THREE-FAMILY PERTURBATIVE STRING VACUA: FLAT DIRECTIONS AND EFFECTIVE COUPLINGS

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The properties of a class of quasi-realistic three-family perturbative heterotic string vacua are addressed. String models in this class generically contain an anomalous \( U(1) \), such that the nonzero Fayet-Iliopoulos term triggers certain fields to acquire string scale VEV’s along flat directions. This vacuum shift reduces the rank of the gauge group and generates effective mass terms and effective trilinear interactions. Techniques are discussed which yield a systematic classification of the flat directions of a given string model which can be proven to be \( F \)-flat to all orders. The effective superpotential along such flat directions can then be calculated to all orders in the string (genus) expansion.

1 Introduction

There are several challenges to be faced in the investigation of the phenomenology of string models, including the degeneracy of string models (but as yet no fully realistic one) and the absence of a satisfactory scenario for supersymmetry breaking. However, a class of quasi-realistic models have been constructed in perturbative heterotic string theory, particularly in the free fermionic constructions\(^1\). Models in this class\(^2\) have the ingredients of the MSSM: \( N = 1 \) SUSY, the SM gauge group as part of the gauge structure, and candidate fields for three ordinary families and two electroweak Higgs doublets. Such models typically have an extended gauge structure which includes an anomalous \( U(1)_A \), a number of non-anomalous \( U(1)'s \), and a non-Abelian hidden sector gauge group. The models also contain a large number of additional matter fields, often with exotic SM quantum numbers. The superpotential is calculable in principle to all orders in the nonrenormalizable terms, and has the feature that string selection rules can forbid terms allowed by gauge invariance. After introducing the required soft supersymmetry breaking parameters, the phenomenological implications of these models can be investigated.

The standard anomaly cancellation mechanism\(^3\) leads to the generation of a Fayet-Iliopoulos (FI) term \( \xi = g'^2_{\text{str}} M^2_{\text{Pl}} \text{Tr} Q_A / 192\pi^2 \) to the \( D \)-term of \( U(1)_A \) at genus-one\(^4\). The FI term induces certain scalar fields to acquire string-scale

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\(^a\)Talk given at PASCOS 98, Northeastern University, Boston, MA, March 1998.
\(^b\)Here \( g_{\text{str}} = g / \sqrt{2} \), and \( M_P = M_{\text{Planck}} / \sqrt{8\pi} \), with \( M_{\text{Planck}} \approx 1.2 \times 10^{19} \text{ GeV} \).
VEV’s along $D$- and $F$- flat directions, leading to a restabilized supersymmetric string vacuum. The vacuum shift reduces the rank of the gauge group, and leads to the generation of effective mass terms and trilinear couplings from higher-order terms after replacing the fields in the flat direction by their VEV’s. The classification of the flat directions of a general perturbative heterotic string model was addressed in [5, 6], and the techniques for computing the effective superpotential in [7].

2 Flat Directions

For the sake of simplicity, consideration is restricted to the flat directions involving the (hypercharge preserving) fields which are singlets under the non-Abelian groups of the model. The flatness conditions are given by

$$D_A = \sum_i Q_i^{(A)} |\varphi_i|^2 + \xi = 0$$

(1)

$$D_a = \sum_i Q_i^{(a)} |\varphi_i|^2 = 0$$

(2)

$$F_i = \frac{\partial W}{\partial \Phi_i} = 0; \ W = 0,$$

(3)

in which the index $a$ labels the non-anomalous $U(1)$’s.

The method utilizes the correspondence between $D$- flat directions and holomorphic gauge invariant monomials (HIM’s). The superbasis of all independent one-dimensional HIM’s under the nonanomalous $U(1)$’s is constructed. The elements with anomalous charge opposite in sign to $\xi$ are also $D_A$ flat for particular values of the VEV’s, set by the FI term to be $\sim 0.01 M_{\text{Planck}}$. These elements are the building blocks of the complete set of $D$- flat directions of the model.

The $D$- flat directions are then tested for $F$- flatness. There are two types of dangerous terms in the superpotential that can lift a given flat direction $P$. First, there are terms which involve only the fields in $P$:

$$W_A \sim (\Pi_{i \in P} \Phi_i)^n,$$

(4)

and there are also the terms linear in an additional field $\Psi$ not in the flat direction:

$$W_B \sim \Psi (\Pi_{i \in P} \Phi_i).$$

(5)

\*In more complicated flat directions, there can be some VEV’s that remain undetermined after imposing the $D_A$-flatness constraint.\]
A flat direction for which gauge invariance allows terms of type-A \( W_A \) will remain \( F \)- flat only if string selection rules conspire to forbid the infinite number of \( W_A \) terms, which is difficult to prove in general. In contrast, flat direction exist for which gauge invariance only allows type-B terms \( W_B \). Such type-B flat directions can be proved to be \( F \)- flat to all orders in the non-renormalizable terms (and to all orders in the string genus expansion) \( \mathcal{O}(g) \), by first constructing the finite number of type-B superpotential terms (using the requirements of gauge invariance), then doing a string calculation to verify if the terms are present (or are forbidden by world-sheet selection rules).

Therefore, consideration is restricted to the type-B directions (although in doing so, the possible type-A directions which are truly \( F \)- flat are missed).

The classification of the type-B flat directions has been carried out for the free fermionic models of \( Z = 2, 3 \). For the models considered, in general at least one additional \( U(1)' \) as well as \( U(1)_Y \) is left unbroken.

3 Effective Couplings

For a given flat direction \( P \), effective mass terms can be generated for the fields \( \Psi_i, \Psi_j \) via

\[
W \sim \Psi_i \Psi_j (\Pi_{i \in P} \Phi_i) .
\]

The fields with effective mass terms will acquire string-scale masses and decouple from the theory. In addition to the Yukawa couplings of the original superpotential, effective trilinear interactions for the light fields may also be generated via

\[
W \sim \Psi_i \Psi_j \Psi_k (\Pi_{i \in P} \Phi_i) .
\]

The method for computing these terms is analogous to that of the determination of the type-B superpotential terms. First, the complete set of bilinear and trilinear invariants under the unbroken gauge group is constructed, and gauge invariance is used to determine the possible couplings of such terms to the fields in the flat direction. An explicit string calculation then determines which couplings are present in the superpotential.

The effective trilinear couplings are typically suppressed relative to the trilinear couplings of the original superpotential (which are \( \sim \mathcal{O}(g) \)). Therefore, there are implications for low energy physics (such as a possible origin/explanation of the fermion mass hierarchy).

The analysis is currently under investigation for a number of the type-B flat directions of a prototype string model. Although there is no expectation

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For a review of \( Z' \) physics in string models, see \( \text{[Ref]} \).

See \( \text{[Ref]} \) for a clarification of the determination of the coupling strengths in a general perturbative heterotic string model.
such models will be fully realistic, the analysis sets the stage to address the
generic phenomenological implications of this class of string models.

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