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Recent Progress in Weakly-Coupled Heterotic String Phenomenology *

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Abstract

Some recent developments in the weakly-coupled heterotic string phenomenology are reviewed. We discuss several important issues such as dilaton/moduli stabilization, supersymmetry breaking (by hidden-sector gaugino condensation), gauge coupling unification (or the Newton's constant), the QCD axion, as well as cosmological problems involving the dilaton/moduli and the axion. (Talk given at the 5th International Conference on Supersymmetries in Physics, May 27-31, 1997, Philadelphia, PA, USA)

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Disclaimer

1 Introduction

Superstring theory is known to offer a very powerful scheme of supersymmetry phenomenology, and in the past the heterotic string theory was the most promising candidate. However, the phenomenology of the weakly-coupled heterotic string suffers from a few long-standing problems, such as the stabilization of dilaton/moduli, supersymmetry breaking (by hidden-sector gaugino condensation), coupling unification, the strong CP problem, and cosmological problems involving the dilaton/moduli and the axion [1]. The recent developments of string duality indicate that other superstring theories, including M-theory, are of equal phenomenological importance. On the other hand, string duality itself also implies that some of the problems associated with the weakly-coupled heterotic string theory will probably re-appear in the other perturbative limits (i.e., other weakly-coupled theories) [2]. Right now, it is still unclear how these problems will be solved eventually; one might hope to find a cure in a truly non-perturbative theory. This seems to be a very interesting possibility; however, currently our understanding of such a theory is still limited. Therefore, it is worth studying whether these notorious problems can be solved and how they will be solved in the weakly-coupled heterotic string theory. Here, we would like to see how far one can go in this direction. We study these problems of the weakly-coupled heterotic string theory by adopting the point of view that they arise mostly due to our limited calculational power, little knowledge of the full vacuum structure, and an inappropriate treatment of gaugino condensation. As we shall see, after a more complete and consistent treatment, these problems could be solved or are much less severe.

There are three major new ingredients in our treatment. The first new ingredient is the linear multiplet formalism of the heterotic string effective theory, where the dilaton superfield is represented by a linear supermultiplet L [3]. It was first pointed out in [4] that the field-theoretical limit of the weakly-coupled heterotic string theory should be described by the linear multiplet formalism rather than the chiral multiplet formalism (where the dilaton is represented by a chiral superfield.) On the other hand, there exists a chiral-linear duality between these two formalisms [5], and therefore in principle these two formalisms should be equivalent. However, the chiral-linear duality is apt to be very complicated, especially when full quantum corrections are included. Therefore, there should exist a formalism where the physics allows a simpler description. It has been argued in [6, 7, 8] that, according to the above consideration, the linear multiplet formalism should be the more appropriate formalism.

The second new ingredient is a stringy non-perturbative effect. Our study of superstring phenomenology contains two kinds of non-perturbative effects: the stringy non-perturbative effects generated above the string scale, and the field-theoretical non-perturbative effects of gaugino condensation generated by strongly-interacting gauge groups below the string scale. The existence of significant stringy non-perturbative effects was first conjectured by S.H. Shenker [9]. String duality and D-branes provide further evidence [10] for Shenker's conjecture. It was first noticed by T. Banks and M. Dine that significant stringy non-perturbative effects could have interesting implications [11]. Here we discuss the phenomenological implications of stringy non-perturbative effects using the linear multiplet formalism. It is interesting to note that, in the presence of stringy non-perturbative effects $f(L)$ [8], the coupling of heterotic string effective field theory is $\langle\, L/\,(1+f(L))\,\rangle$ rather than $\langle\, L\,\rangle$ [12, 13]. It is then argued that stringy non-perturbative effects are best described by the linear multiplet formalism [12, 14]. This advantage of the linear multiplet formalism is crucial to our study where both stringy and field-theoretical non-perturbative effects are considered.

Thirdly, in the past gaugino condensate has always been described by an *unconstrained* chiral superfield U corresponding to the bound state of $\mathcal{W}^\alpha \mathcal{W}_\alpha$ in the underlying theory. It was pointed out recently that U should be a *constrained* chiral superfield [5, 15, 16] due to the constrained superspace geometry of the underlying Yang-Mills theory:

$$
\begin{aligned}
U &= -(\mathcal{D}_{\dot\alpha}\mathcal{D}^{\dot\alpha} - 8R)V, \\
\bar{U} &= -(\mathcal{D}^{\alpha}\mathcal{D}_{\alpha} - 8R^{\dagger})V,
\end{aligned} \tag{1}
$$

where V is an unconstrained vector superfield. This constraint emerges from the linear multiplet formalism naturally, and has several non-trivial implications [5, 13, 15]. Finally, full modular invariance, a very important symmetry of closed string theory [17], is always maintained in our construction. It has important predictions [14, 18], which can be obtained only after the above ingredients of heterotic string theory are fully taken into account.

Based on this treatment, a simple $E_8\times E_8$ model was first studied in [8], and a generic orbifold model was studied in [13]. In [12], the analysis of [8, 13] was shown to be valid in a more generic context. A detailed phenomenological discussion was given in [18], and [14] is a complete review. Due to limited space, here we briefly discuss several interesting phenomenological issues only.

2 Dilaton Stabilization

The weakly-coupled heterotic string phenomenology based on gaugino condensation has been long plagued by the infamous dilaton runaway problem [11, 19], and there were claims in favor of the strongly-coupled heterotic string theory by arguing that it is unlikely that the weakly-coupled heterotic string theory can avoid the dilaton runaway. However, string duality implies that the strong coupling limit of heterotic string theory, another weakly-coupled theory (i.e., M-theory compactified on $R^{10}\times S^1/Z_2$ [20]), is plagued by a similar runaway problem[1] [2]. It was first suggested by T. Banks and M. Dine [11] that significant stringy non-perturbative effects could stabilize the dila-

[1]For example, one has to worry about the runaway of the interval, ρ_{11}, along the 11th dimension. In particular, ρ_{11} controls supersymmetry breaking, and supersymmetry is unbroken as $\rho_{11} \to \infty$.

ton. This proposal was studied in [8] and [21][2]. Indeed, the dilaton can be stabilized by significant stringy non-perturbative effects; "significant" means that stringy non-perturbative effects, $f(L)$ (in the Kähler potential), satisfy the condition [8]:

$$f - L\frac{\mathrm{d}f}{\mathrm{d}L} \;\geq\; 2 \qquad \text{for} \quad L \;\geq\; \mathcal{O}(1). \tag{2}$$

This condition is actually very generic [12, 13], and, with reasonable guess of $f(L)$, the dilaton is stabilized in a weak coupling regime [18]. As expected, an unsatisfactory feature is that the vanishing of cosmological constant needs fine tuning (of $f(L)$); however, this is still an improvement in comparison with the racetrack model [22, 23][3]. We emphasize that many aspects of our study are different from those of the racetrack model [13, 18]. For example, dilaton stabilization and supersymmetry breaking are possible for simple as well as for product non-Abelian gauge groups in our study [13].

3 Moduli Physics

3.1 Stabilization at the Self-Dual Point

Our study of a generic orbifold model [13] shows that, along with dilaton stabilization, the compactification moduli, T^I, are stabilized at the self-dual point, $\langle T^I \rangle = 1$. What's more interesting is the fact that, in the vacuum (i.e., at the self-dual point), the F components of T^I vanish. Therefore, although T^I's are stabilized by SUSY breaking effects, T^I's do not contribute to the breaking of SUSY. Only the dilaton contributes to SUSY breaking,

[2]However, [21] did not take into account other aforementioned ingredients of weakly-coupled heterotic string.

[3]Dilaton stabilization in the racetrack model requires a delicate cancellation between contributions from different gaugino condensates, which is not natural. Furthermore, it has a large and negative cosmological constant when supersymmetry is broken.

which leads to the famous dilaton-dominated scenario for soft SUSY breaking. As explained in [13], we emphasize that this unique prediction does not necessarily follow from any framework with modular invariance; in the weakly-coupled heterotic string theory this prediction is the consequence of both modular invariance and an appropriate treatment of gaugino condensation [13][4]. Therefore, the weakly-coupled heterotic string theory offers a rationale for the well-known dilaton-dominated scenario elegantly, and a search for the dilaton-dominated scenario might serve as a test of modular invariance in string theory.

3.2 Mass Hierarchy between Moduli and Gravitino

According to the standard lore of string phenomenology, a naive oder-of-magnitude estimate concludes that the dilaton and moduli have masses of order (or no larger than) the gravitino mass [24]. These light fields with couplings suppressed by the Planck scale lead to the so-called cosmological moduli problem [24, 25, 26]. In order to solve the cosmological moduli problem, there have been attempts at a hierarchy between moduli and squark masses [26, 27]; however, none of them is realistic. There are also possible cosmological solutions to the cosmological moduli problem, such as a weak scale inflation [25].

It turns out that the usual estimate of dilaton and moduli masses is too rough. In our study, the actual calculation of these masses shows that $m_{t^I} \approx (2b/b_+)m_{\tilde{G}}$ [13, 18], where m_{t^I} is the moduli mass and $m_{\tilde{G}}$ the gravitino mass.[5,6] For a realistic scale of gaugino condensation, $b/b_+ \approx 10$ is required for the string models under consideration. Therefore, in contrast to the

[4]This may explain why this prediction is absent in those works [23] where modular invariance is correctly incorporated but the constraint, Eq.(1), was not included.

[5]b is the E_8 β-function coefficient, and b_+ is the β-function coefficient of the (largest if multi-condensation) gaugino condensate.

[6]The dilaton mass $m_d \geq m_{t^I}$ in general [14].

standard lore, there exists a natural hierarchy between the dilaton/moduli and squark/slepton masses, $m_{t^I} \approx 20 m_{\tilde{G}}$. This mass hierarchy could be sufficient to solve the cosmological moduli problem. It may have other non-trivial cosmological implications. Its implication on the primordial black hole constraints has recently been studied in [28].

4 Axion Physics

4.1 The Strong CP problem

The invisible axion is an elegant solution to the strong CP problem. However, it has been argued that QCD cannot be the dominant contribution to the potential of any string axion [29]. For the model-independent axion, it has been argued (using the chiral multiplet formalism) that the model-independent axion cannot be the QCD axion due to stringy non-perturbative effects of order $e^{-c\sqrt{S}}$ in the superpotential[7] [11, 29]. On the other hand, for the linear multiplet formalism where the dilaton is represented by a linear multiplet L, it is simply impossible to write down any L-dependent contribution (e.g., $e^{-c/\sqrt{L}}$) to the superpotential – a constraint from holomorphy. Therefore, in our study the QCD axion problem of T. Banks and M. Dine [29] is naturally resolved.

In our study of a generic orbifold model with a simple non-Abelian hidden-sector gauge group [13], the model-independent axion remains massless, and has the right features to be the QCD axion. As for a non-Abelian product gauge group which leads to multiple gaugino and matter condensation, the model-independent axion acquires a mass typically exponentially suppressed relative to the gravitino mass by a small factor of order $\langle \rho_2/\rho_1 \rangle^{1/2}$, where ρ_1 (ρ_2) is the gaugino condensate with the largest (second largest) β-function coefficient [13][8]. If the gauge group G_2 (of ρ_2) is reasonably smaller than G_1

[7] S is the dilaton chiral superfield.

[8] Higher-dimension operators can give extra contributions to the mass of this axion.

(of ρ_1), then the axion mass can still be small enough to solve the strong CP problem[9].

4.2 Solving A Cosmological Problem

For any of the string axions to solve the strong CP problem, there is a cosmological constraint. The decay constant F_a of the invisible axion should lie between 10^{10} GeV and 10^{12} GeV (the axion window [30]). The upper bound, $F_a \leq 10^{12}$ GeV, is due to the requirement that the energy density of the coherent oscillations of the axion be less than the critical density of the universe. However, in superstring theory the axion decay constant F_a is naturally of order the Planck scale, and therefore this upper bound is seriously violated. Although it was shown in [31] that F_a of the model-independent axion for the weakly-coupled heterotic string actually is $\approx 10^{16}$ GeV, this is still much larger than this upper bound. However, cosmological constraints can be quite scheme-dependent; for example, entropy production produced by the decays of massive particles can dilute the axion density and therefore raise this upper bound [32]. Based on the above idea, [33] proposed a refined scenario where Polonyi fields with masses larger than about 10 TeV (in order to keep successful primordial nucleosynthesis) are natural candidates for the entropy production, and the model-independent axion is almost consistent with the new upper bound on F_a. Although these Polonyi fields with masses ≥ 10 TeV seem un-natural according to the standard lore, this scenario of [33] does naturally occur in our study, where moduli fields ($m_{t^I} \approx 20 m_{\tilde{G}} \approx 20$ TeV) serve the purpose of raising the upper bound on F_a to a value consistent

However, these contributions may be argued to be negligible using discrete R symmetry [11].

[9] Unlike the racetrack model, in our study a delicate cancellation between the condensates of G_1 and G_2 is *not* required. Successful models can be constructed for the single-condensate case as well as the multi-condensate case with G_2 reasonably smaller than G_1.

with the model-independent axion.[10]

5 Newton's Constant

It is often stated that one can determine from the low-energy values of gauge couplings the precise value of the gauge coupling unification scale, M_{GUT}, to be the $M_{GUT}^{(MSSM)} = 3 \times 10^{16}$ GeV based on the MSSM. This is a misleading statement since most string models constructed so far that hold a claim for being realistic include new forms of matter which perturb the evolution of the gauge couplings at some intermediate threshold [34]. In fact, as for string models considered in our study, the unification scale M_{GUT} should naturally be the string scale M_s [35]. Furthermore, the compactification scale M_{comp} is also close to the string scale because the compactification moduli are stabilized at the self-dual point, $\langle T^I \rangle = 1$. Therefore, one naturally expects $M_{GUT} \sim M_s \sim M_{comp}$.

Let's make a short remark on the Newton's constant G_N. For the weakly-coupled heterotic string theory, it has been shown by E. Witten [36] that there exists a lower bound on the Newton's constant:

$$G_N \geq \frac{\alpha_{GUT}^{4/3}}{M_{comp}^2}. \tag{3}$$

If one simply takes M_{comp} to be $M_{GUT}^{(MSSM)}$, the resulting lower bound on the Newton's constant is indeed too large. On the other hand, in our study the compactification moduli are actually stabilized at the self-dual point, $\langle T^I \rangle = 1$. Therefore, the compactification scale is quite close to the string scale. According to the previous discussion, one should take M_{comp} to be of order M_s, and the resulting lower bound on the Newton's constant is of order $\alpha_{GUT}^{4/3}/M_s^2$. This lower bound is certainly small enough [14].

[10]Note that, in our study [18], due to stringy non-perturbative effects the F_a of model-independent axion is smaller than the $F_a \approx 10^{16}$ GeV obtained in [31] by a factor of 1/50. Therefore, in our study the value of F_a is well below the new upper bound [33].

6 Soft Supersymmetry Breaking Parameters

In contrast to the studies of moduli and axion, the analysis of soft supersymmetry breaking parameters is much more sensitive to the very details of a string model. A detailed discussion can be found in [14, 18]. Here we only discuss an issue about the dilaton-dominated scenario. As explained in Section 3.1, $\langle T^I \rangle = 1$ and the vanishing of their $\langle F \rangle$ components are non-trivial results of taking into account the aforementioned ingredients of weakly-coupled heterotic string theory, and they lead to the well-known dilaton-dominated scenario. It is generally believed that a dilaton-dominated scenario results in universal soft SUSY breaking parameters at a high energy scale due to the universality of dilaton couplings [37], which is a potential advantage for the FCNC constraints. However, we would like to point out some uncertainty about this statement by studying the soft scalar masses for a generic orbifold [13]. The Kähler potential K and the Green-Schwarz counterterm V_{GS} are

$$K = k(V) + \sum_I g^I + \sum_A e^{\sum_I q_I^A g^I} |\Phi^A|^2 + \mathcal{O}(|\Phi^A|^4), \tag{4}$$

$$V_{GS} = b \sum_I g^I + \sum_A p_A e^{\sum_I q_I^A g^I} |\Phi^A|^2 + \mathcal{O}(|\Phi^A|^4), \tag{5}$$

where $g^I = -\ln(T^I + \bar{T}^I)$, $k(V)$ is the Kähler potential for the modified linear multiplet V [8], Φ^A's are gauge nonsinglet chiral superfields and q_A^I's are their modular weights. Note that V_{GS}, to our knowledge, is uncertain up to modular invariant corrections in Φ^A (parametrized by p_A's). According to [18], the scalar masses are:[11]

$$m_A \approx \frac{|1 - p_A/b_+|}{1 + p_A\langle \ell \rangle} m_{\tilde{G}}. \tag{6}$$

As expected, m_A does not depend on q_A^I due to $\langle T^I \rangle = 1$ and the vanishing of their $\langle F \rangle$ components. It is clear that m_A's are universal – and unwanted

[11] If string threshold corrections are determined by a holomorphic function, they cannot contribute to the scalar masses.

FCNC is thereby suppressed – if p_A's are universal [37]. Unfortunately, so far there is little knowledge of p_A's. In general, m_A is sensitive to the – as yet unknown – details of Φ^A-dependent corrections to V_{GS}. These corrections have not been considered by the analyses of dilaton-dominated scenario in the past [37], and the possibility of non-universal p_A's can lead to non-universal soft SUSY breaking parameters even for the dilaton-dominated scenario. The phenomenology of several possible choices for p_A's was discussed in [18].

7 Concluding Remarks

As expected, the origin of the cosmological constant remains a mystery here although it is indeed under better control in our treatment. Again, a final resolution of this problem might have to wait for a complete understanding of superstring dynamics. The other unsettled issue is the soft SUSY breaking pattern. Although our study always predicts a dilaton-dominated scenario, in contrast to the standard lore of string phenomenology we point out that whether a dilaton-dominated scenario predicts universal soft SUSY breaking parameters actually depends on whether the matter couplings to the Green-Schwarz counterterm are universal. To settle this issue, a better understanding of the matter dependence of the Green-Schwarz counterterm for generic string models is certainly required; it deserves further studies and could lead to a rich phenomenology. In conclusion, we emphasize that this work is certainly not final, and it is very important to understand more about the non-perturbative aspects of superstring theories, realistic string model building and the phenomenology. After a careful re-examination of the problems of the weakly-coupled heterotic string theory, it is also hoped that confusion about the current status of weakly-coupled heterotic string theory is clarified by this work.

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