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String theory and fundamental forces/Théorie des cordes et forces fondamentales

D-brane models and flux supersymmetry breaking

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Abstract

We describe recent work on constructing four-dimensional string models with moduli stabilized by field strength fluxes and chiral gauge sectors close to the Standard Model from D-brane configurations. We discuss how the interplay of both ingredients relates to phenomenological issues, in particular the appearance of soft terms on the D-brane gauge sector induce from non-supersymmetric flux backgrounds. ***To cite this article: A.M. Uranga, C. R. Physique 5 (2004).***

Résumé

Modèles de D-branes et brisure de supersymétrie par flux. Nous décrivons des travaux récents de constructions de modèles de cordes à 4 dimensions ayant des modules stabilisés par des flux, ainsi que des secteurs chiraux de jauge proches du modèle standard, réalisés à partir de configurations de D-branes. Nous expliquons comment les liens entre les différents ingrédients relient des aspects phénoménologiques, en particulier l'apparition de termes doux dans le secteur de jauge des D-branes à partir de champs de fonds non-supersymétriques avec flux. ***Pour citer cet article : A.M. Uranga, C. R. Physique 5 (2004).***

Keywords: D-brane; Four-dimensional string models; Flux background

Mots-clés : D-brane ; Modèles de cordes à 4 dimensions ; Champs de fonds avec flux

1. Introduction

The general question of understanding the dynamics of D-branes in string theory backgrounds with NSNS/RR field strength fluxes is an exciting new avenue to obtain novel results in diverse applications in string theory. One example is provided by the gauge/string correspondence, where fluxes are responsible for the holographic description of confinement and other non-trivial strong dynamics in gauge theories (e.g. [1,2]). Another context, described in this talk, is in four-dimensional compactifications of string theory with fluxes and D-branes. In particular, we emphasize application to phenomenological model building, although some results are of more general interest.

Our purpose is to put together two recent advances in string compactification:

- The construction of D-brane configurations with non-abelian gauge symmetries and charged chiral fermions on their world-volume (leading to spectra potentially close to the (MS)SM).

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• Compactification with field strength fluxes, which lead to new interesting features, like moduli stabilization, warped geometries and supersymmetry breaking.

The general question we would like to address is the computation of the effects of (supersymmetric or non-supersymmetric) fluxes on the gauge theory on the D-brane world-volume.

2. The D-brane configurations

There has been intense recent work on model building with D-branes, leading a large set of explicit string compactifications with semirealistic spectrum, see later for one particular example. More important than these particular constructions is the general lesson of the pattern in which string theory may reproduce the structure of the Standard Model.

The gauge factors of the Standard Model are associated to different stacks of D-branes,[1] leading to a typical product structure of the form $\prod_a U(N_a)$. Insisting on supersymmetry of such D-brane stacks (to guarantee their stability in the simplest fashion), they may correspond to A- or B-type branes in Calabi–Yau compactifications [3]. The former correspond to stacks of D6-branes wrapped on special lagrangian 3-cycles (leading to the picture usually known as intersecting brane worlds), while the latter correspond to D-branes wrapped on holomorphic cycles and carrying holomorphic gauge bundles (or for more mathematically purist readers, coherent sheaves).

Given these ingredients, the theory generically reproduces a chiral spectrum, given by a set of chiral fermions in bi-fundamental representations of the different gauge factors, and which arise with a replicated multiplicity. For A-type D-branes the multiplicity of chiral fermions charged under two gauge factors is given by the intersection number of the corresponding 3-cycles. While for B-type branes it is given by the index of the Dirac operator coupled to the ('difference' of the) corresponding gauge bundles. It is remarkable that this structure is nicely suitable to describe the three families of chiral fermions of the Standard Model. Again, explicit models realizing this idea have been constructed.

Of course, these constructions based on D-brane are not more fundamental than other constructions in string theory, like M-theory on G_2 holonomy manifolds, or heterotic compactifications on Calabi–Yau threefolds. Rather, all such models are dual (in fact, the A- and B-type models mentioned above are related by mirror symmetry), and represent different descriptions of the same underlying structure in different regimes or corners in moduli space.

However, one particular advantage of D-brane models is the locality of the gauge sector. Namely, the D-branes are sensitive only to the local background around them. Our purpose is to use models of D-branes to learn more about four-dimensional compactifications of string theory with potential phenomenological interest.

For concreteness we center on type IIB string theory compactified on orientifolds of Calabi–Yau threefolds (or more generally on compactification of F-theory on Calabi–Yau fourfolds). This implies the gauge sector should be localized on B-type branes. There are two very tractable classes of brane configurations of this kind, which have been employed in model building

• Magnetised D-branes, namely D-branes wrapped on products of two-tori in toroidal compactifications, carrying constant world-volume magnetic fields. Introduced in [4], these models have been recently studied in [5–7], in particular in connection with their T-dual (mirror) version as intersecting brane worlds. See also the contribution by D. Lust in these proceedings.

• D-branes at singularities, which can be regarded as D-branes wrapped on the holomorphic cycles collapsed at the singular point.[2] The basic examples are provided by D3-branes at orbifold singularities, studied using the techniques in [9].

For concreteness, we center on the latter, although analogous constructions and results have been obtained for the former. This set of models is rich enough to be interesting in model building, and in particular explicit semirealistic models have been constructed using configurations of D3- and D7-branes at local $\mathbf{C}^3/\mathbf{Z}_3$ orbifold singularities [10] (see also [11]). In addition, this choice is particularly simple, since the physics of D-branes at orbifold singularities is to a large extent inherited from the physics of D-branes in flat space, upon imposing the orbifold projection. Moreover, the intermediate results obtained in the flat space situation may be of interest in other applications, where chirality is not essential, for instance the discussion in Section 4.3.

To have a concrete model in mind, Fig. 1 describes the quiver for the gauge theory on a set of D3/D7-branes at a $\mathbf{Z}_3$ orbifold singularity, as described in [10].[3] Each node represents a gauge factor, while each arrow represents a chiral fermion in the bi-fundamental representation of the gauge factors associated to nodes at the arrow endpoints. Outer/inner nodes correspond to D7/D3 branes (or vice-versa, depending on the construction).

[1] More properly, the hypercharge is given by a linear combination of the $U(1)$ factors in the product structure.

[2] A proper geometric interpretation however requires extrapolating the fractional D-branes from the orbifold point in Kahler moduli space to the large volume regime, see [8] for an example.

[3] The precise model under discussion is in fact an improved modification, which was described in [12] in the mirror version.

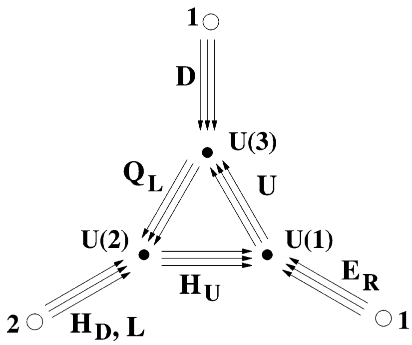


Fig. 1. Quiver diagram for a gauge sector close to the MSSM localized on the world-volume of D3/D7-brane systems.

3. Introducing flux backgrounds

Much recent activity in string compactification has centered on the introduction of field strength fluxes in the internal space. In the setup of type IIB compactifications on Calabi–Yau threefolds, relevant to our purposes, the introduction of NSNS/RR 3-form field strength fluxes, denoted H_3, F_3 in what follows, has been described in e.g. [13–16]. The main features of the resulting models are:

• The appearance of a scalar potential leading to stabilization of the dilaton τ and the complex structure moduli. This potential can be derived from the superpotential [17]

$$W = \int_{X_6} G_3 \wedge \Omega, \tag{1}$$

where Ω is the CY_3 holomorphic 3-form, and $G_3 = F_3 - \tau H_3$, with τ the IIB complex coupling. This potential is minimized for imaginary selfdual (ISD) flux density $*_6 G_3 = i G_3$, unless the configuration includes further contributions to the scalar potential.

• Regarding supersymmetry of the configuration [18], $N = 1$ supersymmetry is preserved if G_3 is a primitive $(2,1)$-form (for generic CY space the primitivity condition is automatically satisfied). For $(0,3)$ fluxes, supersymmetry is broken but the flux is still ISD hence compactification to 4d Minkowski space satisfies the equations of motion. Finally, configurations with imaginary anti-selfdual (IASD) fluxes leads to a runaway potential upon compactification to 4d Minkowski space.

• The fluxes backreact on the spacetime geometry, deforming it to a warped, conformally Calabi–Yau, compactification. The warp factor may be roughly homogeneous, for roughly homogeneous flux density distributions, or lead to strongly warped throats as in [2,16].

• The compactifications naturally include D3- and D7-branes (or other (p,q) seven-branes). As discussed above, these objects provide a natural setup for building interesting gauge sectors. In particular, explicit models of chiral gauge sectors localized on D-branes in flux compactifications have been carried out in toroidal orbifold models [19,20] (see also the recent [21]), with homogeneous flux distributions, and in [22] in strongly warped throats.

A particularly interesting class of models is obtained by considering a supersymmetric set of D-branes embedded in flux compactifications. Our purpose in this talk is to compute the effect of fluxes on such D-brane sectors. Concretely, the fluxes induce diverse new terms in the action for the D-brane world-volume theory, which correspond to supersymmetry breaking soft terms induced by non-supersymmetric flux components, and superpotential terms induced by supersymmetric flux components. For simplicity we refer to all of these as soft terms (since even superpotential terms can be regarded as softly breaking the extended supersymmetry on D-branes in (locally) flat space).

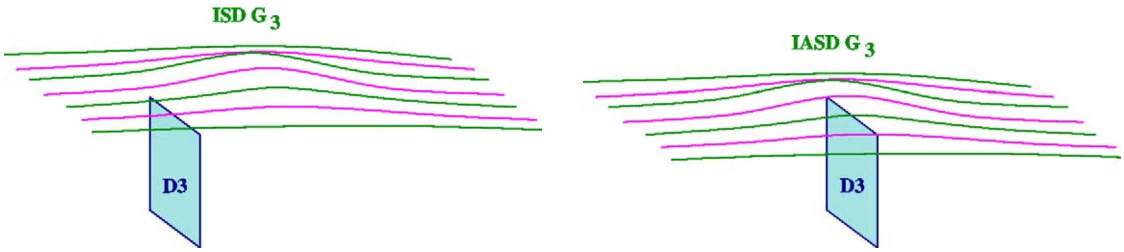
4. Supersymmetry breaking soft terms

The computation of these soft terms has been carried out in [23–25] for D3-branes, and in [26] (see also [27]) for D3/D7-brane systems. There are essentially two different approaches, that lead to equivalent results:

• Since D-branes are sensitive only to local background around them, we can consider D-brane world-volume action coupled to the local supergravity background, and expand perturbatively on the fluxes.

• We can describe effect of fluxes in the 4d effective Lagrangian, which contains gauge sectors corresponding to the D-branes. The computation of the effects of fluxes on D-branes.

Let us briefly sketch the computations in the two approaches in turn.



(a) (b)

Fig. 2. D3-branes in the presence of ISD or IASD fluxes.

4.1. The local analysis

Let us briefly discuss the first approach, in a qualitative fashion, directing the reader to the references for more details. We start with the simpler configuration of a stack of n D3-brane in flat space. The world-volume gauge theory is a 4d $N=4$ $U(n)$ gauge theory. In $N=1$ terms, it contains a vector multiplet $V=(A_\mu,\lambda)$, and three adjoint chiral multiplets $\Phi_i=(\Phi_i,\Psi_i)$. In the latter, the scalars are Goldstone bosons of the spontaneously broken translational symmetries in the transverse directions. Hence vevs for these scalars correspond to the transverse coordinates of the D3-brane.

This also implies that the DBI + CS action for world-volume fields describes the dynamics of the D3-brane. Conversely, determining the dynamics of the D3-brane in the flux background will determine the action for the world-volume fields, including the flux-induced soft terms.

One may work in a sort of expansion in the flux density. At lowest order we have the D3-brane in flat space without fluxes. The D3-brane world-volume action is $N=4$ super-Yang–Mills (SYM). Equivalently, $N=1$ SYM coupled to three adjoint chiral multiplets with a superpotential $W=\operatorname{tr}\Phi_1[\Phi_2\Phi_3]$.

Introducing the effect of fluxes induces soft terms for this theory. These effects depend strongly on the ISD/IASD properties of the flux density G_3, as follows, see Fig. 2.

• An ISD flux has positive tension and RR 4-form charge. A D3-brane in its background experiences effects from gravitational attraction and Coulomb-like repulsion. The cancellation implies that there are no soft terms generated in this situation.

• An IASD flux has positive tension and negative RR 4-form charge. Gravitational and Coulomb effects on D3-brane add up, and D3-branes are attracted to region of maximum IASD flux density. The non-trivial potential for the D3-brane position implies non-trivial soft terms.

Let us sketch the computation of the soft terms underlying the above qualitative picture. One starts with the D3-brane action, whose bosonic Dirac–Born–Infeld and Chern–Simons pieces are as follows [28]. The DBI part can be expressed:

$$S_{\mathrm{DBI}}=-\mu_3\int \mathrm{d}^4x\,\mathrm{Tr}\Big(\mathrm{e}^{-\phi}\sqrt{-\det\big(\mathrm{P}\big[\mathrm{E}_{\mu\nu}+\mathrm{E}_{\mu m}(\mathrm{Q}^{-1}-\delta)^{mn}\mathrm{E}_{n\nu}\big]+\sigma\mathrm{F}_{\mu\nu}\big)\det(\mathrm{Q})}\Big), \tag{2}$$

where $P[M]$ denotes the pullback of the 10d background M onto the D3-brane worldvolume, and

$$\begin{aligned}&E_{MN}=G_{MN}-B_{MN},\\&Q^m_n=\delta^m_n+\mathrm{i}\sigma[\phi^m,\phi^p]E_{pn},\\&\sigma=2\pi\alpha'.\end{aligned} \tag{3}$$

The CS part is given by

$$S_{\mathrm{CS}}=\mu_3\int \mathrm{Tr}\bigg(\mathrm{P}\bigg[\mathrm{e}^{\mathrm{i}\sigma\mathbf{i}_\phi\mathbf{i}_\phi}\bigg(\sum_{\mathrm{n}}\mathrm{C}^{(\mathrm{n})}+\frac{1}{2}\mathrm{B}_2\wedge\mathrm{C}_2\bigg)\mathrm{e}^{-\mathrm{B}}\bigg]\mathrm{e}^{\sigma\,\mathrm{F}}\bigg), \tag{4}$$

where $i_\phi C_{(p)}$ denotes contraction of a leg of the p-form, transverse to the D3-brane, with the associated world-volume scalar [28].

It is important to recall the interpretation of world-volume scalars as coordinates in transverse space, via

$$x^m=2\pi\alpha'\phi^m. \tag{5}$$

The dependence of the above action on the D3-brane is thus transformed into a dependence on the world-volume scalars. By expanding the supergravity background in powers of x^m around the D3-brane location, one obtains a set of higher-dimension operators in the world-volume scalars, deforming the original $N=4$ super-Yang–Mills theory. A rather general ansatz for the supergravity background around the branes is

$$\begin{aligned}
&\mathrm{d}s^2 = Z_1(x^m)^{-1/2}\eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + Z_2(x^m)^{1/2}\,\mathrm{d}s^2_{CY},\\
&\tau=\tau(x^m),\\
&G_3=\frac{1}{3!}G_{lmn}(x^m)\,\mathrm{d}x^l\,\mathrm{d}x^m\,\mathrm{d}x^n,\\
&\chi_4=\chi(x^m)\,\mathrm{d}x^0\,\mathrm{d}x^1\,\mathrm{d}x^2\,\mathrm{d}x^3,\\
&F_5=\mathrm{d}\chi_4+*_{10}\,\mathrm{d}\chi_4.
\end{aligned}\tag{6}$$

Since we are in principle interested only in the most relevant terms, up to dimension three in the world-volume action, it is enough to truncate the expansion of the supergravity background as follows

$$\begin{aligned}
&Z_1^{-1/2}=1+\tfrac{1}{2}K_{mn}x^m x^n+\cdots,\\
&Z_2^{1/2}=1+\cdots,\\
&\tau=\tau_0+\tfrac{1}{2}\tau_{mn}x^m x^n,\\
&\chi_4=\bigl(\text{const.}+\tfrac{1}{2}\chi_{mn}x^m x^n+\cdots\bigr)\,\mathrm{d}x^0\,\mathrm{d}x^1\,\mathrm{d}x^2\,\mathrm{d}x^3,\\
&G_{lmn}(x^m)=G_{lmn}+\cdots.
\end{aligned}\tag{7}$$

Following [24], the quantitative results upon computation of the world-volume action in a general flux background are, for soft terms up to dimension three gives

$$\begin{aligned}
&\text{Scalar masses } m\text{:}\quad \mathrm{Tr}\,m^2=\frac{g_s}{6}\Bigl(\sum|G^-_{lmn}|^2-\mathrm{Re}(G^-_{lmn}\overline{G}^+_{lmn})\Bigr),\\
&\text{Scalar trilinears } A\text{:}\quad \frac{g_s}{3}G^-_{lmn}\phi^l\phi^m\phi^n,\\
&\text{Fermion masses } M\text{:}\quad (g_s^{1/2}/\sqrt{2})G^-_{lmn}\Psi\Gamma^{lmn}\Psi.
\end{aligned}\tag{8}$$

We see that they all vanish for pure ISD flux $G_3^-=0$. A particular example of IASD flux induced soft terms is provided by a $(3,0)$ G_3 flux

$$m^2=\frac{g_s}{6}|G_{123}|^2,\quad M^a=\frac{g_s^{1/2}}{\sqrt{2}}G_{123},\quad A^{ijk}=-\epsilon^{ijk}\,g_s\,G_{123}\tag{9}$$

which correspond to the dilaton-dominated soft terms in susy phenomenology.

An important observation is that the conclusions are reversed if the gauge sector is localized on anti-D3-branes: Soft terms arise for ISD flux, and vanish for IASD flux. This may be relevant in some scenarios with anti-D3-brane [29].

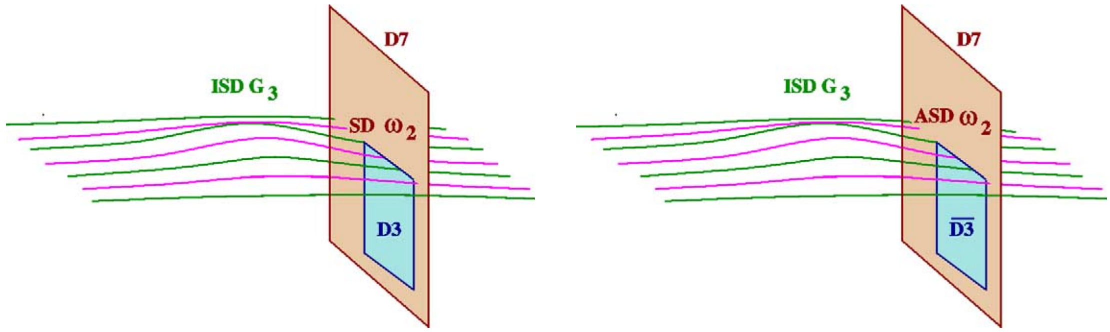
One can perform a similar local analysis for D7-branes [26], which is nevertheless more involved since D7-branes wrap 4-cycles Σ_4 in X_6, and the 4d physics depends strongly on the 4-cycle geometry. In particular, the local symmetry of the configuration is only $\mathrm{SO}(4)\times\mathrm{SO}(2)$, far smaller that the SO(6) of D3-brane systems. It is thus convenient to decompose the ISD and IASD pieces of G_3 under $\mathrm{SO}(4)\times\mathrm{SO}(2)$, as follows

$$\begin{aligned}
&\text{ISD}\quad \mathbf{10}=(3,1)_+ + (1,3)_- + (2,2)_0,\\
&\text{IASD}\quad \overline{\mathbf{10}}=(3,1)_- + (1,3)_+ + (2,2)_0.
\end{aligned}\tag{10}$$

Let us denote by G and G' the ISD pieces in the $(3,1)_+$ and $(1,3)_-$ representations, and by $\widetilde{G}$ and $\widetilde{G}'$ the IASD ones in the $(3,1)_-$ and $(1,3)_+$.

A further subtlety for D7-branes is that in the presence of field strength fluxes there are non-trivial consistency conditions for brane wrapping, namely the cohomology class of the pullback of H_3 on the 4-cycle should be trivial. In certain examples, most notably the toroidal models to be considered below, this could lead to inconsistency of the configuration. The problems are avoided if the components in the $(2,2)_0$ are absent, as we consider henceforth.

Finally, after determining the 8d world-volume action including the flux-induced terms, one needs to perform a Kaluza–Klein reduction to 4d. This requires a detailed knowledge of the wrapped 4-cycle, hence our discussion below assumes a particularly simple case, the four-torus. Partial results for other case are described in [26].



(a) (b)

Fig. 3. D7-branes in the presence of ISD flux which is SD or ASD when restricted to its world-volume.

For a D7-brane on $\mathbf{T}^4 \times \mathbf{C}$, the 4d effective action, in the absence of fluxes is an $N = 4$ $U(n)$ gauge theory, with the one complex scalar Φ_3 associated to the D7-brane position in transverse complex plane, and two, denoted Φ_1, Φ_2 associated to Wilson line degrees of freedom. Skipping the detailed computation, the results for the soft terms are

Transverse position scalar masses

$$-\frac{g_s}{18}\Big\{\big[(\widetilde{G}^*)^2+(G'^*)^2\big]\Phi^3\Phi^3+\text{h.c.}+\frac{1}{2}\big(|\widetilde{G}|^2+|G'|^2\big)\Phi^3\Phi^{\bar{3}}\Big\}. \tag{11}$$

Scalar trilinears

$$-\frac{g_s}{18}\Big\{\big(\Phi^{\bar{1}},\Phi^{\bar{2}}\big)(\widetilde{G}\cdot\sigma)\begin{pmatrix}\Phi^1\\ \Phi^2\end{pmatrix}+\big(\Phi^{\bar{1}},\Phi^2\big)(G'\cdot\sigma)\begin{pmatrix}\Phi^1\\ \Phi^{\bar{2}}\end{pmatrix}\Big\}\Phi^3+\text{h.c.} \tag{12}$$

Fermion masses

$$-\frac{g_s}{6\sqrt{2}}\Big\{(\bar{\lambda},\bar{\Psi}^3)(G'\cdot\sigma)\begin{pmatrix}\lambda\\ \Psi^3\end{pmatrix}+(\Psi^1,\Psi^2)(\widetilde{G}\cdot\sigma)\left(\begin{pmatrix}\Psi^1\\ \Psi^2\end{pmatrix}\right)+\text{h.c.}\Big\}. \tag{13}$$

The results, and in particular the fact that only G' and $\widetilde{G}$ appear in the soft terms, suggest a simple physical interpretation. Consider splitting $\mathbf{X}_6$ locally as $\Sigma_4 \times R^2$, and the 3-form G_3 in $\mathbf{X}_6$ as 2-form ω_2 on Σ_4 and a 1-form on R^2. Roughly speaking, we write $G_3 = \omega_2 \wedge \mathrm{d}z_3$, etc. Due to certain world-volume couplings on the D7-branes, a selfdual/anti-selfdual (SD/ASD) ω_2 induces a lower-dimensional D3/anti-D3-brane on the world-volume. The appearance or not of soft terms can be understood as the existence or not of interaction between the induced branes and the flux background.

Hence, centering on ISD 3-form fluxes, we may split them in pieces corresponding to SD/ASD ω_2 on the D7-brane world-volume. In the former case, Fig. 3(a), we have an induced D3-brane on the D7-brane world-volume. The latter has no interaction with the ISD flux. Hence the configuration leads to no soft terms. In the latter case, Fig. 3(b), we have and induced anti-D3-brane on the D7-brane world-volume. The latter interacts non-trivially with the ISD flux. Hence there are non-trivial soft terms. (Similar conclusions follow for an IASD G_3 with ASD/SD ω_2.)

Besides the quantitative results, the main novelty of this configuration, as compared with the D3-brane case, is that there are non-zero soft terms even with ISD fluxes. Since these fluxes can appear in global compact models, the latter are string compactification with supersymmetry breaking and non-trivial soft terms, solving classical supergravity equations of motion. It is important to emphasize that these are the first string models of this kind.

An additional interesting comment is that bundle moduli, namely Wilson line moduli, or moduli associated to instanton backgrounds (for instance D3–D7 fields) do not get soft masses. This is ultimately related the origin of these scalars as modes of the 8d gauge bosons, for which mass terms are forbidden by 8d gauge invariance.

Once the results for D-branes in flat space are known, it is straightforward to perform an orbifold quotient and obtain the soft terms for semirealistic models like that in Fig. 1. The main features of these phenomenological soft breaking are???

The soft term scale M_{soft} is the local flux density. For roughly homogeneous compactifications this is given by $\alpha'/R^3 = M_s^2/M_P$. Hence one need to choose $M_s \simeq 10^{11}$ GeV to obtain TeV soft terms. On the other hand, inhomogeneous configurations, in particular with warped throats, may lead to a different pattern.

Embedding the MSSM group on D3-branes leads to interesting soft terms patterns. In particular, naturally universal squark masses, relations between soft terms, like $M = A$, etc. Concerning the μ-term, it is allowed only for some orbifolds, but when it exist, it is roughly of the size similar to other soft terms.

Embedding the MSSM group on D7-branes leads to many features similar to above, with perhaps even better prospects [30]. However a full exploration requires further work, both from the formal viewpoint and from explicit constructions.

4.2. The 4d effective action approach

Let us conclude by mentioning that these results can be recovered from the second approach, namely from the 4d effective Lagrangian. Consider the 4d effective action including the D3- and D7-gauge sectors, including only the dependence on the overall Kahler modulus. This contains the gauge kinetic functions

$$f_{D3} = -\mathrm{i}\tau; \quad f_{D7} = \rho$$

the Kähler potential for the diverse geometric and brane moduli [31]

$$\begin{aligned} K = {} & -\log(S+S^*) - 3\log(T+T^*) \\ & + \frac{|\Phi_{77}^3|^2}{(S+S^*)} + \frac{1}{(T+T^*)}\left[\left(\sum_{a=1}^{3}|\Phi_{33}^a|^2\right) + \left(\sum_{b=1}^{2}|\Phi_{77}^b|^2\right) + \left(|\Phi_{37}|^2 + |\Phi_{73}|^2\right)\right], \end{aligned} \tag{14}$$

and the superpotential (1).

In this language, flux components correspond to auxiliary fields of dilaton, Kähler and complex structure moduli chiral multiplets. The breaking of supersymmetry by fluxes correspond to an spontaneous breaking of supersymmetry in the closed string sector. For instance, the (3, 0) and (0, 3) flux components correspond to vevs for auxiliary fields of the dilaton and overall Kähler moduli

$$F_\tau \simeq \int {G_{(3)}}^* \wedge \Omega, \qquad F_\rho \simeq \int G_{(3)} \wedge \Omega.$$

Introducing these relations in the supergravity expressions [32–34], results in a set of soft terms in full agreement with the above sketched local analysis, see [26] for details.

4.3. An application in KKLT construction

Our above analysis for the effect of fluxes on D7-branes has an important spin-off regarding the KKLT proposal [29] to stabilize Kahler moduli via non-perturbative effects. These may arise as contributions to the superpotential, depending on Kahler moduli, arising from strong infrared dynamics on the D7-brane world-volume gauge theory. In many compactifications, however, matter fields charged under the gauge group might seem to render the gauge theories non-asymptotically free, thus preventing the effect to take place.

Our analysis has shown that D7-brane vector-like world-volume fields generically acquire mass terms, even in ISD flux compactification. This implies that the world-volume gauge theories on D7-branes tend to have less matter, and therefore stronger infrared dynamics, than in standard compactifications. Thus the effect of fluxes on D7-branes facilitates the appearance of non-perturbative superpotentials from these gauge sectors. This observation, already mentioned in [29], has been discussed in [35,36,26].

5. Conclusions

Flux compactifications provide a canonical way to stabilize a large number of moduli in string compactifications. We have reviewed the construction and its properties in the setup of type IIB compactifications on CY_3 with 3-form fluxes.

The models lead to interesting new effects, including warped geometries, and a tractable mechanism for supersymmetry breaking. Nicely enough, it is possible to combine these techniques with previously studied D-brane model building. Chiral models from D-branes at singularities and intersecting/magnetised D-branes, combined with fluxes, provide the best phenomenological constructions from string theory. Both because they succeed in stabilizing large number of moduli, and also because they address important issues concerning the hierarchy problem, either via strongly warped throats, or via spontaneously broken supersymmetry. In the latter respect, we have discussed the qualitative features of flux-induced soft terms on semirealistic configurations of D-branes.

We hope much progress in exploring these and other applications of flux compactifications to cosmological and particle physics model building.

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