# Inflation from String Theory

James M. Cline (McGill University)

3/6/07–10/6/07

## 1 Overview of the Field

The paradigm of inflation continues to be confirmed by experiments like WMAP, and will be probed more deeply by the Planck satellite in the near future. Because of the extremely high energies present in the early universe during inflation, string theorists have put great effort into making predictions for cosmology which might be the only way of verifying the theory experimentally. Inflation from string theory has developed rapidly during the last few years, with ref. [1] setting the trend for a new level of mathematical rigor in the subject. While the early models had to make numerous assumptions, for example concerning the stability of the extra dimensions of string theory, the current trend is to eliminate assumptions as much as possible in favor of rigorous calculations, so that the models become increasingly derived from the highly constrained mathematical framework of string theory, rather than merely inspired by it.

## 2 Recent Developments

One of the most highly studied proposals for inflation from string theory is that inflation is due to the relative motion of D-branes, higher dimensional objects intrinsic to string theory, within the compact internal dimensions which are equally essential. The main realizations involve D3- and anti-D3 branes (where 3 denotes the spatial dimension) and D3 and D7 branes. The major challenge is to find ways of making the potential between the branes sufficiently flat to support a long period of inflation, during which the size of the universe grew by a factor of at least $e^{60}$. This question cannot be fully addressed until stability of the size of the extra dimensions has been assured by some mechanism, since the dynamics of this compact space has a strong effect on the force between the branes. Warped compactifications in type IIB string theory have provided a mathematically rigorous framework for stabilizing the extra dimensions, and have thus made the problem of constructing a flat potential well-posed.

The accepted method for studying this problem is to derive a low energy effective lagrangian for the position of the inflationary D3 brane in the language of 4D supergravity. An essential ingredient is thus the superpotential, which leads to the potential. In ref. [1], it was recognized that there should exist corrections to the superpotential describing the force on a D3 brane in a warped throat which could potentially be tuned to give a flat potential [1], but these corrections had never been explicitly calculated, only parametrized. Thus the details of how flatness could be achieved in a specific string background remained to be elucidated. An important step in this direction was taken by the Princeton group, [3], which computed the string theory corrections to the superpotential. Our previous team effort at BIRS in 2006 was able to quickly capitalize on the results of this paper, by showing that inflation does not work when the D7 branes are embedded in the extra dimensions of the throat in a certain way (the Ouyang embedding), which we believed to be quite typical [2]. Our well-cited work influenced the Princeton group to consider a wider class of embeddings, and they found one (the Kuperstein embedding) which was compatible with inflation. This discovery, which we helped to inspire, led to two highly influential papers from them, ref. [4], which set the new standard for the state-of-the-art brane-antibrane inflation model derived from string theory. This was the status of the subject when we began our meeting in 2007.

# 3 Directions of research

We pursued two different research directions in response to the recent progress of ref. [4]. One was to start a more in-depth study of the inflationary dynamics in the framework developed in those papers, since their emphasis was on the construction of the model, with more of a preliminary analysis of the details of inflation and comparison to current experimental constraints. We quickly discovered a novel feature which the authors of [4] had not noticed: for some range of parameters, one could find a *minimum* in the number of $e$-foldings of inflation, $N_e$. This is quite different from the usual behavior, where $N_e$ is a monotonic function of the parameters of the potential. Since it is usually difficult to get the experimentally required minimum number $N_e > 60$, this finding was rather striking.

Our second line of attack was to try to improve the method of lifting up the potential from negative values, typical of supergravity and which would lead to anti-de Sitter rather than approximately de Sitter solutions to Einstein's equations. The usual method of doing so, employed in [4], is to include anti-D3 branes in the throat, which explicitly break supersymmetry, and which therefore call into question the consistency of an approximately supersymmetric description of the dynamics. Prompted by recent studies of the $\alpha'$ (higher derivative) corrections to the low energy action from string theory, in particular corrections to the Kähler potential, as well as the effects of spontaneously breaking supersymmetry by turning on magnetic flux on the D7-branes [5], we attempted to get uplifting from the $\alpha'$ corrections, and to search for a new inflationary scenario in which the attraction of the D3 brane toward the bottom of the warped throat might be counteracted by its attraction to the D7 branes, due to the magnetic fluxes.

# 4 Outcome of the Meeting

The research we started resulted in two papers, one of which has been accepted for publication in JHEP [6], and the other recently submitted to Phys. Rev. D [7]. The first paper did not succeed in finding a new inflationary scenario as we had initially hoped, but it did obtain new results concerning the potential of the moduli in the modified setup (where magnetization of the D7 branes and $\alpha'$ corrections were included), in particular the minima of the angular directions in the warped throat, and it also succeeded in uplifting the negative vacuum energy without explicit supersymmetry breaking, which was one of the goals. The second paper used Monte Carlo Markov chain techniques to numerically explore the parameter space of the D3 brane inflation model as developed by ref. [3]. It succeeded in finding parameters where all experimental constraints (the spectral index and amplitude of power of CMB fluctuations) are satisfied, which had never been done in previous papers. Furthermore it found an optimal region in the parameter space where the fine tuning problem pointed out by the original authors is eliminated. Near this region, acceptable inflation models are found in which any given parameter need only be adjust to a part within a few. This represents an improvement by 8 orders of magnitude in the fine-tuning problem for the original choice of parameters by the authors of [3]. It is a striking result because usually at least a tuning of one part in 100 is needed to get 60 $e$-foldings of inflation.

Both of the papers which came out of our team meeting were realized with the collaboration of graduate students. The benefits of BIRS thus extended to these students, even though they were not present as official team members.

# References

[1] S. Kachru, R. Kallosh, A. Linde, J. Maldacena, L. McAllister and S. P. Trivedi, "Towards inflation in string theory," JCAP **0310** (2003) 013 [hep-th/0308055].

[2] C. P. Burgess, J. M. Cline, K. Dasgupta and H. Firouzjahi, "Uplifting and inflation with D3 branes," JHEP **0703**, 027 (2007) [arXiv:hep-th/0610320].

[3] D. Baumann, A. Dymarsky, I. R. Klebanov, J. M. Maldacena, L. P. McAllister and A. Murugan, "On D3-brane potentials in compactifications with fluxes and wrapped D-branes," JHEP **0611**, 031 (2006) [arXiv:hep-th/0607050].

[4] D. Baumann, A. Dymarsky, I. R. Klebanov and L. McAllister, "Towards an Explicit Model of D-brane Inflation," JCAP **0801**, 024 (2008) [arXiv:0706.0360 [hep-th]]; D. Baumann, A. Dymarsky, I. R. Klebanov, L. McAllister and P. J. Steinhardt, "A Delicate Universe," Phys. Rev. Lett. **99**, 141601 (2007) [arXiv:0705.3837 [hep-th]].

[5] V. Balasubramanian and P. Berglund, "Stringy corrections to Kaehler potentials, SUSY breaking, and the cosmological constant problem," JHEP **0411**, 085 (2004) [arXiv:hep-th/0408054];

D. Cremades, M. P. Garcia del Moral, F. Quevedo and K. Suruliz, "Moduli stabilisation and de Sitter string vacua from magnetised D7 branes," JHEP **0705**, 100 (2007) [arXiv:hep-th/0701154].

[6] F. Chen and H. Firouzjahi, "Dynamics of D3-D7 Brane Inflation in Throats," arXiv:0807.2817 [hep-th].

[7] L. Hoi and J. M. Cline, "How Delicate is Brane-Antibrane Inflation?," arXiv:0810.1303 [hep-th].