Inflation from String Theory

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Abstract

I review some aspects of obtaining inflation from string theory, in particular brane-antibrane inflation within the framework of KKLMMT, and racetrack inflation. Further, I discuss recent work on the problem of reheating after brane-antibrane annihilation, and possible distinctive features of production of cosmic string and brane defects at this time.

1 Introduction

Many experiments are now yielding exciting, high-precision results about the universe, concerning the cosmic microwave background, large scale structure through galaxy surveys, Lyman α forest observations and weak gravitational lensing, and the dark energy via distant type Ia supernovae. Particle physics experiments, on the other hand, are presently quite limited in what they can tell us about physics at the most fundamental level, for which string theory is a very attractive candidate theory. For these reasons many string theorists have turned to the early universe as a possible laboratory for testing the theory.

In this talk I will focus on string theory as a source of inflation, various aspects of which have been investigated in references [1]-[5]. I will start by reviewing the KKLT [6] and KKLMMT [7] picture, then describe our attempt to embed this in a more realistic theory including the standard model [1], as well as a variant dubbed “racetrack inflation” [2]. Following the discussion of these inflationary models, I will then turn to the issues surrounding the end of inflation, namely how reheating may be realized [3], the production of cosmic superstring defects [4], and the question of whether our universe itself could be a 3-brane defect created at the end of inflation [5].

2 Brane-antibrane inflation in flux compactifications

Intuitively it is quite appealing to imagine that inflation could have been driven by the potential energy which gives rise to the attractive force between a brane and antibrane in the early universe [8, 9], and that reheating results from their mutual annihilation. However it was initially not easy to get this simple idea to work in detail. First, the potential was not automatically flat enough to get inflation, so it was necessary to look for means to get around this problem [10, 11]. Even then, there remained a serious shortcoming: various moduli parametrizing the size and shape of the compact dimensions were considered to be fixed without specifying the mechanism. It was not clear whether an actual stabilization mechanism would preserve whatever degree of flatness one had managed to achieve for the inflaton potential.

The problem of modulus stabilization received a big boost within the context of type IIB string theory through reference [12] (GKP), where the paradigm of stabilization by fluxes of NS-NS and R-R gauge fields in 3-cycles of the Calabi-Yau manifold appeared (figure 1). A nice feature of this approach is that a warped throat with an exponentially large hierarchy could be generated from a small hierarchies in the ratio of the fluxes. Such throats provide a way of solving the hierarchy problem [13] for an observer living on a brane in the bottom of the throat. In this compactification the dilaton and complex structure (shape) moduli are stabilized, but not the overall volume (Kähler) modulus.

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The GKP idea was put into a cosmological context in reference [6], where nonperturbative effects like gaugino condensation were invoked to generate a superpotential for the Kähler modulus, $T$,

$$W = W_0 + Ae^{-aT}$$  \hfill (1)

where the constant piece $W_0$ was already arising within GKP. This gives rise to a supergravity F-term potential

$$V_F = e^K \left( K^{ab} D_a W \bar{D}_b W - 3 |W|^2 \right)$$  \hfill (2)

with a supersymmetric AdS (negative energy) minimum, where $T$ is stabilized. For cosmological purposes one would like to raise this minimum to a positive value to obtain deSitter space. KKLT realized that this could be achieved by putting an anti-D3 brane, which breaks SUSY, into the throat. The antibrane gives an additional contribution to the potential,

$$V_{\bar{D}3} = \frac{k}{T^2}$$  \hfill (3)

which can raise the minimum of the potential to a positive value. The resulting minimum was only metastable, with the decompactified theory at $T \rightarrow \infty$ being the true minimum, but it was shown that the lifetime of the deSitter vacuum could easily be cosmologically long.

The step from eternal deSitter space to inflation was made in [7] (KKLMMT) by adding to this picture a mobile D3 brane which would fall down the throat due to its attraction to the antibrane. (Note that there should actually be more than one antibrane in the throat since we want inflation to end with Minkowski space, not AdS, which would result from the annihilation of the antibrane if there was only one of them.) This was the first example of brane-antibrane inflation where the problem of modulus stabilization was addressed in a rigorous way. The idea would have worked perfectly, in that the effect of warping in the throat was to make the potential of the inflaton (the brane-antibrane separation) naturally small and thus flat:

$$V_{inf} = \frac{k'}{T^2 |\psi - \psi_0|^4}$$  \hfill (4)

Here $\psi$ and $\psi_0$ are the positions of the brane and antibrane respectively, and the coefficient $k'$ is suppressed by exponentially small warp factors. However, this nice picture was spoiled by a crucial technicality. Namely, the brane can only be consistently introduced if the volume modulus appearing in the Kähler
function $K$ and in the $1/T^2$ factors in (3) becomes $T - f(|\psi|^2)$ instead of just $T$. The function $f$ can be expanded as $|\psi|^2 + O(\psi^3)$ near $\psi = 0$. Thus the inflaton gets a large additional contribution to its mass which is of order the total potential, $V/M_p^2 \sim H^2$, ruining the slow-roll condition. To counteract this, it was necessary to imagine some source of $\psi$-dependence in the superpotential, which would be fine-tuned to cancel the unwanted contributions [7, 14, 15].

3 Realistic brane-antibrane inflation

One might also wonder where the standard model (SM) is living in this picture. In [1] we considered a construction in which the SM brane is at a singular fixed point of a 4-torus in the bottom of the throat, which has been orbifolded under a $Z_N$ symmetry (figure 2). These singularities have the advantage of admitting chiral gauge theories and are thus good candidates for placing the SM. Each singularity (of which there are many) bring with it a new a modulus, a blowing-up mode described by a chiral field $B_i$.

We were interested to see if these modes could have a significant effect on inflation. To investigate this, we simplified the problem by keeping only one of these modes.

The resulting potential is complicated, and depends on three complex fields, the brane position $\psi + i\phi$, the Kähler modulus $T = \sigma + i\tau$ and the blowing-up mode $B + i\beta$:

$$V = \frac{e^{2B^2}}{\rho^3} \left( 2 \frac{AC(ra + 4B^2 - 2cB)\cos(\tau - \beta)}{e^{a\sigma/2}e^{cB}} + 2 \frac{AW_0(ra + 4B^2)\cos\tau}{e^{a\sigma/2}} + 4 \frac{BCW_0(2B - c)\cos\beta}{e^{cB}} + \frac{A^2(12B^2 + 6ra + r\sigma a^2)}{3e^{a\sigma}} + \frac{C^2(2B - c)^2}{(e^{cB})^2} + 4B^2W_0^2 \right)$$

where $r = \sigma - \psi^2$. The kinetic energy is also complicated. However one finds that most of the fields are heavy and can be integrated out, with the exception of $\sigma$ and $\psi$. In principle the $\sigma$ field could also be
integrated out, but since its nontrivial minimum is a delicate feature, we keep track of its dynamics. In the right regime of parameters, the potential looks like figure 3, with a trough in the $\psi$ direction at the value of $\sigma$ where it is stabilized.

![Local Minimum vs. Steep Trough](image)

Fig. 3: Inflaton potential not yet tuned to be sufficiently flat. There is a local minimum (left) leading to eternal deSitter space, or else it rolls too quickly to give enough inflation (right).

We found that it is possible to tune parameters so that the trough is sufficiently flat, without introducing any new source of $\psi$ dependence such as in the superpotential. Hence this is in way a simpler realization than was suggested in KKLMMT. Detailed study of the inflaton dynamics shows that the degree of fine-tuning needed is rather severe however. Figure 4 shows that the value of $k$ needed to get a given number of e-foldings of inflation, for some fixed values of the other parameters, must be tuned to a part in 1000 to get 60 e-foldings.

![Inflaton Dynamics](image)

Fig. 4: To obtain a flat trough (left), strong tuning of parameters is required (right).

Nevertheless, other models of inflation also require tuning to get a flat potential, so it is worthwhile to reserve judgment and consider whether the theory has any distinctive predictions. One prediction is that the scalar spectral index may have significant deviations from $n = 1$ and some level of negative running, $dn/d\ln k < 0$, as illustrated in figure 5, for a model where the COBE fluctuations are produced between 30 and 40 e-foldings after the beginning of inflation.
Fig. 5: Left: deviation of scalar spectral index from 1 as a function of $N \sim \ln k$, over the range visible in the CMB for a particular choice of model parameters. Right: WMAP, 2DF galaxy redshift survey and Lyman alpha combined constraints.

Unfortunately such predictions are only indicative and not robust, since one can always tune the potential to be even more flat, to further suppress the deviations from $n = 1$. However the fact that more tuning would be required encourages one to believe that the most natural situation is one in which inflation lasted for only a short time (the minimal canonical 60 e-foldings), which leads to the largest deviations from $n = 1$ which are not yet ruled out. Interestingly the constraints are becoming stronger with the combination of Lyman alpha forest data from the Sloan Digital Sky Survey with WMAP data [16], claiming a determination of $n = 0.98 \pm 0.02$.

It is also interesting that one can find more exotic inflaton trajectories in which the Kähler modulus plays a role, by opening up a gap in the trough through which $\sigma$ can escape, as shown in figure 6. (To be realistic, these would require additional metastable minima at larger values of $\sigma$ to prevent decompactification of the extra dimensions.) Such complications could give rise to isocurvature fluctuations, and to bumpy features in the scalar spectrum as shown in figure 7. Although there is not yet evidence of such features, we can hope they will appear in future data, giving a valuable fingerprint that will help to identify which inflationary model is correct.

Fig. 6: Examples of inflation with combined motion of brane and Kähler moduli.
4 Racetrack inflation

In [2] we considered a variant of the KKLMMT model which is simpler, in that no mobile D3 brane is required. Instead we enlarge the gauge group in which the gauginos are condensing to be a product, SU(N) × SU(M), which generalizes the superpotential to

\[ W = W_0 + A e^{-aT} + B e^{-bT} \]  

(6)

where \( a = 2\pi/N \) and \( b = 2\pi/M \). Remarkably, this sufficient to obtain inflation from the Kähler field itself, which marks perhaps the first time where string moduli have been successfully used for inflation in a rigorous setting. The potential is simply the F-term [2] and the antibrane term [3]. The former by itself would be the conventional racetrack potential which has been previously studied for modulus stabilization.

Writing \( T = X + iY \), the potential can be viewed as in figure 8. Since it has two degenerate minima, it provides an example of topological inflation: there will be separated domains of the universe in different minima, and between them inflating domain walls which guarantee the existence of regions in the universe where the initial conditions are correct for inflation to take place.

![Fig. 8: The racetrack inflation potential](image_url)
Unfortunately this model is just as fine tuned as the previous one. For sample values of the parameters given by $A = \frac{20}{1000}$, $B = -\frac{34}{1000}$, $a = \frac{2\pi}{100}$, $b = \frac{2\pi}{90}$, the term $W_0$ must lie in the narrow range $-\frac{1}{20389} \leq W_0 \leq -\frac{1}{20400}$, constituting a 1 part in 2000 tuning. On the positive side, the predictions of this model are more robust than in the previous one. We find that regardless of how long inflation lasts, the spectral index 60 e-foldings before the end of inflation is always near $n = 0.95$, as shown in figure 9. It is interesting that such values may already be starting to feel pressure from the observational constraints.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig9.png}
\caption{spectral index of the racetrack model}
\end{figure}

5 The reheating problem in brane-antibrane inflation

It is not as obvious how reheating will work in brane-antibrane inflation as in conventional inflation models. The brane-antibrane case is almost like hybrid inflation, but there is an important difference, illustrated in figure 10. In both cases, the end of inflation is signaled by a field orthogonal to the inflaton becoming tachyonic. In the hybrid case this second field rolls to a stable minimum, oscillates around it, and causes conventional reheating (or preheating). In the string-theory case, the tachyonic field is described by Sen’s effective action (for a review see [17]),

$$S = -\int d^{p+1}x e^{-|T|^2/a^2} \left( \sqrt{1 - |\partial T|^2} \right)$$

(7)

Here $a$ is the string length scale, and $T$ now stands for the mode of the open string between a brane and antibrane which becomes tachyonic when their distance becomes smaller than some critical value. The potential is minimized only as $T \to \infty$, with no oscillations that can give reheating in the usual way. In fact the whole action vanishes in this limit. At zero string coupling, the coherent tachyon condensate would persist forever, with the equation of state of cold dark matter, and the universe would never reheat. At nonzero string coupling, the tachyon fluid quickly decays into closed strings. There is a danger that these closed string states will naturally decay into the ground state of the closed string, namely gravitons. If this is the whole story, then there is still no reheating, since the gravitons are not visible radiation.

In [3] we have pointed out a very simple solution to this problem, namely that inflation should take place in a separate throat from that where the SM is living, as depicted in figure 11(a). This is already a very natural assumption to make from the standpoint of the hierarchy problem, since large warping in the SM model throat is needed to explain the smallness of the Higgs mass, whereas we need a larger energy scale hence smaller warping in the inflation throat to get the right level of density fluctuations.

To see why two throats help solve the reheating problem, notice that the geometry of the throats is like that of the Randall-Sundrum model [13]:

$$ds^2 = a^2(y) dx^2 + dy^2 + y^2 d\Omega_5^2$$

(8)
where $y$ represents distance along the throat and $\Omega_5$ are the orthogonal directions of the 6D Calabi-Yau space. The warp factor is an exponential, $a(y) = e^{-ky}$. The idea is that the closed string states which result from the decay of the tachyon condensate have the right quantum numbers to decay into Kaluza-Klein graviton excitations. Consider then the wave functions of these KK states along the $y$ direction. Schematically they have the form shown in figure 12: they are exponentially enhanced inside the throats, relative to outside. Because of this exponential enhancement, the KK gravitons decay with the largest branching fraction into particles on branes in the most strongly warped throats. The KK gravitons couple to SM model like ordinary gravity, but with a suppression of the TeV scale rather than the Planck scale. Thus efficient reheating of the SM brane is guaranteed so long as it lives in the deepest throat.

![Fig. 10: potentials for hybrid inflation (left) and brane-antibrane inflation (right).](image)

Fig. 10: potentials for hybrid inflation (left) and brane-antibrane inflation (right).

![Fig. 11: (a) the two-throat scenario; (b) schematic view of KK graviton wave function (showing envelope but not oscillations) in the two-throat model, with a fictitious Planck brane between the throats.](image)

Fig. 11: (a) the two-throat scenario; (b) schematic view of KK graviton wave function (showing envelope but not oscillations) in the two-throat model, with a fictitious Planck brane between the throats.

There is another reason why this scenario for reheating is attractive. Recently there has been intense interest in the possibility that superstrings survive as cosmological remnants [18, 19]. Although they cannot be the dominant source of density fluctuations, a small contribution could be detectable in the CMB. The gravity waves created by kinks and cusps on such strings could also be observable in future pulsar timing measurements, and especially the LIGO gravitational wave interferometer experiment [20]. It is very exciting that cosmic superstrings could provide the strongest signal for LIGO, if the string tension $\mu$ is sufficiently low. The warp factor of the inflationary throat provided by the flux compactification scenario gives the dial needed for adjusting $\mu$ to low enough scales. However the stability of relic superstrings requires that the SM brane (and other branes) be separated from the remnant strings within the extra dimensions—otherwise the strings can reconnect to branes and break up. The two-throat picture we propose for reheating is just what is needed to also allow for the survival of string relics.
6 Overproduction of cosmic superstrings?

At the end of brane-antibrane inflation, the fate of the false vacuum energy in the tension of the annihilating branes is determined by the dynamics of the tachyon field in (7). Because it is a complex field, it is possible for defects of codimension two to form. These are topological defects, where the phase of the field winds around the core of the defect. On annihilating 3-branes, they would be cosmic D-strings, as illustrated in figure 12. It has been rigorously established that the defects which form from unstable branes or annihilating branes are actually consistent with being D-branes themselves, of smaller dimensionality [17].

Fig. 12: formation of a cosmic string defect from annihilating 3-branes.

In the conventional formation of string defects, as in a GUT phase transition, the initial density of would-be defects is set by a microphysical scale, the inverse mass of the fields forming the defect. But in these theories the large initial gradient energy can be minimized by unwinding of the phase. This occurs through the annihilation of nearby defects with opposite winding number. Such unwinding can occur between defects that are in causal contact, but in an expanding universe, strings in different Hubble volumes cannot interact. This is the basis for the Kibble mechanism, guaranteeing at least of order 1 defect surviving per Hubble volume during the initial stages of defect formation. It is worth noting however that this is only a lower bound. If the defects were less efficient in annihilating, many more could survive this initial stage of unwinding.

The unusual form of the action (7) leads to precisely to such an expectation for cosmic superstrings, that their initial density will be much higher than the minimum dictated by Kibble’s argument. This is because of the exponential suppression factor $e^{-|T|^2/a^2}$ which multiplies the kinetic term as well as the potential. Because of this, the restoring force which would normally attract defects to antidefects quickly becomes negligible as the tachyon field rolls from its unstable maximum. As a result, we observe a high density of initial defects forming from the vacuum quantum fluctuations of the $T$ field, as shown in figure 13.
Fig. 13: Growth of defects from initial fluctuations for the open string tachyon field. Distances are in units of the string length scale.

Even though this initial string density is many orders of magnitude greater than the Kibble argument lower bound, there appear to be no observational consequences, thanks to the scaling property of string networks. In the subsequent evolution, long strings start to self-intersect, chopping off small loops which decay away by gravitational radiation. The steady-state solution is one where the energy density in strings scales with that of radiation. We have investigated the approach to the scaling solution and found that scaling sets in after a few Hubble times, regardless of how overdense the initial network was. This is illustrated in figure 14(a).

Fig. 14: (a) Evolution of different components of the energy density in a string network, starting from equal parts of energy in strings and radiation. Not shown is the gravitational radiation component. (b) Schematic illustration of domain walls forming in large dimensions $x_2, x_3$.

However, there is one kind of situation where the initial overdensity can make an important difference. This is when the original annihilating branes were higher than 3-dimensional. For example, in the annihilation of 5-branes, the resulting defects will be 3-branes. However, the original 5-branes had to wrap two compact dimensions, so the defects may appear to a 3D observer to be strings, domain walls, or 3-branes, depending on how they are oriented with respect to the compact directions. This is illustrated in fig. 14(b) for the case of domain wall production. Domain walls are highly constrained relics since they quickly come to dominate the energy density of the universe. Unlike strings, they do not generically shed their energy by self-intersections (which would pinch off a closed surface that could decay through gravitational radiation). Therefore the defect overproduction problem would at first sight appear to rule
out inflation driven by higher-dimensional branes. One might question this conclusion based on the fact that the defects in question are always close to each other in one of the small compact directions. Would this not cause them to annihilate efficiently? But they can be separated from each other widely in the large transverse direction, which is growing with the Hubble expansion. We therefore consider it an open question, subject to more detailed simulations of domain wall network evolution in the case where one of the dimensions tranverse to the walls is compact and small.

7 Could our universe be a defect?

The previous discussion also has implications for another idea for reheating at the end of brane-antibrane inflation. It was suggested in [21], and more convincingly argued in [5], that our universe could have arisen just as described above: a 3-brane defect created at the end of 5-brane annihilation. In this case the directions transverse to the defect are all compact ones, so it should be easier for defects to annihilate within this compact space. One can imagine getting around this objection within a multi-throat picture, where defects and antidefects fell into different throats and were thus preserved from annihilating each other. And in the previous section we overcame another argument against the idea, namely the prejudice that defects can only form in regions larger than the Hubble radius, whereas the compact dimensions are smaller than $H^{-1}$. The previous analysis shows that in fact many such defects can initially form within the small dimensions, provided they are at least a few string lengths in extent.

The main motivation for this picture was that radiation within one of the final state branes would be very efficiently produced by its coupling to the time-dependent background tachyon field. This can be seen by looking at Sen’s action in the presence of U(1) gauge fields originally living on the brane or antibrane:

$$S = -\int d^{p+1}x \, e^{-|T|^2/a^2} \left( \sqrt{-\det M^{(1)}} + \sqrt{-\det M^{(2)}} \right)$$

where

$$M^{(i)}_{MN} = g_{MN} + F^{(i)}_{MN} + \frac{1}{2} \left( D_M T D_N T^* + \text{c.c.} \right)$$

$$D_M = \partial_M - i A_M^{(1)} + i A_M^{(2)}$$

Here the combination $A^{(1)} - A^{(2)}$ gets a VEV, which is part of the defect, and the orthogonal combination $A^{(1)} + A^{(2)}$ plays the role of a massless photon. We find that there is strong production of $A^{(1)} + A^{(2)}$ due to its coupling to the violently changing background $T(t, x)$. Thus reheating would not be a problem in such models. But we are left with the question of why only 3-branes or cosmic strings would be produced by 5-brane annihilation, since the domain walls should appear with equal likelihood, and overclose the universe. Unless there is a mechanism to suppress domain walls, we must conclude that it is unlikely our universe arose as a defect itself, which was created at the end of inflation.

8 Conclusions

I find it encouraging that we now have string inflation models which are starting to come under pressure from the data. Although not all of the predictions are hard, some such as those of the racetrack model are. At last, a falsifiable prediction coming from string theory!

I would find models of stringy inflation more compelling if they were able to address the fine tuning problem (for recent progress see [15, 23]). On the other hand, the tuning problem tells us that the most natural situation, which is least fine-tuned, is the one with the minimal amount of inflation needed to explain what is observed. This opens the door for us to expect nongeneric features in the power spectrum: departures from flatness, running of the spectral index, isocurvature fluctuations, bumps and wiggles in the spectrum. . . Such features would obviously make the interaction between theory and observation more interesting, and I hope the observers will find them soon.

In this talk I have argued that two-throat models of brane-antibrane inflation naturally solve the problem of reheating, explaining the hierarchy between the inflation scale and the TeV scale of the standard model, and they help to preserve possible cosmic superstring defects. It is a very exciting
prospect that gravitational waves observed by LIGO could be first signal of string theory in the laboratory. Although it may be challenging to distinguish cosmic superstrings from conventional cosmic strings, in principle this is a good counterexample to the the naysayers of string theory’s testability.

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