Fluxes, moduli fixing and MSSM-like vacua in Type IIA String Theory

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We review some of the features of Type IIA compactifications in the presence of fluxes. In particular, the case of $T^6/\Omega(-1)^F\sigma$ orientifolds with RR, NS and metric fluxes is considered. This has revealed to possess remarkable properties such as vacua with all the closed string moduli stabilized, null or negative contributions to the RR tadpoles or supersymmetry on the branes enforced by the closed string background. In this way, Type IIA compactifications with non trivial fluxes seem to constitute a new window into the building of semi-realistic models in String Theory.

1 Introduction

One of the most pressing problems in string theory is the issue of moduli fixing. There is great arbitrariness in the compactification of the theory to four dimensions, usually parametrized in terms of a broad moduli space. For trivial supergravity backgrounds, the scalar potential in the moduli space remains flat and the low energy spectrum has plenty of massless scalars. However, if Superstring Theory pretends to be a unified theory of all particles and interactions, it should provide us with a mechanism which lifts these scalars from the low energy spectrum.

Recently there has been remarkable progress by considering the possibility of having diluted backgrounds of the RR and NSNS forms [1]. From the effective supergravity perspective, these induce non-trivial superpotentials which stabilize some (or even all) of the original moduli so they become massive. Most of the work up to now has been done in the context of Type IIB String Theory with three form fluxes. In that case, the minima of the superpotentials are associated to warped solutions of Type IIB supergravity [2] and the backreaction of the fluxes represents a conformal deformation of the Calabi Yau metric. Thus, one can fairly consider the moduli space in the presence of diluted fluxes as a smooth deformation of the original one.

Unfortunately, all of these models correspond to no-scale solutions on which the Kähler moduli have to be stabilized through some alternative mechanism, such as non-perturbative effects which are always difficult to deal with. Moreover, at the minimum of the scalar potential, the fluxes contribute to the RR tadpoles with the same sign as D3-branes do and one usually is enforced to take manifolds with large Euler numbers in order to fulfill the tadpole conditions and at the same time stabilize the moduli at large values where the $\alpha'$ and $g_s$ corrections are under control.

In the last couple of years analogous setups have been considered in the context of Type IIA String Theory [3]-[9]. In that case, one can switch on fluxes in both the even and the odd dimensional cycles of the internal manifold so the induced superpotential in principle depends on both the complex structure and the Kähler moduli.

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Although the ten dimensional supergravity description of this kind of vacua is not always well understood, in the limit of diluted fluxes the scale of the masses induced by the fluxes is much smaller than the Kaluza-Klein scale and thus to consider the moduli space of the fluxed manifold as a smooth deformation of the original space still seems to be a fairly good approximation.

The particular case of $T^6/(\Omega(-1)^{F_L} \sigma)$ orientifolds has been recently analyzed in [3]. In that case, the orientifold projection allows in addition for some set of metric fluxes corresponding to the gauging of some of the original isometries of the torus [9]-[13]. This renders the manifold into a twisted torus with reduced homology. This kind of geometric deformations very often survive to the action of an orbifold group, even though this kills all the original isometries, so one expects to have similar deformations in more generic half-flat manifolds.

Type IIA compactifications with fluxes and torsion have revealed to possess several interesting properties for model building. First of all, the fluxes can contribute to the tadpoles with any sign or even not contribute. This gives additional freedom for cancelling the RR tadpoles in semirealistic models. In addition, one can find AdS vacua with all the closed string moduli stabilized and on which the supersymmetry on the branes is enforced by the background fluxes.

Here we will briefly overview some of the features found in [3] for Type IIA $T^6/(\Omega(-1)^{F_L} \sigma)$ orientifolds in presence of fluxes. Thus, in section 2 we will review the moduli space of Type IIA toroidal orientifolds and the possibility of having metric fluxes. In section 3 the vacuum structure of the scalar potentials induced by the fluxes will be discussed. Section 4 will be devoted to the consistency conditions of stacks of intersecting D6-branes in these vacua. Finally, a concrete example of $N=1$ MSSM-like vacua with all the moduli stabilized in AdS will be presented in section 5 and some last comments will be made in section 6.

2 Type IIA orientifolds and twisted tori

We will concentrate in the case of Type IIA compactified to four dimensions in a simple $T^6/(\Omega(-1)^{F_L} \sigma)$ orientifold, where $\Omega_P$ is the world-sheet parity operator, $(-1)^{F_L}$ is the space-time fermionic number for the left-movers and $\sigma$ is an order two involution of the 6-torus acting in the Kähler 2-form and in the holomorphic 3-form respectively as

$$\sigma(J) = -J \quad ; \quad \sigma(\Omega) = \Omega^*$$

Moreover, we will assume the 6-torus to be factorized. Then, a suitable cohomology basis will be given by a set of 3-forms $\{\alpha_i, \beta_i\}$ with $i = 0 \ldots 3$, a set of $\sigma$-odd (1,1)-forms $\{\omega_a\}$ and its Poincaré dual set of $\sigma$-even (2,2)-forms $\{\tilde{\omega}_a\}$, with $a = 1 \ldots 3$. The 3-forms $\alpha_i$ ($\beta_i$) are taken in such a way that are even (odd) under the orientifold involution and $\int_{T^6} \alpha_i \wedge \beta_j = \delta_{ij}$. The fixed point of $\sigma$ corresponds to $M_4 \times [\alpha_0]$ and it is the locus of 16 O6-planes.

It has been shown [5] that the moduli space for this kind of orientifold compactifications is better described in terms of the complexified forms

$$J_c = B + iJ \quad ; \quad \Omega_c = C_3 + i \text{Re}(C \Omega)$$

with $B$ the NSNS 2-form, $C_3$ the RR 3-form and $C$ a compensator field specified by

$$C = \sqrt{\text{Vol}(T^6)} e^{-\phi} e^{K_{cs}/2} \quad ; \quad K_{cs} = -\log \left[ \frac{i}{8} \int_{T^6} \Omega \wedge \Omega^* \right]$$

The moduli parameters then can be obtained by expanding the above forms in the corresponding cohomology basis

$$U_l = i \int_{T^6} \Omega_c \wedge \beta_l \quad ; \quad T_a = -i \int_{T^6} J_c \wedge \tilde{\omega}_a$$
Here $T_a$ parametrize the possible Kähler deformations of the torus whereas $U_l$ with $l \neq 0$ correspond to complex structure deformations. $S \equiv -U_0$ is the usual moduli for the dilaton.

One can define then a metric in the moduli space through the Kähler potential

$$K = -\log \left[ \frac{4}{3} \int J \wedge J \wedge J \right] - \log \sqrt{\text{Vol}(T^6)} e^{-\phi}$$

which in terms of the above moduli parameters takes the standard logarithmic form for toroidal compactifications

$$K = -\log(S + S^*) - \sum_{i=1}^{3} \log(T_i + T_i^*) - \sum_{i=1}^{3} \log(U_i + U_i^*)$$

(5)

As advanced in the introduction, for Type IIA compactifications the orientifold projection may allow in addition for some geometric deformations of the original manifold which render it into a half-flat manifold. In particular, one can introduce a set of metric fluxes $\omega_{pq}^k$ in the torus

$$ds^2 = \sum_k (dx^k + \omega_{pq}^k x^q dx^p)^2$$

(6)

so the tangent 1-forms $\eta^i$ are no longer closed forms

$$d\eta^k = -\frac{1}{2} \omega_{pq}^k \eta^p \wedge \eta^q$$

(7)

Due to this, some of the original cycles of the torus will disappear from the homology in the presence of metric fluxes.

We will consider here the most general set of metric fluxes compatible with the symmetry of a factorable $T^6$ and the orientifold projection. This is given by

$$\begin{pmatrix} \omega_{11}^1 \\ \omega_{22}^2 \\ \omega_{33}^3 \end{pmatrix} = \begin{pmatrix} \omega_{56}^1 \\ \omega_{64}^2 \\ \omega_{45}^3 \end{pmatrix} : \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} = \begin{pmatrix} -\omega_{23}^1 & \omega_{54}^1 & \omega_{26}^1 \\ \omega_{34}^2 & -\omega_{53}^2 & \omega_{61}^2 \\ \omega_{45}^3 & \omega_{65}^3 & -\omega_{32}^3 \end{pmatrix}$$

(8)

It has been shown (see e.g. [10]) that toroidal compactifications with metric fluxes are equivalent to compactification on a twisted torus, on which some of the isometries $Z_i$ of the original torus have been gauged. Then, for consistency of the twisted torus structure [15], the metric fluxes in general will be quantized and the $a_i$ and $b_{ij}$ parameters will only take integer values. This could be in part expected, since some of the metric fluxes are related to Type IIB NSNS fluxes by T-duality [16, 17].

On the other hand, either from the Jacobi identity of the algebra engendered by the isometries or from the Bianchi identity of eq.(7), one finds that the metric fluxes must satisfy

$$\omega_{[mn}^p \omega_{r]}^k = 0$$

(9)

This constrains the set of metric fluxes which one can switch on$^1$. Concretely, one has

$$b_{ij} a_j + b_{ji} a_i = 0 \quad i \neq j$$

$$b_{ik} b_{kj} + b_{kk} b_{ij} = 0 \quad i \neq j \neq k$$

(10)

We would like now to consider the addition of non-trivial background fluxes for the Type IIA NSNS and RR forms. This will be done in the following section.

$^1$ It can further be shown that $\omega_{\mu \nu}^0 = 0$ [14]. However this is automatically satisfied by the set of metric fluxes allowed by the orientifold projection.
3 Vacuum structure

It has been shown by applying gauged supergravity techniques \[9\]-\[13\] or directly by dimensional reduction of the ten dimensional supergravity action \[4\]-\[7\] that, from the point of view of the four dimensional effective theory, a background for the NSNS and the RR Type IIA field strengths induces a non trivial superpotential of the form

$$W = \int_{T^6} [\Omega_4 \wedge (H_3 + dJ_3) + e^{J_6} \wedge \mathcal{F}_{RR}]$$

(11)

where \(\mathcal{F}_{RR}\) represents a formal sum over the RR fluxes.

We will consider therefore a general background of the NSNS 3-form and the even rank RR forms and we will expand it in the cohomology basis of the factorized torus

$$\mathcal{F}_3 = \sum_{i=0}^{3} h_i \beta_i \quad \mathcal{F}_6 = -m \quad \mathcal{F}_2 = \sum_{a=1}^{3} q_a \omega_a \quad \mathcal{F}_4 = \sum_{a=1}^{3} e_a \bar{\omega}_a$$

(12)

Since the fluxes are quantized over the corresponding \(p\)-cycles, the coefficients of this expansion will be integer values. Moreover, we will assume the field strengths to have dimensions of \((\text{length})^{-1}\) so the moduli fields will be dimensionless.

Plugging this into eq.\((11)\), one can easily check that the superpotential is a cubic polynomial of the moduli

$$W = e_0 + i h_0 S + \sum_{i=1}^{3} [(i e_i - a_i S - b_{i1} U_1 - \sum_{j \neq i} b_{ij} U_j) T_i - i h_i U_i]$$

$$- q_1 T_2 T_3 - q_2 T_1 T_3 - q_3 T_1 T_2 + i m T_1 T_2 T_3$$

(13)

In addition, the fluxes in general will contribute to the RR tadpoles \[6\][13]. The relevant piece of the ten dimensional action is given by

$$\int_{M_4 \times \mathbb{R}^6} [C_7 \wedge (m H_3 + dF_2)] + \sum_a N_a \int_{M_4 \times \Pi_a} C_7$$

(14)

where we are considering the possibility of having stacks of \(N_a\) D6-branes wrapping factorized 3-cycles

$$\Pi_a = (n_{a1}^L, m_{a1}^L) \otimes (n_{a2}^L, m_{a2}^L) \otimes (n_{a3}^L, m_{a3}^L)$$

(15)

Plugging our background into \((14)\) then gives rise to the following tadpole cancellation conditions

$$\sum_a N_a n_{a1} m_{a2} n_{a3}^3 + \frac{1}{2} (h_0 m + a_1 q_1 + a_2 q_2 + a_3 q_3) = 16$$

$$\sum_a N_a n_{a1}^2 m_{a2}^2 n_{a3}^3 + \frac{1}{2} (m h_1 - q_1 b_{11} - q_2 b_{21} - q_3 b_{31}) = 0$$

$$\sum_a N_a m_{a1}^2 n_{a2}^2 m_{a3}^3 + \frac{1}{2} (m h_2 - q_1 b_{12} - q_2 b_{22} - q_3 b_{32}) = 0$$

$$\sum_a N_a m_{a1} n_{a2} m_{a3}^2 n_{a3}^3 + \frac{1}{2} (m h_3 - q_1 b_{13} - q_2 b_{23} - q_3 b_{33}) = 0$$

(16)

Note that since the metric fluxes modify the homology of the original torus, in principle not every 3-cycle \(\Pi_a\) will be a consistent cycle on which to wrap the D6-branes. Considerations about consistency for D6-branes in presence of metric fluxes will be made in section 4.

The vacuum structure of the scalar potential induced by \[6\] and \[13\] has been analyzed in detail in \[3\]. There, one can see how the fluxes induce a broad landscape of vacua consisting of both Minkowski and AdS vacua with broken or unbroken supersymmetry. Here we will briefly summarize some of the main results.
3.1 Supersymmetric Minkowski models

For the particular case of supersymmetric Minkowski vacua it was found in [3] that it is required the presence of metric fluxes and $m = 0$. In addition, generically one finds a large number of flat directions, being able to fix at most three linear combinations of complex moduli. The fluxes contribute to the RR tadpoles with the same sign as D6-branes do, or do not contribute. This last possibility represents a novelty with respect to the Gukov-Vafa-Witten scenarios, where the fluxes always contributed positively to the RR tadpoles.

3.2 No-scale models

As ‘no-scale’ we distinguish models in which the superpotential is independent of three of the moduli, so the explicit form of the Kähler potential [5] guarantees a cancellation of the cosmological constant at tree-level, even though supersymmetry is broken [18]. These minima has very similar properties to the ones found for the Minkowski models. In particular, again there is a large number of moduli which remain unstabilized and the fluxes always contribute to the RR tadpoles as D6-branes.

3.3 AdS models

This kind of vacua possesses a different qualitative behavior than the Minkowski ones. In particular, generically all the moduli are stabilized but some linear combinations of complex structure axions. As it will be shown along next section, this is actually required for consistency with the presence of D6-branes. Moreover, in the cases with non vanishing metric fluxes, one has examples on which the fluxes do not contribute to the RR tadpoles or contribute with the same sign as the orientifold planes do. This provides us with new possibilities for model building. In particular, in section 5 we will see a concrete example on which the tadpole contributions of the setup of branes are cancelled by the effect of the fluxes, without the aid of an extra orbifold twist.

4 D6-branes in presence of fluxes

Since the inclusion of metric fluxes modifies the homology, there will be 3-cycles of the original torus which are no longer closed in the presence of metric fluxes. In this section we will see how there can appear inconsistencies in the low energy effective action when wrapping D6-branes on these submanifolds.

In fact, the gauge fields living in the worldvolume of a stack of D6-branes couple to the closed string axions through the following piece of the action

$$\int_{M_4 \times \Pi_a} (C_3 \wedge F_a \wedge F_a + C_5 \wedge F_a) = \sum_{I=0}^3 \int_{M_4} [p_I^a (\text{Im} U_I) F_a \wedge F_a + N_a c_I^a C_I^{(2)} \wedge F_a]$$

(17)

where $C_I^{(2)}$ is the Poincaré dual in 4d to $\text{Im} U_I$ and the coefficients $\{p_I^a, c_I^a\}$ are given in terms of the wrapping numbers as

$$c_0^a = m_a n_a m_a n_a m_a n_a n_a n_a n_a$$
$$c_1^a = m_a n_a m_a n_a m_a n_a n_a n_a n_a$$
$$c_2^a = n_a m_a n_a m_a n_a n_a n_a n_a n_a$$
$$c_3^a = n_a m_a n_a m_a n_a n_a n_a n_a n_a$$
$$p_0^a = n_a m_a n_a m_a n_a n_a n_a n_a n_a$$
$$p_1^a = n_a m_a n_a m_a n_a n_a n_a n_a n_a$$
$$p_2^a = m_a n_a m_a n_a n_a n_a n_a n_a n_a$$
$$p_3^a = m_a n_a m_a n_a n_a n_a n_a n_a n_a$$

These couplings have revealed to play an important role in the cancellation of mixed $U(1)$ gauge anomalies through diagrams on which the gauge bosons exchange complex structure (and dilaton) axions [9]. In this sense, the scalars $\phi^a = \sum_I c_I^a \text{Im} U_I$ behave as Goldstone bosons, giving Stückelberg masses to the corresponding $U(1)$’s and transforming with a shift under the gauge transformations. We have seen however that the NSNS and metric fluxes induce terms in the superpotential which are linear in $\text{Im} U_I$ and therefore generically do not respect these transformation properties. Thus, in order to restore consistency
and gauge invariance one has to impose the following condition on the 3-cycle $\Pi_a$ which the brane is wrapping
\[ \int_{\Pi_a} (\mathcal{H}_3 + dJ_c) = 0 \]  
(18)

In this way, the linear combinations of axions which become massive due to the Green-Schwarz mechanism will be orthogonal to the ones which become massive due to the effect of the fluxes. This constraint actually constitutes the generalization of the Freed-Witten anomaly cancellation condition to the case of a twisted torus and in fact, when $\omega = 0$, one recovers the usual constraint for an ordinary torus.

Given a background for the NSNS 3-form and metric fluxes, the condition (18) will determine what are the 3-cycles on which it is consistent to wrap the stacks of D6-branes. In the particular case of AdS vacua, this imposes $\Pi_a$ to be a special lagrangian cycle, so for this kind of models the closed string background restricts the brane content to supersymmetric configurations of D6-branes (i.e. with all Fayet-Iliopoulos terms vanishing) [3].

5 An example of MSSM-like vacua

As an illustration of all the above ideas, we will reproduce here a particular example of $N = 1$ MSSM-like vacua with all the closed string moduli stabilized in AdS, which was already presented in [3].

We will consider a general isotropic background of NSNS, RR and metric fluxes given by $b_{ji} = -b_{ii} = b_i$, $a_i = a$, $q_i = -c_2$ and $e_i = c_1$ so there is just one overall Kähler moduli $T_1 = T_2 = T_3 = T$ and the superpotential reduces to
\[ W = e_0 + 3ic_1T + 3c_2T^2 + i\hbar S - 3aST - \sum_{k=0}^3 (ih_k + b_kT)U_k \]  
(19)

This choice of metric fluxes automatically satisfies (10).

We are interested in the supersymmetric AdS minima of the induced scalar potential. These can be obtained by imposing the vanishing of all the F-terms, i.e. $D_TW = D_UW = 0$, but $W \neq 0$. With this one gets that all the real parts of the moduli are fixed in terms of the fluxes
\[ a\text{Re } S = 2\text{Re } T(c_2 - m\text{Im } T) ; \quad 3a\text{Re } S = b_k\text{Re } U_k ; \quad 3a^2(\text{Re } T)^2 = 5h_0^2\lambda(\lambda + \lambda_0 - 1) \]  
(20)

where $\lambda$ is determined by the following cubic equation
\[ 160\lambda^3 + 186(\lambda_0 - 1)\lambda^2 + 27(\lambda_0 - 1)^2\lambda + \lambda_0^2(\lambda_0 - 3) + \frac{27a^2}{m\hbar_0^2}(e_0a - c_1b_0) = 0 \]  
(21)

and $\lambda_0 = 3c_2a/(m\hbar_0)$.

Concerning the imaginary parts, the reader can check that the Kähler axions are completely fixed by the fluxes whereas only a linear combination of complex structure and dilaton axions is stabilized
\[ \text{Im } T = (\lambda + \lambda_0)\frac{\hbar_0}{3a} ; \quad 3a\text{Im } S + \sum_{k=1}^3 b_k\text{Im } U_k = 3c_1 + \frac{3c_2}{a}(3\hbar_0 - 7a\text{Im } T) - \frac{3m}{a}\text{Im } T(3\hbar_0 - 8a\text{Im } T) \]  
(22)

Additionally, the following constraint is required in order to stabilize the real parts of the moduli at positive values
\[ 3b_ka + h_0b_k = 0 \quad k = 1, 2, 3 \]  
(23)
Let us concentrate now in the particular case of $c_2 = 2 - h_i$, $a_i = 16$, $m = b_i = 4$ and $h_0 = -12 h_i$, which automatically satisfies eq. (23). The reader can check that choosing the fluxes in such a way the tadpole conditions read

\[ \sum_a N_a n_a^1 n_a^2 n_a^3 = 64 \quad ; \quad \sum_a N_a n_a^i m_a^j m_a^k = -4 \quad i \neq j \neq k \quad (24) \]

Moreover, for large values of $h_0$ one has that the four dimensional dilaton scales as $e^{\phi} \simeq h_0^{-2}$, the ten dimensional one as $e^\phi \simeq h_0^{-1/2}$ and the flux density as $h_0^{-1/2}$. Thus, taking $h_0 \gg 1$ one may stabilize the moduli at regions where the $\alpha'$ and $g_s$ corrections are under control and the effective supergravity approach remains valid.\footnote{Quantum corrections may play however an important role in the lifting of these vacua to dS, as discussed in [21, 22].}

One can add now the following supersymmetric setup of D6-branes [3, 20] in order to satisfy (24)

| $N_i$ | $(n_i^1, m_i^1)$ | $(n_i^2, m_i^2)$ | $(n_i^3, m_i^3)$ |
|-------|-----------------|-----------------|-----------------|
| $N_a = 4$ | (1, 0) | (3, 1) | (3, -1) |
| $N_b = 1$ | (0, 1) | (1, 0) | (0, -1) |
| $N_c = 1$ | (0, 1) | (0, -1) | (1, 0) |
| $N_{h_1} = 3$ | (2, 1) | (1, 0) | (2, -1) |
| $N_{h_2} = 3$ | (2, 1) | (2, -1) | (1, 0) |
| $N_o = 4$ | (1, 0) | (1, 0) | (1, 0) |

Table 1 A MSSM-like model with tadpoles cancelled by fluxes. Branes $h_1$, $h_2$ and $o$ are added in order to cancel the RR tadpoles.

After separating some of the branes and after two of the $U(1)$’s get St"uckelberg masses, the gauge group becomes $SU(3) \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \times [U(1) \times SU(3)]^2$ with three generations of quarks and leptons, two doublets of Higgses and extra matter fields involving the auxiliary branes $h_1$, $h_2$ and $o$. More details about the spectrum can be found in [3]. In this way, we have constructed an example of consistent $N = 1$ AdS vacuum with all the closed string moduli fixed and semi-realistic chiral spectrum.

6 Discussion

We have reviewed along the lines of [3] some of the main properties for the vacua of simple $T^6/\Omega(-1)^{F_L} \sigma$ Type IIA orientifolds with non trivial RR, NSNS and metric fluxes. Unlike the Type IIB case, the richness of the flux options leads to a full stabilization of all closed string moduli in AdS without the need of non-perturbative effects. Moreover, one can find vacua on which the flux contribute to the RR tadpoles with the same sign as the O6-planes do or even do not contribute, so there is more freedom to find consistent models with all the moduli stabilized at the perturbative regions of the scalar potential.

An interesting property of these models is that geometric fluxes survive the orientifold projection. These modify the homology of the original torus and constrains the open string sector. From the point of view of the low energy effective theory, this is reflected in the appearance of possible gauge inconsistencies in the worldvolume of the D6-branes. In the particular case of AdS models, this enforces the setup of D6-branes to be supersymmetric. As an illustration of these ideas, we have presented an example of $N = 1$ MSSM-like vacua with all the closed string moduli stabilized in AdS.

However, still a lot of work has to be done in order to fully understand Type IIA compactifications with non trivial background fluxes. This involves the description of the ten dimensional supergravity solutions outside the approach of effective supergravity, the understanding of the geometric deformations beyond the toroidal geometry or the lift of these vacua to dS. We hope to come back to all these issues in the near future.
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