\sim M_P^{-3}V_0^{3/2}(5.3\times10^{-4})^{-1}m_\sigma^{-2} \sim10^{-4}\ \text{GeV}\left(\frac{V_0}{(10^5\ \text{GeV})^4}\right)^{3/2}\left(\frac{V_0/M_P^2}{m_\sigma^2}\right), \tag{2.11}$$

where σ_{COBE} is is the expectation value of the inflaton when scales explored by COBE leave the horizon. Here we have used the simplest potential for the inflaton field, $V(\sigma)=V_0+m_\sigma^2\sigma^2$.

Obviously, the bare mass for the σ field is required to be smaller than $\sqrt{V_0/M_P^2}$. If supersymmetry is broken on the brane and the transition to the bulk fields occurs at the tree level, one can estimate an *upper* limit for the soft mass by dimensional analysis [1],

$$m^2_{modulus}\sim G_{4+n_E}\frac{|F_{brane}|^2}{R_E^{n_E}}, \tag{2.12}$$

where G_{4+n_E} is the gravitational constant in $4+n_E$ dimensions and F_{brane} denotes the supersymmetry breaking on the brane. Without additional symmetries or mechanisms, the soft masses for the modulus are expected to be a few orders smaller than the above upper limit. The lower limit will be given by the requirement from the conventional soft supersymmetry breaking terms in the supersymmetric extension of the standard model. Then the required supersymmetry breaking on the brane is about $F_{brane}\geqslant$ TeV. If the mass for the inflaton is required to be much smaller than the above lower limit, the model requires peculiar fine-tunings or specific mechanisms to forbid the soft mass, even if one uses D-term inflation [21,22]. This problem arises when the scale of D-term inflation is much smaller than the required F terms on the brane [23]. In our model, the energy density during inflation can be derived from the D term, but the scale is assumed to be larger than the TeV scale. Thus in our case we may assume $|F_{brane}|^2<V_0$ during inflation.

To be more explicit, here we consider a model with $V_0\sim M_*^4\sim(10^5\ \text{GeV})^4$ and $m_\sigma\sim0.1\times\sqrt{V_0}/M_P$. Then the required value is $\sigma_{COBE}\sim10^{-2}$ GeV, which is smaller than the expected value of the field when the trigger field terminates inflation at $\sigma\sim M_*^{-1}$. As inflation ends at $\sigma\sim10^5$ GeV, the CMB anisotropy produced becomes much smaller than the requirement from the COBE measurement. Thus we conclude that the fluctuation of the inflation in our model cannot produce the required structure of the Universe, if the scale of inflation is as low as the TeV scale.

In our model, the energy density on the brane has a limit $V_0<M_*^4$, where M_* is the fundamental scale. On the other hand, σ_{COBE} is bounded from below, because inflation is terminated at $\sigma\sim M_*$. Considering the above limits, we can find a bound for the fundamental scale in order to satisfy the requirement from the COBE mesurement. After simple calculations, we find $M_*>10^6$ GeV, which is weaker than the bound for the original model for hybrid inflation.

Our conclusion in this section is the following. Although the serious constraint from the loop correction is removed in our model, it is still difficult to produce the required CMB anisotropy by inflation with a low energy scale. The requirement is $M_*>10^6$ GeV, which is an improvement from the original model for hybrid inflation.

III. CONCLUSIONS AND DISCUSSION

In this paper, we have proposed a new idea for brane inflation, which does not utilize the tachyon. Our model may also be considered as a novel realization of hybrid inflation, which has not been discussed yet.

In any model for brane Universe, it is natural to think that some fields are localized on branes at a distance. It is also

[3]In Ref. [20], it is discussed that an alternative model, which is called inverted hybrid inflation, can evade the above serious constraints and works even at the TeV scale.

natural to expect that these fields may have $O(1)$ couplings when branes are on top of each other. If the interaction destabilizes a potential, our idea for hybrid brane inflation works.

With these things in mind, we have constructed two explicit examples. There are two advantages compared to the previous models for tachyonic brane inflation or standard hybrid inflation. The most attractive point is that reheating is natural in our model. It is also attractive that the serious constraint from the loop correction is evaded. As we stated above, our settings are quite natural in models for the braneworld.

ACKNOWLEDGMENTS

We wish to thank K. Shima for encouragement, and our colleagues in Tokyo University for their kind hospitality.

[1] I. Antoniadis, N. A. Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B **436**, 257 (1998); I. Antoniadis, *ibid.* **246**, 377 (1990); N. A. Hamed, S. Dimopoulos, and G. R. Dvali, *ibid.* **429**, 263 (1998).

[2] G. R. Dvali and G. Gabadadze, Phys. Lett. B **460**, 47 (1999); T. Matsuda, Phys. Rev. D **65**, 103502 (2002), **66**, 023508 (2002); **65**, 107302 (2002); **66**, 047301 (2002); **64**, 083512 (2001); J. Phys. G **27**, L103 (2001); A. Masiero, M. Peloso, L. Sorbo, and R. Tabbash, Phys. Rev. D **62**, 063515 (2000); A. Mazumdar, Nucl. Phys. **B597**, 561 (2001); Phys. Rev. D **64**, 027304 (2001); A. Mazumdar and A. Perez-Lorenzana, *ibid.* **65**, 107301 (2002); R. Allahverdi, K. Enqvist, A. Mazumdar, and A. Perez-Lorenzana, Nucl. Phys. **B618**, 277 (2001); A. Pilaftsis, Phys. Rev. D **60**, 105023 (1999); R. Allahverdi, K. Enqvist, A. Mazumdar, and A.P. Lorenzana, Nucl. Phys. **B618**, 377 (2001); S. Davidson, M. Losada, and A. Riotto, Phys. Rev. Lett. **84**, 4284 (2000).

[3] N. Kaloper and A. D. Linde, Phys. Rev. D **59**, 101303 (1999); D. H. Lyth, Phys. Lett. B **466**, 85 (1999).

[4] N. Arkani-Hamed, S. Dimopoulos, N. Kaloper, and J. March-Russell, Nucl. Phys. **B567**, 189 (2000).

[5] R. N. Mohapatra, A. Perez-Lorenzana, and C. A. de S. Pires, Phys. Rev. D **62**, 105030 (2000).

[6] A. M. Green and A. Mazumdar, Phys. Rev. D **65**, 105022 (2002).

[7] T. Matsuda, Phys. Rev. D **66**, 107301 (2002).

[8] D. H. Lyth, Phys. Lett. B **448**, 191 (1999); **466**, 85 (1999).

[9] K. Dimopoulos and D. H. Lyth, hep-ph/0209180.

[10] G. R. Dvali and S. H. Henry Tye, Phys. Lett. B **450**, 72 (1999); G. R. Dvali, *ibid.* **459**, 489 (1999);

[11] C. P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh, and Ren-Jie Zhang, J. High Energy Phys. **07**, 047 (2001); C. Herdeiro, S. Hirano, and R. Kallosh, *ibid.* **12**, 027 (2001); K. Dasgupta, C. Herdeiro, S. Hirano, and R. Kallosh, Phys. Rev. D **65**, 126002 (2002); R. Blumenhagen, B. Kors, D. Lust, and T. Ott, Nucl. Phys. **B641**, 235 (2002); M. Sami, P. Chingangbam, and T. Qureshi, Phys. Rev. D **66**, 043530 (2002); M. C. Bento, O. Bertolami and A. A. Sen, *ibid.* (to be published), hep-th/0208124.

[12] J. Garcia-Bellido, R. Rabadan, and F. Zamora, J. High Energy Phys. **01**, 036 (2002); M. Gomez-Reino and I. Zavala, *ibid.* **09**, 020 (2002); Ph. Brax and D. A. Steer, *ibid.* **05**, 016 (2002); N. Jones, H. Stoica, S.-H. Henry Tye, *ibid.* **07**, 051 (2002); R. Blumenhagen, B. Kors, D. Lust, and T. Ott, Nucl. Phys. **B641**, 235 (2002); C. P. Burgess, P. Martineau, F. Quevedo, G. Rajesh, and R.-J. Zhang, J. High Energy Phys. **03**, 052 (2002); Bum-seok Kyae and Q. Shafi, Phys. Lett. B **526**, 379 (2002); J. H. Brodie and D. A. Easson, ''Brane Iinflation and Reheating,'' hep-th/0301138.

[13] G. Shiu and I. Wasserman, Phys. Lett. B **541**, 6 (2002); G. Shiu, S. H. Tye, and I. Wasserman, Phys. Rev. D (to be published), hep-th/0207119; A. Frolov, L. Kofman, and A. A. Starobinsky, Phys. Lett. B **545**, 8 (2002); L. Kofman and A. Linde, J. High Energy Phys. **07**, 004 (2002); G. W. Gibbons, K. Hori, and P. Yi, Nucl. Phys. **B596**, 136 (2001); M. Majumdar and A. Christine-Davis, J. High Energy Phys. **03**, 056 (2002); S. L. Shatashvili, Phys. Lett. B **311**, 83 (1993); S. Sugimoto and S. Terashima, J. High Energy Phys. **07**, 025 (2002); J. A. Minahan, *ibid.* **07**, 030 (2002).

[14] J. M. Cline, H. Firouzjahi, and P. Martineau, J. High Energy Phys. **11**, 041 (2002); Shiu, Tye, and Wasserman [13]; Yun-Song Piao, Rong-Gen Cai, Xin-min Zhang, and Yuan-Zhong Zhang, Phys. Rev. D **66**, 121301 (2002); Yun-Song Piao, Qing-Guo Huang, Xin-min Zhang, and Yuan-Zhong Zhang, ''Non-minimally Coupled Tachyon and Inflation,'' hep-ph/0212219.

[15] P. R. Ashcroft, C. van de Bruck, and A. C. Davis, Phys. Rev. D **66**, 121302 (2002); M. C. Bento, O. Bertolami, and A. A. Sen, *ibid.* **67**, 023504 (2003); D. Langlois, R. Maartens, and D. Wands, Phys. Lett. B **489**, 259 (2000); M. C. Bento, O. Bertolami, and A. A. Sen, Phys. Rev. D **67**, 023504 (2003); M. C. Bento and O. Bertolami, *ibid.* **65**, 063513 (2002).

[16] A. Sen, J. High Energy Phys. **08**, 012 (1998); **12**, 027 (1999); A. Sen and B. Zwiebach, *ibid.* **03**, 002 (2000); N. Berkovits, A. Sen, and B. Zwiebach, Nucl. Phys. **B587**, 147 (2000).

[17] D. E. Kaplan and T. M. P. Tait, J. High Energy Phys. **11**, 051 (2001); **06**, 020 (2000); N. Haba and Y. Shimizu, hep-ph/0210146; Phys. Lett. B **535**, 271 (2002).

[18] A. Vilenkin and E. P. S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, England, 1994).

[19] A. D. Linde, Phys. Rev. D **49**, 748 (1994).

[20] E. J. Copeland, D. Lyth, A. Rajantie, and M. Trodden, Phys. Rev. D **64**, 043506 (2001).

[21] E. Halyo, Phys. Lett. B **387**, 43 (1996); P. Binetruy and G. Dvali, *ibid.* **388**, 241 (1996).

[22] T. Matsuda, Phys. Lett. B **423**, 35 (1998).

[23] E. Halyo, J. High Energy Phys. **09**, 012 (1999).