String Model Building in the Age of D-Branes

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The string duality revolution calls into question virtually all of the working assumptions of string model builders. A number of difficult questions arise. I use fractional charge as an example of a criterion which one would hope is robust beyond the weak coupling heterotic limit.

1. The String Duality Revolution

Recent developments in string theory have radically altered our view of what superstrings are and what properties or symmetries are fundamental in the nonperturbative regime. The heterotic, Type I, Type IIA, and Type IIB superstrings now appear to be different weak coupling limits of the same underlying nonperturbative theory. Furthermore there is strong evidence that this theory has at least one more well-defined limit, called “M theory”, which is not a weak coupling limit and does not admit a world-sheet description. In addition the existence of D-brane backgrounds in the Type I and II strings implies that we will have to go beyond the world-sheet description to correctly incorporate the effects of dynamical D-branes.

These developments must be characterized as revolutionary since they call into question the very idea that string theory is a theory of “strings”. At this point the world-sheet and world-sheet symmetries seem less fundamental in string theory than string duality symmetries and “global symmetries” like spacetime supersymmetry. This paradigm shift holds real promise for giving us at long last a tangible hold on nonperturbative string dynamics at some point in the not-too-distant future. However, as with most revolutions, we must expect some strong doses of pain and confusion during the interregnum.

2. Assumptions of String Model Builders

For those in the already difficult business of spinning gossamer threads between string theory and particle physics, we are left with the disturbing fact that the current revolution calls into question virtually all of the working assumptions of string model builders. Without being exhaustive, let me gather these assumptions into three groups:

• The heterotic/conformal field theory assumptions.
• The assumptions about relations between scales and couplings.
• The assumptions about how gauge groups are realized.

Let us consider in turn some of the questions which arise with respect to these assumptions.

2.1. Whither heteroticity?

All of the promising attempts at connecting string theory to the standard model take as their starting point the weakly-coupled 10 dimensional heterotic string. In this limit string theory was assumed to be rigorously described by modular invariant conformal field theory.

However we know now that there are special regions in moduli space which exhibit singular be-
behavior associated with stringy solitons becoming massless. This behavior is simply absent in the conformal field theory description, even though it occurs at arbitrarily weak coupling. Thus we are forced to conclude that, even in the weak coupling heterotic limit, conformal field theory may give an incomplete description of essential physics like the massless spectrum.

Q: Can we somehow generalize conformal field theory to handle these singular behaviors?

Q: Does it matter? Are these behaviors mere curiosities, or do they infect the phenomenologically important regions of moduli space?

Model builders have focused on the heterotic string because it did not appear possible to embed the standard model gauge group and chiral fermions into the Type I or Type II string compactifications. However these arguments are now known to be invalidated by the presence of D-branes.

Q: Was the no-go theorem \[1\] for the Type II string premature? Can we embed the standard model into the weak coupling limit of Type II?

We must worry, moreover, whether it makes sense to extract phenomenology from any weak coupling limit of the string. We already have a strong argument that stabilizing the dilaton vev requires that we are in a region of moduli space with no weak coupling interpretation. In fact the only compelling reason to believe that weak coupling string theory has any connection to the real string ground state is the phenomenological success of heterotic string models in reproducing standard model physics. This makes it seem likely that exact string symmetries protect the important features of these models as we move in moduli space from the weak coupling limit towards the real ground state.

Still, it is not premature to wonder about the phenomenological properties of M-theory:

Q: Can we embed the standard model gauge group and three generations of standard model fermions into compactifications of M-theory?

Q: If there are “realistic” models in several different limits of string theory, how do they map into each other?

This latter question could be of key importance, if it turns out that there are trajectories of realistic string vacua that flow from one string limit to another.

2.2. Scales and couplings

String model building has heretofore assumed the relations between scales and couplings derived in the perturbative heterotic string. Thus, the effective gauge couplings are assumed to have the form \[2\]:

$$
\frac{1}{g_a^2(p)} = \frac{k_a}{g_{\text{string}}^2} + \frac{b_a}{16\pi^2} \log \frac{M_{\text{string}}^2}{p^2} + \frac{\Delta_a}{16\pi^2}
$$

where \(b_a\) are one-loop beta function coefficients and \(\Delta_a\) are model-dependent threshold corrections. The Kac-Moody levels \(k_a\) are positive integers, except for the \(U(1)\) hypercharge parameter \(k_1\), which is a continuous (real) free parameter \(\geq 1\). The effective gauge coupling unification scale \(M_{\text{string}}\) is determined by the dilaton dependence of the heterotic one-loop effects:

$$
M_{\text{string}} \sim g_{\text{string}}M_{\text{Planck}}
$$

This simple picture has inspired many fruitful collaborations between field theory and string theory model builders. Each group is instructed to do their own thing, and then attempt a graceful link-up with the other side over the narrow no-man’s land between 3\times10^{16} and 5\times10^{17} GeV. Below this scale we have an effective unified gauge theory. Gauge coupling unification occurs somewhere between the string scale and (if there are large threshold effects) the LEP preferred scale 3\times10^{16} GeV.

The bottom line is that in the standard scenario there is basically one high scale: \(M_{\text{string}} \approx 5 \times 10^{17}\) GeV. Above this scale we have stringy effects and quantum gravity. Below this scale we have an effective unified gauge theory. Gauge coupling unification occurs somewhere between the string scale and (if there are large threshold effects) the LEP preferred scale 3\times10^{16} GeV.

This simple picture was inspired by the relations between scales and couplings in string theory. At least on the surface it appears that the relationships between scales and couplings in string theory are highly dependent on where you are in moduli space. The relationships above which hold for the weakly-coupled heterotic string are modified for the other weak coupling limits of the string. In the M-theory limit it has been suggested that there may not even be a simple transition from a stringy regime to an effective 4 dimensional field theory. Instead gravity may remain geometric and be lost in the background.
GeV, while the gauge interactions remain effectively 4 dimensional and unify at $3 \times 10^{16}$ GeV \[^2\].

As of now, it is difficult to put any meaningful limits on what can occur in the murky depths of the strong and intermediate coupling region of string theory. To the extent that the theory is essentially quantum in nature, geometrical reasoning is likely to be unsound. Thus, for example, one cannot argue that a large hierarchy of scales or couplings necessarily corresponds to some compactification radius becoming large. It is possible that inherently stringy physics is not confined to scales near $M_{\text{Planck}}$, and may even be lurking at scales within reach of future colliders \[^3\].

Q: What are the physically distinct scales of string theory, and how tight are the relationships between them?

2.3. Gauge groups

String model builders have assumed that gauge fields in string models arise from the intrinsic $E_8 \times E_8$ or $SO(32)$ gauge groups of the 10 dimensional heterotic string, plus the Kaluza-Klein gauge fields arising from compactification. This implies that the gauge group of the effective 4 dimensional gauge theory has rank $\leq 22$, and is restricted in other ways which become more and more restrictive for higher Kac-Moody levels $k_a$.

This rank restriction is now known to be incorrect at certain points in moduli space, even for the weak-coupling limit of the heterotic string \[^5\]. Additional gauge bosons can arise as massless solitons of string theory. For example, in a 6 dimensional $K3$ compactification of the $SO(32)$ heterotic string (which can obviously be compactified further to produce 4 dimensional examples), the compactification requires a nontrivial gauge background with instanton number 24. There is a point in moduli space where the size of all 24 instantons shrinks to zero, and at this point the rank of the gauge group increases by 24:

$$SO(32) \rightarrow SO(32) \times Sp(48)$$

(3)

Conformal field theory misses this entirely – there are no conformal currents corresponding to these gauge fields. Roughly speaking, the Kac-Moody level of this $Sp(48)$ is effectively zero.

Q: Can this happen in realistic models?

Q: Could the standard model gauge bosons be massless solitons as viewed from the heterotic limit? Is this consistent with the existence of the standard model chiral fermions?

Q: Can the physical information encoded in Kac-Moody levels be generalized beyond conformal current algebras?

The latter question is important because in modular invariant conformal field theory, the Kac-Moody level restricts the massless spectrum of the string model. Furthermore, gauge coupling unification in the strict sense only occurs (at tree-level) if $k_3/k_2 = 5k_3/3k_1 = 1$. Kac-Moody levels—in the standard scenario—have been a powerful tool for classifying superstring phenomenology.

3. Fractional Charge

Superstring phenomenology has so far produced few predictions, and very few of these could be meaningfully called generic. The existing examples of string models which embed the standard model gauge group and precisely three standard model generations do have some important features in common: they have a hidden sector, the possibility of extra $U(1)$ gauge factors, and highly restricted superpotential couplings.

An appealing generic prediction of string phenomenology was Schellekens’ theorem \[^6\], which states that under a broad and specific set of circumstances string models must contain particles which violate the standard model charge quantization condition (e.g. colorless particles with electric charge 1/2, color triplets with charge 1/6, etc.). Since the lightest fractionally charged particle is of necessity stable, this is an interesting prediction even if these particles are very heavy.

Briefly, Schellekens’ theorem states that in any string model which contains the standard model gauge group one of the following must be true:

1. There are particles with fractional electric charge.
2. The model has $SU(5)$ unbroken at the string scale.
3. The standard model gauge group is realized at Kac-Moody levels greater than one.

Unfortunately, this theorem is proved using conformal field theory and modular invariance of the weakly-coupled heterotic string. Thus one of the most interesting generic results of string phenomenology is now in doubt.
Q: Can we say anything about the possibility or necessity of fractional charge beyond the weak coupling heterotic limit?

4. Fractional charge and Kac-Moody levels

I have argued above that both Kac-Moody levels and Schellekens’ theorem have been useful tools of superstring phenomenology, tools which we should try hard to generalize in the “new” string theory. To emphasize this point I will close by classifying some (most) of the existing three generation string models along these lines.

1. Models with $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the string scale, with $k_3=k_2=1$, $k_1=5/3$:
   - The known examples are the various fermionic models of Faraggi [8]. Schellekens’ theorem says there must be fractional charge, and indeed there are fractionally charged states in the massless spectrum. These exotics are vectorlike, and some or all of them may get superheavy masses by coupling to singlet vevs.

2. Models with $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the string scale, with $k_3=k_2=1$, $k_1 \neq 5/3$:
   - The known examples are the $Z_3$ and $Z_3 \times Z_3 (0,2)$ abelian orbifolds [8], as well as the fermionic models of Chaudhuri et al [9]. These models have fractionally charged exotics as above.

3. Models which embed $SU(3)_c \times SU(2)_L \times U(1)_Y$ into a larger group at the string scale (subsequently broken by Higgs vevs), with $k_3=k_2=1$:
   - There are two cases. The gauge group can be $SU(5) \times SU(5)$, in which case we have the models of Finnell and Maslikov et al [10]. Because of the unbroken $SU(5)$, these models need not have fractionally charged particles, and indeed they do not. The only other way to have a GUT-like unified group with $k_3=k_2=1$ is the “flipped $SU(5)$” fermionic model [11]. Because this is not standard $SU(5)$ there are fractionally charged exotics. However flipped $SU(5)$ has the nice property that these exotics are also 4’s and 4̄’s of a hidden $SU(4)$; thus fractional electric charge is confined.

4. Models which embed $SU(3)_c \times SU(2)_L \times U(1)_Y$ into a larger group at the string scale (subsequently broken by Higgs vevs), with $k_3=k_2>1$:
   - Until recently the only examples were uninteresting because they had chiral color sextet exotics. However there is now an example of $SO(10)$ model with Kac-Moody level three [12]. There is no fractional charge.

5. Models with $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the string scale, with $k_3=k_2>1$:
   - This case is interesting because it employs the second of the two loopholes in Schellekens’ theorem. Until recently there were no known examples. However one can argue that the existence of the Finnell model also implies the existence of models of this type. A detailed examination of the superpotential in the Finnell model indicates that the $(5,5)$ and $5,5$ Higgs fields are probably moduli. In such a case Higgs breaking is equivalent to continuous Wilson line breaking, indicating that there are $SU(3)_c \times SU(2)_L \times U(1)_Y$ string vacua with $k_3=k_2=2$, $k_1=10/3$.

   - In fact, we now have a direct fermionic construction of a three generation model of this type [13]. The full gauge group is

\[
\left[ SU(3)_c \times SU(2)_L \times U(1)_Y \right] \times \left[ SU(2) \times SU(2) \right]_{\text{hidden}} \times [U(1)]^7 \times U(1)_{\text{anomalous}}
\]

   - Some or all of the extra $U(1)$’s will be broken by the Green-Schwarz mechanism which eliminates the anomalous $U(1)$.

The complete massless matter spectrum, not including standard model singlets, consists of the following $N=1$ chiral superfields:

- three standard model generations plus up and down type Higgs.
- five $(3,1)+(\bar{3},1)$ vectorlike pairs of exotic charge $\pm 1/3$ quarks.
- eight pairs of charge $\pm 1$ weak doublets.
- two pairs of charge $\pm 1$ $SU(3)_c \times SU(2)_L$ singlets.

As expected, there are no fractionally charged particles.

5. Conclusion

The phenomenology of the three generation weakly-coupled heterotic string models is trying to tell us something profound about particle physics. Clearly also the string duality revolution is telling us something profound about string theory. Somehow we must find a way to pay heed to both messages.
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