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Cosmic String Production Towards the End of Brane Inflation

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Abstract

Towards the end of the brane inflationary epoch in the brane world, cosmic strings (but not texture, domain walls or monopoles) are copiously produced during brane collision. These cosmic strings are Dp-branes with $(p-1)$ dimensions compactified. We elaborate on this prediction of the superstring theory description of the brane world. Using the data on the temperature anisotropy in the cosmic microwave background, we estimate the cosmic string tension μ to be around $G\mu \simeq 10^{-7}$. This in turn implies that the anisotropy in the cosmic microwave background comes mostly from inflation, but with a component (of order 10%) from cosmic strings. This cosmic string effect should also be observable in gravitational wave detectors and maybe even pulsar timing measurements.

Keywords : Inflation, Brane World, Superstring Theory, Cosmic String, Cosmology

I. INTRODUCTION

With the support of the cosmic microwave background (CMB) data [1,2], the new inflationary universe scenario [3] is generally recognized to be the most likely explanation of the origin of the big bang. However, the origin of the inflaton and its potential is not well understood. Recently, the brane world scenario suggested by superstring theory was proposed, where the standard model of the strong and electroweak interactions are open string (brane) modes while the graviton and the radions are closed string (bulk) modes. Natural in the brane world is the brane inflation scenario [4], in which the inflaton is a brane mode identified with an inter-brane separation, while the inflaton potential emerges from the exchange of closed string modes between branes; the latter is the dual of the one-loop partition function of the open string spectrum, a property well-studied in string theory [5]. Inflation ends when the branes collide, heating the universe that starts the big bang.

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This brane inflationary scenario may be realized in a number of ways [6,7]. The scenario is simplest when the radion and the dilaton (bulk) modes are assumed to be stabilized by some unknown non-perturbative bulk dynamics. Since the inflaton is a brane mode, and the inflaton potential is dictated by the brane mode spectrum, it is reasonable to assume that the inflaton potential is insensitive to the details of the bulk dynamics. As a consequence, the overall brane inflationary picture is very robust [7].

Because the inflaton and the ground state open string modes responsible for defect formation are different, and that the ground state open string modes become tachyonic and develop vacuum expectation values only towards the end of the inflationary epoch, various types of defects (lower-dimensional branes) may be formed. (The tachyonic modes themselves are in general not good inflaton candidates because their potentials are typically too steep for enough e-foldings.) Apriori, defect production after inflation may be a serious problem. Fortunately, it is argued in Ref. [7] that, following the properties of superstring/brane theory and the cosmological evolution of the universe, the only defects copiously produced are cosmic strings. (Cosmic string properties in the early universe is a well-studied topic [8]) Here, we elaborate on this point and consider some of its observational consequences:

- Topologically, a variety of defects may be produced. Because they have even codimensions with respect to the branes that collide, they have specific properties [9,10].

- Cosmologically, since the compactified dimensions tangent to the brane is smaller than the Hubble size, the Kibble mechanism works only if all the codimensions are tangent to the uncompactified dimensions. As a consequence, only cosmic strings may be copiously produced [7].

- The cosmic strings may be D1-branes, but most likely, they are Dp-branes wrapping around $(p-1)$-cycles in the compactified dimensions. In this case, the cosmic string tension $\mu = M_s^2/(4\alpha\pi) \simeq 2M_s^2$, where α is the gauge coupling, with $\alpha \simeq 1/25$.

- Dynamically, open superstring field theory analysis [11] strongly indicates that the tachyon potential has the form that gives a second order phase transition. This allows one to estimate the initial cosmic string density, which is close to one string segment per Hubble volume. The resulting cosmic string network is expected to evolve to the scaling solution [12].

- Using the density perturbation in the CMB data from COBE [1], the superstring scale is estimated to be $M_s \simeq 2 \times 10^{15}$ GeV [7]. With G being the Newton's constant, this yields $G\mu \simeq 10^{-7}$.

- This implies that the anisotropy in the CMB comes mostly from the inflationary epoch, while a component of order $10^6 G\mu \simeq 10\%$ comes from cosmic strings. This is perfectly consistent with all present CMB data [2], but will be tested by MAP and PLANCK. Gravitational waves from this cosmic string network is likely to be measured by gravitational wave interferometers like LIGO II/VIRGO and LISA.

- Although the production of defects other than cosmic strings are suppressed, it is possible that the level of their production may be detectable.

Although hybrid inflationary models with cosmic string production after inflation can be constructed, they are just possible scenarios among many others. The difference here is that the production of cosmic strings towards the end of inflation seems inevitable in brane inflation. The detection of cosmic string signatures will fix the string scale. Since the string scale is determined by the amplitude of the anisotropy in CMB, we can learn a lot about the superstring/braneworld realization of our universe from cosmological observations.

II. TACHYON CONDENSATION AND DEFECT FORMATION

The topological properties of defect formation in tachyon condensation is understood in superstring theory [9,10]. Suppose we have $U(N)$ Chan-Paton bundles on one stack of Dp-branes and $U(N+M)$ Chan-Paton bundles on a second stack of Dp-branes, which is at an angle θ with respect to the first stack. They are also separated by a distance y in some orthogonal directions. In brane inflation, y is essentially the inflaton. Figure 1 shows a schematic view of the collision of branes at a fixed angle. As these two stacks of Dp-branes approach each other towards the end of the inflationary epoch, the ground state open string mode T becomes tachyonic. Open strings ending on all possible pairs of branes will give rise to a $U(M+N)\times U(N)$ gauge fields, and the tachyon field T is in the $(M+N,\bar{N})$ (bi-fundamental) representation of the gauge group. Together with $T^{\dagger}$, they form the "superconnection", and the defect properties may be elegantly described by K-theory [10]. Upon collision, the Higgs mechanism takes place as T develops a vacuum expectation value T_0 :

$$U(N)\times U(N+M)\rightarrow U(N)\times U(M)$$

To simplify the problem, we may take $M=0$. The minimum of the tachyon potential corresponds to the vacuum manifold

$$\mho(N)=\frac{U(N)\times U(N)}{U(N)} \tag{1}$$

which is topologically equivalent to $U(N)$. In the simplest situation where the angle between the two stacks of branes is $\theta=\pi$, we have a stack of N Dp-brane and a stack of anti-Dp-branes (which have opposite RR charges); so their collision results in annihilation.

The spontaneous symmetry breaking will support defects in codimension $2k$, classified by the homotopy groups $\pi_{2k-1}(\mho(N))=\mathbf{Z}$ (for stable values of N). These defects are simply D$(p-2k)$-branes (and anti-D$(p-2k)$-branes) inside the Dp-branes. In the compactified case, the net RR-charge must be conserved. They may appear as, respectively, monopoles, cosmic strings or domain walls if 3, 2 or 1 of the codimensions are tangent to the 3 uncompactified spatial dimensions. To be specific, let us consider D5-branes wrapping a 2-cycle, with the remaining 3 dimensions uncompactified (spanning our observable universe). The collision of these D5-branes allows the formation of D$(5-2k)$-branes. For $k=1$, the defects are D3-branes with all possible orientations. Those that wrap around the same 2-cycles will appear as cosmic strings, while those that do not wrap the 2-cycles appear as blobs. If there are non-trivial 1-cycles inside the 2-cycles, D3-branes can wrap around that and appear as domain walls. For $N=1$, these are the only defects. Here, the cosmic strings are akin to the vortices in Abelian Higgs model.

FIGURES

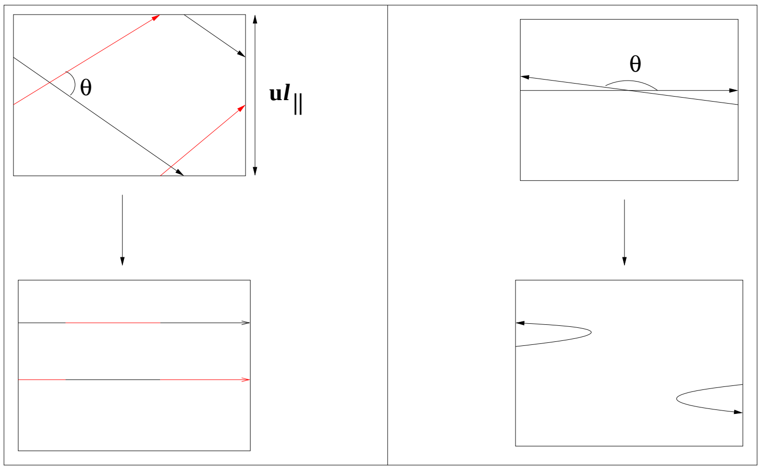

FIG. 1. Collision of Branes at angle θ. In the left figures, the two branes wrap around different 1-cycles of a torus with sides $\ell_{||}$ and $u\ell_{||}$. For small u, $\theta \simeq 2u$. They are separated in compactified directions orthogonal to the torus. When that separation approaches zero, they collide, resulting in two branes. The resulting brane tensions are cancelled by orientifold planes in the model. In the right figures, when the angle θ is close to π, annihilation takes place.

For $N > 1$, D1-branes (for $k = 2$) will also be produced and they may appear as cosmic strings. If there are non-trivial 1-cycles inside the 2-cycles, then they may wrap around the 1-cycles and will appear as monopoles in our universe. For $N > 1$, textures may also be formed topologically.

III. COSMOLOGICAL PRODUCTION OF COSMIC STRINGS

Imagine a string model that describes our universe today. In the early universe, our universe contains branes of all types. The higher-dimensional branes collide to produce lower-dimensional branes and branes that are present today. Consider the last two branes with 3 uncompactified spatial dimensions that are not in today's string model ground state. As they approach each other, the universe is in the inflationary epoch. After inflation ends, the collision of these two branes may produce lower-dimensional branes, which appear as defects.

A large density of such defects produced after inflation may destroy the nucleosynthesis or even overclose the universe (like the old monopole problem). Fortunately, the fact that they can be produced topologically does not necessarily imply that they will be produced cosmologically. To see what types of defects are produced towards the end of inflation, let us assume second order phase transition (a point we shall come back) and estimate the production rate using the Kibble mechanism. During the brane collision, the tachyon acquires the value T_0. Since the vacuum manifold is non-trivial, T can take different values at different spatial point. The existence of the particle horizon implies that T cannot be correlated on scales larger than the horizon length H^{-1}, where H is the Hubble constant. Therefore, non-trivial vacuum configurations, i.e., defects, will be produced, with a density of order one per Hubble volume.

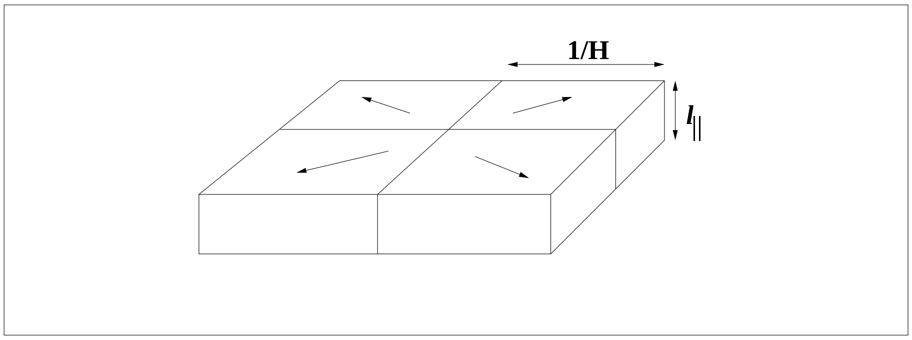

FIG. 2. A schematic picture for the Kibble Mechanism. The two large directions represent the uncompactified dimensions while the vertical direction represents a compactified direction that the p-branes wrap around. The arrows indicate the phase value of T for a non-trivial vacuum configuration.

At this time, the particle horizon size H^{-1} is given by

$$H^2 \simeq \frac{8\pi G V}{3} \simeq \frac{V}{3M_P^2} \tag{2}$$

where $M_P = 2.4 \times 10^{18}$ GeV. Here $1/H$ is typically much bigger than the compactification sizes that the branes wrap around,

$$\frac{1}{H} \simeq \frac{M_P}{M_s^2}\frac{(2\pi)^{3/2}}{\theta} \simeq \frac{10^5}{M_s} \gg \ell_{||} \tag{3}$$

where $V_{||} \simeq \ell_{||}^{p-3}$, $\theta \simeq 1/10$ and $M_s\ell_{||} \simeq 10$. In Figure 2, we show schematically two (large) uncompactified dimensions and one small compactified dimension. As a consequence of the smallness of $\ell_{||}$, the Kibble mechanism does not happen in the compactified directions. That is, the codimensions of the defects must lie in the uncompactified dimensions. Since the codimension is always even, and there are only 3 uncompactified dimensions, only the defects with codimension 2 ($k = 1$), i.e., cosmic string-like defects, can be formed via the Kibble mechanism (see Figure 2). They are D$(p-2)$-branes wrapping the same compactified space as the original Dp-branes, with one uncompactified dimension. If the Dp-brane collision can produce D$(p-4)$-branes, their production will also be suppressed since there is less than one Hubble volume in the compactified directions. This implies that the production of domain walls and monopole-like objects by the Kibble mechanism are heavily suppressed, while the production of cosmic strings is not. Generically, there may be closed and stretched cosmic strings, and they form some sort of a cosmic string network that evolves to the scaling solution. In Ref. [7], it is argued that thermal production of any defect is probably negligible.

IV. COSMIC STRING TENSION

If the D1-brane is the cosmic string (i.e., $p = 3$), its tension is simply the cosmic string tension:

$$\mu = \tau_1 = M_s^2/(2\pi g_s) \tag{4}$$

However, we expect the string coupling generically to be $g_s \gtrsim 1$. To obtain a theory with a weakly coupled sector in the low energy effective field theory (i.e., the standard model of strong and electroweak interactions with weak gauge coupling constant α), it then seems necessary to have the brane world picture [13]. This argument leads us to consider the Dp-branes for $p > 3$, where the $(p-3)$ dimensions are compactified to volume $V_{\|} \sim \ell_{\|}^{p-3}$. Now the cosmic strings are D$(p-2)$-branes, with the $(p-3)$ dimensions compactified to the same volume $V_{\|}$. Noting that a Dp-brane has tension $\tau_p = M_s^{p+1}/(2\pi)^p g_s$, the tension of such cosmic strings is

$$\mu = \frac{M_s^{p-1} V_{\|}}{(2\pi)^{p-2} g_s} = \frac{M_s^2 v_{\|}}{2\pi g_s} = \frac{M_s^2}{4\alpha\pi} \simeq 2M_s^2 \tag{5}$$

where

$$g_s \simeq 2 v_{\|} \alpha, \qquad \alpha \simeq 1/25 \tag{6}$$

For $v_{\|} \sim 10$, $g_s \sim 1$ while α is small. For $N = 1$, only this type of cosmic strings are produced topologically. For $N > 1$, the D1-branes may also be allowed topologically, but they are not produced cosmologically. So $\mu \simeq 2M_s^2$ is quite generic.

To get an order of magnitude estimate of M_s, we may use the small θ case, which is argued to be the most likely inflationary scenario. In Ref. [7], the string scale is determined by the anisotropy in CMB [1]

$$\delta_H \simeq 1.9 \times 10^{-5} \quad \Longleftrightarrow \quad M_s \simeq 2 \times 10^{15} GeV \tag{7}$$

This gives

$$G\mu \simeq 10^{-7} \tag{8}$$

Note that the determination of M_s is somewhat sensitive to the details of the brane inflationary scenario and the specific string model realization. It is easy for M_s to vary by a factor of 2 or more. As we shall see, the observability of the cosmic string effect can be very sensitive to this uncertainty. Let us estimate the range of μ within the brane inflationary scenario. For the brane-anti-brane scenario, M_s determined by the COBE data is somewhat smaller. However, the force between the brane-anti-brane system is stronger than that for branes at a small angle. As a consequence, the brane-anti-brane system will need some fine-tuning (so they are separated far enough apart) to give enough inflation. Such fine-tuning is avoided if branes are at a small angle θ, where θ is fixed by the wrapping of the branes. Allowing the various possibilities, we have

$$10^{-6} \geq G\mu \geq 10^{-10} \tag{9}$$

V. TACHYON POTENTIAL AND THE INITIAL COSMIC STRING DENSITY

That the Kibble mechanism allows the production of cosmic string in the early universe is only a necessary condition. To see if cosmic strings are dynamically produced towards the end of inflation, we have to examine the tachyon potential more carefully. Fortunately, our understanding of superstring theory and open superstring field theory allows us to address this issue.

- In the full superstring theory, does the tachyon potential have the shape that yields second-order phase transition? Apriori, this is not clear. Tachyon couplings to excited string states will induce higher powers of $T^\dagger T$ (after integrating out the heavy string modes) into the tachyon potential, resulting in a tachyon potential that depends on $T^\dagger T$ to all orders. Naively, the potential can develop non-trivial shapes such that the phase transition may be first order (or even more complicated). However, recent open superstring field theory analysis strongly suggests that this is not the case [11]. That is, the superstring corrections change the smooth potential only quantitatively.

- Even with a smooth potential that monotonically decreases towards the minimum at T_0, the evolution of T as a function of time can have unusual behaviors, since the full superstring field theory action involves time derivatives of T to all orders. Again, as shown by Sen [14], naive field theory properties essentially hold for the tachyon model here. This allows us to make an order of magnitude estimate of the production of cosmic strings.

To simplify the problem, let us consider the brane-anti-brane ($\theta = \pi$) case here. Let the $U(M+N)$ brane positions be ($(M+N) \times (M+N)$ matrix) ϕ^I and the $U(N)$ anti-brane positions be ($N \times N$ matrix) $\tilde{\phi}^I$, where $I = 1, 2, ...$ is the transverse coordinate. The matrix property of ϕ and $\tilde{\phi}$ is the origin of the non-commutative geometry in string theory. The tachyon potential has the form:

$$V(\phi, \tilde{\phi}, T) = V_l + (M+2N)\tau_p + \frac{M_s^2}{2(2\pi)^2} Tr\left[\phi^I T T^\dagger \phi^I + T\tilde{\phi}^I \tilde{\phi}^I T^\dagger - 2\phi^I T \tilde{\phi}^I T^\dagger\right]$$
$$- \frac{M_s^2}{4} Tr(TT^\dagger) + O(T^4) \qquad (10)$$

where V_l is the potential due to the closed string exchange. It is essentially the inflaton potential. We shall ignore it here. Also, to avoid the complication due to the non-commutative geometry, let $M = 0$ and $N = 1$; then $y = \phi - \tilde{\phi}$ is the brane-anti-brane separation in the compactified dimensions orthogonal to the branes. Recall also that $(p-3)$ dimensions of the brane is compactified with volume $V_{\|}$. At $y = 0$, when the brane is on top of the anti-brane, we have, for a single complex scalar field T,

$$V(T) = 2\tau_p V_{\|} - \frac{M_s^2 T^\dagger T}{4} + \frac{\lambda}{4}(T^\dagger T)^2 + ... \qquad (11)$$

where λ and the higher terms may be calculated in open superstring field theory [11]. For our purpose, we shall truncate it to the fourth order term, but demand that the potential is zero at its minimum $T = T_0$ [15]. That is $V(T_0) = 0$. This condition fixes λ,

$$\lambda = \frac{M_s^4}{32\tau_p V_{\|}} = \frac{\pi^3 \alpha}{2} \simeq 0.62 \qquad (12)$$

where we have used Eq.(6). This resulting tachyon potential has the same shape as that obtained from open superstring field theory [11] and should be well within a factor of 2 of the true potential for $T \leq T_0$. For generic y, we now have

$$V(T,y) = \frac{M_s^4}{16\lambda} - \frac{1}{2}(\frac{M_s^2}{2} - \frac{M_s^4 y^2}{(2\pi)^2})T^\dagger T + \frac{\lambda}{4}(T^\dagger T)^2 \tag{13}$$

Now we would like to make an order of magnitude estimate of the initial density of cosmic strings, following an approach in condensed matter physics [16]. Let us introduce a length scale ξ_S, so that the initial density is $1/\xi_S^2$. The effective thickness of a cosmic string (as a function of y) is simply the correlation length ξ_C given by the inverse of the tachyon mass $M_T(y)$:

$$\xi_C(y) = \frac{1}{M_T(y)} = \frac{1}{M_s}(\frac{1}{2} - (\frac{M_s y}{2\pi})^2)^{-1/2} \tag{14}$$

As T approaches T_0, a cosmic string may be locked in if the vacuum configuration is non-trivial. When T can easily fluctuate back to zero, the vacuum configuration, and so the cosmic string, is not locked in. Let ξ_G be the largest length scale on which quantum fluctuations from T_0 to $T = 0$ are probable; that is, the Ginsburg length ξ_G measures the "fuzziness" factor. When the fuzziness is larger than the thickness of the cosmic string, i.e., $\xi_G > \xi_C$, the cosmic string can simply fluctuate away and disappear; that is, it is not really formed. A cosmic string is truly formed when $\xi_C > \xi_G$. Initially, $\xi_G > \xi_C$; but, as y decreases, ξ_G decreases faster than ξ_C, so at some y, $\xi_C > \xi_G$ and the formation of cosmic strings is locked in. This allows us to estimate the initial cosmic string density by demanding $\xi_S = \xi_G$ when $\xi_C = \xi_G$. Now, to estimate ξ_G, we note that the quantum fluctuation during this epoch is close to that in deSitter space, namely $\tilde{H}/(2\pi)$, where the Hubble constant $\tilde{H}$ is given by

$$\tilde{H}^2 = \frac{V(T_{min}, y)}{3M_P^2} \tag{15}$$

This allows us to define ξ_G as given by:

$$\xi_G^3(y)V_o(y) = \frac{\tilde{H}}{2\pi} \tag{16}$$

where $V_o(y)$ is the height of the unstable maximum of the tachyon potential (at $T = 0$) taken with respect to the minimum of the potential, i.e., $V_o(y) = V(T = 0, y) - V(T_{min}, y)$. (For $y = 0$, $T_{min} = T_0$). Using the potential (13) for both V_o and $\tilde{H}$, we obtain

$$\xi_G^3(y) \simeq \sqrt{\frac{\lambda}{3}} \frac{M_s^2}{2\pi M_P} \xi_C^4(y) \tag{17}$$

For large lengths, $\xi_G(y) > \xi_C(y)$, but $\xi_G(y)$ decreases faster than $\xi_C(y)$ as the branes approach each other. Now the length scale ξ_S is determined by the condition $\xi_G(y) = \xi_C(y)$, giving,

$$\xi_S \sim 1.6 \times 10^4 M_s^{-1} \tag{18}$$

This happens at $y = y_S$, where $M_s y_S = 4.442752$, which is very close to the critical value of $M_s y = M_s y_c = \sqrt{2}\pi = 4.442879$ (when T just becomes tachyonic). Around these values of y, the reheating process has yet to begin, so the temperature of the universe is essentially zero. This justifies the above approach where only quantum fluctuation is considered. Also, V_l is not big at $y = y_S$, so it may be ignored, as we have done in the estimate. During this epoch, the branes are moving towards each other quite rapidly. The time it takes for the branes to move from y_c to y_S is of order $\Delta t \sim 1/M_s$. So both $\xi_C(y)$ and $\xi_G(y)$ decrease rapidly from the value ξ_S as the branes move closer.

The Hubble (or particle horizon) size is given by Eq.(2):

$$H^{-1} \simeq 6 \times 10^3 M_s^{-1} \tag{19}$$

So the cosmic string density scale set by the tachyon potential and the scale set by the Kibble mechanism are comparable. This initial cosmic string density (somewhere between $1/\xi_S^2$ and H^2) is high enough for the cosmic string network to to evolve towards the scaling solution [12].

VI. OBSERVATIONAL CONSEQUENCES

The evolution of the cosmic string network after its initial production is well-studied [12]. After the initial production of cosmic strings, they continue to interact among themselves. When two cosmic strings intersect, they reconnect or intercommute (see Figure 1, where the diagrams are reinterpreted for cosmic strings in the uncompactified dimensions). When a cosmic string intersects itself, a closed string loop is broken off. Such a loop will oscillate quasi-periodically and gradually lose energy by gravitational radiation. Its eventual decay transfers the cosmic string energy to gravitational waves. Higher initial string density brings higher interaction rate so, not surprisingly, the cosmic string network evolves towards a scaling solution. As a consequence, the physics is essentially dictated by the single parameter $G\mu$.

In this brane inflationary scenario, we see that the density perturbation (and the CMB anisotropy) comes from two sources: the inflaton fluctuation during inflation and the cosmic string network. Here, let us get a crude estimate of the magnitude of these two components. The COBE data roughly yields $G\mu \simeq 10^{-6}$ if the scaling solution of the cosmic string network is the sole source of the density perturbation. Since $\Delta T/T \propto G\mu$, we have, in terms of the spectrum of the CMB, namely, C_l (l the partial wave integer);

$$\begin{aligned} C_l &= (1-a)C_l^I + aC_l^S \\ a &\simeq \frac{G\mu}{10^{-6}} \simeq 10\% \end{aligned} \tag{20}$$

where C_l^I comes from inflation while C_l^S comes from cosmic strings. So, with $G\mu \simeq 10^{-7}$, the cosmic string network contributes of order 10 % of the anisotropy in the CMB data. As shown in Ref. [17], the present CMB data [2] can easily accommodate up to $a = 20\%$, so the cosmic string production towards the end of brane inflation is perfectly compatible with the present CMB data [2], while future data from MAP and PLANCK will be able to test this scenario. It is obviously very important to estimate a more carefully in the cosmic string network in a phenomenologically realistic superstring model. Since a is most sensitive to the string scale M_s, the CMB data may be a very good way to eventually determine the value of M_s.

The cosmic string network also generates gravitational waves that may be observable. This has been studied extensively in the literature. The gravitational wave spectrum has an almost flat region that extends from $f \sim 10^{-8}$ Hz to $f \sim 10^{10}$ Hz. Within this frequency range, both LIGO II/VIRGO (sensitive at around $f \sim 10^{2}$ Hz) and LISA (sensitive at around $f \sim 10^{-3}$ Hz) are expected to reach the sensitivity of $G\mu \lesssim 10^{-7}$. Other possible detections of cosmic strings may be pulsar timing experiments, CMB polarization measurements etc.

If the cosmic string network of oscillating loops involve cusps and kinks of the cosmic strings, then strong beams of high-frequency gravitational waves are emitted by these cusps and kinks. This scenario is studied by Damour and Vilenkin [18]. In this scenario, the sharp bursts of gravitational waves should be easily observable. LIGO II/VIRGO and LISA may detect them for values down to $G\mu \simeq 10^{-13}$. Although present pulsar timing measurement is compatible with $G\mu \lesssim 10^{-6}$, a modest improvement on the accuracy can detect a network of cuspy cosmic string loops down to $G\mu \simeq 10^{-11}$. To conclude, if cusps and kinks happen to a small but reasonable fraction of the cosmic strings, gravitational wave detection will be able to critically test the brane inflationary scenario. If detected, it will further shed light on the specific brane inflationary scenario.

VII. SUMMARY

Brane inflation is a natural realization of inflation in the brane world scenario. For the string scale close to the GUT scale (the case we are interested in), presumably any phenomenologically realistic string model is dual to another string model that has a brane world interpretation. In this sense, brane inflation is generic. In Ref. [6,7], it is shown that the brane inflation scenario is robust, that is, the probability that the universe has an extended inflationary epoch before big bang is of order unity. This excludes the scenarios where the tachyon is the inflaton (which may evade the production of defects, but typically the potential is far too steep for enough e-foldings). The bottom line is that cosmic strings will be copiously produced in any robust brane inflationary scenario. Other defects, if exist topologically, may also be produced, though with suppressed rates. In conclusion, we find that brane inflation has interesting predictions beyond that of the slow-roll inflationary scenario, and provides a testing ground for superstring theory to confront experiments. Existing data is perfectly compatible with brane inflation. It is exciting that future experiments will likely provide non-trivial tests of the scenario.

The key is the determination of the string scale M_s. The observability of the cosmic string effect in brane inflation is very sensitive to the value of M_s. Although we use $M_s \simeq 2 \times 10^{15}$ GeV in this paper, there is easily a factor of 2 or 3 uncertainty in its extraction from the CMB data. A more careful analysis of the CMB data in the framework of more realistic superstring models will be very important.

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REFERENCES

[1] G.F. Smoot et. al., Astrophy. J. **396** (1992) L1;
C.L. Bennett et. al., *4-year COBE DMR Cosmic Microwave Background Observations: Maps and Basic Results*, Astrophy. J. **464** (1996) L1, astro-ph/9601067.

[2] A.T. Lee et. al. (MAXIMA-1), *A High Spatial Resolution Analysis of the MAXIMA-1 Cosmic Microwave Background Anisotropy Data*, astro-ph/0104459;
C.B. Netterfield et. al. (BOOMERANG), *A measurement by BOOMERANG of multiple peaks in the angular power spectrum of the cosmic microwave background*, astro-ph/0104460;
C. Pryke, et. al. (DASI), *Cosmological Parameter Extraction from the First Season of Observations with DASI*, astro-ph/0104490.

[3] A.H. Guth, *The Inflationary Universe: A Possible Solution To The Horizon And Flatness Problems*, Phys. Rev. **D23** (1981) 347;
A.D. Linde, *A New Inflationary Universe Scenario: A Possible Solution Of The Horizon, Flatness, Homogeneity, Isotropy And Primordial Monopole Problems*, Phys. Lett. **B108** (1982) 389;
A. Albrecht and P.J. Steinhardt, *Cosmology For Grand Unified Theories With Radiatively Induced Symmetry Breaking*, Phys. Rev. Lett. **48** (1982) 1220.

[4] G. Dvali and S.-H.H. Tye, *Brane Inflation*, Phys. Lett. **B450**(1999) 72, hep-ph/9812483.

[5] J. Polchinski, String Theory, Cambridge University Press, 1998.

[6] G. Dvali, *Infrared Hierarchy, Thermal Brane Inflation and Superstrings as Superheavy Dark Matter*, Phys. Lett. **B459** (1999) 489, hep-ph/9905204;
E.E. Flanagan, S.-H.H. Tye and I. Wasserman, *A Cosmology of the Brane World*, Phys. Rev. **D62** (2000) 024011, hep-ph/9909373;
S.H. Alexander, *Inflation from $D-\bar{D}$ Brane Annihilation*, Phys. Rev. **D65** (2002) 023507, hep-th/0105032;
E. Halyo, *Inflation from rotation*, hep-ph/0105341;
G. Dvali, Q. Shafi and S. Solganik, *D-Brane Inflation*, hep-th/0105203;
C. P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh and R. J. Zhang, *The Inflationary Brane-Antibrane Universe*, JHEP **07** (2001) 047, hep-th/0105204;
G. Shiu and S.-H.H. Tye, *Some Aspects of Brane Inflation*, Phys. Lett. **B516** (2001) 421, hep-th/0106274;
C. Herdeiro, S. Hirano and R. Kallosh, *String Theory and Hybrid Inflation/Acceleration*, JHEP **0112** (2001) 027, hep-th/0110271;
B.-S. Kyae and Q. Shafi, *Branes and Inflationary Cosmology*, Phys. Lett. **B526** (2002) 379, hep-ph/0111101;
C. P. Burgess, P. Martineau, F. Quevedo, G. Rajesh and R.-J. Zhang, *Brane-Antibrane Inflation in Orbifold and Orientifold Models*, hep-th/0111025;
J. Garcia-Bellido, R. Rabadan, F. Zamora, *Inflationary Scenarios from Branes at Angles*, JHEP **01** (2002) 036, hep-th/0112147;
R. Blumenhagen, B. Kors, D. Lust and T. Ott, *Hybrid Inflation in Intersecting Brane Worlds*, hep-th/0202124;
K. Dasgupta, C. Herdeiro, S. Hirano and R. Kallosh, *D3/D7 Inflationary Model and M-theory*, hep-th/0203019.

[7] N. Jones, H. Stoica and S.-H.H. Tye, *Brane Interaction as the Origin of Inflation*, hep-th/0203163.
[8] See e.g., E.W. Kolb and M.S. Turner, The Early Universe, Addison-Wesley Publ. Co., 1990;
M.B. Hindmarsh and T.W.B. Kibble, *Cosmic Strings*, hep-ph/9411342;
A. Villenkin and E.P.S. Shellard, Cosmic strings and other topologiocal defects, Cambridge University Press, 2000.
[9] A. Sen, *Stable non-BPS bound states of BPS D-branes*, JHEP **9808** (1998) 010, hep-th/9805019; *SO(32) spinors of type I and other solitons on brane-antibrane pair*, JHEP **9809** (1998) 023, hep-th/9808141.
[10] E. Witten, *D-branes and K-theory*, JHEP **9812** (1998) 019, hep-th/9810188;
P. Horava, *Type IIA D-branes, K-theory, and matrix theory*, Adv. Theor. Math. Phys. **2** (1999) 1373, hep-th/9812135.
[11] N. Berkovits, *The tachyon potential in open Neveu-Schwarz string field theory*, JHEP **0004** (2000) 022, hep-th/0001084;
N. Berkovits, A. Sen and B. Zwiebach, *Tachyon condensation in superstring field theory*, Nucl. Phys. **B587** (2000) 147, hep-th/0002211;
P. Smet and J. Raeymaekers, *Level 4 approximation to the tachyon potential in superstring field theory*, JHEP **0005** (2000) 051, hep-th/0003220.
[12] A. Albrecht and N. Turok, *Evolution of Cosmics Strings*, Phy. Rev. Lett. **54** (1985) 1868;
D.P. Bennett and F.R. Bouchet, *Evidence for a Scaling Solution in Cosmic-String Evolution*, Phy. Rev. Lett. **60** (1988) 257;
B. Allen and E.P.S. Shellard, *Cosmic-String Evolution: A Numerical Simulation*, Phy. Rev. Lett. **64** (1990) 119
[13] G. Shiu and S.-H.H. Tye, *TeV Scale Superstring and Extra Dimensions*, Phys. Rev. **D58** (1998) 106007, hep-th/9805157;
Z. Kakushadze and S.-H.H. Tye, *Brane World*, Nucl. Phys. **B548** (1999) 180, hep-th/9809147.
[14] A. Sen, *Rolling Tachyon*, hep-th/0203211.
[15] A. Sen, *Tachyon condensation on the brane antibrane system*, JHEP **9808** (1998) 012, hep-th/9805170.
[16] T.W.B. Kibble and A. Vilenkin, *Density of strings formed at a second-order cosmological phase transition*, hep-ph/9501207.
[17] C. Contaldi, M. Hindmarsh and J. Magueijo, *CMB and density fluctuations from strings plus inflation*, Phys. Rev. Lett. **82** (1999) 2034, astro-ph/9809053;
R.A. Battye and J. Weller, *Cosmic structure formation in Hybrid Inflation models*, Phys. Rev. **D61** (2000) 043501, astro-ph/9810203;
F.R. Bouchet, P. Peter, A. Riazuelo and M. Sakellariadou, *Evidence against or for topological defects in the BOOMERanG data ?*, astro-ph/0005022;
A. Gangui, L. Pogosian and S. Winitzki, *Cosmic String Signatures in the Cosmic Microwave Background Anisotropies*, astro-ph/0112145.
[18] T. Damour and A. Vilenkin, *Gravitational waves bursts from cusps and kinks on cosmic strings*, Phys. Rev. **D64** (2001) 064008, gr-qc/0104026.