Phenomenology and Cosmology with Superstrings

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We discuss how realistic low-energy physics can arise from the $E_8 \otimes E_8$ superstring. A key role is played by the discrete symmetries which typically arise after compactification. Cosmological problems are avoided because the discrete symmetry that we employ is shown to be effectively embedded in a Peccei-Quinn symmetry. The models we present seem to satisfy the known phenomenological and cosmological constraints. In particular, they possess a harmless axion. The existence of topologically stable superconducting vortices (strings), surviving until today, is also predicted.

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The discovery of anomaly-free superstring theories[1] and the subsequent development of the $E_8 \otimes E_8$ heterotic theory[2] has fueled expectations that we may have at hand a theory which provides a consistent unification of gravity with the other three forces. Compactification of the $E_8 \otimes E_8$ theory on Calabi-Yau (CY) spaces can lead to chiral fermion families, a must for any realistic theory, and even delivers an unbroken $N=1$ supersymmetry.[3] However, attempts to obtain a realistic low-energy phenomenology and a consistent cosmology must face up to some formidable problems. For instance, there are potential dangers from sources such as rapid proton decay, $\sin^2\theta_W$, flavor-changing neutral currents, neutrino masses, domain walls, visible axions, etc. Moreover, the model-independent axion in superstring theories[4] does not satisfy the standard astrophysical and cosmological constraints.

In this Letter we wish to attempt a unified approach to these and some other related questions. Our aim is to come up with a model which, in addition to satisfying all of the above constraints, makes some predictions. Perhaps the most striking one, in the class of models considered, is the presence of topologically stable vortices which are superconducting and possibly detectable in our galaxy through their astrophysical effects.

Before embarking on the actual model building and the ensuing consequences, we need to clarify a number of points. First, let us state some of our main assumptions:

(i) The compactification of the ten-dimensional $E_8 \otimes E_8$ superstring theory on a suitable CY space gives rise to three generations of chiral massless fermions (contained in the **27**'s of E_6). In addition, there will be a certain number of chiral matter multiplets arising from incomplete **27**'s and **27***'s of E_6.[5,6]

(ii) The CY space is nonsimply connected thus allowing for nontrivial Wilson loops.[3] The effective gauge group below the compactification scale M_C is a subgroup G of E_6 and, depending on the details of the symmetry breaking, possesses rank five or six.[5] Clearly, G must contain $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ (3-2-1) as a subgroup.

(iii) There exists some mechanism of spontaneous supersymmetry breaking, presumably triggered by the hidden E_8 sector,[7] which gives rise to the weak scale M_W. Gravitational-strength interactions are assumed to give rise to (mass)^2 terms of order M_W^2 for the scalars. We will assume that these terms do not violate the local as well as possible global symmetries of the effective four-dimensional theory.

Next, in order to obtain a phenomenologically acceptable theory, it seems necessary, even in the case of a three-family model, that many of the extra fields in the **27** acquire an intermediate mass M_I, which is much larger than M_W. Some reasons for such an intermediate scale are the following: (a) The requirement of perturbative unification. (b) The possibility of creating some mixing between the Higgs doublets $\bar{H}$ and H which give masses to the up quarks and the down quarks (and the charged leptons). The mixing is important in order to obtain tree-level electroweak breaking without the need for large Yukawa couplings that certainly are absent for H. (c) The possibility of having an acceptable proton lifetime without the imposition of exact baryon-number conservation, which helps in the creation of baryon asymmetry in the Universe.

The most plausible intermediate scale in superstring models appears to be $\sim (M_W M_C)^{1/2} \equiv M_I \sim 10^9$–$10^{10}$ GeV for $M_C \sim 10^{17}$ GeV. Its appearance requires the existence of at least one light 3-2-1 singlet from a **27**, accompanied by a corresponding singlet from a **27***, plus the existence of D and F flat directions in the potential of this singlet.[8,9]

Having convinced ourselves that superstring models ought to possess an intermediate scale M_I at which a part of the gauge group G is broken, we will argue that at least one independent global symmetry (presumably broken at M_I) be present in order that the models not be phenomenologically and cosmologically unacceptable. The reasons for this include the following:

(1) The absence of large flavor-changing neutral currents which are generally present in models with several light Higgs doublets. In superstring models there are at least six such doublets. On the basis of their quantum numbers with respect to the local symmetries there is no reason why some of them are heavy and the others light, or why some of them couple to quarks and leptons and the others do not. If, however, there is a suitable global symmetry which differentiates between them the problem can be overcome.

(2) The absence of large masses for the known neutrinos. Unless an extra global symmetry is present neutrino masses generally turn out to be much too large.[6]

(3) An acceptable proton lifetime. The presence of a global symmetry eliminates some of the undesirable couplings which otherwise would lead to a much too rapid proton decay.[5,6,8,9]

An obvious candidate for the global symmetry in a superstring model is the discrete symmetry that typically arises after compactification of a superstring theory on a CY space.[5] Such a symmetry may help in the avoidance of large neutrino masses and a rapid proton decay. It should be remembered, however, that discrete symmetries create severe domain-wall problems if they are spontaneously broken.

The domain-wall problem would be neatly resolved if the discrete symmetry could effectively be embedded in some continuous (global) symmetry. Before proceeding to a discussion of what we consider an attractive candidate for the continuous symmetry, let us remark that the continuous symmetry could not reasonably be expected to be a symmetry of the complete four-dimensional theory, including all the nonrenormalizable interactions. It can, at best, be expected to be the symmetry of all those field operators that could affect the relevant physics between M_C and the QCD scale.

In order to motivate the nature of the continuous global symmetry, let us recall the model-independent axion in superstring models.[4] The decay constant for such an axion is close to M_C, much larger than the upper bound of 10^{12} GeV allowed by standard cosmological arguments.[10] The presence of an additional global U(1) Peccei-Quinn (PQ) symmetry[11] (in the sense mentioned above) broken at an intermediate scale resolves the axion problem in a neat way. The true axion is now an appropriate linear combination of the two fields, the model-independent axion and the PQ axion, and couples to $F\tilde{F}$ with a decay constant characterized by $M_I \sim 10^{10}$ GeV.[12] (For this to hold in the event that the hidden sector is strongly interacting, we must require that this sector carries zero PQ charge.) It is only natural to identify the desired continuous global symmetry with the $U(1)_{PQ}$ symmetry.

To summarize, our task now is to construct an acceptable axion model based on the field content suggested by the $E_8 \otimes E_8$ superstring. We also should identify the relevant discrete symmetry which is effectively embedded in $U(1)_{PQ}$. The problem of constructing CY spaces which lead to such a discrete symmetry and, in addition, have all the other desirable features is, of course, a formidable one and is not addressed in this paper.

Several attempts to construct an acceptable superstring axion model based on rank-six subgroups of E_6 were unsuccessful. This is largely due to the small number of couplings allowed by the local symmetry. The PQ symmetry is broken completely only at the weak scale, and one ends up with an unwanted visible axion. It is also difficult to arrange for an acceptable proton lifetime together with some baryon-number nonconservation in the model, avoid flavor-changing neutral currents, and arrange for the decay of all the heavy particles. We therefore turn to a rank-five subgroup of E_6.

In the following we present a model based on the subgroup[5]

$$G \equiv SU(3)_C \otimes SU(2)_L \otimes U(1)_L \otimes U(1)_R$$

which appears to have all the desirable features. The standard hypercharge generator is proportional to the direct sum of the generators of the U(1)'s.

In order for this model to develop an intermediate scale the CY space must have other (1,1) harmonic forms besides the Kähler form.[8] We also need two 3-2-1 singlets with different global charges in order to break $U(1)_{PQ}$ at M_I. These singlets come from **27**'s and are accompanied by their mirrors from **27***'s. We denote them S_1 and S_2. Their mirrors are denoted $\tilde{S}_1$ and $\tilde{S}_2$. The fields in **27**'s with the same local quantum numbers as S_1 and S_2, but which do not have light mirrors, are denoted by N.

It turns out that we need additional fields which come from incomplete **27**'s (and **27***'s). For reasons that will become clear later we introduce four doublets, H'', H''', $\bar{H}''$, and $\bar{H}'''$, and their mirrors, $\tilde{H}''$, $\tilde{H}'''$, $\tilde{\bar{H}}''$, and $\tilde{\bar{H}}'''$, as well as two color triplets g' and their mirrors $\tilde{g}'$. Table I gives the quantum numbers of the various fields with respect to G and a global Z_9 symmetry which we impose on the model. Gauge

TABLE I. Field content, multiplicity, and quantum numbers. For Z_9 the (global) charges are clearly defined only modulo 9.

	$SU(3)_C$	$SU(2)_L$	$U(1)_L$	$U(1)_R$	Global	N_m
Q	3	2	1	0	0	F
L	1	2	−1	−2	8	F
H	1	2	−1	−2	−12	1
$\bar{H}$	1	2	−1	4	14	1
U_c	$\bar{3}$	1	0	−4	−14	F
D_c	$\bar{3}$	1	0	2	12	F
E_c	1	1	2	4	4	F
g	3	1	−2	0	−10	F
g_c	$\bar{3}$	1	0	2	7	F
H'	1	2	−1	−2	−2	$F-1$
$\bar{H}'$	1	2	−1	4	−1	$F-1$
N	1	1	2	−2	−2	$2F$
S_1	1	1	2	−2	3	1
S_2	1	1	2	−2	−7	1
$\tilde{S}_1$	1	1	−2	2	−3	1
$\tilde{S}_2$	1	1	−2	2	7	1
H''	1	2	−1	−2	−2	1
$\tilde{H}''$	1	2	1	2	2	1
$\bar{H}''$	1	2	−1	4	−1	1
$\tilde{\bar{H}}''$	1	2	1	−4	1	1
H'''	1	2	−1	−2	−2	1
$\tilde{H}'''$	1	2	1	2	2	1
$\bar{H}'''$	1	2	−1	4	−1	1
$\tilde{\bar{H}}'''$	1	2	1	−4	−9	1
g'	3	1	−2	0	−10	2
$\tilde{g}'$	$\bar{3}$	1	2	0	20	2

superfields in both the known and the hidden sectors are assumed to be Z_9 singlets. Also listed is the multiplicity N_m of each field. F denotes the number of families (three).

The superpotential of the model contains (identifying fields with the same quantum numbers) the following dimension-three ($d=3$) terms: $\bar{H}QU_c$, HLE_c, QD_cH, $H\bar{H}N$, gg_cS_1, $g_cg_cU_c$, gD_cN, $H'H'E_c$, $\bar{H}'LS_2$, $H'\bar{H}'S_1$, $\tilde{H}''\tilde{\bar{H}}''\tilde{S}_1$, $\tilde{H}'''\tilde{\bar{H}}'''\tilde{S}_2$. The $d=4$ terms are as follows: $\tilde{H}''\tilde{H}''H'H'$, $\tilde{H}''\tilde{H}''LH$, $\tilde{H}''\tilde{\bar{H}}''gg_c$, $\tilde{H}''\tilde{\bar{H}}''H'\bar{H}'$, $\tilde{H}''\tilde{\bar{H}}'''L\bar{H}'$, $\tilde{\bar{H}}''\tilde{\bar{H}}''\bar{H}'\bar{H}'$, $\tilde{H}''\tilde{g}'gH$, $\tilde{\bar{H}}'''\tilde{g}'g\bar{H}'$, $\tilde{H}''\tilde{S}_1H'S_1$, $\tilde{H}''\tilde{S}_1LS_2$, $\tilde{H}''\tilde{S}_2HS_1$, $\tilde{H}''\tilde{S}_2H'S_2$, $\tilde{\bar{H}}''\tilde{S}_1H'E_c$, $\tilde{\bar{H}}''\tilde{S}_1\bar{H}'S_1$, $\tilde{\bar{H}}'''\tilde{S}_2H'E_c$, $\tilde{\bar{H}}'''\tilde{S}_2\bar{H}'S_1$, $\tilde{\bar{H}}''\tilde{S}_2HE_c$, $\tilde{\bar{H}}''\tilde{S}_2\bar{H}'S_2$, $\tilde{\bar{H}}'''\tilde{S}_1QD_c$, $\tilde{\bar{H}}'''\tilde{S}_1LE_c$, $\tilde{g}'\tilde{S}_1gS_2$, $\tilde{S}_1\tilde{S}_1S_1S_1$, $\tilde{S}_1\tilde{S}_2S_1S_2$, $\tilde{S}_2\tilde{S}_2S_2S_2$, $\tilde{S}_1\tilde{S}_2NN$. Although we have imposed only a discrete Z_9 global symmetry, the important thing is to know the actual symmetries of the theory. It turns out that, if we restrict ourselves to terms in the superpotential with $d \leqslant 4$, the theory possesses a larger global symmetry than Z_9, namely, a $U(1)_{PQ}$ in which the Z_9 is embedded. The maximal symmetry of the model is $G \otimes U(1)_{PQ}$. The $U(1)_{PQ}$ charges of the various fields are the same as the Z_9 ones given in Table I. The gauge supermultiplets of both the known and the hidden sectors have zero PQ charge. The Z_9 symmetry is also sufficient to guarantee the absence of $d>4$ terms (e.g., $S_1S_1S_1\tilde{S}_2\tilde{S}_2\tilde{S}_2$) which violate the $U(1)_{PQ}$ symmetry and whose absence is important for the PQ mechanism. Finally, the supersymmetry-breaking terms are assumed to respect the Z_9 symmetry and consequently the effective PQ symmetry.

At this stage, we can also justify the presence of some 3-2-1 nonsinglets like $\tilde{H}''$ and $\tilde{\bar{H}}''$ belonging to incomplete **27***'s. They are needed to create terms like $\tilde{H}''\tilde{\bar{H}}''\tilde{S}_1$ and thereby break the Z_2 symmetry under which only fields belonging to a **27*** transform nontrivially. The $\tilde{H}''$, $\tilde{\bar{H}}''$, $\tilde{H}'''$, and $\tilde{\bar{H}}'''$ are also important for the development of vacuum expectation values (VEV's) by $\tilde{S}_1$ and $\tilde{S}_2$.

Through the couplings gg_cS_1, $H'\bar{H}'S_1$, $\bar{H}'LS_2$, $\tilde{H}''\tilde{\bar{H}}''\tilde{S}_1$, and $\tilde{H}'''\tilde{\bar{H}}'''\tilde{S}_2$, the 3-2-1 singlets S_1, S_2, $\tilde{S}_1$, and $\tilde{S}_2$ can develop a negative (mass)^2 and acquire VEV's $\langle S_1\rangle = \langle \tilde{S}_1\rangle^*$, $\langle S_2\rangle = \langle \tilde{S}_2\rangle^*$, all of the order of M_I. These VEV's break $U(1)_{L\text{-}R} \otimes U(1)_{PQ}$ down to a Z_{40} generated by $(e^{-3\pi i/20}, e^{2\pi i/10})$. The couplings $NN\tilde{S}_1\tilde{S}_2$ and $H\bar{H}N$ create a mixing between H and $\bar{H}$ ($M_I^2M_C^{-1}H\bar{H}N^*$) necessary for tree-level electroweak breaking. For suitable values of the parameters of the theory, H, $\bar{H}$, and N acquire VEV's of order M_W.[9] These VEV's break the Z_{40} down to a Z_{20} generated by $(e^{-3\pi i/10}, e^{2\pi i/5})$. No other field is supposed to develop a VEV.

We now justify the introduction of the extra (light) color triplets g' and $\tilde{g}'$. Let us assume for the moment that they are absent. The $U(1)_{PQ}$ is known to be explicitly broken at the QCD scale, because of its color anomaly, down to a Z_N discrete subgroup[13] [$N = \sum Q_{PQ}$, where the sum is over all fermion color triplets (and antitriplets) and Q_{PQ} is their $U(1)_{PQ}$ charge]. In our model (without g' and $\tilde{g}'$), $N=-15$ and the global symmetry is Z_{15}, which is broken by $\langle S_1\rangle$ and $\langle S_2\rangle$. We will see later that a Z_5 subgroup of $U(1)_{PQ}$ can be embedded in G. Therefore, the breaking of the discrete Z_{15} leads to the formation of Z_3 domain walls (associated with the breaking of Z_{15} to Z_5).

The problem of PQ domain walls is not new and is sometimes solved by the inflating away of the PQ strings formed at the phase transition at which $U(1)_{PQ}$ breaks spontaneously. This method does not seem to be applicable in our case. Because of the fact that the fields (S_1, S_2) responsible for the intermediate scale have masses $\sim M_W$, there is no phase transition until the temperature falls to $T_C \sim M_W$. The $U(1)_{PQ}$ phase transition is therefore unlikely to be inflationary. For the same reason, one is not allowed to break any discrete symmetry in this class of models. Another way of solving the PQ domain-wall problem[14] is to add new color triplets and modify the PQ color anomaly such that instanton effects break $U(1)_{PQ}$ down to Z_5, which is then embedded in G. This explains the role of g' and $\tilde{g}'$.

To finish with the PQ domain walls we show that the Z_5 subgroup of $U(1)_{PQ}$ is embedded in G. Consider the element $(e^{2\pi iN/3}, e^{2\pi iM/2}, e^{i\alpha}, e^{i\beta}, e^{i\theta})$ of $G \otimes U(1)_{PQ}$. One can verify that its action on all the fields is equal to the identity if $\theta = (2\pi/5)k \pmod{2\pi}$, $\alpha = (2\pi/6)l \pmod{2\pi}$, $\beta = (2\pi/6)l - (2\pi/5)k + \pi r \pmod{2\pi}$, $M = l \pmod 2$, $N = l \pmod 3$ (k,l,r integers).

The model has baryon- and lepton-number nonconservation due to the presence of the couplings $g_c g_c U_c$ and $H'H'E_c$. For reasonable values of the couplings ($\sim 10^{-1}$–10^{-2}) the proton lifetime is acceptable and possibly experimentally accessible. The dominant modes are of the type $l^+ l'^- M^+ \nu(\bar{\nu})$ [$l(l')$ denotes a lepton, and M denotes a meson].

The $U(1)_{PQ}$ also ensures the absence of unacceptably large neutrino masses. Their actual values depend on the unknown parameters of the underlying theory.

The (one loop) renormalization-group equations are consistent with $M_C \simeq 10^{17}$ GeV, $M_I \simeq 10^{10}$ GeV, $\alpha_s(M_W) \simeq 0.11$, and $\sin^2\theta_W(M_W) \simeq 0.22$. For $F=3$, $\alpha_G \simeq 0.14$ and the calculation therefore seems reliable.

The spontaneous breaking of $U(1)_{L\text{-}R}$ symmetry produces topologically stable vortices (strings). They have mass per unit length of order $M_I^2 \sim (10^{10}\ \mathrm{GeV})^2$ and thickness $\sim M_W^{-1}$. They are superconducting by virtue of the fact that there are charged fermions (including known quarks and leptons and g,g_c quarks) which couple to Higgs fields (S_1, S_2, $\tilde{S}_1$, $\tilde{S}_2$, N, H, and/or $\overline{H}$) whose phases change by integral multiples of 2π around the vortex. The fermions are trapped in zero modes along the vortex which leads to superconductivity.[15]

Because of the unusual nature of the $U(1)_{L\text{-}R}$ phase transition (i.e., it does not occur until temperatures of order M_W are reached) the strings do not experience an inflationary phase, if there was one, and so should be present in the Universe. It has been suggested that they might be observable as synchrotron sources.[15,16]

Before concluding, we briefly mention three more things. First, variations of the above model can also be constructed. For instance, if one insists that all extra color triplets have masses $\sim M_I$, then this is accomplished by introducing a new 3-2-1 singlet field S_3 (and its mirror) with PQ charge 23. The corresponding discrete symmetry turns out to be Z_{26}. Secondly, the models discussed here offer exciting new possibilities for generation of the required baryon asymmetry (from the decay of g,g_c fields which remain massless and in abundance until the temperature has fallen to M_W) and for neat evasion of the gravitino problem. Finally, one could imagine extending our discussion to the case of a non-Abelian discrete symmetry. In such a case one would need a non-Abelian continuous symmetry. A family symmetry could be a possible candidate.

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