The Benefits of String Cosmology

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Abstract

In this paper we discuss D-Brane/Antibrane inflation as a concrete example of a bottom-up approach in string cosmology. After introducing the standard cosmology, inflation, we turn to the dynamics of D-branes, and find that an open string mode between the branes becomes tachyonic when the branes get to a critical distance. We then obtain a realization of hybrid inflation with two relevant fields having well defined stringy origin. Furthermore, a cascade scenario is proposed with a configuration of a gas of branes and antibranes with four large dimensions.

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1 Introduction

String theory and cosmology might be two of the most ambitious intellectual projects ever undertaken. The former seeks to describe all of the elements of nature and their interactions in a single coherent framework, while the latter seeks to describe the origin, evolution, and structure of the universe as a whole.

Recently, instead of some sporadic discussions in these two fields emerging, more and more concrete results have been worked out and make it a hot topic. This is quite natural since, although we have a very successful framework for discussing the evolution of the universe back to relatively early times and high temperatures, cosmology needs an underlying theory to answer the basics questions of the successful scenarios such as inflation[1, 2] or any alternatively[3, 4] way to address the problem inflation solves. On the other hand, string theory, which stands paramount among the laws of Nature, still needs to confront the real physics and somehow be tested by experiment. One possibility is its low-energy phenomenology. With more and more accuracy of the CMB experiments[5] that have provided a great deal of information on the scalar density perturbations of the cosmic microwave background; the recent observational discoveries that seem to indicate the effective cosmological constant is not exactly zero; and the planned experiments in a not too far future, such as MAP and PLANCK, all those precision experimental tests in cosmology make them turn out to be potentially the main avenue to probe the string theory in the future.

Finally, the study of cosmological implications of string theory can shed some light into the better understanding of the theory itself. For instance, the study black hole backgrounds in string theory has led to the explicit calculation of the black hole entropy and the identification of the AdS/CFT correspondence[6], which provides a concrete realization of the holographic principle[7]. In particular, cosmology presents probably the most important challenges for string theory: the initial singularity, the cosmological constant, the definition of observables, the identification of initial conditions, realization of de Sitter or quintessential backgrounds of the theory, etc.

In this paper, I will try to give a self-consistent introduction to the field of string cosmology and try to show how it works, concentrating on the general motivations. Due to the limitation of my knowledge and the huge number of articles on different aspects of the subject owing to string cosmology's relatively immaturity, I will only focus on the concrete example of D-brane inflation formulated in the context of string theory.

The paper is organized as follows: Section 2 gives an overview of the standard big-bang cosmology that introduces the physical parameters and notations. Section 3 introduces the motivation for inflation, presents basic inflationary model, and discuss under what particular conditions it works. Section 4 is about D-brane inflation, or more exactly, D-brane/antibrane inflation. Finally, in Section 5, I will try to extract the general features independent of model building and give some comment on them.

2 The Standard Cosmology

The homogeneity and isotropy on large length scales of our universe allow us to describe spacetime on cosmological scales by the Friedmann-Robertson-Walker (FRW) metric:

$$ds^2 = -dt^2 + a^2(t)\Big[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\Big]. \tag{2.1}$$

The curvature parameter $k = -1, 0, 1$ determines if the Universe is open, flat, or closed, respectively, G is Newton's constant and the scale factor $a(t)$ is given by solving Einstein's equations

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}. \tag{2.2}$$

For many cosmological applications we can assume that the universe is dominated by a perfect fluid, in which case the energy-momentum tensor is specified by an energy density ρ and pressure p: $T_{00} = \rho$; $T_{ij} = pg_{ij}$; where indices i, j run over spacelike values $\{1; 2; 3\}$. The quantities ρ and p will be related by an equation of state; many interesting fluids satisfy the simple equation of state $p = w\rho$; where w is a constant independent of time. The conservation of energy equation $\nabla_\mu T^{\mu\nu} = 0$ then implies $\rho \propto a^{-3(1+w)}$

Plugging the Robertson-Walker metric into Einstein's equations yields the Friedmann equation, they are

$$H = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \tag{2.3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p), \tag{2.4}$$

with H the Hubble parameter $H \equiv \dot{a}/a$. The value of the Hubble parameter at the present epoch is the Hubble constant, H_0. Another useful quantity is the density parameter of a species i,

$$\Omega_i = \frac{8\pi G}{3H^2}\rho_i = \frac{\rho_i}{\rho_{crit}}, \tag{2.5}$$

where the critical density is defined by $\rho_{crit} = 3H^2/8\pi G$. In terms of the total density parameter $\Omega = \sum_i \Omega_i$, the Friedmann equation (2.3) can be written as:

$$\Omega = 1 + \frac{k}{H^2 a^2}. \tag{2.6}$$

From this we can clearly see that a flat universe ($k = 0$) corresponds to a critical density ($\Omega = 1$) whereas open ($k = -1$) and closed ($k = 1$) universes correspond to ($\Omega < 1$) and ($\Omega > 1$) respectively.

With all this information in mind, we just assume that the early universe corresponds to an expanding gas of particles and, with the input of the standard model of particle physics, and some thermodynamics, we can trace the evolution of the system. After the "Hot Big Bang", the universe expands and cools down. At the atomic physics energy scale, the universe is cold enough for atoms to form and the photons leave equilibrium, giving rise to the famous cosmic microwave background. At approximately the same time the universe changes also from being radiation dominated ($w = 1/3$) to matter dominated ($w = 0$). After this, the formation of structures such as clusters and galaxies can start, leading to our present time.

3 Inflationary Scenario

In the past, the inflationary universe[1] was introduced to offer a possible solution to flatness, horizon, and monopole problems, which arose largely on the initial conditions required for the Hot Big Bang, while by far the most important property of inflation is that it can generate irregularities in the Universe, which may lead to the formation of of the structure and explanation for the possible CMB anisotropies.

- Horizon problem. Horizons exist because there is only a finite distance that photons can travel within the age of the universe. The CMB is isotropic to a high degree of precision, even though widely separated points are completely outside each others' horizons. Hence, if we observe two widely-separated parts of the CMB with non-overlapping horizons; they were causally disconnected at recombination. Nevertheless, they are observed to be at the same temperature to high precision. The question then is, how did they know ahead of time to coordinate their evolution in the right way, even though they were never in causal contact?

- Flatness problem. From Eq. (2.6), we know that the density parameter Ω evolves with time as aH depend on time t. We also know that the present density parameter

Ω_0 is close to 1 as we live in a ordinary matter and radiation ($w > -1/3$) dominate universe. It implies that at early times, $|\Omega - 1|$ must be extremely small (as small as 10^{-60}), which quires finely tuned initial conditions.

- Homogeneity and Isotropy problem. Before even starting the investigation of density perturbations and structure formation, one should explain why the universe is nearly homogeneous on the horizon scale. We need to understand why all directions in the universe are similar to each other, why there is no overall rotation of the universe. etc.

- Structure formation problem. If we manage to explain the homogeneity of the universe, how can we explain the origin of inhomogeneities required for the large scale structure formation?

- Unwanted relics. If the we assume a unified theory exists in the early universe , different topological defects, such as domain walls, cosmic strings, monopoles to GUT should be present today. The expected relic abundance calculated is always too big and conflicts with the current observations.

The main idea behind inflation is that in the early universe there is a short time when the universe expanded *very quickly*, usually an exponential expansion. If the inflationary period is *long enough*, it flattens the universe quickly (solving the flatness problem). It would also explain why some regions could be in causal contact with each other, solving the horizon problem. Finally the fast expansion would dilute many objects, such as monopoles and other unwanted massive particles in such a way as to make them harmless for the over-closure of the universe.

The simplest realization of inflation is to introduce a scalar field with a potential $V(\psi)$, the value of the potential provides an effective cosmological constant. We can easily see that if the potential energy dominates over the kinetic energy and $V \sim \Lambda > 0$ we have the $w = -1$ case with exponential expansion $a \sim e^{Ht} \sim \exp(\sqrt{\Lambda/3})$ for $k = 0$. Then we see the scale factor increase exponentially, therefore solving the horizon, flatness and monopole problems.

The Friedmann's equation for this system becomes:

$$H^2 = \frac{8\pi G}{3}\Big(V + \frac{\dot{\psi}^2}{2}\Big) - \frac{k}{a^2}, \tag{3.1}$$

where equation of motion for the the scalar field is

$$\ddot{\psi} + 3H\dot{\psi} = -V', \tag{3.2}$$

where $V' \equiv dV/d\psi$. Notice that the second term in this equation acts like a friction term for a harmonic oscillator (for a quadratic potential) with the friction determined by the Hubble parameter H.

The *slow-roll approximation* for inflation can be summarised in two useful equations, known as the slow roll conditions:

$$\epsilon = \frac{M_{Plank}^2}{2}\Big(\frac{V'}{V}\Big)^2 \ll 1, \tag{3.3}$$

$$\eta = M_{Plank}^2\Big(\frac{V''}{V}\Big) \ll 1, \tag{3.4}$$

If the first condition is satisfied the potential is flat enough as to guarantee an exponential expansion. If the second condition is satisfied the friction term in equation (3.2) dominates and therefore implies the slow rolling of the field on the potential, guaranteeing the inflationary period lasts for sufficient time.

Probably the most relevant property of inflation is that it can provide an explanation for the density perturbations of the CMB and therefore indirectly account for the large scale structure formation. Quantum fluctuations of the scalar field give rise to fluctuations in the energy density that at the end provide the fluctuations in the temperature observed at COBE[5].

The amplitude of the density perturbation ($\delta\rho/\rho$) when it re-enters the horizon, as observed by Cosmic Microwave Background (CMB) experiments is given by:

$$\delta_H = \frac{2}{5}\mathcal{P}_{\mathcal{R}}^{1/2} = \frac{1}{5\pi\sqrt{3}}\frac{V^{3/2}}{M_p^3 V'} = 1.91 \times 10^{-5}, \tag{3.5}$$

where $\mathcal{P}_{\mathcal{R}}$ is the power spectrum. Here the value of δ_H is implied by the COBE results[5].

In order to study the scale dependence of the spectrum, we define an effective *spectral index* $n(k)$ as: $n(k) - 1 \equiv d\ln\mathcal{P}_{\mathcal{R}}/d\ln k$. One can then calculate $n(k)$ and its derivative by using the slow roll conditions defined above[2], and they are given by

$$n - 1 = \frac{\partial \ln \mathcal{P}_{\mathcal{R}}}{\partial \ln k} \simeq 2\eta - 6\epsilon, \frac{dn}{d\ln k} \simeq 24\epsilon^2 - 16\epsilon\eta + 2M_P^2\frac{V'V'''}{V^2}. \tag{3.6}$$

Showing that for slow rolling ($\eta, \epsilon \ll 1$) the spectrum is almost scale invariant ($n \sim 1$).

Here we introduce a concrete paradigm, the Hybrid inflation model[8]. The simplest case is the theory of two scalar fields with the effective potential

$$V(\sigma, \phi) = \frac{1}{4\lambda}(M^2 - \lambda\sigma^2)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2. \tag{3.7}$$

The effective mass squared of the field σ is equal to $-M^2 + g^2\phi^2$. Therefore for $\phi > \phi_c = M/g$ the only minimum of the effective potential $V(\sigma,\phi)$ is at $\sigma = 0$. The curvature of the effective potential in the σ-direction is much greater than in the ϕ-direction. Thus at the first stages of expansion the field ϕ roll slowly and remain large for a long time induce the inflation. At the moment when the inflation field ϕ becomes smaller than $\phi_c = M/g$, the field σ changes from being massive to tachyonic and the inflation abruptly ends at $\phi = \phi_c$.

4 D-Brane/Antibrane Inflation

Before brane cosmology, it was difficult to construct a scalar-field inflation as there was not much known about the scalar potential arising from string theory and, in general, the potentials derived were too steep to inflate.

The interactions between D-branes offer a new avenue to investigate these issues and have led to the first concrete examples of scalar-field inflation from string theory, providing a nice geometrical and stringy picture of the inflationary process, as well as the termination of inflation.

Consider a brane/antibrane pair with the opposite RR charges. We take as our starting point the following low-energy effective action governing the inter-brane interactions: $S = S_{Bulk} + S_D + S_{\bar{D}}$, where the bulk action is

$$S_{Bulk} = \frac{1}{2}\int d^4x d^d z\sqrt{-\gamma}[M_s^{d+2}e^{-2\phi}R + \cdots], \tag{4.1}$$

Here ϕ is the dilaton, R is the full $(4+d)$-dimensional scalar curvature, and M_s is the string scale (here in string applications, $d = 6$)

The dynamical variables of the brane actions are the brane positions, x_i^μ , with $i = 1, 2$ refering to the brane and antibrane, respectively, and $\mu = 0, ..., 3 + d$. The relevant part of the action in the expansion is:

$$S_D = -\int d^4x d^{p-3}y\sqrt{-\gamma}[T_p + \cdots], \tag{4.2}$$

where $\gamma_{ab} = g_{\mu\nu}\partial_a x_i^\mu \partial_b x_i^\nu$ is the induced metric on the brane, and $T_p = M_s^{p+1}e^{-\phi}$ is the brane tension. We will assume the branes to be parallel and the separation is given by $Y^m \equiv (x_1 - x_2)^m$. Expanding in powers of $\partial_a Y^m$ we get:

$$S_D + S_{\bar{D}} = -\int d^4x d^{p-3}Y\sqrt{-\gamma}T_p\Big[2 + \frac{1}{4}g_{mn}\gamma^{ab}\partial_a Y^m \partial_b Y^n + \cdots\Big], \tag{4.3}$$

We assume the dominant interaction between the branes at large distances (compared to $1/M_s$) to be due to the exchange of massless bulk modes, including the metric, dilaton and any other massless bosons which couple to the branes. Any such interaction gives an inter-brane potential energy (per unit brane area) which falls with large separation like

$$V_{int} \sim 1/Y^{d_\perp - 2} \tag{4.4}$$

where $d_\perp \equiv 9 - p$ is the number of spatial dimensions transverse to the branes. Combining the tension term which is derivative dependent in Eq. (4.3) with the inter-brane potential energy of Eq. (4.4), we get

$$V(Y) = A(r_\perp, d_\perp) - \frac{B(r_\perp, d_\perp)}{Y^{d_\perp - 2}}, \tag{4.5}$$

where $r_\perp$ is the radius of the space perpendicular to the brane. To see whether this potential gives rise to inflation, we check the slow roll conditions we compute the constants ϵ and η and find that $\epsilon < \eta$ as usual, and:

$$\eta = E(d_\perp)\Big(\frac{r_\perp}{Y}\Big), \tag{4.6}$$

where E is a parameter of order 1.

For the flat bulk, $\left(\frac{r_\perp}{Y}\right) \gg 1$ as the separation of the branes is assumed to be much smaller compared to the size of the extra dimension for the approximation of the potential to be valid. Therefore, it violates the slow rolling conditions. The situation is improved by relaxing $Y \ll r_\perp$ in the periodic dimensions of the the potential. Consider the simplest case of a square torus, with the compactified transverse manifold a $d_\perp$- dimensional square torus with a uniform circumference $r_\perp$. When the brane-antibrane separation is comparable to $r_\perp$, we have to include contributions to the potential from p-brane images, i.e., we have to study the potential in the covering space of the torus, which is a $d_\perp$-dimensional lattice, $(R/Z)^{d_\perp}$.

The potential at the position of the antibrane is

$$V(\vec{r}) = A - \sum_i \frac{B}{|\vec{r} - \vec{r_i}|^{d_\perp - 2}}, \tag{4.7}$$

where the parameters A and B are defined in Eq. (4.5), $\vec{r}$ and $\vec{r_i}$ are the vectors denoting the positions of the p-branes and antibranes in the $d_\perp$-dimensional coordinate space, and the summation is over all the lattice sites occupied by the brane images, labelled by i.

Consider now the antibrane placed near the center of the hypercubic cell. If we expanded the potential in terms of power series of the small displacement $\vec{z}$ from the centre, we would find the odd powers and the quadratic terms vanish (See[9] and appendix of[10] for a detailed calculation). We can therefore model the relative motion of the branes in a quartic potential

$$V(Y) = A - \frac{1}{4}Cz^4, \tag{4.8}$$

and derive for this potential the slow roll parameter η and the density perturbation δ_H

$$\eta \approx -3\gamma\Big(\frac{z}{r_\perp}\Big), \delta_H \approx \frac{2}{5\pi}\sqrt{\frac{\gamma}{3}}\frac{N^{3/2}}{M_{Planck} r_\perp}. \tag{4.9}$$

We can see that slow-roll is guaranteed for sufficiently small z. Furthermore, using the number of e-foldings $N \approx 60$[2] and the experimental value $\delta_H \approx 1.9 \times 10^{-5}$ of the density fluctuations, as measured by COBE, we obtain the compactification radius $r_\perp^{-1} \approx 10^{12}$ GeV corresponding to an intermediate string scale $M_s \approx 10^{13}$ GeV. The spectrum index $n \approx 1 - 3/N$ and $dn/d\ln(k) \approx -3/N^2$ are also consistent with the current data.

Furthermore string theory also provides a way to end inflation by obtaining hybrid inflation[8]. Considering the interaction of the brane antibrane as the exchange of closed strings between the two branes, the amplitude can be computed by calculating the one-loop open string amplitude corresponding to a cylinder[11]. It has a divergence appearing at a critical distance $Y_c = \sqrt{2\alpha'}\pi$ and develops a negative mode when the distance between a brane and antibrane shrinks to M_s^{-1}, which signals the appearance of tachyonic open strings connecting the branes to the antibranes. The mass of the tachyon is a function of the inter-brane distance and is given by $M_T^2 = Y^2/(2\pi\alpha')^2 - 2/\alpha'$. The corresponding tachyon potential has been proposed to take the approximate form:

$$V(Y,T) = \frac{1}{4\alpha'}\Big(\frac{Y^2}{2\pi^2\alpha'} - 1\Big)T^2 + CT^4 + \cdots, \tag{4.10}$$

with C a constant, T the tachyon field. We can immediately see, that taking the effective potential as a function of both T and Y, gives us a potential precisely of the form proposed for hybrid inflation!

Moreover, the tachyon potential has been studied in some detail during the past few years and its general structure has been extracted. In particular, Sen conjectured that at the overlap point ($Y = 0$) the potential should be of the Mexican hat form with the height of the maximum equal to the sum of the brane tensions $2T_p$. The minimum would correspond to the closed string vacuum being supersymmetric where the potential vanishes. Hence, we could also obtain a reasonable reheating temperature $T_{RH} \sim 10^{13} GeV$ for $p = 5$[12] and the topological defects which correspond to $D(p-2)$ branes (and antibranes)[13].

We could obtain a general cascade mechanism if we consider more. According to a famous conjecture of Sen[13], if the tachyon has non-trivial winding, then stable, lower-dimensional branes will be formed after it condenses instead of annihilating. We then imagine a configuration of a gas of branes and antibranes. Most of the times they will interact and annihilate each other without giving rise to inflation but upon collision they will keep generating $p-2$ branes (See the detailed arguments in Ref. [9, 10]); these ones will generate $p-4$ branes and so on, implying a cascade of daughter branes out of the original ones. In this system at some point a pair of branes will be at a separation close to the equilibrium point and that will give rise to inflation, dominating the expansion of the universe and rendering the issue of initial conditions for inflation more natural. Notice that as usual, once inflation is generated it dominates. This makes us conjecture that the brane gas originates from just one pair of a $D9/\bar{D}9$ branes[9].

Another interesting thing is that it allows for some speculations about the dimensionality of spacetime based on Brandenberger-Vafa scenario[14]. As the winding modes tend to compactify the space dimensions where they are winding around, leaving the expansion of the rest dimensions to be large if the some winding and anti-winding strings annihilate. The winding strings with $p = 1$ cannot annihilate in dimensions larger than $2(p+1) = 4$, This can be generalized to p branes in D dimensions for which the critical dimension is:

$$D_{critical} = 2p + 2, \tag{4.11}$$

which makes a rough argument why D3-brane worlds may survive annihilation in predicted 10 or 11 dimensions in string theory.

This scenario is certainly very interesting and encouraging. It provides a string-derived potential that gives rise to inflation and also has a stringy mechanism to end inflation by the appearance of the open string tachyon at a critical distance. It then shares all the good experimental success that inflation has at present, in terms of the spectrum of CMB fluctuations. It provides many other interesting features like the apparent critical dimensionality of 3-branes.

It was in built, however, with several assumptions. First, it is assumed that an effective 4D FRW background is valid (implying that we have to be in a regime where the effective field theory description of string theory is valid). Second, the branes were assumed to be parallel and velocity effects were neglected. Actually, several attempts have been made to consider these problems[10, 15, 16], like intersecting branes[16]. They may partly solve the problems above but add other problems[12]. The major assumption of the D-brane inflation scenario, however, is considering the moduli ($r_\perp$ in this case) and dilaton to have been already fixed by some unknown stringy effect. This is a very strong assumption that prevents from claiming that this is a full derivation of inflation from string theory. The assumption of having fixed the moduli refers to having found a mechanism that compensates the NS tadpole terms and induces a minimum for the moduli potential. This is not impossible, but needs to be addressed and tree level terms are in principle dominant.

Moreover the reheating mechanism is not completely understood, in particular, the tachyon's relaxation to its minimum is not standard in field theory. Several recent discussions in this direction have arrived at the positive results[17]. More attempts have been worked to ask if the tachyonic potential can give rise to inflation by itself, based on Sen's work "*Rolling tachyon*"[18]. But the absence of small parameters in the potential that can be tuned made it hard to give rise a slow roll condition[20](See more detail about the problems with moduli and tachyon condensation[13] in Iggy's report[19]).

5 Remarks

In this paper we have discussed D-Brane/Antibrane inflation. The attractive potential between the brane pair necessary to obtain inflation was shown to be calculated from string theory[9, 10]. Furthermore, an open string mode becomes tachyonic when the branes get to a critical distance, thus providing an instability which results in giving us a realization of the hybrid inflation scenario[8], with the two relevant fields having well defined stringy origin. Furthermore, a cascade scenario is proposed with brane gas originating from a pair of $D9/\bar{D}9$ branes with four large dimensions.

It is interesting to ask what we can obtain from string cosmology, taking the D-Brane/Antibrane inflation as a concrete example. From the above discussion, we see that the hybrid inflation scenario[8], as a concrete case, could be realized in the framework of D-Brane/Antibrane interaction and annihilation. Not only does the inflation finds an underlying theoretical support, more practically, it makes the hybrid inflation superior to the other mechanisms in the sense of requiring a bottom-up approach. So string cosmology helps us narrow down the possible models which is necessary owing to a paucity of experimental data. More generally speaking, making connections in different fields always help us to select the truth! String theory can also sometimes cure the real cosmology problems and open a door for the new mechanism, the case is to use the time-dependent orbifolds to make the smooth transition from big crunch to big bang[21]. On the other hand, cosmology also helps the string theory develop further. Taking our above discussion as the case again, to make the extensions of the above discussions. We could consider some new proposals for a consistent string cosmology. The S-brane ideas[22], dS/CFT correspondence[23] and the rolling tachyon[18] are certainly interesting avenues to explore. The most important impact I believe is that it helps us to find a standard stringy world which tells us about Nature, like building up Standard model as the interference of Quantum Field Theory and particle phenomenology. With the help of making connections with cosmology and trying to build up a observable model-independent cosmology, we maybe find what is really needed to be generic in describing our universe and what is not? If not, are there any particular "*selection-rules*" or even "*hidden symmetries*" behind, like $SU(3)_c \times SU(2)_L \times U(1)_R$ symmetries in our Standard Model???

Let's end the paper by one of my favorite words: "*It is probably true quite generally that in the history of human thinking the most fruitful developments frequently take place at those points where two different lines of thought meet. These lines may have* *their roots in quite different parts of human culture, in different religious traditions: hence if they actually meet, that is, if they are at least so much related to each other that a real interaction can take place, then one may hope that new and interesting developments may follow.*"

Werner Heisenberg

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