

Inflationary string theory?

C P BURGESS

Physics Department, McGill University, 3600 University Street, Montréal, Québec,
Canada, H3A 2T8

E-mail: cliff@hep.physics.mcgill.ca

Abstract. The inflationary paradigm provides a robust description of the peculiar initial conditions which are required for the success of the hot Big Bang model of cosmology, as well as of the recent precision measurements of temperature fluctuations within the cosmic microwave background. Furthermore, the success of this description indicates that inflation is likely to be associated with physics at energies considerably higher than the weak scale, for which string theory is arguably our most promising candidate. These observations strongly motivate a detailed search for inflation within string theory, although it has (so far) proven to be a hunt for a fairly elusive quarry. This article summarizes some of the recent efforts along these lines, and draws some speculative conclusions as to what the difficulty in finding inflation might mean.

Keywords. Strings; branes; cosmology.

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1. Introduction

Recent years have seen many detailed comparisons between observations and the hot Big Bang model of cosmology, within which the early universe consists of a hot soup of elementary particles. This picture bears up to scrutiny very well, at least for all times after the epoch of Big Bang nucleosynthesis (BBN). Embedded within this success are some baffling puzzles, however, including the following three:

- What is the nature of the dark energy whose energy density appears to presently make up over 70% of the energy density of the universe?
- What is the origin and nature of the dark matter which dominates the mass of galaxies and which makes up the lion's share of the universal energy density once the dark energy is removed?
- Why does the universe start out in the extremely homogeneous and isotropic initial state which observations require?

The inflationary universe proposal [1] addresses itself to the third of these questions. It is based on the compelling observation that the flatness, isotropy and homogeneity of the universe during the current epoch could naturally and robustly

follow if the universe were to undergo a dramatic, accelerated expansion during some earlier epoch. Furthermore, an accelerated exponential expansion can actually occur for reasonable choices for the equation of state for the universe's matter content. In particular, it arises if the potential energy of some scalar field were to temporarily dominate the energy density of that part of the universe within which we now live.

This much was known more than 20 years ago, but the relatively new development is the realization that the same inflation which was designed to solve the horizon and flatness problems can also very naturally explain the observed fluctuations in the cosmic microwave background (CMB). It can do so because the required dramatic universal expansion required by inflation can also stretch ordinary quantum fluctuations from microscopic up to cosmological length scales. Indeed, this picture can provide an attractive explanation for many features of the *spectrum* of these fluctuations, including their nearly scale-invariant spectrum, their Gaussianity, and so on [2].

The successful description of the *amplitude* of inflationary fluctuations is related to the value of the universal expansion rate, $H = \dot{a}/a = [V/(3M_p^2)]^{1/2}$, at that epoch during inflation when the currently-observed CMB fluctuations were leaving the horizon [2a]. As such, it is also sensitive to the energy scale, V , of the physics whose equation of state generates the inflationary behavior. Typically, for inflation associated with the slow roll of a scalar field, one finds that the combination $\delta^2 = (1/150\pi^2)(V/M_p^4\epsilon)$ must satisfy $\delta \approx 2 \times 10^{-5}$ in order to reproduce correctly the observed fluctuation amplitude [3]. The small quantity $\epsilon = \frac{1}{2}(M_p V'/V)^2$ which appears here is a measure of how flat the potential V is as a function of the relevant (canonically-normalized) slowly-rolling scalar field, or inflaton.

For ϵ not too small, in this way one finds $V^{1/4}$ only a few orders of magnitude smaller than M_p , which places it well beyond the reach of relatively well-understood physics. Indeed, being so close to the Planck scale, this suggests the physics appropriate to inflation is related to the physics of gravity at high energies. Happily, there are not many candidates for consistently describing gravitational physics at such high energies, with only one theory so far – string theory – having been explored well enough to try to make detailed contact with inflationary dynamics.

The possibility of such a connection is extremely exciting. Whereas inflation can be described as a successful phenomenological explanation for observations which is groping for a theoretical framework, string theory is an extremely well-motivated theory of very short-distance physics searching for observations which it can explain. The possibility that inflation might provide the long-sought-for bridge between string theory and observations provides a strong incentive for exploring the circumstances under which string theory might give rise to inflation.

As might be expected, given such good motivation, the search for inflation within string theory is an old one [4]. The main lesson of these early searches is that inflation would not be easy to find, and in retrospect this can be attributed to two basic reasons. First and foremost of these was the problem of moduli: for technical reasons the best-explored string vacua are supersymmetric, and these vacua typically have many massless scalar fields with strictly vanishing scalar potentials. Besides the quite general cosmological problems which the existence of such moduli potentially raises [5], they also obstruct the search for inflation. They do so

because these scalars cannot remain massless once supersymmetry breaks, and because the inflaton potential is (by design) very shallow its slope can be dominated by relatively small contributions to the scalar potential, such as can occur when the moduli acquire their potential through the breaking of supersymmetry. Furthermore, very general results imply that this supersymmetry breaking cannot occur at all within perturbation theory. As a result progress becomes difficult because an understanding of the cosmology of these fields was held hostage to the development of a non-perturbative understanding of how supersymmetry breaks.

The second obstacle to model building in these early years was the belief at the time that the string scale must be near the Planck scale. This made it more difficult to achieve potentials for which the fluctuation amplitude had the right size, because the natural scale of the problem was M_p and the small dimensionless parameters were typically extremely small – often $\sim e^{-(4\pi)^2/g^2}$ for some small coupling constant g – given the non-perturbative nature of the potentials required.

The search for stringy inflation has had a recent revival because of developments within string theory itself, which have suggested new ways around both of the above difficulties. The most important development was the discovery of D-branes and other kinds of branes. This discovery of branes – which consist of surfaces to which strings can attach – fundamentally changes what the low-energy limit of string theory can look like.

First, branes introduce non-perturbative string physics which is much more accessible to calculation than were the previous non-perturbative approaches. In particular, some quantities like brane tensions vary as inverse powers of string coupling and so branes themselves are able to evade previous perturbative no-go theorems which precluded supersymmetry breaking. Consequently, the examination of brane dynamics opens up the possibility for the semiclassical study of supersymmetry-breaking effects like the generation of potentials for moduli. For inflationary purposes the most actively pursued direction along these lines has been to have supersymmetry break due to the presence of both branes and anti-branes, with the inflaton being associated with the relative motion of the brane/anti-brane pair.

Second, the existence of branes opens up the possibility that the string scale, M_s , can be much smaller than M_p . One way this could happen would be through the *brane-world* scenario, within which all known low-energy particles but the graviton were to be trapped on the surface of a brane. In such a situation different interactions (like electromagnetism and gravity) can ‘see’ different numbers of dimensions and this complicates the inference of the string scale from the observed value of Newton’s constant, in such a way as to allow $M_s \ll M_p$. This allows the possibility that scalar potentials of order $V \sim M_s^4$ could lie in a range of interest for describing the amplitude of density fluctuations within the CMB.

It is also clear that cosmology must change dramatically within any brane-world picture, since appearance on the branes of localized sources of energy implies that the overall distribution of energy throughout the universe is dramatically different from the homogeneous and isotropic configurations which were entertained in the earlier proposals. All of these considerations have spurred new progress in understanding how inflation might arise within a string-theoretic context.

The remainder of this paper is organized in the following way: Section 2 provides a very short description of how brane physics has been used to make progress on the

moduli-fixing problem within the context of the compactification to four dimensions of Type IIB string vacua. Section 3 follows this with a very recent simple proposal for using these ideas to obtain inflation, using one of the geometrical moduli as the inflaton. Section 4 describes the better-explored alternative wherein inflation uses the relative position of various branes as the putative inflaton. Some preliminary conclusions are drawn from these explorations in §5. For reasons of space and focus the topics described in this summary are limited to work on which I have been directly involved myself, forcing the omission of other interesting lines of development such as those of ref. [6].

2. Modulus fixing

Although it was realized early that branes could break supersymmetry and so potentially help address the modulus problem, the decisive step forward required the embedding of this observation into concrete compactifications of string vacua to four dimensions in a way which preserves $N = 1$ supersymmetry. This was achieved for Type IIB vacua [7,8] by generalizing the construction of the earlier Calabi–Yau heterotic compactifications [9] to include various D3 and D7 branes, together with their orientifolds. The inclusion of these branes, as well as the warping and various fluxes which they source, turn out to generate a potential for the many complex-structure moduli of the Calabi–Yau vacua, while leaving 4D $N = 1$ supersymmetry unbroken and without generating a potential for the various Kähler moduli (of which there is always at least one).

Within this context further progress was then made by focussing on those Calabi–Yau spaces having the fewest unlifted Kähler moduli. In ref. [10] KKLТ focussed their attention on those spaces having just one such modulus, T , with attention then paid to how this last modulus might be lifted. This was studied in the low-energy 4D supergravity described by these vacua using the standard $N = 1$ supergravity potential [11],

$$V_F = e^K \left[K^{i\bar{j}} (W_i + K_i W) (W_{\bar{j}} + K_{\bar{j}} W)^* - 3|W|^2 \right], \quad (1)$$

where $K(\phi^i, \phi^{i*})$ is the low-energy supergravity’s Kähler potential and $W(\phi^i)$ is its superpotential. In this expression the quantity $K^{i\bar{j}}$ represents the matrix inverse of the Kähler metric, $K_{i\bar{j}}$, where here and above subscripts denote differentiation with respect to ϕ^i or ϕ^{i*} .

The explicit form for K and W can be obtained semiclassically, along the same lines as originally performed for Calabi–Yau compactifications [12], with the result

$$W = W_0 \quad \text{and} \quad K = -3 \ln(T + T^*), \quad (2)$$

where W_0 is T -independent. This has the form of a *no-scale* model [13], for which the classical potential, V_F , vanishes identically even though supersymmetry breaks for any finite T . This flatness of the potential for T reflects the fact that the 4D compactifications of ref. [7] do not lift Kähler moduli such as T .

The lifting of the degeneracy along the T direction requires additional physics, and in ref. [10] this was assumed to be achieved through non-perturbative effects,

such as through gaugino condensation [14,15] of a low-energy gauge sector localized on one of the D7 branes. In this case the superpotential becomes modified from eq. (2) to

$$W = W_0 + A e^{-aT}, \quad (3)$$

where A and a are calculable. This superpotential generates a non-trivial potential, V_F , for T , typically stabilizing it at finite T with $V_F < 0$. The resulting minimum preserves $N = 1$ supersymmetry and has an anti-de Sitter 4D space-time geometry with no remaining moduli.

The remaining supersymmetry may also be broken, with V_F at the minimum raised to positive values, through the artifice of introducing an anti-D3 brane into the underlying string configuration. (Generalizations of these results to more complicated superpotentials have also been considered [16].) Alternatively, the same effect as the anti-D3 branes can be obtained by turning on magnetic fluxes on the D7 branes [17], or by choosing more complicated local minima of the flux-induced potential [18].

As has recently been noticed [19,20], it can happen that the non-perturbative physics required to generate superpotentials of the form of eq. (3) may not be permitted for the simplest Type IIB vacua, and in particular might not arise for the single-modulus vacua considered in ref. [10,20a]. As of this writing it remains open whether this conclusion can be avoided for more complicated constructions (such as those involving orbifolding of the simplest ones) or if the minimal constructions must require two or more moduli.

3. Race-track inflation

Perhaps the simplest approach to obtaining inflation within string theory is to try to do so using the superpotential of eq. (3), but this turns out not to lead to sufficiently flat potentials. Slow-roll inflation does become possible for a minor generalization of this superpotential, however [21]. The required generalization is what would arise if the non-perturbative physics which is responsible for the superpotential involves gaugino condensation for a low-energy sector involving a product of gauge groups [22]. This leads to a superpotential which has the modified race-track form [22a]:

$$W = W_0 + A e^{-aT} + B e^{-bT}, \quad (4)$$

where A , B , a and b are known constants (e.g. $a = 2\pi/N$ and $b = 2\pi/M$ for a pure gauge theory with gauge group $SU(N) \times SU(M)$).

The potential V_F produced by this superpotential has stationary points which can occur at large values of $\text{Re}T$, provided we choose $|N - M| \ll N, M$. This is a good thing, since a large value for $\text{Re}T$ is required for the consistency of the supergravity analysis in terms of effective 4D fields because $\text{Re}T$ is proportional to the volume of the internal 6D space, and this was the original motivation for developing race-track models in the first place [23]. Since the value of the potential at the minimum is negative, this corresponds to an anti-de Sitter vacuum in four dimensions.

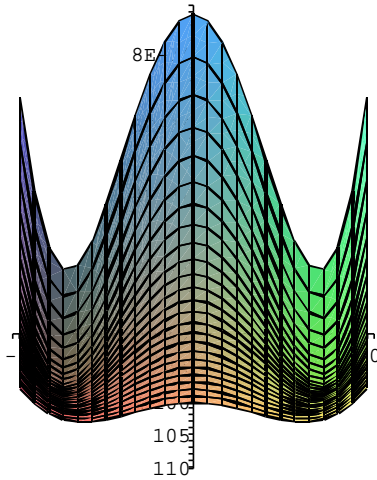


Figure 1. Plot for a race-track type potential illustrating the local minima between which a saddle point exists on which inflation can start. Units are $M_p = 1$.

It turns out that this minimum can be lifted to zero or positive values, much like the situation for the KKL T solution, by adding an anti-brane. For an appropriately chosen brane this adds a new term $\delta V = E/(\text{Re } X)^2$, where E is T -independent. Once this is done, slow-roll inflation becomes possible starting from the saddle point which appears for some choices of parameters between the various minima [21]. The minima are illustrated in figure 1, while figure 2 shows a close up of the saddle point in between. These figures are drawn using the parameter values

$$A = \frac{1}{50}, \quad B = -\frac{35}{1000}, \quad a = \frac{2\pi}{100}, \quad b = \frac{2\pi}{90}, \quad W_0 = -\frac{1}{25000}. \quad (5)$$

It is possible to adjust the quantities A , B , a , b and W_0 so that the slow-roll parameters are small at the position of the saddle point. Writing $T = X + iY$ and using canonically normalized fields, the η parameter at the saddle point is given by the expression $\eta_{\text{saddle}} = 2X^2V''/3V$, with the primes denoting differentiation with respect to Y and with the result evaluated at the saddle point: $Y = 0$ and $X = X_{\text{saddle}}$. This leads to the following slow-roll parameters:

$$\epsilon_{\text{saddle}} = 0, \quad \eta_{\text{saddle}} = -0.006097, \quad (6)$$

for the values of the parameters taken above. It should be emphasized that successful inflation is not generic and requires a tuning of parameters at the level of a part in 100.

Such an adjustment need not be a problem for this model because it can predict eternal inflation. If causally separated regions of the universe randomly sample different vacua, then even if the probability for inflation in any one domain may be strongly suppressed, the possibility of having eternal inflation infinitely rewards

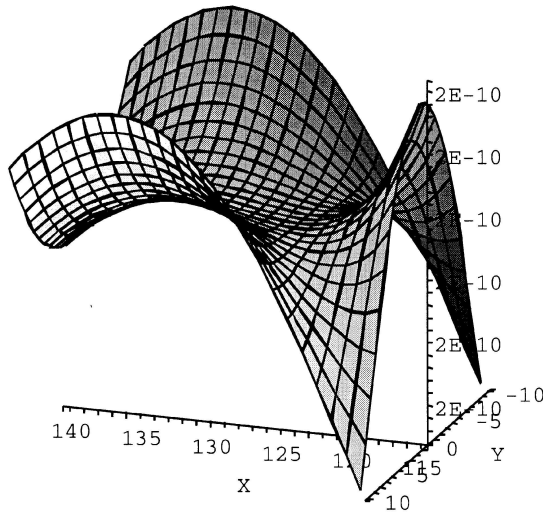


Figure 2. Plot for the same potential as for figure 1, showing a close up of the saddle point which lies between the two local minima. Units are $M_p = 1$.

those domains where inflation occurs (see [24] for a discussion of this issue). It should be stressed that eternal inflation is not an automatic property of any old inflationary model. But inflation is eternal in all models where it occurs near the flat top of an effective potential, with a nearby fall-off to local minima (such as the ones here) [25,26,26a].

The spectrum of CMB fluctuations predicted by this scenario is worked out in detail in ref. [21]. The spectrum is typically red, as is typical for inflationary models having negative curvature, with a representative parameter set giving $n_s \cong 0.95$ in the COBE region of the spectrum. For the same parameter choices, the slope of the spectrum is $dn_s/d \ln k \cong -0.001$, which is negligible in comparison with the current experimental sensitivity. It is interesting that observations will eventually be able to discriminate for or against this kind of model in the relatively near future. Measurable tensor fluctuations are not expected in this model since the scale of inflation is $V^{1/4} \sim 10^{14}$ GeV, which is well below the 3×10^{16} GeV threshold needed for producing observable gravity waves.

A particularly interesting feature of the potential generated by the superpotential, eq. (4), is that it provides what is perhaps the simplest realization of what has recently come to be called the string-theory landscape [28]. This landscape consists of a vast number of local minima having few or no moduli, which can reasonably be expected to arise for any system having very many degrees of freedom (like string theory) once the protection afforded to moduli is removed by supersymmetry breaking. In particular, the modified race-track superpotential can have an enormous number of physically distinct vacua if either of the parameters a or b should be irrational. A great virtue of the supergravity obtained using this superpotential is the ability to explicitly explore these vacua, and so to see what physical implications their existence may imply. For instance, ref. [21] provides a preliminary examination of the implication of such an enormous number of distinct vacua for the cosmological constant problem.

4. Brane–anti-brane inflation

The main idea identified to date for obtaining inflation from string theory in a calculable way is based on the relative motion of branes and anti-branes through a background geometry under the influence of their mutual attraction. In this picture it is the relative motion of the branes and anti-branes which plays the role of the inflaton, rather than a geometrical mode as in the race-track inflation discussed in the previous section.

The first proposal to use the relative motion of a configuration of branes as an inflaton [29] supposed all these branes to be BPS, i.e. all the branes preserved a common supersymmetry and so experienced no inter-brane forces in the static limit. Although it was promising that the resulting inter-brane potential should therefore by necessity be very shallow, the fact that the corrections to exact flatness must be non-perturbative proved to be an obstacle to further progress through explicit calculations.

The possibility of calculable inflaton potentials emerged with the suggestion to use the relative motion of both branes and brane–anti-branes as the inflaton, as was first simultaneously proposed in refs [30,31]. The calculability of this scenario is founded on the long-range forces which branes and anti-branes experience due to the mediation of massless fields like gravity in the intervening bulk. At first sight these forces might be expected to be sufficiently weak at large distances to produce slow-roll inflation, due to the r^{-k} fall off of the Coulomb interaction in $d_{\perp} = k + 2$ transverse dimensions [31]. However, on closer inspection this expectation proves to be incorrect within a compact space, due to the inability to separate branes by more than the size of the internal dimensions within which they live [30].

The problem with compact spaces can be seen directly from the predictions for the slow-roll parameters when $V(r) = A + B/r^k$ [30]:

$$\eta = \frac{M_{\text{p}}^2 V''}{V} \approx \frac{ck(k+1)B}{A} \left(\frac{R}{r}\right)^{k+2}, \quad (7)$$

where it is assumed that the constants A , B and c are set (up to order-unity factors) by the appropriate power of the string length, ℓ_s , and that the inter-brane separation, r , is much larger than ℓ_s . In this expression the constant, c , and the volume, $V_{\perp} = R^{k+2}$, of the transverse extra dimensions enter through its appearance in the 4D Planck mass, $M_{\text{p}}^2 = cV_{\perp}$. Given that the constants A , B and c are set by the string scale, it is clear that η generically cannot be small because the inter-brane separation typically cannot exceed the size of the space, $r \leq R$.

Because of this last observation the search for inflation becomes a search for special configurations for which inter-brane forces are particularly weak, and there have been a number of proposals for doing so. The first suggestion involved minimizing the net inter-brane force by placing the branes and anti-branes at antipodal points in the compact space [30], but this runs into difficulties due to the necessity for projecting out bulk-space zero modes when computing the inter-brane interactions [32] (see also [33]). Other proposals include using branes which are slightly misaligned relative to one another (i.e. branes at angles) [34], using bulk moduli as the inflaton but with inter-brane interactions as the driving force [35], using the $N = 2$ supersymmetry of D3–D7 brane interactions [36], and so on.

The approach within which the modulus-stabilization issue is best addressed (so far) uses a minor extension [32] of the stabilization construction of ref. [10]. In this construction the underlying warped Calabi–Yau space is chosen with its fluxes adjusted to ensure the presence of a long warped throat, whose tip consists of a smoothed-off singularity. Within this throat the geometry of five of the dimensions – consisting of the large 4D space-time directions together with the radial coordinate which measures the distance down the throat – is approximately described by 5D anti-de Sitter space. Following [10], one or more anti-D3 branes is imagined to reside at the tip of this throat, and this breaks the 4D $N = 1$ supersymmetry of the background geometry. Finally, a D3 brane is imagined to be sliding down the throat towards the anti-brane, and it is the relative motion of these last-mentioned branes which plays the role of the inflaton.

Inflation may be obtained in this picture, but only at the expense of carefully adjusting the system parameters to the (0.1–1)% level. The difficulty in obtaining inflation arises because of an interplay between the potential which stabilizes the moduli and the potential of the putative inflaton [32]. From the point of view of the low-energy supergravity, this is a special case of the well-known η -problem [37] with obtaining inflation from a supergravity F -term potential.

A further generalization of this construction also allows a semi-realistic low-energy world to be located within this scenario, by locating the standard model onto a system of intersecting D3 and D7 branes somewhere within the six internal dimensions [38]. Identifying where potentially realistic low-energy physics can reside inside this kind of inflationary construction can be important, in as much as this opens up the possibility of asking key post-inflationary questions, like the nature of the reheating which ultimately leads to our later hot Big Bang. Calculations of the density-fluctuation spectrum to be expected in these models differs from the race-track models discussed earlier in as much as the spectral index tends to be slightly bluer, with $n_s \sim 1.03$ – 1.08 [38]. A plot of several successful inflaton trajectories superimposed onto the effective inflaton potential is shown in figure 3.

The possibility of having inflation occur within a throat having strong warping at its tip might open up several attractive possibilities for cosmology. In particular, since the warping tends to reduce the effective tension of the D3 brane as it falls down the throat, the energy density released by the final brane/anti-brane annihilation is likely to be set by a lower scale than the string scale. If this sufficiently suppresses the energy density released when the brane and anti-brane annihilate compared with the string scale, it can suppress the fraction of energy which ends up in the bulk relative to the energy which gets dumped into spectator branes. If so, then the warping of the throat may act to improve the efficiency with which inflationary energy gets converted into reheating standard model degrees of freedom as opposed to populating phenomenologically problematic bulk states.

An exciting possibility which has emerged from these studies is the possibility of generating cosmic strings at the end of inflation [30,39]. Since these need not arise within the race-track inflation scenario discussed in the previous section, the formation of such strings is not a generic prediction of string theory and inflation. But such strings are generic to brane/anti-brane models, and so long as the resulting strings are sufficiently long-lived and have a reasonable energy density they could be detectable through their effects on CMB fluctuations.

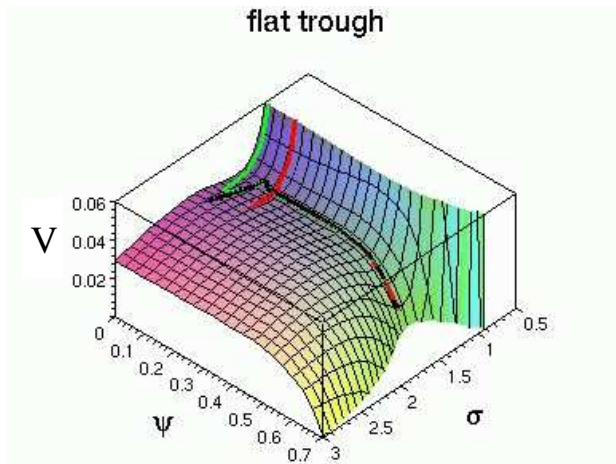


Figure 3. Plot showing the inflationary potential as a function of the inter-brane separation, ψ , and the internal-space volume, σ . Also shown are several inflaton trajectories starting from different initial field values. Units are $M_p = 1$.

5. Discussion

The search for inflation within string theory is still in its infancy, but considerable progress has been made over recent years due to the incorporation of the existence of branes into the search. Branes help with the search for inflation because they can source flux fields which stabilize moduli, and because their slow relative motion followed by their annihilation can provide an attractive geometric realization of hybrid inflation [40].

To date two pictures have emerged as to which field might play the role of the inflaton: either inter-brane separations (brane inflation) or geometric moduli (race-track inflation). Explicit models exist which lead to density fluctuations for which $n_s - 1$ has either sign, and it is intriguing that of the presently-known models race-track inflation seems to give $n_s < 1$ while brane-inflation models tend to give $n_s > 1$. Whether this correlation is robust or is just an artefact of the first few models is not yet clear. For some of the constructions presently known it is also possible to identify where our low-energy world resides, making possible more detailed discussions of reheating and defect formation.

Although it is possible to obtain 60 e -foldings of inflation in these models, this is not generic and having this much inflation requires some fine-tuned adjustment of the vacuum properties. One point of view to take is that in a universe for which different vacua are chosen in different causal regions, those rare domains which inflate become infinitely rewarded by dominating the volume of the subsequent universe. This is a particularly attractive point of view in the presence of eternal inflation, such as generically arises when inflation occurs near the local maximum of a potential with multiple nearby local minima. This is the situation encountered in the race-track inflation solutions discussed in §3.

It is more difficult to take such a sanguine attitude for the brane inflation scenarios which have been found up to this point, such as those of §4. This is because these fall into the hybrid inflation category, which need not produce eternal inflation. In this case it is worth standing back and asking whether string theory is trying to tell us something if inflation were to arise in this way, and if it remains true that inflation is not so easy to achieve.

Although it is comparatively difficult to produce a full 60 e -foldings within a hybrid inflation scenario like brane/anti-brane inflation, 10 to 20 e -foldings are much easier to obtain. The problem basically arises because the scale of the potential in these models is set by the string scale, and there are no small numbers to use to make the inflaton potential sufficiently shallow. Perhaps this suggests that string theory prefers to give only a small number of e -foldings during any inflationary phase up at the string scale (which is where the observed temperature fluctuations in the microwave background are produced). If so, any remaining e -foldings of inflation required by the flatness and homogeneity problems would have to occur during later epochs, perhaps at the weak scale due to the supersymmetry breaking potential for some of the ubiquitous supersymmetric moduli. This suggests a picture of two-stage, late time inflation [41]. If so, it would provide a natural explanation for effects like a running spectral index, which may have been observed in the primordial fluctuation spectrum. More detailed studies of cosmologies of this sort are warranted given the motivation this kind of picture may receive both from string theory and the current data.

In summary, inflation is beginning to be found within effective field theories which capture the essential features of the low-energy limit of some string vacua having most of their moduli fixed at the string scale. But this is probably just the beginning of the exploration of inflation in string vacua, and much remains to be done towards the goal of a systematic searching for string-based inflation.

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