EFFECTS OF STRINGS IN INFLATION AND REHEATING

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We argue that many models of inflation in string theory require the usual ten-dimensional compactification geometry to be modified during inflation. Based on arguments from the four-dimensional effective theory, we propose a modified ten-dimensional geometry in which the four-dimensional effective theory is just consistent. We also discuss the implications of the light modes in reheating, following inflation. (*Based on work in progress with Anupam Mazumdar and Robert Myers.*)

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Recently, many models have been proposed for the embedding of inflation in string theory [1–11], mostly generating an inflationary potential through a brane/anti-brane interaction. One reason for the resurgence of interest in the past year is the compactification models of KKLT [12], which provide a laboratory for cosmological scenarios in string theory. For example, [7] recognized that brane/anti-brane inflation must occur in a warp factor and that all the compactification moduli must be stabilized at a sufficiently high mass scale. Indeed, KKLT compactifications stabilize all moduli and have warped product metrics

$$ds^2 = e^{2A} g_{\mu\nu} dx^\mu dx^\nu + ds_6^2 \ , \tag{1}$$

where $g_{\mu\nu}$ is the 4D cosmological metric, and ds_6^2 is conformally Calabi-Yau in the vacuum state. Rather than discussing particulars of these inflationary models, we will ask three questions about inflation in string compactificatons:

- Are there circumstances in which string theoretic or higher dimensional effects could become important?
- How might the compactification geometry be modified during inflation?
- What mechanisms might be important for reheating? Particularly, could string physics play a role?

For specificity, we will focus on KKLT compactifications and brane/anti-brane inflation, although similar considerations should apply to other models.

Consider the case in which the standard model (SM) lives on D3-branes separated from the inflationary branes, in a region of small warp factor $e^A \ll H/M_P$

for 4D Hubble scale H.[a] This would occur, for example, if the SM hierarchy is provided solely by warping (as in [13]), in which case $e^A \sim M_w/M_P$. In KKLT compactifications, a typical region of significant warping is described by deformed conifold throats [14, 15], with a small warp factor at the tip of the throat, which we denote by subscript t.[b] Since the 4D theory measures scales with respect to $g_{\mu\nu}$, the effective string length at the tip is

$$\ell_{s,t} = e^{-A_t}\sqrt{\alpha'} \gg 1/H \ , \tag{2}$$

which is also approximately the Kaluza-Klein mass scale for gravitons in the SM throat, so we immediately see that string and 10D physics can be important. One indication that string physics enters is the curvature, which, in the putative 4D effective theory is greater than the string scale. In ten dimensional terms, the curvature of metric (1) for $g_{\mu\nu}$ inflationary with Hubble scale H is

$$R = 12H^2 e^{-2A} + R_6 - 8\nabla_6^2 A - 4(\nabla_6 A)^2 \ , \tag{3}$$

where ∇_6 is with respect to ds_6^2. At the tip of the throat, the first term dominates and is much more than $1/\alpha'$. There are also additional difficulties due to (2). In the 4D effective theory, the action of a string-creating instanton is only $2/H^2\ell_{s,t}^2$, so string creation would seem to be prodigious. Another way to think of this problem is to recognize that the de Sitter temperature $H/2\pi$ would be much higher than the Hagedorn temperature $1/\ell_{s,t}$, so string physics would completely dominate the usual supergravity description. Additionally, since the Kaluza-Klein scale is set by $\ell_{s,t}$, we expect that higher-dimensional physics will also play an important role during inflation. The answer to our first question is then definitively "yes."

We can see now the importance of our second question. Clearly, taking the vacuum metric (1) and inserting high-scale inflation into $g_{\mu\nu}$ is invalid in regions of significant warping. Due to the detailed 10D structure of the compactification without inflation [15], we might expect the modified geometry to approximate the supergravity solution for D3-branes with de Sitter worldvolumes. Unfortunately, this solution is unknown, so we will use some general insights about physics during inflation. Specifically, we know during inflation that light scalar fields can acquire VEVs over Hubble length scales. In the SM throat, besides light string modes and Kaluza-Klein modes, there is a light modulus (the deformation parameter of the conifold) with mass give roughly by $1/\ell_{s,t}$. This modulus also happens to control the warp factor at the tip of the throat [15]; we propose that this deformation modulus will acquire just the correct VEV to lift the tip warp factor e^{A_t} just enough that $\ell_{s,t} \lesssim 1/H$. If this proposal is correct, string and extra-dimensional physics will be visible (for example, in CMB perturbations), but the supergravity description and effective 4D theory will still be (marginally) viable.

[a]For simplicity, we will ignore the hierarchies between the 4D and 10D Planck scales, the string scale, and the compactification scale.

[b]In this model of brane/anti-brane inflation, the inflationary branes would live in a separate throat with a warp factor $e^A \sim (H/M_P)^{1/2}$ at the tip.

We have now argued that, during inflation, a significantly warped SM throat (or other warped region) will be shortened so that string theoretic and extra-dimensional physics are just becoming important. The last point we hope to address is how such physics can affect reheating, especially because the SM is decoupled from the inflationary sector by separation in the compact dimensions. One potential reheating mechanism is contained in the SM throat; as the deformation parameter relaxes to its ground state after inflation, the SM D-branes in that throat could become excited. In fact, we expect an energy density of order H^4 in the SM throat during inflation, which is available (modulo redshifting) for reheating the SM. Further, we might guess that the rate for this reheating would be given by the fundamental scale of the ground state, $\Gamma \sim 1/\ell_{s,t}$. Additionally, there can be reheating from the inflationary sector, which we can understand from a higher-dimensional point of view. In brane/anti-brane inflation, inflation ends with annihilation of the branes, which produces both cosmic strings and gravitational radiation in the inflationary throat (see [16]). Following [17, 18], the gravitational radiation, which starts out localized in the inflationary throat, can tunnel to the SM throat. We can roughly estimate the tunneling rate to be $\Gamma \sim (H/M_P)^{3/2} H \sim 10^2$ TeV for $H = 10^{13}$ GeV (this rate could be increased or reduced depending on the parameters of the compactification). Once in the SM throat, these closed string modes could excite the SM branes, also. Potentially, then, either of these mechanisms could provide significant SM reheating. Even at this point, string physics can play an important role; due to the large string length $\ell_{s,t}$, SM reheating might first lead to a gas of long open strings on the SM branes. There are two classes of open string polarizations, longitudinal and transverse to the SM branes. These can respectively decay by splitting and by radiating SM quanta with rates (for string lengths ℓ and N_D SM branes)

$$\Gamma_{split} = \frac{(2\pi)^3}{2\sqrt{2}} \frac{N_D g_s}{\ell_{s,t}} \left(\frac{\ell}{\ell_{s,t}}\right) \left[\frac{1}{\pi} \ln\left(\frac{\ell}{4\ell_{s,t}}\right)\right]^{-3} , \quad \Gamma_{rad} = \frac{\sqrt{2}(2\pi)^4}{8} \frac{N_D g_s}{\ell} . \tag{4}$$

Typically, we expect that strings shorter than some critical value will be transversely polarized (and longer, longitudinally). Therefore, we can have a picture of open strings stretching with the expansion of the universe and then splitting once reaching a critical length; all the time, these strings are radiating SM quanta. Generally speaking, we would follow the string network with a transport equation approach (see [19, 20]), but equilibrium open strings are an interesting special case. At high enough densities, equilibrium open strings have low pressure [21] (redshifting like matter), and they lose energy to radiation at a rate $\dot{\rho} \sim N_D^3 g_s/\ell_{s,t}^5$. This is a novel, string theoretic, stage in reheating.

Of course, there are many open questions: What precisely is the 10D description of the compactification during inflation? Since string and extra-dimensional physics is not highly suppressed during inflation, do they leave a signature in the CMB? What is the complete picture of reheating in this type of inflationary scenario? We have just scratched the surface, but we have provided a framework for the discussion.

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