Spinflation from geometric tachyon

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ABSTRACT: We study the assisted inflation scenario from the rolling of N BPS D3-brane into the NS5-branes, on a transverse geometry of $R^3 \times S^1$, coupled to four dimensional gravity. We assume that the branes are distributed along S^1 and the probe D3-branes spin along R^3 plane. Qualitatively this process is similar to that of N-tachyon assisted inflation on unstable D-branes. We further study the spinflation scenario numerically and analyze its effect.

KEYWORDS: D-branes, Tachyon Condensation.

Contents

1. Introduction

Inflation provides us a useful answer for the homogeneity and isotropy of the present day observed universe [1, 2]. It can solve dynamically the flatness and horizon problem of the universe. Inflation should therefore be emerged from any theory, e.g. string theory, considered to be a fundamental theory. It is not surprising therefore that de Sitter like inflationary vacua can be constructed in string theory [3]. Several attempts have been made for deriving inflation from various string inspired models [4 – 6]. There are in fact a large number of such examples in string theory. One class of such models based on open-string tachyon condensation are capable of providing slow-roll inflation, see [7 – 16]. The open-string tachyon is a unique candidate and has a inflationary potential [17, 18], but in general, the simple type of models are plagued with the same large η-problem as the conventional models and are not favoured for slow-roll inflation, see [19]. Although, this difficulty can be avoided by allowing a large number of tachyons to simultaneously roll down and *assist* the inflation [12, 15]. This naive idea is also known as assisted inflation [20]. Some recent developments on N-flation and multi-brane inflation can be found in [21 – 27]. Other inflationary models based on brane-intersection at special angles [28], the D3/D7 models where the distance modulus (like in our present study) plays the roll of inflaton field [29, 30] and some of the race-track models driven by the Kähler modulus [31], are other interesting cases where the inflation is omnipresent in string theory constructions, (see e.g. [32 – 34]). However, one can see for a wider recent review [35].

A geometric tachyon is the geometrical interpretation of the perturbative open string tachyon field in terms of the radial distance between the in-falling D-brane into a stack of NS5-branes [38, 39]. Once this equivalence was proposed, it was tested both from the view point of effective field theory by looking at the Dirac-Born-Infeld action of the probe

D-brane in the NS5-brane geometry (and other Dp-brane background) [40], and from the full string theory view point by looking at various boundary states of rolling branes in this background [41]. More recently in [42], it was shown that one can get qualitatively all the behaviour of unstable D-branes in flat space with that of BPS and non-BPS branes in NS5-brane background when the NS5-branes have a transverse geometry of $R^3 \times S^1$. It was observed [39] that the dynamics of D-branes, which are BPS in flat ten dimensional spacetime, propagating in the background of k NS5-branes on the transverse space $R^3 \times S^1$ are remarkably similar to that of BPS and non-BPS branes in ten dimensions. Further, it was found out that what looks to be a BPS or non-BPS branes in six dimensions is actually the same object-the BPS D-brane in ten dimensions wrapped or unwrapped around the extra S^1.

The cosmological solution has also been found out by looking at the D3-brane motion into the NS5-brane geometry [43]. The inflationary scenario has been worked out in this picture. In particular the assisted inflation from the geometric tachyon has been discussed in [16], where a large number of D3-branes have been shown to roll simultaneously to get the slow roll parameters. However it has been found out that the radion should acquire trans-stringy vev. This also assumes the number of D3-branes to be very large. We try to improve upon this situation in the present paper by assuming that the D3-brane rolls and spins simultaneously into the NS5-branes on $R^3 \times S^1$. We look at the assisted inflationary scenario in this background geometry by allowing N D3-branes to simultaneously roll and spin into this geometry. Due to the extra spin on the D3-brane, the process of 'falling' into the NS5-branes will be delayed further, and there is a fair chance of getting the slow roll parameters better. We have examined this process of spinflation in the present paper. Originally the idea of spin-flation in the brane-inflation has been studied in [44]. We shall be assuming that both the D3-branes and NS5-branes are distributed along S^1 in addition to the other longitudinal directions and the rolling branes also spin along the R^3-plane. We will show that even without the spin along R^3 plane and for a small radius of the compact circle along which the N D3-branes are distributed, (and for a very weak string coupling), we get the number of D3-branes required for slow roll to be small indeed. On the other hand, one has to keep the number of NS5-branes under control. Nevertheless the vev of the geometric tachyon still seem to be trans-stringy ($\langle \Phi \rangle > M_s$) which is not so bad as that can be achieved by placing D-branes far away from the NS-branes. Then we assume that the D3-branes are spinning into the NS5-branes, and study the effect of slow roll numerically. We will show that at the initial stages the tachyons roll very slowly, and afterwards the motion resembles with that of the zero-angular momentum case.

The rest of the paper is organized as follows. In section-2, we study the probe D3-brane motion into the NS5-brane on a transverse space which is $R^3 \times S^1$, where the branes are distributed along S^1 of radius $R' > l_s$. For the range $z \gg R'$, where z is the radial direction in R^3, we identify the radial mode, which behaves like the open string tachyon and write down the relevant potential at a distance far away from the NS5-branes. Next we couple this system with that of four dimensional gravity and solve the equations of motion and find out the effective potential for studying the slow roll. We write down the conditions for slow roll and find out the number of D3-branes that we need for the assisted inflation.

section-3 is devoted to study spinflation from the geometric tachyon, where we assume a conserved angular momentum on the D-brane along R^3. We write down the equations of motion and study the spinflation numerically and compare the result with that of zero angular momentum case. Finally in section-4 we present our conclusions.

2. NS5-D3 brane system on $R^3 \times S^1$

2.1 Geometric tachyon

We start with k NS5-branes on a transverse $R^3 \times S^1$ space, which we will label by the coordinates $(\vec{z}, y)$, with $\vec{z} \in R^3$ and $y \sim y + 2\pi R'$ (R' being the radius of the S^1). The five-branes are located at the point $\vec{z} = y = 0$. The background geometry generated by this is [45, 46]

$$
\begin{aligned}
ds^2 &= dx_\mu dx^\mu + h(\vec{z}, y) \left(d\vec{z}^2 + dy^2\right), \\
e^{2(\phi-\phi_0)} &= h(\vec{z}, y), \\
\mathcal{H}_{mnp} &= -\epsilon_{mnpq}\partial^q \phi.
\end{aligned}
\tag{2.1}
$$

The $x^\mu \in R^{5,1}$ label the worldvolume of the five-branes. ϕ_0 is related to the string coupling far from the five-branes, $g_s = \exp\phi_0$. The harmonic function h has the form

$$
h = 1 + \frac{k\alpha'}{2R'|\vec{z}|} \frac{\sinh(|\vec{z}|/R')}{\cosh(|\vec{z}|/R') - \cos(y/R')}.
\tag{2.2}
$$

For our purpose, we are interested in the geometry very far away from the NS5-branes. So for $|z| \gg R'$, the harmonic function is given by

$$
h = 1 + k\alpha'/(2R'|z|),
\tag{2.3}
$$

and thus the y-direction acts as an isometry direction. The effective action on the world volume of Dp-brane in this background is governed by the DBI action:
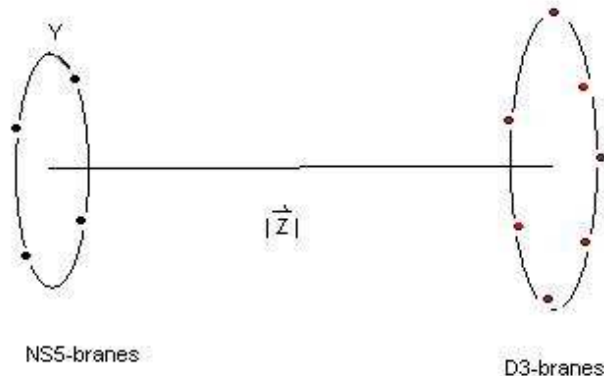
$$
\begin{aligned}
S_p &= -T_p \int d^{p+1}\xi \; e^{-(\phi-\phi_0)} \sqrt{-\det(G_{ab} + B_{ab})} \\
&= -\tau_p \int d^{p+1}x \frac{1}{\sqrt{h(Z)}} \sqrt{1 + h\partial_a Z \partial^a Z}
\end{aligned}
\tag{2.4}
$$

where in the first line G_{ab} and B_{ab} are the induced metric and the B-field, respectively, onto the world volume of the Dp-brane. Comparing it with the open string tachyon effective action

$$
\mathcal{S}_{tach} = -\int d^{p+1}x \; V(T)\sqrt{1 + \partial_a T \partial^a T},
\tag{2.5}
$$

one gets the so called radion-tachyon map:

$$
dT/dZ = \sqrt{h(Z)} = \sqrt{1 + Q^2/Z}
\tag{2.6}
$$

Figure 1: k NS5-branes and N D3-branes are uniformly spread over transverse y-circle but are separated along 3-dimensional Z-space.

where Z is the radion field, which is tachyonic. Solving the above differential equation, one gets

$$T = Z\sqrt{1 + Q^2/Z} + Q^2 \log(Z^{1/2} + (Q^2 + Z)^{1/2}) \tag{2.7}$$

where $Q^2 \equiv k\alpha'/(2R')$. This for large Z gives $T \simeq Z$. In this asymptotic region the tachyon potential becomes

$$V(T) = \frac{1}{\sqrt{h(Z)}} \simeq 1 - \frac{Q^2}{2T} \ . \tag{2.8}$$

2.2 Simultaneous rolling and assisted inflation

Our aim is to study the four dimensional cosmological solution that one gets out of this system explained above while coupling to four dimensional gravity. For this purpose, we will solve the equations of motion derived from the effective action of the 'geometric tachyon' with the above potential for the D3-brane falling in the background of NS5-brane on $R^3 \times S^1$ coupled with four dimensional gravity action. The system is depicted in the figure 1. In what follows we will only consider the homogeneous mode. To make it look more familiar with that of the open string tachyon effective action on unstable D-branes

to the quadratic order, we make a simple rescaling of the tachyon field $T \to \sqrt{\alpha'}T$. After the rescaling the effective action and the potential for the tachyon can be written as[1]

$$S = -\sum_{i=1}^{N} \int d^4x V_i(T_i) \sqrt{-\det(g_{\mu\nu} + \alpha' \partial_\mu T_i \partial_\nu T_i)} \tag{2.9}$$

where in the action above, all the potentials have same functional form, that is

$$V_i(T_i) = V(T_i) = \tau_3 \left(1 - \frac{Q^2}{2\sqrt{\alpha'} T_i}\right). \tag{2.10}$$

This form of potential is however valid only in the asymptotic region where respective T_i's are very large. One can see that the equations of motion for tachyon fields decoupled from each other. Hence we would specifically like to assume that all D3-branes roll into the NS5-brane at the same time. We will have the following simultaneity ansatz for the purely time dependant configuration

$$T_1(t) = T_2(t) = T_3(t) = \cdots = T_N(t) = \Phi(t)$$
$$V_1(T_1) = V_2(T_2) = V_3(T_3) = \cdots = V_N(T_N) = V(\Phi(t)) \tag{2.11}$$

We shall be coupling this system to that of the four dimensional gravity given by

$$S_{\text{grav}} = \frac{M_p^2}{2} \int d^4x \sqrt{-g} R . \tag{2.12}$$

The field equations we will solve combining gravity and the N geometrical tachyon effective action are as follows:

$$\ddot{\Phi} = -(1 - \alpha' \dot{\Phi}^2) \left(M_s^2 \frac{V_{,\Phi}}{V} + 3H\dot{\Phi}\right)$$
$$H^2 = \frac{8\pi G}{3} \left(1 - \frac{k}{2\tilde{R}\Phi}\right) \frac{\tau_3 N}{\sqrt{1 - \alpha' \dot{\Phi}^2}} \tag{2.13}$$

where $\tilde{R} = \frac{2R'}{l_s}$. where we have assumed the ansatze in (2.11). As $k \ll 2\tilde{R}\Phi$ and assuming $\alpha' \dot{\Phi}^2 \ll 1$, keeping only the leading order terms we get

$$\ddot{\Phi} = -\left(M_s^3 \frac{Q^2}{2\Phi^2} + 3H\dot{\Phi}\right) + O(\Phi^{-3})$$
$$H^2 = \frac{8\pi G \tau_3 N}{3} \left(1 - \frac{k}{2\tilde{R}\Phi} + \frac{\alpha' \dot{\Phi}^2}{2}\right)$$
$$= \frac{8\pi G}{3} \frac{\tilde{N}}{g_s} \left(V_{\text{eff}} + \frac{\dot{\Phi}^2}{2}\right), \tag{2.14}$$

---

[1]Though we are taking large number of D3-branes, the NS5-branes are much heavier ($\sim \frac{1}{g_s^2}$) than the Dp-branes ($\sim \frac{1}{g_s}$) in the weak string coupling regime. For sufficiently weak coupling, the back reaction of these probe branes can be ignored. We restrict ourselves to the non-interacting geometric tachyon modes only in the DBI action. Further, we ignore other excitations on the world volume of D3-branes including gauge fields. Hence in the lowest order analysis only geometric tachyons will contribute.

where in the last line we have used

$$V_{\text{eff}}(\Phi) = M_s^4 \left(1 - \frac{kM_s}{2\tilde{R}\Phi} \right), \quad \tilde{N} = \frac{N}{(2\pi)^3}, \quad \tau_3 = \frac{1}{(2\pi)^3 g_s \alpha'^2}, \quad \Phi \to \sqrt{\alpha'}\Phi. \quad (2.15)$$

One can also define a new field $\psi \equiv \sqrt{\frac{\tilde{N}}{g_s}}\Phi$, which leads to the canonical form of equation

$$H^2 = \frac{8\pi G}{3} \left(V_{\text{eff}} + \frac{\dot{\psi}^2}{2} \right) \quad (2.16)$$

in which case

$$V_{\text{eff}}(\psi) = \frac{\tilde{N}M_s^4}{g_s} \left(1 - \sqrt{\frac{\tilde{N}}{g_s}} \frac{kM_s}{2\tilde{R}\psi} \right), \quad (2.17)$$

This form of potential will be used next to obtain various slow roll quantities.

2.3 Slow-roll parameters

The slow-roll parameters for this multi-field system are now [36]

$$\epsilon = \frac{M_p^2}{2} \left(\frac{V_{,\psi}}{V} \right)^2 \simeq \frac{g_s}{2\tilde{N}} (\frac{k}{2\tilde{R}})^2 \frac{M_p^2}{M_s^2} \left(\frac{M_s}{\Phi} \right)^4$$

$$\eta = M_p^2 \frac{V''}{V} \simeq -4 \frac{g_s}{2\tilde{N}} (\frac{2\tilde{R}}{k})^2 \frac{M_p^2}{M_s^2} \left(\frac{kM_s}{2\tilde{R}\Phi} \right)^3 \quad (2.18)$$

where $'$ indicate derivatives with respect to field ψ. The r.h.s are reexpressed in terms of Φ. To little bit simplify these expressions, we now define a new quantity $\frac{1}{\omega^2} = \frac{g_s}{\tilde{N}}(\frac{2\tilde{R}}{k})^2 \frac{M_p^2}{M_s^2}$. Then we can write

$$\epsilon = -\frac{1}{4}\eta \left(\frac{kM_s}{2\tilde{R}\Phi} \right), \quad \eta = -\frac{2}{\omega^2} \left(\frac{kM_s}{2\tilde{R}\Phi} \right)^3 \quad (2.19)$$

Let us note that we are working in the asymptotic regime where

$$\left(\frac{kM_s}{2\tilde{R}\Phi} \right) \ll 1 \quad (2.20)$$

holds good. Note that this can be achieved by adjusting k, R' and Φ.[2] However, for the sake of simplifying the analysis let us set from now onwards that during the slow roll

$$\left(\frac{kM_s}{2\tilde{R}\Phi} \right) \simeq .01. \quad (2.21)$$

From the observational bounds on $\eta_{obs} \leq .02$, we determine that, following (2.21) and (2.19), we should have

$$\omega^2 \geq \frac{2}{\eta_{obs}} \left(\frac{kM_s}{2\tilde{R}\Phi} \right)^3 \simeq (.01)^2.$$

---

[2]The special advantage here compared to the case of [16], where NS5-branes were on transverse R^4, is that we could now vary the ratio $\frac{k}{2\tilde{R}}$ by varying the radius R' of S^1.

Thus to be reasonable we shall take $\omega^2 \sim .001$ in the following analysis.

Let us now look at the amplitudes of scalar perturbations. During slow roll the square of the amplitudes can be obtained as

$$\delta_s^2 \simeq \frac{1}{150\pi^2\epsilon}\frac{V_{eff}}{M_p^4} \approx \frac{1}{150\pi^2\epsilon}\omega^2\left(\frac{2\tilde{R}}{k}\right)^2\frac{M_s^2}{M_p^2} \tag{2.22}$$

Note that the amplitudes are bounded as $\delta_s^2 < 10^{-10}$ [37]. Similarly, during slow roll the Hubble parameter is

$$H^2 \simeq \frac{V_{eff}}{3M_p^2} \approx \frac{\tilde{N}}{g_s}\frac{M_s^4}{3M_p^2} = \omega^2\left(\frac{2\tilde{R}}{k}\right)^2\frac{M_s^2}{3} \ . \tag{2.23}$$

It is desirable to keep $H \ll M_s$, so that stringy effects are suppressed. Working with $\omega^2 \approx .001$ (which is the safest to choose in case one chooses larger initial values of $\frac{kM_s}{2\tilde{R}\Phi}$), the bound $H \ll M_s$ can be achieved so long as we ensure $\frac{k}{2\tilde{R}} \geq \frac{1}{\sqrt{30}} \approx .18$. For this to happen, equation (2.21) tells us that

$$\Phi \simeq 18M_s \ .$$

It means that $D3$-branes have to be sufficiently far away from the NS5-branes initially. This would correspond to the trans-stringy situation.

Now, from eq. (2.21) and the observational bounds on η we determine that

$$\epsilon \simeq \frac{\eta}{4}\frac{k}{2\tilde{R}}\frac{M_s}{\Phi} \sim 10^{-3}$$

and from (2.22) we can find

$$\delta_s^2 \approx 10^{-2}\frac{M_s^2}{M_p^2} \tag{2.24}$$

Since the bounds on the amplitudes are $\delta_s \leq 1.9 \times 10^{-5}$, it fixes that the string scale to be in the range

$$M_s \leq 10^{-4}M_p \ . \tag{2.25}$$

Hence, the number of 3-branes goes as

$$\frac{N}{(2\pi)^3} = g_s\omega^2\left(\frac{2\tilde{R}}{k}\right)^2\frac{M_p^2}{M_s^2} \sim g_s10^6 \ . \tag{2.26}$$

Actual number however will depend upon the strength of weak string coupling in a given cosmological vacuum. Nevertheless for a very weak string coupling the number of 3-branes required for assisted inflation could be very low indeed. A value of $g_s \sim 10^{-5}$ is acceptable in our model, which makes the number of the D3-branes to be small about 10^3 or so. We note that $g_s > 10^{-4}$ is not acceptable in our model.[3]

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[3]This is because in the probe approximation we must have $\frac{k}{g_s^2} \gg \frac{N}{g_s}$, i.e. $\frac{k}{Ng_s} \gg 1$. Since $N \sim (2\pi)^3 g_s10^6 \approx 2.5 \times 10^8 g_s$, for $k = 2$ we must have $g_s < 10^{-4}$ in order that probe approximation holds good. Also a large number density of D3-branes may not be allowed due to topological restrictions on CY coming from tadpole charge cancellations.

A few comments as compared to [16], where we considered the D3-branes falling into the NS5-brane on transverse R^4, are in order. First the number of probe D3-branes seem to be much smaller (of the order 10^3) than in the paper [16]. Further, in the present case, we have the liberty of varying the ratio like $\frac{k}{2\tilde{R}}$, by varying the radius of the circle S^1, instead of varying k, that roughly fixes the radion in terms of string mass M_s.

Before closing this section let us discuss few facts regarding the 4D physics out of our system. The typical relationship between 4D Planck mass and the string mass is

$$M_p^2/M_s^2 = v_0/((2\pi)^7 g_s^2) \tag{2.27}$$

where $v_0 = \text{Volume}/(l_s)^6$ is the overall volume factor of the compact 3-fold. Presumably, to control stringy corrections this CY3 must have a large volume, $v_0 \gg 1$. We consider the asymmetric CY3 with the volume factor $v_0 \sim 10^3$ which is also preferred by a small value of string coupling. Let us assume that the directions along CY3 are x^4, x^5, z_i, y. Out of this we make the assumption that the compact y-coordinate has radius $R' > l_s$, and that size of z-coordinates goes as $|z| \gg l_s$ ($|Z| \sim 18l_s$). We further note that for $\frac{M_s}{M_p} \sim 10^{-4}$ and taking $g_s \sim 10^{-5}$ as determined above, we find from (2.27) that $v_0 \sim 10^{13} g_s^2 \simeq 10^3$. It also gives 3-brane density $N/v_0 < 1$. It is a quantity which says that there is no more than one D3-brane per unit CY3 volume measured in the units of string length. A higher density will induce backreaction on the CY3 in question. With a volume cutoff, of course, we cannot take Z to be very large, because the displacement of 3-branes will further be restricted by the size of the internal CY3. Further note that we cannot take very small g_s either, as that can reduce the volume factor $v_0 \sim O(1)$ which is not preferred. Hence $g_s \simeq 10^{-5}$ seems to be just perfect choice. We will show numerically in the next section that with the above conditions, a slow roll inflation is possible. However, there is the issue of stabilization of various moduli that arises due to the compactification. Strictly speaking all the moduli have to be stabilized for a consistent inflationary model [4]. Studying the full fledged moduli stabilization with fluxes in this particular model is beyond the scope of the present paper. We wish to come back to this issue in future. In the next section we study the effect of conserved angular momentum in the system.

3. Spin-flation

We now consider a case where the rolling 3-branes have a spin along the R^3 plane. The corresponding conserved angular momentum will appear as scalar modes, θ^r, in the DBI action. The action will then read as

$$S_3 = -\tau_3 \int d^{3+1} x \sqrt{-g} V(Z) \sqrt{1 + h(\partial_a Z \partial^a Z + \partial_a \theta^r \partial^a \theta^s \tilde{g}_{rs})}. \tag{3.1}$$

where $V = \frac{1}{\sqrt{h(Z)}}$. The metric $\tilde{g}_{rs}$ is the metric on the θ^r angular space. In our notation, it is a metric of the spherical polar coordinate type, $\tilde{g}_{rs} = \text{diag}(Z^2, Z^2 \sin^2 \theta_1)$. We shall take for conserved angular momenta, l_r, and the product as $l^2 = l_r l_s \tilde{g}^{rs}$. The conservation equation in the FRW background which follows from the above action is

$$\gamma a(t)^3 h^{1/2} \dot{\theta}^r \tilde{g}_{rs} \equiv l_s \tag{3.2}$$

where $a(t)$ is the scale factor in the metric and γ is the factor generated by the non-standard kinetic term

$$\gamma = \sqrt{(1 + l^2/a^6)/(1 - h\dot{Z}^2)} \ . \tag{3.3}$$

The gravitational equation is

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \tau_3 V \gamma \tag{3.4}$$

this is also the constraint equation. We also write down the evolution equation

$$\dot{H} = -4\pi G \tau_3 \frac{V}{\sqrt{1 - h\dot{Z}^2}} \frac{(h\dot{Z}^2 + l^2/a^6)}{\sqrt{1 + l^2/a^6}} \tag{3.5}$$

The Z-equation can be similarly obtained as

$$\ddot{Z} + \frac{h'}{2h}\dot{Z}^2 + \dot{Z}(1 - h\dot{Z}^2)\left(3H + \left(\frac{\dot{Z}}{Z} + 3H\right)\frac{l^2 a^{-6}}{(1 + l^2 a^{-6})}\right)$$
$$- \frac{1}{2h\gamma^2}\left(\frac{h'}{h} + \frac{l^2}{a^6}\left(\frac{h'}{h} + \frac{2}{Z}(1 - h\dot{Z}^2)\right)\right) = 0 \quad (3.6)$$

Considering now a simpler case when the D3-branes are moving in an equatorial plane in R^3 transverse space. The branes are assumed to be fixed along S^1. We will have $\dot{\theta}_1 \neq 0$, $\dot{\theta}_2 = 0$, and let the orbital angular momentum in the plane to be L. Then eq.(3.4) will reduce to

$$H^2 = \frac{8\pi G \tau_3}{3}\sqrt{\frac{1 + L^2 Z^{-2} a^{-6}}{h(1 - h\dot{Z}^2)}} \tag{3.7}$$

As we notice that all L dependence is contained in the L^2 term in the above equation. The L dependent terms modify the tachyon rolling process by adding to the initial value of Hubble parameter H. We notice that when $L = 0$ these equations directly reduce to zero angular momentum case. The equations (3.5) to (3.6) shall be used for studying inflationary numerical solutions.

3.1 Numerics

We shall be considering the case of orbital motion in the (Z, θ) plane as discussed in the previous section. Let us take the orbital momentum to be L. For studying the numerical aspects we the use following equations of motion

$$\ddot{Z} + \frac{h'}{2h}\dot{Z}^2 + \dot{Z}(1 - h\dot{Z}^2)\left(3H + \left(\frac{\dot{Z}}{Z} + 3H\right)\frac{L^2 Z^{-2} a^{-6}}{(1 + L^2 Z^{-2} a^{-6})}\right)$$
$$- \frac{1}{2h\gamma^2}\left(\frac{h'}{h} + \frac{L^2}{Z^2 a^6}\left(\frac{h'}{h} + \frac{2}{Z}(1 - h\dot{Z}^2)\right)\right) = 0 \, ,$$

$$\dot{a}(t)^2 = \frac{q}{3}a(t)^2\sqrt{\frac{1 + L^2 Z^{-2} a^{-6}}{h(1 - h\dot{Z}^2)}} \tag{3.8}$$

where we defined $q \equiv 8\pi G N \tau_3$ and we shall be using $h(Z) = 1 + \frac{k l_s}{2RZ}$. Considering the fact that the BPS D3-branes are initially very far away, $Z(0) \gg R' > l_s$, and roll
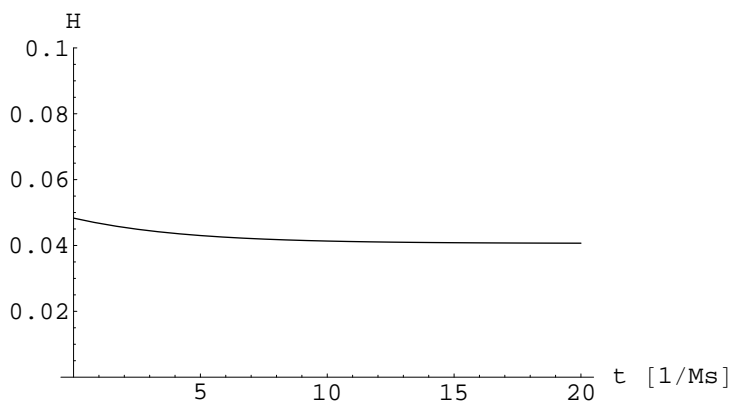
Figure 2: $H(t)$ as a function of time for initial epoch of time. It is clear that initial higher value that L terms dominate the expansion and later on H sets to its plateau value during inflation.
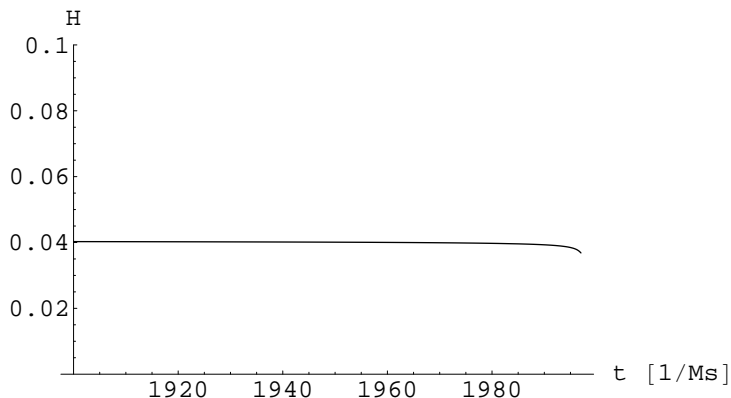
Figure 3: Inflation ends at about the time when $t \sim 2000 M_s^{-1}$. From the area under the H-curve we estimate the number of e-folds being around 80.

down with zero initial velocity, $\dot{Z}(0) \simeq 0$, the initial value of Hubble parameter is given by $\frac{q}{3}\sqrt{1 + L^2 Z(0)^{-2} a(0)^{-6}}$. We shall be setting $a(0) = 1$ and it is useful to have $\frac{L}{Z(0)}$ finite in order to study the effect of orbital motion on the inflationary dynamics. As the universe will have an accelerated expansion the L dependant terms will be heavily suppressed during evolution even though Z will decrease in time as we shall see. Thus the essential contribution from L terms will come at the time of initial epoch only.
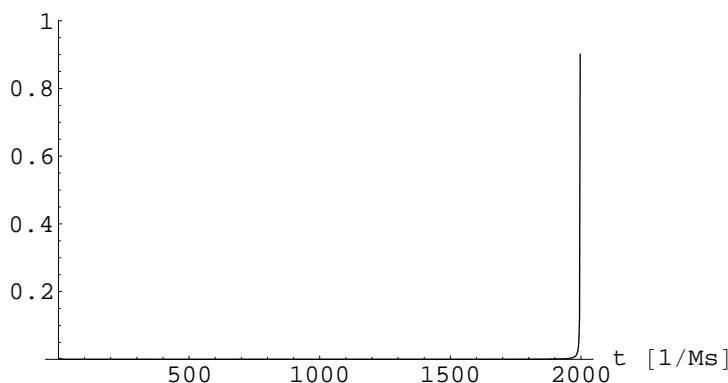
Figure 4: The plot of $h(Z)\dot{Z}^2 \equiv \dot{T}^2$. It shows that tachyon velocity $\dot{T}^2$ tends to 1 when inflation ends. It is the time when tachyon condensation takes place.

Keeping with our discussion on the slow-roll in the previous sections, we can take[4]

$$q = \frac{1}{200}, \ \frac{k}{\tilde{R}} = 0.8, \ L = 20 \ .$$

We shall work in the units of $\alpha' = l_s^2 = 1$. The initial values are taken as $\dot{Z}(0) = -.003$, $Z(0) = 20$, $a(0) = 1$ so that the bounds $Z \gg R' > l_s$ are respected. The evolutions of Hubble parameter and velocities are plotted in figures 2 to 4 for various intervals of time. The number of e-folds could be estimated by finding out total area under the $H(t)$ curve in the plateau regions. We find that the number of e-folds are more when $L \neq 0$, but this number does not change very much even if we take $L = 20$. For a comparison, in the figures 6 to 9, we have plotted $H(t)$ for $L = 0$ case also while keeping everything else the same. The inflation ends slightly earlier in the $L = 0$ case as compared to the $L = 20$ case. This behaviour is on the expected lines since the D3-branes spin around the NS5-brane as they slide towards them. But due to accelerated expansion the effect of L/a^3 terms dies out much faster. The visible effect of the angular momentum appears only near to the beginning of the rolling process. In the absence of any angular momentum the branes will slide faster thus ending the inflation a little early. We also find that the number of e-folds increases marginally if we choose smaller initial value of $\dot{Z}(0)$ which is expected. Note that we have chosen the values of various parameters such that H remains throughout very small compared to string mass. This is along the lines of discussion in the previous section so that stringy effects are suppressed.

4. Conclusions

We have studied, in this paper, the assisted inflation from the homogeneous rolling of the

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[4]The value $\frac{k}{\tilde{R}} = .8$ confirms to a situation where we can have around 2 NS5-branes spread over the transverse circle of radius $R' = 1.25 l_s$ or 4 NS5-branes spread over the transverse circle of radius $R' = 2.5 l_s$.
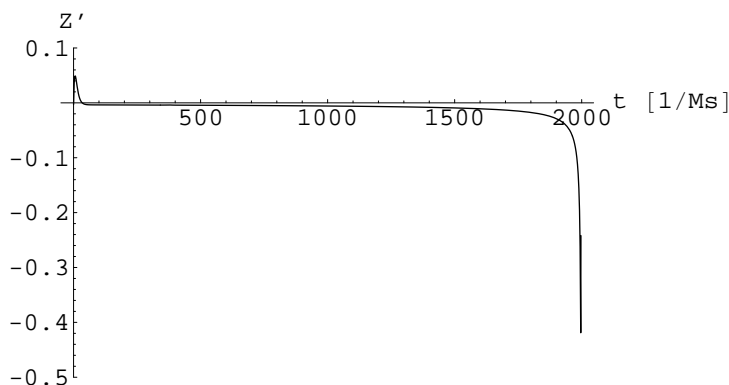
Figure 5: The negative radion velocity $\dot{Z}$ indicating that 3-branes are moving towards NS5-branes. The positive initial values indicate that due to angular-momentum effect the D-branes initially move away from NS-branes. When effect of L/a^3 terms is diluted away due to expansion of space the D-branes again fall towards the center.
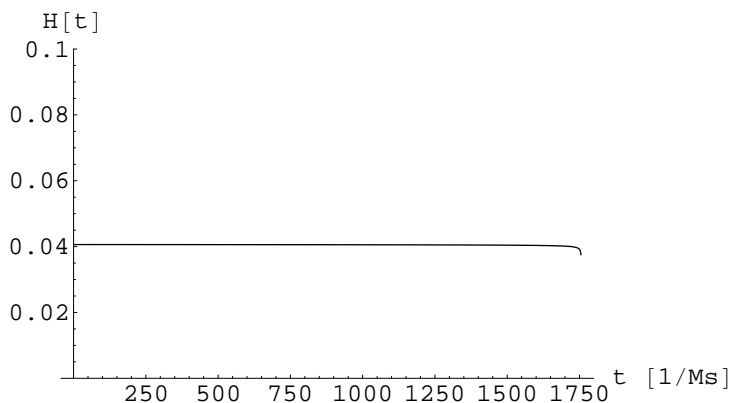
Figure 6: $H(t)$ graph for $L = 0$ case. The inflation ends slightly early in this case at about $t = 1750/M_s$. The number of e-folds is reduced to 70.

D3-branes into the NS5-branes on $R^3 \times S^1$ coupled to four dimensional gravity, where the branes are distributed along the S^1. We have shown that the number of D3-branes needed for the assisted inflation are indeed very low, for a sufficiently weak string coupling and for a small radius of the S^1 circle. The number of e-foldings and other slow roll parameters are shown to be similar to that of N-tachyon assisted inflation. We have further studied the assisted inflation when there is a conserved angular momentum for D3-branes along a plane in R^3. We have studied this effect of spin numerically. We have shown that the effect of angular momentum indeed slows down the process of rolling, which is not very surprising, as the D-branes while slide into the NS5-branes, also spin along a plane. The
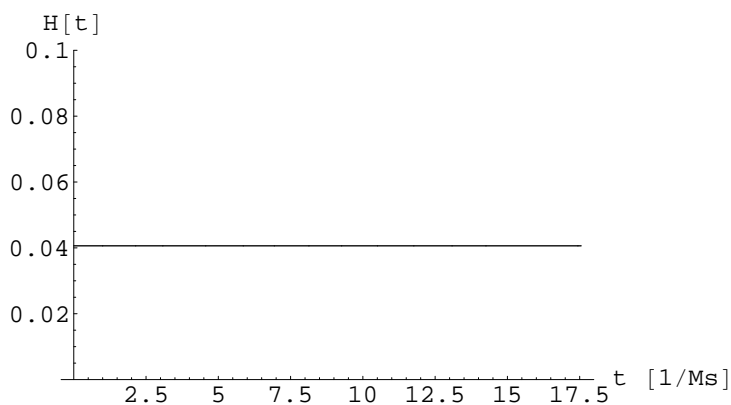
Figure 7: $H(t)$ for initial epoch of time when $L = 0$. We compare it with $L = 20$ case.
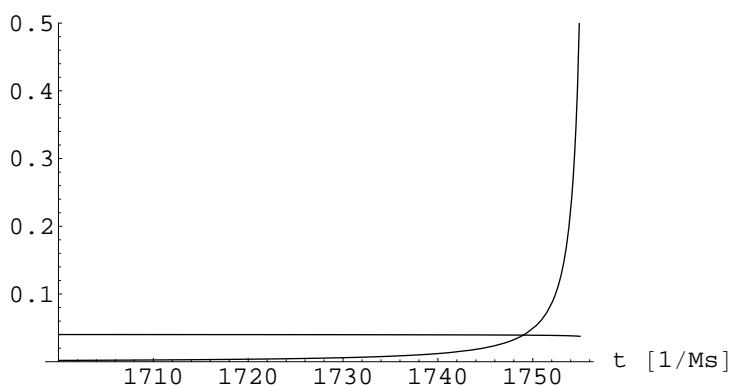
Figure 8: H and $h(Z)\dot{Z}^2$ (the rising curve) for $L = 0$.

inflation has been shown to end at a later time compared to the zero angular momentum case. This effectively adds more e-folds to the inflation. However, the effect of spin can be observed for a very short duration at the initial stage of inflation only. So this may not have any effect on the last 50-60 e-folds of inflation although overall number of e-folds will increase.

This results of the present paper can be extended in few ways. A simple exercise could be to extend this idea of spin-flation in [16] to add conserved angular momentum and see how exactly it affects the inflation. It would also be interesting to include spin in the brane inflation in other warped backgrounds and study the process.
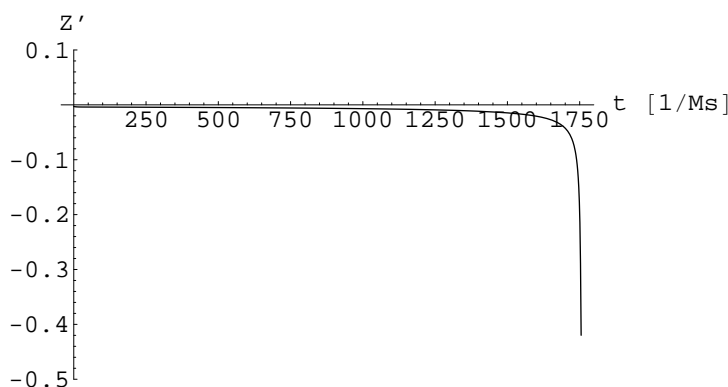
Figure 9: $\dot{Z}$ as a for $L = 0$. The D-branes smoothly fall towards the center.

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