Accelerating universes in string theory

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We review recent constructions of deSitter universes and inflationary universes in string theory. The constructions are based on flux vacua in string theory which lead to controlled moduli stabilization and supersymmetry breaking. The emerging picture is that of a complicated landscape with many different vacua. This is likely to be quite important for future developments in string theory.

I. Introduction

Recent progress in cosmology is of great significance for string theory and more generally for any complete microphysical theory of nature. The observational data strongly suggests that we live in an accelerating universe today[1]. A likely explanation is a small positive cosmological constant. It also provides good support for inflation – a period of rapid expansion in the early history of the universe.

It is important to understand whether these features can arise in string theory. In fact this is both a challenge and an opportunity for the theory. A challenge because it requires us to develop string theory further, incorporating in particular the breaking of supersymmetry and the stabilization of moduli. And an opportunity because data of such direct significance for string theory is difficult to come by and will surely guide future developments in the theory.

This review will deal with progress in understanding how spacetimes with positive cosmological constant, called deSitter universes, can arise in string theory, and also how inflation can arise in string theory. The progress is relatively recent but is already beginning to have important consequences for our understanding of the phenomenological and cosmological consequences of string theory. As string theory is developed further, motivated in part by what we are learning in cosmology, this interplay promises to get even more exciting.

The review is organized as follows. We start with some more motivation from a string theory viewpoint in section II. Then turn to discussing a specific proposal, developed in collaboration with Kachru, Kallosh and Linde[2], for moduli stabilization and deSitter vacua in section III. The discussion will be divided into two parts, we will consider moduli stabilization in section III and the breaking of supersymmetry in section IV. Our discussion on inflation begins in section V, with some general comments. A specific model for obtaining inflation in string theory is discussed next in section VI. Finally, we end with some conclusions in section VII.

There is one significant omission in this review. The idea that the standard model degrees of freedom live on a 3 + 1 dimensional domain wall, called a brane, while gravity lives in higher dimensions, has gained much attention recently and is of considerable interest in cosmology. This is a huge subject and we will leave much of it untouched in the discussion below except for some discussion of how branes might be relevant in inflation and for supersymmetry breaking. For more discussion we refer the reader to some good reviews already in the literature[3,4].

II. More motivation

There is a good reason, internal to string theory itself, for being interested in the question of deSitter universes. There has been considerable progress in our understanding of string theory over the past few decades. Most of this has focussed on understanding the theory in situations with unbroken supersymmetry and in fact with unbroken $\mathbf{N} \geq 2$ supersymmetry. It is well known that deSitter space can only arise if supersymmetry is broken. Thus thinking of this question brings us to the frontiers of our understanding of string theory today.

Some attempts to construct deSitter vacua have been made in the past. These have not been successful and have lead to various no-go theorems[5]. In the discussion below, we will see how these can be circumvented.

Breaking supersymmetry in string theory requires us to come face-to-face with an important issue called the problem of 'moduli stabilization'. In a string theory vacuum, with $\mathbf{N} \geq 2$ supersymmetry, there are many flat directions, or moduli. The energy as we go along these directions in field space is a constant and in fact vanishes identically. There are $O(100)$ flat directions in a typical compactification.

These flat directions are bad news from the point of both phenomenology and cosmology. Phenomenologically, physical constants like G_N, a_{em}, vary along these directions. One would like to be able to compute the values of these constants in a string vacuum and compare with the observed values. But for this one needs to be able to lift the flat directions and understand where the resulting mimima lie. Cosmologically, flat directions give rise to light and weakly coupled scalars. These cause problems in the standard model of cosmology, e.g. they ruin the successful predictions of Big Bang nucleosynthesis.

For vacua with $\mathbf{N} \leq 1$ supersymmetry, which is the case of phenomenological relevance, one expects the flat directions to be typically lifted. This is good news. Unfortunately, given our understanding of string theory today, we have a limited understanding of the resulting potential that develops. In regions of field space where the potential can be calculated with control one finds no minima. This inability to find minima in which the flat directions are lifted is called the moduli stabilization problem.

Recently, a new class of string compactifications, called flux compactifications, has gained prominence[6,7]. In these compactifications, besides curling up the extra directions present in string theory to small size, fluxes are also turned on along the compactified directions. The fluxes include higher form generalizations of magnetic flux in electromagnetism. Turning them on changes the potential in moduli space so that now minima arise in regions of field space where the potential can be calculated with control. The value of the cosmological constant in these minima can also be calculated, those with a positive value give rise to deSitter universes.

We now turn to describing a specific proposal to stabilize all minima, break supersymmetry, and obtain deSitter vacua. Our strategy will be to try and proceed in a controlled manner. As a first step, we will describe how all moduli can be lifted while preserving $\mathbf{N} = 1$ supersymmetry. This will give rise to vacua with negative cosmological constant, corresponding to anti-deSitter space. The second step will be to break supersymmetry with control. This will result in vacua with positive cosmological constant.

III. The proposal

We will work with IIB string theory (more generally F-theory). The starting point is a six-dimensional Calabi–Yau orientifold compactification. Calabi–Yau manifolds are a well-known class of string theory compactifications. The orientifold is obtained after identifying points related by a Z_2 discrete symmetry in the manifold. The moduli in this compactification arise due to various size and shape deformations. There is also the dilaton, e^{-f}, whose expectation value is the string coupling and its axion partner, a. Together, we will denote them as $t = a + ie^{-f}$.

IIB string theory has three-form RR, NS fluxes and the five-form RR flux respectively. We will denote these as, F_3, H_3, F_5, respectively. These will all be turned on in the compactification. In addition, D7 and D3 branes can also be present. An important point to bear in mind is for a typical Calabi–Yau space many different choices of flux are possible. A number of order 10^{100} is typical. Several important features about flux compactifications that we will discuss later are tied to this vast number of choices.

It is well known that turning on flux gives rise to a superpotential at tree-level that depends on the shape moduli and the dilaton-axion. This takes the form[6,8],

$$W_{\text{tree}} = \int G_3 \wedge \Omega,$$

where $G_3 = F_3 - tH_3$, and Ω is the holomorphic three-form in the Calabi–Yau space. The dependence on the dilaton-axion is explicit in this superpotential. The dependence on the shape moduli enters through Ω. The requirements of supersymmetry typically lift all these moduli.

Corrections to the superpotential can arise at the non-perturbative level. These were explored in ref. 9 and related works. There are two ways in which these could happen. First, due to Euclidean D3-branes wrapping 4-cycles. Second, due to gaugino condensation or more generally strong coupling dynamics in the world volume gauge theory of coincident D7 branes. Both corrections take the form

$$W_{\text{NP}} = \text{A}e^{iar_{\text{i}}}. \tag{1}$$

Here r_{i} (more correctly its imaginary part) is a size modulus, the prefactor A depends in general on the shape moduli, and a is determined by the non-perturbative effect which gives rise to the correction. These non-perturbative effects could stabilize all the size moduli.

Thus all the shape and size moduli, related axion fields, and the dilaton–axion could be lifted in the presence of flux.

An example

It is worth examining a toy model in more detail. We consider the case where there is only one size modulus, which we denote as r. The shape moduli, we saw above, get lifted due to tree-level effects. Therefore for large volume these will be heavier than the size modulus. After integrating them out one gets an effective theory involving only r. The superpotential in this theory takes the form:

$$W = W_0 + Ae^{iar}.$$

W_0 is a constant which arises from the tree-level superpotential, W_{tree}, and the second term arises from W_{NP}. The Kahler potential for r if of the no-scale type,

$$K = -3\log(-i(r - \bar{r})).$$

The potential can be calculated from the superpotential and the Kahler potential using standard supergravity formulae.

We simplify things by setting the axion in the r modulus to zero, and letting $r = is$. To simplify things further, we assume that A, a and W_0 are all *real*. It is easy to see that this potential does have a supersymmetric critical point at negative W_0.

$$DW = 0 \rightarrow W_0 = -Ae^{-a\sigma_{\text{cr}}}(1 + 23as_{\text{cr}}).$$

The potential at the minimum is negative and equal to

$$V_{\mathrm{AdS}} = (-3\mathrm{e}^{K} W^{2})_{\mathrm{AdS}} = -\frac{a^{2} A^{2} \mathrm{e}^{-2a\sigma_{\mathrm{cr}}}}{6\sigma_{\mathrm{cr}}},$$

which shows that we have a supersymmetric AdS minimum in this case. It is important that the AdS minimum is quite generic. As an example we can take, $a = 1$; $W_0 = -1$; $A = 20$ for which $\sigma_{\mathrm{cr}} \sim 113$, and the value of the potential (in Planck units) at the AdS minimum is $\sim -2.5 * 10^{3}$ (Figure 1).

Thus we see concretely in this example that all the moduli can indeed be stabilized, while preserving susy.

We are working within the framework of low-energy supergravity above. There are two sources of corrections to the potential we have used. First there are corrections due to the α' expansion. These will be small as long as the volume (or σ_{cr}) is large. We see from the discussion above that small W_0 will give rise to large σ_{cr}. The second source of corrections is due to the g_{s} expansion. These corrections are small if g_{s} is small, this can be arranged by suitable choosing the RR and NS three-form flux. The requirement of small W_0 does impose a restriction on the choice of flux. However, since there are many possible values of flux to begin with $\sim O(10^{100})$ as mentioned above, this should still leave many vacua with the volume stabilized at a large value.

IV. Supersymmetry breaking and deSitter vacua

We now turn to breaking supersymmetry. This will be done by introducing an anti-D3 brane in the compactification. One additional feature of flux compactifications will be important in controlling the resulting potential and preventing the AdS minimum discussed above from destabilizing completely. This is the fact that flux gives rise to warping. This feature is familiar from the study of the $\mathrm{AdS}_5 \times S^5$ solution in string theory where the warping gives rise to an 'infinite' throat. Here we will be interested in situations where the resulting throat is finite and terminates at a minimum value of the redshift, which we will denote by Z. A good example of this is provided by the Klebanov–Strassler solution[10]. One considers a Calabi–Yau space close to a conifold point. The Calabi–Yau space has a small non-vanishing S^3 which is threaded by the RR three-form flux, in addition NS three-form flux and F_5 flux are also excited. The resulting warping is significant in the vicinity of the small S^3 and gives rise to a finite throat.

By introducing an anti-D3-brane at the bottom of this throat there is an additional contribution to the potential energy given by

$$V_{\mathrm{antibrane}} = \frac{2T_3 Z^4}{\sigma^2}.$$

Adding this to the potential obtained in the previous section one finds that for a suitable range of values for the AdS minimum is uplifted to a minimum with positive cosmological constant.

By changing the value of Z, and the other parameters, W_0, a, A the resulting cosmological constant can take different values, of both positive and negative sign.

For the model $W_0 = -10^{-4}$, $A = 1$, $a = 0.1$ $D = 3 \times 10^{-9}$ we find the potential (multiplied by 10^{15}) (Figure 2):

A few comments are worth making about the deSitter vacua. The effects of flux and also supersymmetry breaking, both go to zero as the volume tends to infinity. This means there is a supersymmetry preserving vacuum at infinite volume. As a result, the deSitter vacuum is only metastable. It can decay in two ways. Either due to a Coleman–Delucia instanton which can be thought of as tunnelling under the barrier, or due to a Hawking Moss instanton which can be thought of as going over the barrier due to the finite temperature of deSitter space[1]. Both effects give rise to a rate which is bigger than the Poincaré recurrence rate associated with the deSitter space due to its entropy[12]. One expects that at least in some fraction of the vacua the transition rate of the deSitter vacuum can be made much smaller than the age of

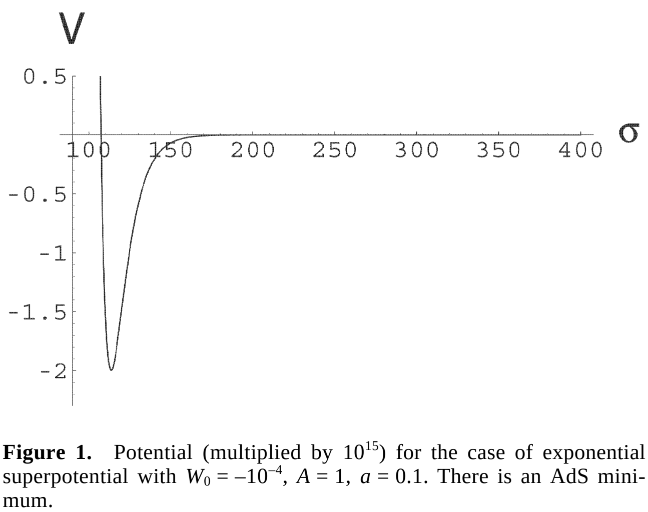

Figure 1. Potential (multiplied by 10^{15}) for the case of exponential superpotential with $W_0 = -10^{-4}$, $A = 1$, $a = 0.1$. There is an AdS minimum.

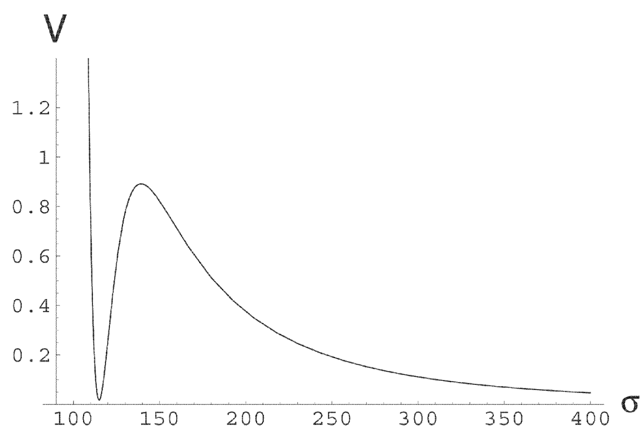

Figure 2. Potential (multiplied by 10^{15}) for the case of exponential superpotential and including a D/σ^3 correction with $D = 3 \times 10^{-9}$ which uplifts the AdS minimum to a dS minimum.

the universe, so that the metastability has no observable consequences.

Recent progress and future directions

It is worth summarizing some recent progress in implementing the KKLT proposal and issues which would be worth pursuing in the future. The non-perturbative effects that can stabilize the Kahler moduli have been studied in more detail. In particular, in ref. 13 it was shown that non-perturbative effects due to Euclidean D3-brane instantons can stabilize all Kahler moduli in several Calabi–Yau orientifolds. Gaugino condensation was studied in a simple example in some detail in ref. 14 and it was shown that fluxes can lift all 7-brane moduli giving rise to pure $\mathbf{N} = 1$ gauge theories which then generate a non-perturbative superpotential due to gaugino condensation.

The breaking of supersymmetry due to F-terms without including anti D3-branes was studied by Saltman and Silverstein[15]. Implicitly the discussion above assumed that anti D3-brane give rise to D-type supersymmetry breaking. This needs to be understood better, for some related work which provides support see refs 16, 17.

Replacing the anti-D3-brane by turning on appropriate susy breaking flux on a 7-brane was examined in papers[18].

There is clearly need to have an explicit implementation of the KKLT proposal, in terms of an explicit Calabi–Yau space, choices of three-form flux, etc. A set of concrete examples will help in guiding the discussion further and in particular in sharpening possible worries. Some progress in this directions can be found in ref. 19. It is also important to understand some of the corrections to the analysis better. The discussion above was in the supergravity approximation. Corrections arise due to the a' expansion and due to string loops. Some of these have been calculated[20] and were shown to make a small corrections to the vacuum as would be expected at large volume[21,22]. It would be good to calculate other corrections to ensure that they are all under control. The AdS minima which were discussed above, without any supersymmetry breaking are interesting in their own right. Understanding them better in terms of dual field theories would be also worthwhile. For some progress along this direction see ref. 23. There is also a proposal for constructing deSitter vacua using the non-critical string[24]. This too should be developed further.

Finally there is some recent work on understanding the statistics of flux vacua[25–28].

V. Inflation

Inflation refers to a period of rapid expansion in the early history of the universe. The idea is attractive for a number of theoretical reasons and is increasingly well supported by observation[29–32]. In this section we will turn to asking if inflation can be realized in string theory.

A canonical model of inflation goes by the name of 'slow-roll' inflation. The idea is to have a scalar field, called the inflation, with a potential that is positive and that slowly slopes to its minimum. To the extent the potential is nearly constant one gets, after coupling to gravity, the exponential expansion of deSitter space. The small slope provides a way for the cosmological constant to slowly relax and for the inflationary phase to eventually end.

The slowly varying nature of the potential can be quantified in terms of the two slow roll parameters:

$$e = \frac{1}{2}\left(\frac{V'}{V}\right)^2 M_{\mathrm{Pl}}^2,$$

and

$$h = \frac{V''}{V} M_{\mathrm{Pl}}^2.$$

Both are dimensionless (the derivatives are with respect to the canonically normalized inflation). For inflation to occur, both e, h must be much smaller than unity. Note that h is related to the (mass)^2 of the inflation, in the discussion below its smallness will be the more severe constraint.

Additional conditions on the potential arise from the requirement that one gets adequate expansion. At least 60 e-foldings or so are typically needed. And from the condition that the required density perturbations can arise during inflation. This takes the form:

$$d_H = \frac{1}{\sqrt{75p}} \frac{V^{3/2}}{|V'|\, M_{\mathrm{Pl}}^3} \simeq 1.9 \times 10^{-9}.$$

There are additional issues to worry about in constructing a satisfactory model of inflation. There is the question of whether inflation can end by appropriately reheating the universe. And the question of whether the initial conditions can be right for inflation to have begun in the first place. These are both important issues, but for now we will ignore them and ask simply whether a potential can arise in string theory which gives rise to slow roll inflation with adequate expansion and the required density perturbations. Towards the end of the discussion in section 6 we will return to these issues and briefly comment on them.

VI. Warped brane inflation

The scenario we will explore is motivated by our discussion of moduli stabilization above. The idea will be to stabilize all closed string moduli as in the discussion above of the KKLT proposal. And consider what happens in this set-up if a D3-brane is present in the vicinity of a Klebanov–Strassler (KS) throat that contains an anti-brane at its bottom. It is clear that the D3-brane will experience a force of attraction to the anti D3-brane. One would like to know if the location of the brane can play the role of the inflation and its resulting potential meets the two slow-roll conditions.

This scenario falls within the general class of models called brane inflation. The first paper which pointed out that inflation might be realized in this manner was by Koyama *et al.*[33]. Some subsequent literature is in refs 34–36. Here following ref. 37, we will consider this scenario in the presence of warping. The force between the brane and anti-brane can be easily calculated and takes the form:

$$V^B(\vec{r}) = 2T_3 Z^4 \left(1 - \frac{1}{2p^3}\frac{Z^4 T_3}{M_{10}^8 \, |\vec{r} - \vec{r}_1|^4}\right). \tag{2}$$

Here T_3 is the tension of the brane, Z^4 is the redhsift at the bottom of the K–S throat. M_{10} is the ten-dim. Planck scale which is related to the four-dimensional Planck scale $M_{\rm Pl}$ and the size of compactification by

$$M_{\rm Pl}^2 = M_{10}^8 L^6.$$

Finally, $\vec{r}$, $\vec{r}_1$ stand respectively for the location of the brane and anti-brane. The first term in the formula above arises due to the tension of the brane and anti-brane. The second term arises due to the brane–anti-brane interaction, and has the correct power law dependence on the distance between them for a harmonic function in 6 dimensions.

The requirement that $h \ll 1$ then gives rise to the condition

$$|\vec{r} - \vec{r}| \gg Z^{2/3} L.$$

Note that this condition can be met together with the requirement that the brane–anti-brane separation is smaller than L because the warp factor $Z \ll 1$. Once the condition for $h \ll 1$ is met it is easy to see that the requirement that $e \ll 1$ is also satisfied. And thus both slow-roll conditions are met and we seem well on our way to meeting the requirements of slow roll inflation.

However, there is one important point that we have overlooked in the analysis above. The dynamics required for stabilizing all the closed string moduli is in fact not independent of the location of the D3-brane. Since the analysis is a bit technical we will skip some of the steps in this review and refer the reader to ref. 37. The essential point is that a non-perturbative effect of the form eq. (1) which was used above to stabilize the volume modulus gives rise to a conformal coupling for the inflation:

$$dV = \frac{1}{6} r f^2,$$

where $f = \sqrt{T_3} r$ is the canonically normalized inflation field. Once this term is added in the potential, one finds that the resulting value of $h \sim O(1)$ and the slow-roll conditions cannot be met.

This difficulty can be overcome. Let us outline one way to do so below[38] (Figure 3).

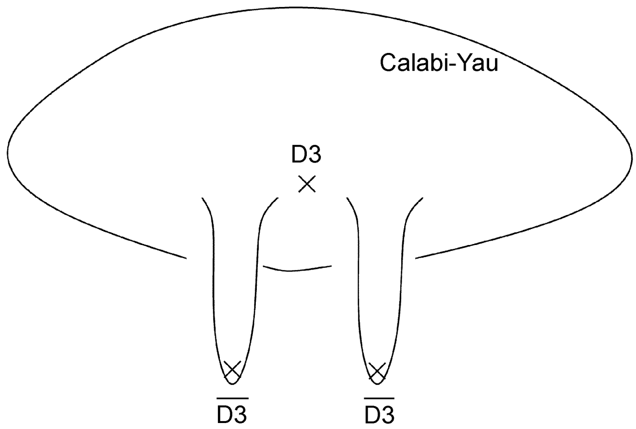

Figure 3. Two symmetrically located Klebanov–Strassler throats in Calabi–Yau space. Anti-D3-branes are at the bottom of each throats and mobile D3-brane is in between.

Two throats

Consider a situation where there are two KS throats that are symmetrically placed about a point of reaction symmetry. And consider the D3 brane located in the vicinity of the point of enhanced symmetry which we take to be the origin. The brane–anti-brane potential now has two terms each of the form V^B above, eq. (2), now coming due to the anti-branes at $\vec{r}_1$ and $-\vec{r}_1$ respectively.

Including both these terms as well as the conformal coupling one finds that the point of enhanced symmetry $r = 0$ will be a maximum of the potential which meets the condition $r \ll 1$ if

$$r_1 \sim Z^{2/3} L. \tag{3}$$

The requirement that $e \ll 1$ is then met if one starts sufficiently close to the top of the maximum.

The requirement that there are at least 60 efoldings is easily incorporated. Requiring that the density perturbations are of appropriate magnitude imposes a condition on the redshift factor Z which takes the form

$$\frac{1}{\sqrt{3}} \frac{Z^{4/3}}{L M_{\rm Pl}} \sim \frac{3}{1.8} \times 10^{-4} \, |h|. \tag{4}$$

It is worth summarizing the basic picture above in words: the idea is to realize a maximum in the landscape by looking for a point of enhanced symmetry. Then by dialling the fluxes, etc. appropriately one can explore if this maximum is broad enough to meet the requirement that h is small. Once this is true by starting close to the top the condition $e \ll 1$ is also met. Dialling the fluxes, etc. one can then explore whether this requires number of efoldings and the required density perturbations can also be obtained.

In the model above we have seen how this idea can be implemented in the specific context of brane inflation but it is more general and one expects that as our understanding of the landscape in string theory grows we will be able to find more broad maxima of the required type to support slow roll inflation.

There are some model independent features of the model above which are worth emphasizing. Having fixed the brane–anti-brane separation to meet the condition eq. (3) and the redshift factor to meet the requirement that the density perturbations are of required magnitude eq. (4), one then finds that the scale of inflation is fixed and independent of L and the other parameters in the theory like the string coupling, g_s.

The resulting value of the Hubble scale turns out to be $H \sim 10^{10}$ GeV which corresponds to energy scale, $\Lambda \sim 2 \times 10^{14}$ GeV. The low scale of inflation means that the production of gravity waves is extremely suppressed during inflation in this model. Another consequence of this low-scale is that cosmic strings if they are produced at the end of inflation are not problematic cosmologically. In fact such cosmic strings if long-lived enough could leave behind an interesting gravitational wave background of their own that could potentially be observed by gravity wave detectors in the future[39–42].

Let us end with some comments about reheating and about the beginning of inflation.

Reheating and the beginning of inflation

What happens at the end of inflation when the brane and anti-brane pair collide is a subject of very active investigation at present[43–48]. It is reasonable to assume that in the end the energy in the brane–anti-brane pair is released in graviton and other light closed string modes that couple to the pair. If there are additional branes or anti-branes that are not annihilated, then light open strings ending on them can also be excited. Whether this process gives rise to adequate reheating depends on where the standard model degrees of freedom live in the above construction and is a more model dependent question which needs to be studied further.

One potential worry about incorporating the standard model is worth mentioning[49]. In the KKLT construction the net cosmological constant gets a negative contribution due to the flux potential and a positive contribution due to the susy-breaking effects of the anti-brane. In order to not destabilize the closed string modes during inflation the negative contribution due to flux is of order the inflationary scale, 10^{14} GeV, in magnitude. This means to get a nearly vanishing cosmological constant after inflation ends we would require susy breaking of order 10^{14} GeV. The worry is that this is much too high a scale and would feed-down to standard model and give an unacceptably high Higgs mass. This conclusion can be avoided if in suitably non-generic situations one can get away with a negative contribution that is smaller than the cosmological constant during inflation. Another possibility would be of a Randall–Sundrum like throat where the redshifted string scale at the bottom is much lower than the underlying susy-breaking scale that determines the graviton mass, 10^{14} GeV. The most common examples of a K–S like throat probably will not work for this purpose, since the susy breaking will source mass terms for scalar fields in the dual gauge theory which will cause the throat to terminate at a scale of order the gravitation mass. A final possibility would simply be that the Higgs mass is light due to an unnatural cancellation between the susy breaking-induced mass and fine-tuned m term.

What about the beginning of inflation? This question is even more pressing in a model of the kind described above where the scale of inflation is low compared to the Planck or string scale. One needs to understand why for example the universe did not recollapse within a Planck time of the big bang much before inflation could begin. We do not have any definite answer to this question. The correct initial conditions in string theory is of course an important question and one which deserves much more study. One possibility is that the universe was not created by a big bang but originated instead by a tunnelling event that placed the inflation in the vicinity of the broad maximum in its potential of the kind described in the model above[50,51].

Another possibility is provided by the idea of eternal inflation[52]. It has been argued that a potential with a broad maximum of the kind we have here will give rise to eternal inflation. In the vicinity of the maximum the potential is given by

$$V = V_0 - \frac{1}{2} m^2 f^2,$$

and $m^2 = H^2 \ll 1$. For $f < f_c \sim H^3 = m^2$, quantum fluctuations can drive the scalar field up the hill faster than the classical gradient terms allow it to descend. Since the regions where the cosmological constant is bigger also grow exponentially more rapidly, soon the universe will be dominated by regions where the inflation is at the top of the hill, making the initial conditions irrelevant. The observed universe in this picture would arise when fluctuations cause the inflation to descend far enough from the top so that the classical evolution discussed becomes valid. This is an attractive and fairly plausible picture, but it is somewhat speculative at the moment and needs to be understood better.

Finally it is worth summarizing some other ways in which inflation could arise in string theory. One possibility is that the inflation is not a brane modulus but is one of the closed string moduli, perhaps a pseudoscalar which develops a slowly varying potential. This possibility was explored recently in refs 52, 53, within the context of KKLT stabilization and it was shown that the required slowly varying potential can be obtained. Another possibility is that the inflation is a D3 brane modulus as discussed above but the nonperturbative superpotential that develops to stabilize the volume modulus is different from eq. (1). For example if the superpotential depends on both the volume modulus and the inflation modulus then by appropriately tuning fluxes one could hope to get $h \sim 10^{-2}$, and so to meet the slow roll conditions. This possibility was suggested in ref. 37 and further developed in ref. 54 and in the context of D3–D7 brane inflation in refs 55–57.

VII. Conclusions

The fact that string theory allows for deSitter universes is good news.

As was emphasized above, there are a huge number of choices for flux that are allowed. Even after imposing the restrictions of large volume and small string coupling one therefore expects many-many vacua with widely varying values of the cosmological constant. Other constants of nature would also take varying values in these vacua.

The requirement of inflation imposes additional restrictions. But once again it seems that this condition can also be met and even after imposing it there will be a number of possible choices for allowed vacua.

The picture which emerges is that of a complicated landscape in string theory[58,59], with ~100 directions and between 10^{100} and 10^{1000} vacua. This embarrassment of riches is bad news from the point of view of predicting the standard model from string theory and raises questions which are currently exciting much discussion.

What chooses the vacuum we live in? Are the other possibilities realized, either in different parts of this universe as in the eternal inflation scenario, or in different branches of the wave function describing this universe, or not at all? Do we have to give up on Einstein's dream of understanding all the constants of nature based on a few fundamental principles? Can string theory at least predict some of the important constants of nature? These are some of the questions which the Landscape forces us to think about.

It is the author's belief that whereas discussing these questions is very worthwhile, any conclusions at this stage are at best speculative. The study of supersymmetry breaking and cosmology in string theory is at its earliest stages. One can be sure that there will be many surprises as our understanding progresses. Hopefully string theory will provide answers to some of the questions mentioned above. But the answers and even the precise nature of the questions will probably only be understood within the context of the developments to come.

One thing is certain. The recent attempts to bring string theory closer to cosmology which have been reviewed here are only a preview of things to come. As string theory develops further, a more meaningful dialogue with Cosmology will ensue leading to much more excitement in this field.

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