Consistent de Sitter String Vacua from Kähler Stabilization and D-term uplifting

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Abstract

In this note, we review our construction of de Sitter vacua in type IIB flux compactifications, in which moduli stabilization and D-term uplifting can be combined consistently with the supergravity constraints. Here, the closed string fluxes fix the dilaton and the complex structure moduli while perturbative quantum corrections to the Kähler potential stabilize the volume Kähler modulus in an AdS_4-vacuum. Then, magnetized $D7$-branes provide consistent supersymmetric D-term uplifting towards dS_4. Based on hep-th/0602253.

1   Introduction

Recent developments in string theory have seen the discovery of a whole 'landscape' [1–4] of stable and meta-stable 4d vacua. This represents remarkable progress in the formidable task of constructing realistic 4d string vacua. In particular, the most pressing issues have been how to stabilize the geometrical moduli of a compactification, and at the same time address the tiny, positive cosmological constant that is inferred from the present-day accelerated expansion of the universe. Recently, the use of closed string background fluxes in string compactifications has been studied in this context [5–24]. Such flux compactifications can stabilize the dilaton and the complex structure moduli in type IIB string theory. Non-perturbative effects such as the presence of Dp-branes [25] and gaugino condensation were then used by Kachru *et al* (henceforth KKLT) [2] to stabilize the remaining Kähler moduli in such type IIB flux compactifications (for related earlier work in heterotic M-theory see [26]). Simultaneously these vacua allow for SUSY breaking and thus the appearance of metastable dS_4-minima with a small positive cosmological constant fine-tuned in discrete steps. KKLT [2] used the SUSY breaking effects of an $\overline{D3}$-brane to achieve this. Alternatively the effect of D-terms on $D7$-branes has been considered in this context [27].

Bearing in mind the importance of constructing 4d de Sitter string vacua in a reliable way, one should be aware of the problems in using $\overline{D3}$-branes as uplifts which arise due to their explicit breaking of SUSY. If we replace the $\overline{D3}$-branes by D-terms driven by gauge fluxes on $D7$-branes [27] we therefore retain considerably more control as we remain inside supergravity. In this case the requirements of both 4d supergravity and the $U(1)$ gauge invariance necessary for the appearance of a D-term place consistency conditions on the implementation of a D-term (noted in [27], and emphasised in [28–30]). It has proven difficult to meet these conditions in a concrete stringy realisation of [27], where the proposal was made in the context of KKLT. A consistent mechanism of stabilizing a modulus via D-terms and uplifting its minimum to a metastable dS vacuum has been constructed within the context of 4d supergravity by [30] without, however, having a viable string embedding - a more stringy and consistent model can be found in [29]. Recent further stringy constructions were presented along the lines of [29] where the model-dependent inclusion of charged matter fields renders a modified KKLT superpotential gauge invariant and provides consistent uplifting D-terms, see e.g. [31–33].

Given the subtleties encountered in the D-term uplifting of KKLT potentials, it is appealing that recently the possibility of stabilizing the remaining Kähler volume modulus of type IIB flux compactifications purely by perturbative corrections to the Kähler potential has been studied [34, 35]. The leading corrections which the Kähler potential receives are given by an $\mathcal{O}(\alpha'^3)$-correction [36] and string loop corrections [37]. The α'-corrections have recently been used to provide a realization of the simplest KKLT dS-vacua with F-term uplifting without the need for $\overline{D3}$-branes as the source of uplifting [38–41] (for other recent models using a more general O'Raifaertaigh like F-term uplifting sector see e.g. [42]). Under certain conditions the interplay of both the α'-correction and the loop corrections leads to a stabilization of the volume modulus by the perturbative corrections alone [35]. The corrections to the Kähler potential do not break the shift symmetry of the volume modulus. Therefore, in the present note, we show that such a Kähler stabilization mechanism allows for a consistent D-term uplift, by gauging this shift symmetry with world-volume gauge fluxes on a $D7$-brane. Moreover, from simple scaling arguments one can conclude that the resulting vacuum does not suffer from any tachyonic directions.

2   D-terms uplifts and consistency conditions from 4d $\mathcal{N} = 1$ supergravity

The proposal to use a field dependent FI D-term as a source of uplifting AdS- to dS-vacua was constructed in [27]. Consider a 4d $\mathcal{N} = 1$ compactification of type IIB string theory on an orientifolded Calabi-Yau 3-fold in the presence of closed string fluxes. The $G_{(3)}$-flux fixes the dilaton S and the complex structure moduli U^I. Generically, this procedure leaves

the Kähler moduli unfixed and in particular the universal Kähler volume modulus T. Now, the volume modulus enjoys a Peccei-Quinn type symmetry: $T \rightarrow T + i\alpha$. In the presence of a background 2-form gauge field strength F_{mn}, threading the world-volume of a $D7$-brane wrapped on a 4-cycle Γ of the compact internal manifold, this symmetry is gauged. The corresponding gauge covariant derivative acts on $b = \mathrm{Im}\,T$ as $D_\mu b = \partial_\mu b + iq A_\mu$, with q the charge. The necessary coupling, $qA^\mu \partial_\mu b$, arises from the $a_{(2)} \wedge F_{(2)}$-coupling contained in the world volume action of the $D7$-brane, where b and $a_{(2)}$ are dual fields. Here $a_{(2)}$ denotes the 2-form potential contained in the closed string 4-form $C_{(4)}$ which has the world volume coupling $C_{(4)} \wedge F_{(2)} \wedge F_{(2)}$ to the $U(1)$-gauge field strength $F_{(2)} = dA_{(1)}$ on the $D7$-brane. Note that q turns out to be quantized due to its relation with the effective D3-brane charge carried by the $D7$-brane. As long as we assume just one $D7$-brane its $U(1)$ world volume gauge theory has no local anomalies.

As expected, the gauging goes hand in hand with a D-term potential, and specifically a contribution to the scalar potential for the volume modulus T. This arises from the world-volume action of the wrapped $D7$-brane, as:

$$V_D(T) \sim T_7 \cdot \int_\Gamma d^4 y \sqrt{g_8} F_{mn} F^{mn} \sim \frac{q^2}{(T + \bar{T})^3} \; , \tag{1}$$

where T_7 is the $D7$-brane tension. For simplicity we are assuming a single Kähler modulus, and also the absence of matter fields charged under the $U(1)$ gauge group. This latter assumption may be justified in a model with a single isolated $D7$-brane: The matter fields arising from open strings stretching between the $D7$- and other branes would then become very massive thus driving their VEVs to zero. In the presence of light charged matter fields, one must consider whether their dynamics are such as to minimise the D-term potential at $V_D = 0$, or to allow this supersymmetry breaking contribution.[1]

Recall now that it is a shift symmetry in the Kähler potential K of the chiral superfield T

$$T \rightarrow T + i\alpha \; : \; K = -3\ln(T + \bar{T}) \; \rightarrow \; K \tag{2}$$

that is gauged by the $D7$-brane gauge flux. The joint requirements of gauge invariance and local supersymmetry place tight constraints on the possibility to have a field dependent FI D-term [28, 30]. These constraints require the function

$$G = K + \ln |W|^2 \; , \; W : \text{superpotential} \tag{3}$$

to be gauge invariant under the shift symmetry eq. (2). G determines the scalar potential via

$$V = V_F + V_D = e^G (G^{T\bar{T}} G_T \overline{G_T} - 3) + \frac{1}{2} \left(\mathrm{Re}\, f_{D7} \right)^{-1} D_T^2 \; , \; D_T = iX^T G_T = iX^T \frac{\partial G}{\partial T}. \tag{4}$$

$X^T = iq$ denotes the Killing vector of the isometry eq. (2) and $f_{D7} = T$ the $D7$-brane gauge kinetic function. Notice that $D_T \sim F_T = e^{G/2} G_T$, so that a SUSY-breaking F-term is necessary to observe a non-trivial uplifting effect from the D-term [43]. Then eq. (4) tells us that the form

$$W = W_{\text{flux}}(S, U^I) + A \cdot e^{-aT} \; . \tag{5}$$

that the KKLT superpotential in type IIB flux compactifications generically takes (for the case of just the one universal Kähler modulus T, i.e. the volume) is gauge invariant only if either $W_{\text{flux}} = 0$ or $A = 0$. Thus, if background fluxes are used to stabilize S and the U^I and non-perturbative effects are used to stabilize T, as in KKLT [2], then the shift symmetry that the Kähler potential has cannot be gauged to yield a D-term uplift [30], unless further fields like hidden sector charged matter are introduced [29, 31–33].

Keeping the invariance under shifts (to allow the D-term) while stabilizing T demands that T has to be stabilized by corrections depending solely on $T + \bar{T}$. By holomorphy of the superpotential we are then led to consider stabilization of T by perturbative corrections to the Kähler potential, which depend only on $T + \bar{T}$.

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[1]See [27] for more discussion on this important point.

3 Perturbative corrections to the Kähler potential and volume stabilization

Recently the possibility of stabilizing the volume modulus of type IIB flux compactifications solely by perturbative corrections to the Kähler potential has received some attention [34–36]. This is due to the fact that the two leading corrections have been derived in type IIB string theory explicitly (for a few concrete examples, at least).

Firstly, one has in type IIB compactified on an orientifolded Calabi-Yau threefold an $\mathcal{O}(\alpha'^3)$ R^4-correction to the 10d type IIB supergravity action [36, 44] (all other corrections $\mathcal{O}(\alpha'^3)$ or higher are subleading, see [47, 50]). This generates a correction to the Kähler potential [36]

$$\Delta K_{\alpha'^3}^{R^4} = -(2\pi\alpha')^3 \frac{\hat{\xi}}{(T+\bar{T})^{3/2}} + \mathcal{O}(\alpha'^6) \, , \quad \hat{\xi} = -\frac{1}{4\sqrt{2}} \, \zeta(3) \cdot \chi \cdot (S+\bar{S})^{3/2} =: \xi \cdot (S+\bar{S})^{3/2} \, . \quad (6)$$

Here $\mathcal{V} = (T+\bar{T})^{3/2}$ denotes the Calabi-Yau volume and from now on we set $2\pi\alpha' = 1$.

Next, there exist string loop corrections to the Kähler potential. Ref. [34] studied field theory loop corrections arising in the 4d $\mathcal{N} = 1$ supergravity after compactification of type IIB string theory, which by dimensional analysis start with a correction to the Kähler potential $\sim (T+\bar{T})^{-2}$. The string loop corrections have been calculated explicitly by [37] for compactification of type IIB string theory on the $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ orientifold with Hodge numbers $(h_{11}, h_{21}) = (3, 51)$, and for the $\mathcal{N} = 2$ sector contribution in the $T^6/\mathbb{Z}_6'$ orientifold. In the case of non-hierarchical Kähler moduli it is again the piece $\sim (T+\bar{T})^{-2}$ in $\Delta K^{(g_s)}$ which is the relevant loop correction (for hierarchical Kähler moduli as e.g. in [47, 48] this can be different, see [45]).

Assuming that the dilaton and complex structure are stabilised, $D_S W = 0$ and $D_U W = 0$, then the large volume expansion of the scalar potential induced by all the above corrections starts with [34, 35]

$$V = e^{K^{(0)}} \cdot |W|^2 \cdot \left(\frac{c_1}{(T+\bar{T})^{3/2}} + \frac{c_2}{(T+\bar{T})^2} + \ldots \right) \, , \, c_1 = 3/4 \cdot \hat{\xi} \, , \, c_2 = \beta \cdot (U+\bar{U})^2 \quad (7)$$

where the first piece is the α' correction, and the second is the string loop correction with β a constant.

Now we can see that when $c_2 > 0$ and $c_1 < 0$ (which corresponds to $\chi > 0$) and $|c_2/c_1| \gg 1$ there is inevitably a non-supersymmetric AdS_4-minimum for the scalar potential of $\mathrm{Re}\, T$ containing both corrections at large volume [34] (see also [35]).

Unfortunately, in the only fully calculated example, $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$, we have $\chi = 2 \cdot (h_{11} - h_{21}) < 0$, for which there is no minimum. We may however look to the orientifold $T^6/\mathbb{Z}_6'$ [35, 37] as a promising candidate for the implementation of our scenario. There, $\chi > 0$ and the known $\mathcal{N} = 2$ part of the loop corrections takes the same form as the $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ corrections (the inequivalent $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$-orientifold also has $\chi > 0$ but there the requirement of exotic O-planes [46] may complicate the loop corrections, which are presently unknown).

Finally, we comment (following a similar discussion in [47, 48]) on the stability of the minimum found above with respect to the minima for the complex structure moduli and the dilaton. Prior to the introduction of the perturbative corrections to the Kähler potential, the complex structure moduli and the dilaton were fixed by background fluxes through the conditions $D_U W = 0$ and $D_S W = 0$. Consider now the case that the Kähler corrections, which are negative near to the minimum of T, try to drive away S and/or U from their minima $D_S W = D_U W = 0$. Then the tree level flux potential yields a contribution $V_{\mathrm{flux}} \sim \mathcal{O}(+\frac{1}{\mathcal{V}^2})$, while the Kähler corrections contribute at $\mathcal{O}(-\frac{1}{\mathcal{V}^3})$, which is subleading at large volumes. Thus, the corrections cannot destabilize the original minima of S and U and these remain minima of the full theory including the Kähler corrections which stabilize T. This is an improvement on KKLT where stability may fail, see e.g. [49]. Moreover, similar arguments can of course be used after including the uplifting, to which we now turn.

4 de Sitter vacua from a consistent D-term

It is now easy to see that the perturbative AdS_4-minimum for T discussed in the last Section can be uplifted to a dS_4-minimum with a consistent D-term. The AdS_4-minimum is non-supersymmetric. Moreover, the full theory including the perturbative corrections to the Kähler potential is a function of $T + \bar{T}$ alone. Thus it is fully invariant under the shift $T \to T + i\alpha$ and in particular we have invariance of $G = K + \ln|W|^2$ under this shift symmetry. Therefore, the mechanism of Kähler stabilization of the volume modulus T fulfills the consistency constraints of Sect. 2. This allows us to gauge the shift symmetry, using world-volume fluxes on a $D7$-brane, as described in that section.

The full scalar potential will now contain a D-term piece in addition to the F-term contributions from the Kähler corrections. For the $T^6/\mathbb{Z}'_6$ example the potential, expanded up to $\mathcal{O}(\alpha'^3/(T + \bar{T})^{3/2})$ and to leading order in the string loop corrections, reads

$$V = V_F + V_D = \frac{|W|^2}{(T + \bar{T})^3} \cdot \left(\frac{c_1}{(T + \bar{T})^{3/2}} + \frac{c_2}{(T + \bar{T})^2} \right) + \frac{9\,q^2}{(T + \bar{T})^3} \tag{8}$$

where the constants c_1 and c_2 are evaluated in the minima of U and S determined by $D_U W = D_S W = 0$. Note that V_D has been expanded only to leading order since later tuning will require V_D to cancel V_F to leading order. Taking into account the higher orders in D_T would require to write the higher orders in V_F as well for consistency.[2]
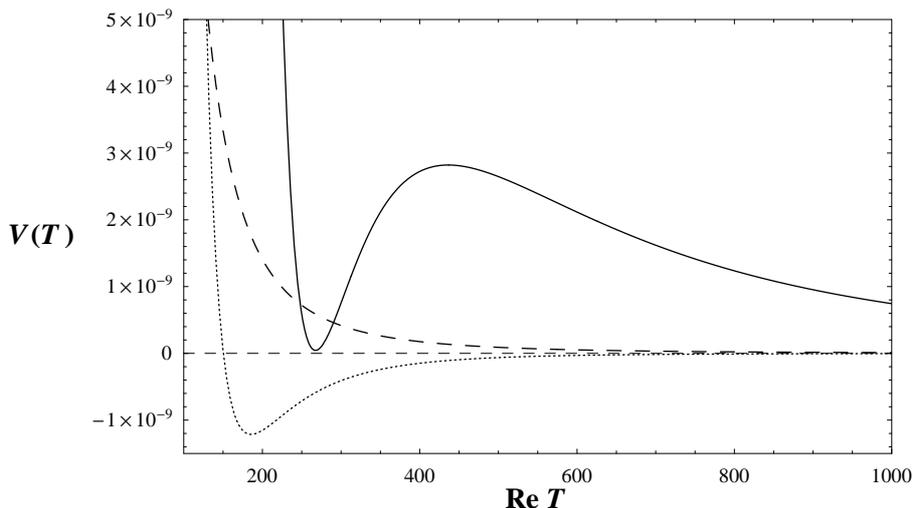

Figure 1: Dotted: The F-term scalar potential $V_F(T)$ leading to perturbative Kähler stabilization of T. Dashed: The uplifting D-term scalar potential $V_D(T)$. Both graphs have been rescaled by 10^{-2} for display reasons. Solid: The scalar potential eq. (8) after uplifting by switching on a gauge field background on a single $D7$-brane. The numbers are chosen in this example as $W_0 = 25.5$, $q = 1$, $\mathrm{Re}\,U = 242$, $\mathrm{Re}\,S = 10$ and $\chi = 48$. Also $\beta = 1/(2\pi^2)$ is taken from the $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ as a guiding example.

Given that $\mathrm{Re}\,T$ is stabilized at large volume $\mathcal{V} = (T + \bar{T})^{3/2}$, and assuming that q^2 is $\mathcal{O}(1)$, we can arrange for a situation where

$$\left| V_F|_{\mathrm{min}} \right| \sim \frac{|W|^2}{\mathcal{V}^3} \sim V_D|_{\mathrm{min}} \sim \frac{q^2}{\mathcal{V}^2} \tag{9}$$

holds by tuning W to larger values such that we get $V_F + V_D \approx 0$ in the minimum.

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[2]For further details see [50].

This situation is displayed in Fig. 1 using the potential given in eq. (8) for the semi-explicit $T^6/\mathbb{Z}_6'$-example. This serves as an indication of how we expect the behavior to be in a fully explicit model. In any case, given the vast landscape of type IIB flux compactifications, we expect that there should be many models in type IIB string theory where our uplifting scenario yields qualitatively the same results as discussed here. We finally mention here that in our scenario the gravitino mass is typically large, i.e. $m_{3/2} = e^{K/2}|W| \sim 10^{-2} \ldots 10^{-3} M_P$ since $W \gtrsim \mathcal{O}(1)$ and $\mathcal{V} \lesssim \mathcal{O}(10^3)$ here (see e.g. [51] for similar results in KKLT based models).

5 Conclusion

In this note we discussed a mechanism for generating de Sitter vacua in string theory by spontaneously breaking supersymmetry with consistent D-terms. This proposal has proven difficult to consistently embed in a stringy scenario.[3] We find that type IIB flux compactifications, with volume stabilization via perturbative corrections to the Kähler potential, provide such a scenario. As discussed in the literature, α'- and string loop corrections allow for stabilization of the T modulus by purely perturbative means without turning to non-perturbative effects such as gaugino condensation. The Kähler corrections preserve the invariance of the theory under a shift symmetry of the T modulus. In the presence of a magnetised $D7$-brane this unbroken shift invariance is gauged which leads to supersymmetric D-terms from string theory which fulfill all the known consistency requirements of 4d $\mathcal{N} = 1$ supergravity. These D-terms then provide a parametrically small and tunable uplift of the perturbatively stabilized AdS_4-minimum towards a metastable dS-minimum. In view of the desire to search the 'landscape' of string theory vacua for those regions where spontaneously broken supersymmetry allows for certain control of the low-energy effective theory, the discussed mechanism of a consistent D-term uplift in string theory promises access to a new class of metastable dS-vacua. The SUSY breaking provided in this scenario is typically a high-scale one with $m_{3/2} \sim 10^{-2} \ldots 10^{-3} M_P$. In a fully explicit model, it would be necessary to calculate the string loop corrections in the presence of gauged symmetries and magnetised D-branes, for example along the lines of [53]. It would also be interesting to study the consequences of this uplifting mechanism for possible realizations of inflation in string theory, as well as the low-energy phenomenology of this type of spontaneous SUSY breaking.

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[3]Note added: for 'hot off the plate' progress on explicit constructions in other scenarios see [52].

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