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# Inflation from D-$\overline{\text{D}}$ brane annihilation

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We demonstrate that the initial conditions for inflation are met when a D5-$\overline{\text{D5}}$ brane annihilates. This scenario uses Sen's conjecture that a codimension two vortex forms on the worldvolume of the annihilated 5-brane system. Analogous to a "big bang," when the five branes annihilate, a vortex localized on a 3-brane forms and its false vacuum energy generates an inflationary space-time. We also provide two possible mechanisms for ending inflation via the decay of a metastable vortex, or radiation of the cosmological constant into the bulk space-time.

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## I. INTRODUCTION

It has been suggested by Rubakov and Shaposhnikov and later by other investigators that our universe may be a defect embedded in a higher-dimensional bulk space-time [1]. Subsequently, Randall and Sundrum (RS) has extended the brane-world idea to solve the gauge hierarchy problem and localize 4D gravity as well as the matter fields of the standard model [2,3]. However, it was demonstrated that the RS scenario in a cosmological setting still exhibits a flatness problem and neccesitates an inflationary epoch [4]. Moreover, recent observations of the cosmic microwave background (CMB) agree with the inflationary scenario which collectively resolves the horizon, flatness, and formation of structure problems of the standard big-bang (SBB) model.

Nonetheless, most brane-world descriptions are constructed from the bottom up, necessitating other forms potential and coupling constant fine tuning. The flatness, structure formation, and especially the trans-Planckian problems strongly suggest that quantum gravitational effects play a significant role in the early universe [5].

In light of the limitations of the effective-field theories applied to inflationary scenarios, inflation should arise as a prediction from string theory, since string theory incorporates natural ways of resolving curvature singularities and field theory divergencies via $S$ and $T$ dualities [6]. Nonetheless, inflation requires very special initial conditions that appeal to the specifics of an effective theory [7,8]. In this paper, we investigate the non-Bogomol'nyi-Prasad-Sommerfield (BPS) sector of superstring theory and show that the initial conditions for inflation are realized quite naturally. We will show that when two five branes annihilate, an inflating three-dimensional hypersurface will emerge as a result.

A key to realizing inflation from D-branes is the fact that they are space-time topological defects. It has been appreciated for a while that topological defects play an important role in the early universe. Indeed, Vilenkin and Linde demonstrates that if the symmetry breaking scale associated with the formation of a defect is on the order of the planck scale, a topological defect will drive inflation free of the fine tuning problems which usually plague inflationary scenarios; hence, inflation becomes an issue of topology [9,10].

Therefore, the idea for D-brane driven inflation is quite simple. A D5 and anti-D5 brane exactly parallel to each other coincide and annihilate, leaving behind a curved D3-brane. During this annihilation process a codimension two vortex of unit winding number[1] forms at the 3D junction on the worldvolume of the D5-$\overline{\text{D5}}$ system [see Fig. 1]. For an observer in the core of the vortex, the false vacuum energy dominates and generates eternal inflation via the topological inflationary scenario. When inflation begins, the tachyon (inflaton) is homogenous and very close to zero near the core of the 3-brane vortex. Outside the core of the three brane, inflation will eventually end and such an observer will see a black 3-brane. Compared to the Hubble length scale these two observers are exponentially separated, so there will be no cosmological problems.

Our analysis assumes that the initial configuration of five branes are exactly parallel. This situation requires unnatural fine tuning. However, all that is needed for inflation is for the D5-$\overline{\text{D5}}$ to be parallel in a region of space that is small compared to the Hubble volume. There will be local attractive forces between the brane and antibrane which will act to produce such a configuration. Thus, the measure of required initial conditions is no longer zero.

In order to discuss D-brane inflation it is necessary to provide an analysis of non-BPS D-branes. In Secs. II and III we review generic properties of BPS and non-BPS D-branes to set the stage for its cosmological relevance. In Sec. IV we will then review, in general, the realization of defect driven

[1]Vortices of higher winding number or multiple coincident vortices may also form. The number of formed vortices is dictated by the initial number of D5-$\overline{\text{D5}}$ branes, while the winding number of the vortex will depend on the number of times the tachyon field wraps around the vacuum manifold corresponding to the broken $U(1)$ of the D5-$\overline{\text{D5}}$ worldvolume theory. Our initial configuration can allow for a higher winding vortex or a number of vortices. However, increasing either the number or winding of the vortices will only enhance the inflationary effect because in both cases, the magnitude of false vacuum energy, which drives inflation, will increase. In our analysis, we tune our initial conditions so that we are dealing with one vortex with winding number, $n=1$. Therefore, our general result, that inflation will occur will not be affected by increasing the winding or number of vortex branes.

 

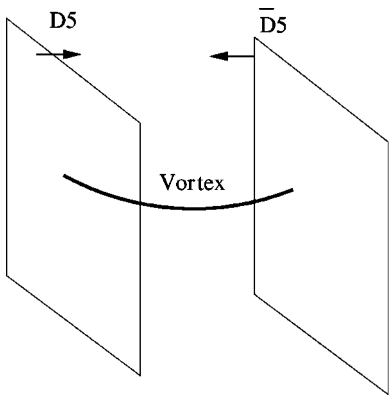


FIG. 1. This is a depiction of the annihilation of two parallel coincident D5-$\overline{D}$5 branes, represented as a two-dimensional surface. After the D5 branes annihilate a vortex, 3-brane, represented as a line, forms on a 3D junction, a submanifold on the D5-$\overline{D}$5 worldvolume. In our mechanism, this vortex initiates an inflating 3D hypersurface, identified as the 3-brane worldvolume.

inflation. In Sec. V we extend the analysis of defect-driven inflation to non-BPS D-brane systems. An explicit analysis and solution of the effective tachyon vortex field theory coupled to gravity is covered in Sec. VI. A discussion of how inflation can end is discussed in Sec. VII. We conclude with some open issues in light of D-brane cosmology and string theory.

## II. GENERIC PROPERTIES OF D-BRANES

At long wavelengths, $\lambda > l_s$ the dynamics of a Dp-brane is well described by the sum of the Dirac-Born-Infeld (DBI) action and a Wess-Zumino (WZ) term:

$$S_p = S_p^{DBI} + S_p^{WZ}. \tag{1}$$

The DBI term is

$$S_p^{DBI} = T_{(p)} \int d^{p+1}x \times \sqrt{\det[(G_{\mu\nu} + B_{\mu\nu})\partial_m Y^\mu \partial_n Y^\nu + 2\pi\alpha' F_{mn}]}, \tag{2}$$

where $F_{mn}$ is the worldvolume Born-Infeld field strength, $B_{\mu\nu}$ is the bulk antisymmetric field, $Y^{\mu\nu}$ are the collective coordinates which describe oscillations transverse to the worldvolume the Dp brane, and $G_{\mu\nu}$ is the target-space metric. The tension of the Dp-brane $T_{(p)}$ is,

$$T_{(p)} = 2\pi(4\pi^2\alpha')^{-(1+p)/2} e^{-\phi} \tag{3}$$

where $\alpha' = l_s^2$. Our conventions are the ten-dimensional target space-time vectors labeled by $\mu = 0, \ldots, 9$. The worldvolume directions are $m, n, \ldots = 0, \ldots, p$, while the directions transverse to the Dp-brane will be labeled $a, b, \ldots = p+1, \ldots, 9$. The low-energy limit of the WZ term in the action (DBI) can be deduced by requiring the absence of chiral anomalies in an arbitrary configuration of intersecting D-branes.

All superstring theories admit a myriad of Dp-brane species. Nonetheless, there are some features that are generic among all D-branes which we aim to exploit in cosmology. The most outstanding generic physical feature of D-branes are their low-energy, long-wavelength behavior. The transverse fluctuations of the D-brane is concretely described by the 9-p+1 scalar fields (more geometrically speaking, the normal bundle). An observer on the brane will see these scalars as the D-term in the corresponding Super-Yang-Mills theory which reside on the the D-brane's worldvolume (WV). Similarly, gauge fields residing in the D-brane's WV describe the longitudinal fluctuation of the D-brane.

Notice that the above action describes a supersymmetric D-brane. As a result, the dynamics of this brane is constrained to locally supersymmetric gravitational backgrounds. Therefore cosmological space-times including de Sitter is inadmissible as they will break supersymmetry on the D3-brane worldvolume. Hence our brane is necessarily non-BPS in order to incorporate dynamical gravity. Therefore, we are led to consider the evolution of a non-BPS 3-brane cosmology. Even in the early Universe any braneworld scenario will have to incorporate the non-BPS sector of string theory, hence non-bps D-branes. But, how do non-bps branes arise from first principles? In particular, we are interested in the cosmological implication of D-brane anti-D brane annihilation since it has been conjectured by Sen that this state is equivalent to vacuum.

## III. NON-BPS D-BRANE

In this section we provide a first-principle approach to non-BPS D-brane that will be compatible with early universe cosmology. One first needs to understand from a stringy perspective how non-BPS D-branes arise and evolve.

Similar to point particles, when a D-brane and an anti-D-brane are coincident they will annihilate. However, unlike point particles, the D-brane annihilation process is more involved since each of these D-branes have a U(1) gauge field theory living on its worldvolume. Therefore, the fate of these gauge fields during and after the annihilation process play a crucial role in determining decay product.

When the branes are coincident a tachyonic instability sets in. The open string connecting the D-$\overline{D}$ brane has a spectrum arising from a Gliozzi-Scherk-Olive (GSO) projection, $(-1)^F$, that is the reverse of the usual one.[2] Usually, the GSO projection acts to get rid of the tachyon in the open strings which end on a Dp-brane. However, for a D-$\overline{D}$ string the tachyon still survives despite the GSO projection. The tachyonic instability signals the eventual annihilation of the coincident brane and antibrane. Sen conjectured that the tensions of the D-anti D-brane pair and the negative-potential energy of the tachyon is exactly zero [13,14].

$$2T_D + V(T_0) = 0, \tag{4}$$

[2]For a review, read [11,12].

where $T_D$ is the tension of the D-brane and $V(T_0)$ is the value of the tachyonic potential at its minimum. Therefore as the branes annihilate the tachyonic fields evolve towards a true vacuum where the tensions of both branes are equivalent to the minimum of the tachyonic potential. In this case the branes will annihilate to the closed string vacuum and there will be no remnant branes. We will be interested in the case when a lower-dimensional brane is created as a by product of the annihilation process.

Let us look at a concrete case of a vortex configuration on a membrane-antimembrane pair in type IIA string theory. Here, the tachyon associated with the open string ending on the membrane and the antimembrane is a complex scalar field *T*. There is a $U(1)\times U(1)$ gauge field living on the worldvolume of the membrane antimembrane system. The tachyon carries one unit of winding charge under these gauge fields. Let $A^1_\mu$ and $A^2_\mu$ denote the gauge fields arising from the D2-brane and the anti-D2-brane, respectively. The resulting kinetic term for the tachyon is

$$|D_\mu T|^2, \tag{5}$$

where

$$D_\mu T = (\partial - iA^1_\mu + iA^2_\mu)T. \tag{6}$$

The form of the perturbative tachyonic potential we employ is [16]

$$V(T) = (|T|^2 - m^2)^2. \tag{7}$$

The general static, finite-energy vortexlike configuration for the tachyon field described in the polar coordinates on the membrane worldvolume in the asymptotic regime takes the form

$$T \simeq T_0 e^{in\theta}, \tag{8}$$

$$A^1_\theta - A^2_\theta \simeq 1, \text{asr} \to \infty. \tag{9}$$

Hence as $r\to\infty$, both the kinetic and potential energy will vanish rapidly. This defect is identified as a stable, finite mass particle in type IIA string theory. This particle carries one unit of magnetic flux associated with the gauge field on the worldvolume of the membrane antimembrane system

$$\oint (A^1 - A^2) dl = 2\pi. \tag{10}$$

Hence, this nontrivial flux implies that the particle carries one unit of D0 brane charge [12]. It has been argued using boundary conformal field theory calculations that this soliton is a D0 brane. The above construction can be trivially generalized to represent the p-brane of type II string theory as a vortex solution on the $(p+2)$-brane anti-$(p+2)$-brane pair [12]. We are of course interested in the case of $p=3$, the D3-brane.

We are interested in knowing the cosmological implications and consequences of the identification of the vortex defect as a codimension 2 D-brane after a brane and an antibrane annihilates.

## IV. INFLATIONARY MECHANISM: THE DEFECT SOLUTION

It has been appreciated for a while that the core of topological defects can undergo cosmic inflation without the need of fine tuning. Both Linde and Vilenkin first calculated the criterion for a defect core to undergo inflation. To make our analysis clear let us consider inflation of a domain wall. The Lagrangian of a domain wall is

$$L = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\lambda}{4}\left(\phi^2 - \frac{m^2}{\lambda}\right)^2, \tag{11}$$

where $\phi$ is a real scalar field. The Lagrangian possesses a $Z_2$ symmetry that is spontaneously broken and hence domains are formed with $\phi = \pm\eta$, where $\eta = m/\sqrt{\lambda}$. These domains are divided by kinks (domain walls) which interpolate between the two minima. The domain wall configuration is represented as

$$\phi = \eta \tanh\left(\sqrt{\frac{\lambda}{2}}\eta x\right). \tag{12}$$

What are the conditions for a universe separated into two domains by a domain wall to inflate? To answer this question we need to show that there is a regime in the parameter space of the domain wall coupling and symmetry breaking scale that will yield an exponentially expanding space-time background.

We first need to find the thickness of the domain-wall (DW) in flat space-time, which is obtained by balancing the gradient and potential energies at the core of the wall. The potential energy strives to keep the domain-wall field configuration on the vacuum manifold, hence minimizes the DW thickness, while the gradient energy provides tension to spread out the wall thickness. The potential-energy density of the wall is obtained by evaluating the potential at $\phi = 0$ since the field configuration is localized in the core of the wall. This gives $\rho_d = \lambda\eta^4$.

The wall thickness, $\delta_0$ in flat space-time is determined by the balance of the gradient and potential energy $(\eta/\delta_0)^2 \sim V_0 = V(\phi=0)$. Hence,

$$\delta_0 \simeq \eta(V_0^{1/2}). \tag{13}$$

From the Friedmann equation the horizon size corresponding to the vacuum energy $V_0$ in the interior of the wall is

$$H_0^{-1} = M_p\left(\frac{3}{8\pi V_0}\right)^{1/2}, \tag{14}$$

where $M_p$ is the Planck mass.

If $\delta_0 \ll H^{-1}$, then gravity will not affect the wall structure in the transverse direction, hence, we do not expect the wall thickness to change. However, for $\delta_0 \gg H_0^{-1}$ the size of the false vacuum region inside the wall is greater than $H_0^{-1}$ in all three directions, and according to the Einstein field equations this region will undergo inflationary expansion. Furthermore, using the above two conditions, we find that inflation will occur when the symmetry-breaking scale associated with the defect formation is in the Planck regime

$$\eta \geqslant M_p . \tag{15}$$

The criterion for inflation stated above carries over to vortices and monopoles as well. Another important point is that once started, topological inflation never ends. Although the field $\phi$ is driven away from the maximum of the potential, the inflating core of the defect, from topology, cannot disappear, unless the field unwinds. It has been shown that the core thickness grows exponentially with proper time [17]. It is also worth noting that these cases have been displayed robustely in numerical simulations.

We are now equipped to address the issue of defect driven inflation in the context of brane-antibrane annihilation in superstring theory.

## V. NON-BPS D-BRANE INFLATION SCENARIO: SET UP

In the previous section we provided robust conditions for topological defects to inflate provided that the core radius is larger than the inverse Hubble radius. Generically, field theories are difficult to understand in the Planck regime, so topological inflation is difficult to realize in this context.

We first wish to briefly discuss the assumptions we are making. We will begin by coupling the worldvolume action for the unstable brane system, including the anomaly canceling term, to the Einstein-Hilbert gravity action. Here we make a assumption that the extra four dimensions are compactified and its associated moduli fields are massive. We will later provide a consistency check of this assumption. Therefore, we will only investigate the evolution of the massless degrees of freedom with respect to the 6D Planck scale and shall use an effective gravity in $5+1$ dimensions.

The 6D Newton constant is

$$G^6 = \frac{(\alpha')^4 g_s^2}{V(T^4)}, \tag{16}$$

where $V(T^4)$ is the volume of the compact four torus.

We are now in a position to make a simple consistency check by solving for the size of the compactified dimensions in terms of the string length scale and coupling constant. As stated in the previous section the universal condition to obtain topological inflation is that the symmetry-breaking scale is on the order of the Planck mass

$$\eta \sim M_p . \tag{17}$$

From the tachyon potential, the symmetry breaking scale is the string length [18],

$$\eta = l_s^{-1} \tag{18}$$

while the six-dimensional Planck mass is

$$M_{pl} = G_6^{-1/4} . \tag{19}$$

Equating Eq. (18) with Eq. (19) we obtain a bound for the size of the compactified volume

$$V(T^4) \geqslant l_s^4 g^2 . \tag{20}$$

Hence, for weak string coupling our effective gravity description is consistent with our compactification. In other words, the vortex has the sufficient thickness in order to undergo inflation.

How does the tachyon couple to our gravitational action? While this issue is still under investigation, we provide the following argument [19,20]. The tachyon is naturally incorporated into boundary string field theory when one rewrites the U(1) field strength as a supercurvature [15,16]:

$$\mathcal{F} = \mathrm{d}\mathcal{A}, \tag{21}$$

where

$$i\mathcal{A} = \begin{pmatrix} iA^+ & \overline{T} \\ T & iA^- \end{pmatrix}. \tag{22}$$

In the Wess-Zumino term the supercurvature has $\alpha'$ as a coupling constant

$$\int_M C \wedge \mathrm{Str}\, e^{2\pi i \alpha' \mathcal{F}} . \tag{23}$$

From Eq. (22), the tachyon also has $\alpha'$ coupling and will couple to gravity via the energy momentum of the U(1) gauge fields in the DBI action. Implicit in this assumption is the observation that the time scale for the vortex configuration to form is much smaller that the 6D Planck time scale, $t_{vortex} \ll t_{6D}^{pl}$. This physically means that the tachyon, in forming a stable vortex configuration, is able to wind around the vacuum manifold to acquire a unit of vortex charge faster than the gravitational field can backreact to anisotropies of the tachyon field dynamics. Hence we can use Birkhoff's theorem to construct a general metric solution. For generality, though, the tachyon field will be time dependent,

$$T = T(t), \tag{24}$$

even after a stable vortex forms. This will be important for the graceful exit problem.

Our system will be investigated with the following action:

$$S_{Tot} = S_{Grav} + S_{DBI}^{D-\overline{D}} + S_{WZ}^{D-\overline{D}} . \tag{25}$$

Before proceeding with the explicit calculation it is worth presenting as clearly as possible a physical picture in analogy with potential driven inflationary scenarios. First, we place the tachyon on the same footing as an inflaton since it is a scalar field which rolls down a potential. The second crucial assumption is that the potential of the tachyon couples minimally to gravity. Nonetheless, the second assumption can be evaded to include nonminimal coupling, which has also demonstrated topological inflation, but this issue shall not be covered in this paper.

Consider now a 5-$\overline{5}$ annihilation. As the five branes annihilate, a non-BPS 3-brane is created. The creation of this 3-brane is important as it will act as the space-time that will inflate. The crucial point here is that the core of the vortex configuration is localized on the whole 3-brane worldvolume. At the center of the core (in this case the 3-brane) the symmetry is restored and the tachyon field vanishes. As a result the vortex always remains at the top of the tachyon effective potential at $T=0$. The false vacuum energy $V(T=0)$ yields a negative pressure equation of state for the tachyon field and will drive an inflationary epoch of the 3-brane worldvolume. The crucial point which differs from ordinary inflation is that this mechanism dynamically tunes the tachyon potential to the optimal value for inflation on the brane by localizing all of the vacuum energy on a $(3+1)$D hypersurface.

## VI. VORTEX INFLATIONARY SOLUTION

Tachyonic condensation in the D-$\overline{\text{D}}$ system flows from the false open string vacua to the closed string vacuum. In our case, there is a remnant D$(p-2)$-brane formed after the tachyonic field winds nontrivially around the vacuum manifold. In the 10 D target space the core of this defect is indeed the worldvolume of the Dp-2 brane and hence has trapped false vacuum energy from the nontrivial winding of the tachyon. Since the system is in the closed string vacuum, where gravitational interactions are turned on, this vortex carries energy momentum. In other words, at the core of the vortex, the space-time dynamics will be dominated by the potential and gradient energy associated with the vortex configuration localized on the 3-brane. This leads to a negative pressure equation of state $p(T)=\rho(T)$. If there is any matter in this region, inflation will dilute it leaving only the potential behind. In our case we will study the cosmic evolution which incorporates a local U(1) gauge field. We are assuming that the tachyonic field has formed the vortex configuration before the gravitational interactions are turned on. This is consistent with the annihilation process since the system first begins in an open string false vacuum state (which has no gravity at weak coupling) and evolves to a closed vacuum.

The defect configuration will impose a most general form of the time-dependent metric. The effective action we will study is

$$S=S_{gravity}+S_{vortex}+S_{WZ}, \tag{26}$$

$$S=-\frac{2}{G_6}\int d^6x\sqrt{-g}[(R-2\Lambda) -2G_6\mathcal{L}_{\rm DBI}+\mathcal{L}_{\rm WZ}], \tag{27}$$

where $R$ is the six-dimensional scalar curvature, $\mathcal{L}_{\rm DBI}$ is the complete D-$\overline{\text{D}}$ Lagrangian, and $G_6$ is the six-dimensional Newton constant. In particular, the tree level effective Lagrangian for the tachyonic field is

$$\mathcal{L}_{\rm DBI}=\frac{1}{g_{\rm YM}^2}\int d^6x\sqrt{-g}[F^{\pm}_{\mu\nu}F^{\pm\mu\nu}-(D_\mu T)^2 -\tfrac{1}{2}(|T|^2-\Psi^2)^2] \tag{28}$$

and the Wess-Zumino term

$$\mathcal{L}_{WZ}=T_{D5}\int_{M_6}C\wedge {\rm Str}\, e^{2\pi i\alpha'\mathcal{F}}, \tag{29}$$

where the supertrace

$${\rm Str}\, M={\rm Tr}(-)^F M={\rm Tr}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}M. \tag{30}$$

For the D5-$\overline{\text{D}}$5 problem the Wess-Zumino term becomes

$$T_{D5}\int_{M_6}C_4\wedge(2\pi\alpha')dT\wedge d\bar{T}. \tag{31}$$

Upon varying the above action we obtain the 6D-Einstein equations

$$G^6_{\mu\nu}=G_{6D}T_{\mu\nu}, \tag{32}$$

where the energy-momentum tensor of the D5-$\overline{\text{D}}$5 system is

$$T_{\mu\nu}=\frac{\delta S}{\delta g^{\mu\nu}}=D_\mu T\overline{D}_\mu\bar{T}+D_\nu T\overline{D}_\mu\bar{T}-g^{\alpha\beta}F^-_{\mu\alpha}F^-_{\nu\beta}+g_{\mu\nu}\mathcal{L}. \tag{33}$$

The tachyon equation of motion (EOM) is

$$D_\mu D^\nu T=\frac{\partial V(T\bar{T})}{\partial\bar{T}}, \tag{34}$$

where $V(T\bar{T})$ is the tachyon potential in Eq. (7), while the EOM for the gauge field is

$$\nabla^\nu F^-_{\mu\nu}=ie(\bar{T}\nabla_\mu T-T\nabla_\mu\bar{T})-2e^2A^-_\mu T\bar{T}. \tag{35}$$

The general time-dependent tachyon vortex solution is

$$T(t,r)=\phi(t,r)e^{in\theta}, \tag{36}$$

$$A^-_\mu=\frac{n}{e}\beta(t,r)\nabla_\mu\theta, \tag{37}$$

subject to the energy-conserving boundary conditions

$$\phi(t,0)=0,\quad \phi(t,\infty)=\Psi,\qquad \beta(t,0)=0,\quad \beta(t,\infty)=1. \tag{38}$$

The vortex configuration is localized on the codimension two hypersurface, identified as a D-3 brane in our case. The energy momentum of the tachyon field is dominated only by the potential and gradient energy, since the vortex is a stable configuration. As stated earlier, inflation will occur because the tachyon field has a negative pressure equation of state

$$p(T)=-\rho(T). \tag{39}$$

Hence, if initially there is matter at the core of the vortex brane the inflation dilutes the matter leaving only the potential behind.

The most general solution of Eq. (32) is

$$ds^2_{5+1}=g_{\mu\nu}dx^\mu dx^\nu+g_{ij}dx^i dx^j, \tag{40}$$

where $g_{\mu\nu}$ and $g_{ij}$ are the brane and transverse metrics, respectively. The general time-dependent solution which satisfies the Einstein field equations with planar symmetry in five space-time directions is

$$ds^2_{5+1}=-dt^2+B(t,r)^2dr^2+H(t,r)^2(dx_1^2+dx_2^2+dx_3^2)+C^2(r,t)r^2d\theta^2. \tag{41}$$

Then the tachyon equation of motion becomes

$$\ddot{T}+\left(\frac{\dot{B}}{B}-\frac{\dot{C}}{C}-\frac{\dot{H}}{H}\right)\dot{T}+\frac{T''}{B^2}+\frac{1}{C^2r^2}T(1-\alpha)^2+T(T^2-\psi^2)=0, \tag{42}$$

where a prime denotes $\partial_r$.

We shall now proceed to solve for the metric coefficients and look for inflating solutions specifically of the codimension two hypersurface, the 3-brane worldvolume. This solution describes a localized 3-brane sourced by the false vacuum energy of the tachyonic vortex, whose core lives on the 3-brane worldvolume. The tachyon vanishes at the core, thus satisfying the condition for defect driven inflation. It has been demonstrated that, in this case, both the 3-brane and the transverse coordinates will undergo exponential inflation [21,22,17].

We will now discuss two separate cases of the space-time solution: (1) The gauge field $A^-=0$, and (2) The gauge field $A^-\neq 0$.

In the latter case the field equations are difficult to solve analytically for all times *t*, since the gauge field is also time dependent. However, around the center of the vortex

$$\frac{\dot{B}}{B}=\frac{\dot{C}}{C}=\frac{\dot{H}}{H}=\sqrt{\frac{8\pi G}{3}V(T=0)}. \tag{43}$$

We immediately see that inflation occurs along the 3-brane worldvolume as well as the transverse directions.

When the gauge field is set to zero the solutions correspond to a global vortex which has been shown by other authors to exhibit a warped geometry with de Sitter expansion of the 3-brane worldvolume directions [22]. It was shown that the general solution interpolates between a $dS_6$ and a $dS_4\times R_2$.

## VII. GRACEFUL EXIT MECHANISM

Most inflationary models, especially those arising from string theory, suffer a graceful exit problem [23]. Furthermore, in earlier versions of topological inflationary scenarios, the inflaton remains at the maximum of the false vacuum yielding eternal inflation. Therefore, there is no end to inflation once it sets in. This phenomenon occurs by virtue of the no hair theorem for de Sitter space: In the core of the defect $(T=0)$ the space-time evolves by its own laws and continues to expand exponentially at all times.

Eternal inflation will occur in our case as well. Effectively, the tachyon stays at the core of the vortex and as long as the vortex remains stable, the possiblity of a graceful exit does not exist. However, in our model we propose two possible ways for inflation to end. In what follows we shall outline these two mechanisms, but they are subject to a separate paper, currently a work in progress [24].

### A. Mechanism I: Unstable defects and graceful exit

It was shown by Lepora and Martin that nontopological (embedded) local defects can also undergo sufficient inflation [26]. As the defect decays, the coupling of the time-dependent gauge field to the scalar field in the core of the defect will cause inflation to end. Likewise if our created vortex is embedded rather than topological, then the tachyon field can unwind and this will cause the equation of state to change from pure cosmological constant to radiation, ending inflation. To make this mechanism concrete in the context of brane annihilation inflation requires a realization of an embedded vortex from the non-BPS sector of string theory. We propose that this is possible with a D5-$\overline{\text{D5}}$ annihilation in type IIA which decays into an unstable D3-brane in type IIA. In a future paper we shall report on this graceful exit mechanism due to inflation in unstable defects, since this issue will require an involved stringy calculation [24].

### B. Mechanism II: Emission of the cosmological constant

In our inflationary scenario the space-time in the core of the vortex is dominated by a cosmological constant $\Lambda_4$ and will inflate due to a negative pressure equation of state. This vortex brane has an extrinsic curvature due to its embedding in the bulk. We wish to make an analogy at this stage with the physics of cosmic strings defined by the Nambu-Goto action. The extrinsic curvature of cosmic strings gives rise to acceleration along the direction normal to the length of string.[3] Similarly, the nucleated vortex in our case will also be curved and possess an acceleration away from the initial position where it was nucleated.

It was demonstrated recently that a curved 3-brane can Unruh radiate a positive cosmological constant into the bulk [27] if it accelerates within the transverse directions. This acceleration is proportional to an Unruh temperature $T_{Unruh}$. Crucial to this effect is the fact that bulk graviton modes see the brane as a mirror. This nontrivial coupling between the fields on the brane to the bulk graviton modes stimulates an emission of thermal radiation from the brane. In our case, since $\Lambda_4$ radiates away, inflation will end; a purely quantum gravitational effect. This graceful exit mechanism is applicable in our case. However, there is a subtlety that requires further investigation; while it was shown that a 3-brane do-

[3] I thank Robert Brandenberger for making this important connection.

main wall in $(4+1)$ dimensions will radiate away $\Lambda_4$, our case is slightly different, since we are dealing with a 3 brane vortex embedded in $5+1$ dimensions. Therefore, it is the topic of a future paper to (1) see if our specific case carries over to the conclusion of [27], and (2) develop this radiation mechanism to calculate the exact time scales relevant to the number of *e* foldings.

### C. The duration of inflation

Assuming the viability of the previously proposed graceful exit mechanisms, it is important to comment on the length of inflation [point (2) of the last section]. We will argue that in both cases it is possible for inflation to last long enough (at least 60 *e* foldings) before it ends. Without a detailed analysis of the decay of the embedded vortex in mechanism I, it is difficult to say exactly how long inflation will last. However, it was shown that embedded defects may be stabilized by plasma effects at high bulk densities and become unstable at low densities [25]. This is quite natural in our scenario where, in general, there are other gauge fields propagating in the bulk. In this case, the time scale for inflation will be long without much fine tuning. In mechanism II, inflation will also last a long time before ending since the graceful exit relies on quantum evaporation, which is a slow process. Therefore, both mechanisms are equipped with fine tuning free features to provide sufficient *e* foldings.

## VIII. CONCLUSIONS AND DISCUSSION

When formulated in conventional quantum-field-theory coupled to gravity, inflation exhibits initial condition fine tuning, singularity, and trans-Planckian problems. We have suggested a dynamical inflationary mechanism resulting from D-$\overline{\text{D}}$ brane annihilation to address these problems. These branes are in the non-BPS sector of superstring theory. This mechanism is physically analogous to a ‘‘big-bang’’ mechanism, in that the branes hit each other, annihilate, and a lower-dimensional inflating brane emerges as a result of the annihilation process. Moreover, we have made a concrete connection with Vilenkin’s and Linde’s realization of topological inflation. In both models, there is little need of fine tuning of potentials. In our model, the tachyon condensate forms a vortex whose core is localized on the D3-brane worldvolume which sets the initial condition neccessary for inflation.

Our mechanism is similar to topological inflation where inflation never ends and there exists no graceful exit in such models. However, we propose two mechanisms. The first mechanism requires that the vortex brane is metastable (an embedded defect) and hence the tachyon field can unwind, causing a change in the equation of state to that of radiation, ending inflation [28]. The second mechanism is based on past work where it was demonstrated that an accelerated brane will Unruh radiate its cosmological constant into the bulk [27]. However, these two mechanisms need more development and is currently being pursued [28,24].

In light of the stringy inflationary mechanism presented in this paper, one is led to a few outstanding puzzles. First, string theory possesses a myriad of D-brane species and this mechanism could, in principle, apply to other inflating hypersurfaces of differing dimensionalities. Is there something unique about an inflating $3+1$ D hypersurface, resulting from annihilating Dp-branes? Nonperturbative data from string theory should shed new light on this question and we leave this issue for future investigations. Interestingly, a similar ‘‘big-bang’’ scenario avoiding an inflationary epoch has been suggested by colliding branes in the context of Horava-Witten compactification [29].

There is a stringy mechanism which selects a large $3+1$D space-time [30] from annihilating D1-branes, namely, the Brandenberger-Vafa scenario (BV) [34,31]. This situation takes the annihilation of a D(p-2) brane into a large p spatial dimenison for $p=3$. If in the BV mechanism we associate this large dimension as a ‘‘brane world’’ then there is a similarity in that our mechanism takes the annihilation of a Dp-brane into an inflating D(p-2) space for $p=5$. These two pictures are intriguingly related to each other by Myer’s dielectric effect [32] which has been employed to resolve gravitational naked singularities [33]. We believe that further investigation of this issue will be illuminating.

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