Inflation From $D - \bar{D}$ Brane Annihilation

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We demonstrate that the initial conditions for inflation are met when a $D_5 - \bar{D}_5$ brane annihilate. This scenario uses Sen’s conjecture that a co-dimension 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 a natural mechanism for ending inflation via the motion of the vortex in the bulk due to its extrinsic curvature. We also suggest a consistent way to end inflation and localize matter on our space-time.

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 spacetime [3]. This idea has reemerged in a more concrete context, namely to solve the gauge hierarchy problem and localize 4-D gravity as well as the matter fields of the Standard Model [2,4]. It was demonstrated that the RS scenario still exhibits a flatness problem and necessitates an inflationary epoch [34]. Moreover, recent observations of the CMB agree with the inflationary scenario which resolves the problems of the standard big bang model (SBB) such as the horizon, flatness and formation of structure problems.

Nonetheless, so far most brane-world descriptions are constructed from the bottom-up necessitating other forms of fine tuning. In light of the flatness, structure formation problems and especially the trans-plankian problems, we expect quantum gravitational effects to become important in the early universe [1].

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 divergences via. and S and T-dualities [24]. Nonetheless, inflation requires very special initial conditions that are usually relinquished to the specifics of an effective theory [8]. In this paper, we investigate the non-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 [8].

Therefore, the idea for D-brane driven inflation is quite simple. When the branes annihilate a co dimension 2 vortex forms at the center of the created three brane, identified as our space-time [see figure 1]. For an observer in this spacetime, the vacuum energy dominates and generates eternal inflation. When inflation begins, it makes the tachyon (inflaton) homogenous and very close to zero near the core of the three 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.
In order to discuss D-brane inflation it is necessary to provide an analysis of non-Bps D-branes. In section [II] and [III] we review generic properties of Bps and non-Bps D-branes to set the stage for its cosmological relevance. In section [IV] we will then review in general the realization of defect driven inflation. In Section [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 section [VI]. A discussion of how inflation can end and matter is localized is discussed in section [VII]. We conclude with some open issues in light of D-brane physics 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,

$$S_p = S_p^{DBI} + S_p^{WZ}$$

The DBI term being

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

Where $F_{mn}$ is the world-volume 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 world volume the D-p Brane, $G_{\mu\nu}$ is the target-space metric. The tension of the D-brane $T_p$ is,

$$T_p = 2\pi(4\pi^2\alpha')^{-\frac{1}{2}-p/2}e^{-\phi}$$

where $\alpha' = l_s^2$. Our conventions are the ten-dimensional target spacetime vectors labeled by $\mu = 0, ..., 9$. The world-volume directions are $m,n,... = 0, ..., p$, while the direction transverse to the D-brane will be labeled $a,b,... = p + 1, ..., 9$. 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 world volume (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 are inadmissible as they will break supersymmetry on the D3-brane worldvolume. Hence our brane is necessarily non-bps in order to incorporate dynamical gravity. We are led to therefore consider the evolution of a non-bps 3-Brane cosmology. Even in the early universe any brane world 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 world volume. 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 $D - D$ brane has a spectrum arising from a GSO projection, $(-1)^F$, that is the reverse of the usual one. Usually, the GSO projection acts to get rid of the tachyon in the open strings which end on a Dp-Brane. However, for a $D - D$ string the tachyon still survives despite the GSO projection. The tachyonic instability signals the eventual annihilation of the coincident brane and anti-brane. Sen conjectured that the Tensions of the D-anti D brane pair and the negative potential energy of the tachyon is exactly zero.

$$2T_D + V(T_0) = 0$$

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

*For a nice review, read [13]
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 the closed string vacuum and there will be no remnant branes. We are of course, interested in the case when a lower dimensional brane is created as a by product of the annihilation process. The corresponding equation describing this process is:

\[ 2T_{Dp+2} + V(T_0) - T_{Dp} = 0 \]  

where \( T_{Dp} \) is the tension of the lower dimensional brane which the higher dimensional branes annihilate into. In this case, there is excess energy density associated with the \( Dp \) brane which is created in 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 anti-membrane is a complex scalar field \( T \). There is a \( U(1) \times U(1) \) gauge field living on the world volume 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:

\[ |D_\mu T|^2 \]  

(6)

where

\[ D_\mu T = (\partial - iA^1_\mu + iA^2_\mu)T. \]  

(7)

The form of the perturbative tachyonic potential we employ is [18]

\[ V(T) = (|T|^2 - m^2)^2 \]  

(8)

The general static, finite energy vortex like configuration for the tachyon field described in the polar coordinates on the membrane world volume in the asymptotic regime takes the form

\[ T \simeq T_0 e^{i\eta \theta} \]  

(9)

\[ A^1_\theta - A^2_\theta \simeq 1, \text{ as } r \to \infty. \]  

(10)

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 world volume of the membrane antimembrane system.

\[ \oint (A^1 - A^2)dl = 2\pi \]  

(11)

Hence, this nontrivial flux implies that the particle carries one unit of \( D0 \) brane charge [11]. It has been argued using boundary conformal field theory calculations that this soliton is indistinguishable from 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 [11].

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 co-dimension 2 D-brane after a brane and an anti-brane annihilates.

**IV. INFLATONARY MECHANISM: THE DEFECT SOLUTION**

It is astonishing 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:

\[ L = \frac{1}{2} (\partial_\mu \phi)^2 - \frac{\lambda}{4} (\phi^2 - \frac{m^2}{\lambda})^2 \]  

(12)

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 \( \eta = \frac{m}{\sqrt{\lambda}} \). These domains are divided by kinks (domain walls) which interpolate between the two minima. The domain wall configuration is represented as

\[ \phi = \eta \tanh(\sqrt{\frac{\lambda}{2}} x). \]  

(13)

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 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 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 spacetime is determined by the balance of the gradient and potential energy,

\[ \left( \frac{2}{\delta_0} \right)^2 \sim V_0 = V(\phi = 0) \]  

Hence,

\[ \delta_0 \simeq \eta(V_0^{1/2}) \]  

(14)
From the Friedmann equation the horizon size corresponding to the vacuum energy $V_0$ in the interior of the wall is
\[ H_0^{-1} = M_p \left( \frac{3}{8\pi V_0} \right)^{1/2} \] (15)
where $M_p$ is the Planck mass.

If $\delta_0 << H^{-1}$, then gravity will not affect affect the wall structure in the transverse direction, hence, we do not expect the wall thickness to change. However, for $\delta_0 \geq H_0^{-1}$ 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
\[ \eta \geq M_p \] (16)

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 $[22]$. It is also worth noting that these cases have been displayed robustly 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 shortly discuss the assumptions we are making. We will begin by coupling the world volume action for the unstable brane system, including the anomaly cancelling terms in the gravity action. Since we will only investigate the evolution of the massless degrees of freedom with respect to the 6D Planck scale, we shall use an effective gravity in 5+1 dimensions. Hence the 6-d Newton constant is
\[ G^6 = \frac{(\alpha')^4 g_s^2}{V(T^4)} \] (17)
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 on the order of the Planck mass.
\[ \eta \sim M_p \] (18)

From the tachyon potential, the symmetry breaking scale is the string length $[19].$
\[ \eta = l_s^{-1} \] (19)
while the six dimensional Planck mass is
\[ M_{pl} = G_6^{-1/4} \] (20)
Equating [19] with 24 we obtain a bound for the size of the compactified volume
\[ V(T^4) \geq l_s^4 g_s^2 \] (21)
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 $[20][23]$. The tachyon is naturally incorporated into boundary string field theory when one rewrites the $U(1)$ field strength as a supercurvature $[18].$
\[ F = dA \] (22)
where
\[ iA = \begin{pmatrix} iA^+ & T \\ T & iA^- \end{pmatrix} \] (23)
In the Wess-Zumino term the supercurvature has $\alpha'$ as a coupling constant.
\[ \int_M C \wedge \text{Str} e^{2\pi i\alpha' F} \] (24)
From eq 24, 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, $t_{vortex} << t_{6D}$. This physically means that the tachyon, in forming a stable vortex configuration, is able to wind around the vacuum manifold to acquire the vortex charge faster than the gravitational field can backreact to anisotropies of the tachyon field dynamics. Hence we can use Birkhoffs theorem to construct a general metric solution. For generality, though, we will the tachyon field will be time dependent,
\[ T = T(t), \quad (25) \]
even after a stable vortex forms. This will be important for the issue of ending inflation.

Our system will be investigated with the following action
\[ S_{\text{tot}} = S_{\text{grav}} + S_{\text{DBI}}^{D-D} + S_{\text{WZ}}^{D-D} \quad (26) \]

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 non minimal coupling, which has also demonstrated topological inflation, but this issue shall not be covered in this paper.

Consider now a $5-5$ 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 spacetime that will inflate. The crucial point here is that the core of the vortex configuration is localized on the whole 3-brane world volume. 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 world volume. 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 $D-\bar{D}$ 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 $10D$ target space the core of this defect is indeed the world-volume of the $Dp-2$ brane and hence has trapped false vacuum energy from the non-trivial winding of the tachyon. Since the system is in the closed string vacuum, where gravitational interactions are turned on, this vortex carries energy-momentum. Although it is not well understood how gravity is incorporated into the tachyon condensation process, we shall argue by the consistency of the six-dimensional coupling constant in the gravitational sector and the perturbative effective field theory describing the energy-momentum of the vortex brane.

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 and evolves to a closed vacuum. Hence, the defect configuration will impose a most general form of the time dependent metric.

The effective action we will study is
\[ S = S_{\text{gravity}} + S_{\text{vortex}} + S_{\text{WZ}} \quad (27) \]
\[ S = -\frac{2}{G_6} \int d^6x \sqrt{-g} \left( R - 2\Lambda - 2G_6 \mathcal{L}_{\text{DBI}} + \mathcal{L}_{\text{WZ}} \right), \quad (28) \]

where $R$ is the 6-dimensional scalar curvature, $\mathcal{L}_{\text{DBI}}$ is the complete $D-\bar{D}$ Lagrangian and $G_6$ is the six dimensional Newton constant. In particular, the tree level effective Lagrangian for the tachyonic field is
\[ \mathcal{L}_{\text{DBI}} = \frac{1}{g_{YM}^2} \int dx^6 \sqrt{-g} \left[ F^+_{\mu\nu} F^\pm_{\mu\nu} - (D_\mu T)^2 - \frac{1}{2}(|T|^2 - \Psi^2)^2 \right] \quad (29) \]

and the Wess-Zumino term
\[ \mathcal{L}_{\text{WZ}} = T_{D5} \int_{M_6} C \wedge \text{Stre}^{2\pi\alpha'} F, \quad (30) \]

where the supertrace
\[ \text{Str} M = Tr(-)^F M = Tr \left( \begin{array}{cc} 1 & 0 \\ 0 & -1 \end{array} \right) M \quad (31) \]

For the $D5-\bar{D5}$ problem the Wess-Zumino term becomes
\[ T_{D5} \int_{M_6} C_4 \wedge (2\pi\alpha')dT \wedge d\bar{T} \quad (32) \]

Upon varying the above action we obtain the 6D Einstein Equations
\[ G_{\mu\nu}^6 = G_6 T_{\mu\nu}, \quad (33) \]

where the energy-momentum tensor of the $D5-\bar{D5}$ system is
\[ T_{\mu\nu} = \delta S \delta g^{\mu\nu} = D_\mu T D_\nu T + D_\nu T D_\mu T - g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta} + g_{\mu\nu} \mathcal{L} \quad (34) \]

The tachyon E.O.M is
\[ D_\mu D^\nu T = \frac{\partial V(T\bar{T})}{\partial T} \quad (35) \]

where $V(T\bar{T})$ is the tachyon potential in eq (8), while the E.O.M for the gauge field is
\[ \nabla^\nu F^\mu_{\nu} = ie(\tilde{T} \nabla^\mu T - T \nabla^\mu \tilde{T}) - 2e^2 A^\mu \tilde{T}. \] (36)

The general time dependent tachyon vortex solution is

\[ T(t, r) = \phi(t, r)e^{i n \theta} \] (37)

\[ A^\mu = \frac{n}{c} \beta(t, r) \nabla^\mu \theta \] (38)

subject to the energy conserving boundary conditions

\[ \phi(t, 0) = 0 \quad \phi(t, \infty) = \Psi, \]

\[ \beta(t, 0) = 0 \quad \beta(t, \infty) = 1. \] (39)

The vortex configuration is localized on the co-dimension 2 hypersurface, identified as a D-3 brane in our case. The most general solution is:

\[ ds^2_{5+1} = g_{\mu \nu} dx^\mu dx^\nu + g_{ij} dx^i dx^j \] (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:

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

Then the tachyon equation of motion becomes

\[ \dot{T} + \left( \frac{\dot{B}}{B} - \frac{\dot{C}}{C} - \frac{\dot{H}}{H} \right) \dot{T} + \frac{T'}{T} + \frac{1}{T} T(1 - \alpha^2) + T(T^2 - \psi^2) = 0 \] (42)

where \( ' \) denotes \( \partial_r \).

We shall now proceed to solve for the metric coefficients and look for inflating solutions specifically of the co-dimension 2 hypersurface; the 3-brane world volume. 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 \[24, 25, 26\].

We will now discuss two separate cases of the space-time solution:

1. The gauge field \( A^- = 0 \)
2. The gauge field \( A^- \neq 0 \)

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

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

We immediately see that inflation occurs along the 3-Brane world volume 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 world volume directions \[8\]. It was shown that the general solution interpolates between a \( dS_6 \) and a \( dS_4 \times R_2 \).

### VII. CURVED VORTEX: HOW INFLATION ENDS AND MATTER REMAINS

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. However, there is a possible way to end inflation quite naturally in the brane case. The vortex lives in a transverse two dimensional hypersurface and has the associated translational invariance. It was shown that the fluctuations of the tachyon field on the vortex are the collective coordinates of the vortex \[27\]. If the vortex moves in the bulk transverse direction, the tachyon field can unwind.

Once the five branes annihilate, the vortex forms about the three dimensional hypersurface in the bulk. However, this vortex will in general have an extrinsic curvature due to its embedding in the curved 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 its relativistic velocity along the direction normal to the length of string \[\parallel\]. Similarly, the nucleated vortex in our case will also be curved and possess a non-zero velocity away from the initial position where it was nucleated. Hence, once inflation sets in on a given space-time hypersurface \( \mathcal{M}_{\text{inf}} \), it will eventually end as the vortex moves away from \( \mathcal{M}_{\text{inf}} \) where inflation was initiated [see fig2].

This occurs because the time dependent tachyon field leaves the top of the false vacuum. The vacuum energy decreases in our space-time and the expansion rate will decrease the further away the center of the vortex is from our initial space-time hypersurface.

One might be worried that the confined \( \text{U}(1) \) gauge field localized on the vortex will leave the hyperurface that is identified as our space-time once the vortex moves away; while we want matter to remain on our space-time. But since our vortex is relativistic there can be relativistic self intersection (cusps) along the vortex \[\parallel\].

It has been demonstrated \[3\] that self intersecting chiral vortices shall emit loops of superconducting cosmic strings \[16\], namely vortons. This could be a viable mechanism for generating matter and density

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\(^1\)I thank Robert Brandenberger for making this important connection.

\(^2\)I am indebted to João Magueijo for pointing this out to me.
Our Inflating Space-Time

FIG. 2. The vortex has extrinsic curvature and will move away from the initial inflating hypersurface it was created on. This causes the tachyon field to roll down the false vacuum potential eventually ending inflation on the hypersurface $M_4$

perturbations in the early universe and is worth further investigations. [For a review see [14],[15].

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 $D-\bar{D}$ brane annihilation to address these problems. These branes are in the non-BPS sector of superstring theory. This mechanism is analogous to a “Big-Bang” mechanism, in that the branes hit each other, annihilate and a lower dimensional inflating brane emerges as 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 world volume which sets the initial condition necessary for inflation.

Since our scenario resembles topological inflation the question of how inflation will end becomes relevant. We argue that inflation will end naturally due to the motion of vortex away from the space time hypersurface within which inflation was initiated. This occurs because the tachyon field defined at the initial hypersurface is a collective coordinate of the vortex and will minimize the vacuum energy as it rolls down the potential which is associated with the motion of the vortex in the bulk away from our initial inflating hypersurface.

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? Non-perturbative 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 [27].

There is a stringy mechanism which selects a large $3+1D$ space-time from annihilating D1-branes, namely the Brandenberger-Vafa scenario (BV) [17],[28]. This situation takes the annihilation of a $D(p-2)$ brane into a large $p$ spatial dimension for $p=3$. If in the BV mechanism we associate this large dimension as a “brane world” then there is a similarity 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 via. Myer’s dielectric effect [30] which has been employed to resolve gravitational naked singularities [31]. We believe that further investigation of this issue will be illuminating.

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