Phenomenology of Superstrings\textsuperscript{1,2}

A. de la Macorra\textsuperscript{3}

Instituto de Fisica UNAM, Apdo. Postal 20-364, 01000 Mexico D.F., Mexico.

Abstract

We consider the low energy phenomenology of superstrings. In particular we analyse supersymmetry breaking via gaugino condensate and we compare the phenomenology of the two different approaches to stabilize the dilaton field. We study the cosmological constant problem and we show that it is possible to have supersymmetry broken and zero cosmological constant. Finally, we discuss the possibility of having an inflationary potential. Requiring that the potential does not destabilize the dilaton field imposes an upper limit to the density fluctuations which can be consistent with the COBE data.

\textsuperscript{1} Invited talk given at the general meeting of the Canadian, American and Mexican Physics Society "CAM 94", Cancun, Mexico.

\textsuperscript{2} To be published by AIP Press

\textsuperscript{3} Email: macorra@teorica0.ifisicau.unam.mx
INTRODUCTION

Superstrings offers the exciting possibility of predicting all the parameters of
the standard model in terms of a single parameter, the string tension. However
in order to realize the full predictive power of the superstring it is necessary to
determine the origin and effects of supersymmetry breaking. Only after SUSY
is broken are the vacuum expectation values (vevs) of moduli determined and
these determine the couplings of the effective low energy theory. Also SUSY
breaking must be responsible for the splitting of supermultiplets allowing for the
superpartners to be heavier than their standard model partners.

The dilaton field $S$ plays a crucial role since it interacts with all scalar fields
and has a generic interaction. In the context of gaugino condensate [1] it is the
dilaton field that sets the mass hierarchy. Its auxiliary field may be responsible
for breaking SUSY in which case the soft supersymmetric breaking terms are
universal. Furthermore, the dynamics of the dilaton field does not allow for the
scalar potential $V$ to inflate [2], [3] and therefore $S$ must be at its minimum before
the universe expands rapidly. Clearly, a potential must be positive to inflate. Is
it then possible to have $S$ stable and $V > 0$?

Due to lack of space we will just give a short presentation of the different pos-
sibilities to stabilize the dilaton field and a discussion of some phenomenological
consequences, vanishing of the cosmological constant and inflation. Unfortu-
nately, we will not be able to talk about many interesting topics like $S$ duality,
fermion masses, the strong CP problem, discrete and accidental symmetries and
the phenomenology of light scalars and axions.

DILATON FIELD AND SUSY BREAKING

In the absence of non-perturbative effects, the dilaton field interacts with all
scalar fields with an $1/S$ interaction, and the scalar potential does not have a
stable solution. There are several possibilities to stabilize the dilaton. Firstly,
one can impose an $S$-duality [4] (analogous to the $T$ dual symmetry) invariance to
the potential. Another possibility is to consider gaugino condensation. Gaugino condensation offers a very plausible origin for SUSY breaking for it is very reasonable to expect such a condensate to form at a scale between the Planck scale and the electroweak breaking scale if the hidden sector gauge group has a (running) coupling which becomes large somewhere in this domain. Non-perturbative studies in effective supergravity theories resulting from orbifold compactification schemes suggest the dynamics of the strongly coupled gauge sector is such that the gaugino condensate will form and trigger supersymmetry breaking.

Using symmetry and anomaly cancelation arguments one derives an effective superpotential for the gaugino condensate $< \overline{\chi}_L \chi_R >$ in terms of $S$

$$W_0 = d(T) e^{-3S/2b_0} \simeq \Lambda_c^3$$

where $\Lambda_c$ is the condensation scale. The scalar potential is given by $V_0 = e^K |W_0|^2 [(1 + \frac{3S}{2b_0})^2 - 3] = | < \overline{\chi}_L \chi_R > |^2 \frac{b_0^2}{36} [(1 + \frac{3S}{2b_0})^2 - 3]$ and it does not have a stable solution. There are two different approaches to stabilize the potential:

(I) Consider two gaugino condensates and chiral matter fields with non-vanishing v.e.v. and slightly different one-loop beta function coefficients $b_1^0 \simeq b_2^0$ with a superpotential

$$W_0 = d_1 e^{-3S/2b_0^1} - d_2 e^{-3S/2b_0^2}.$$

A stable solution is found for vanishing auxiliary field of the dilaton $G_S = W_S - W/S_r \simeq \frac{\partial W_0}{\partial S} = 0$. SUSY will then be broken by the auxiliary field of the moduli field $G_T$.

(II) Consider loop corrections of the 4-Gaugino interaction "à la N-J-L" using the Coleman-Weinberg one-loop potential $V_1$. A stable solution is found for $V = V_0 + V_1$ with a single gaugino condensate. The leading contribution to $V_1$ is given by the gaugino mass $m_g$ and since $m_g^2/\Lambda_c^2 << 1$ one has $V_1 \simeq -\frac{n_g}{32\pi^2} \Lambda_c^2 m_g^2$ where $n_g$ is the dimension of the hidden gauge group. The scalar potential $V =$
$V_0 + V_1$ can then be written as

$$V \simeq e^K [|h|^2 (1 - \delta F_S^2) + |h_T|^2 (1 - \delta |F_T|^2) - 3|W|^2 (1 + 3\delta) - \delta A]$$

$$V \simeq e^K \left[ |h|^2 + |W|^2 \left( \frac{3T^2}{4\pi^2} |\tilde{G}_2(T)|^2 (1 - F_T^2\delta) - 3(1 + 3\delta) \right) - \delta A \right] \quad (1)$$

with $A \equiv h_S h_T - 3W(F_S + F_T) + h.c., h = S_r G_S = S_r W_S - W = F_S W, h_T = \sqrt{3} T_r G_T = F_T W, F_S = -(1 + \frac{3S_r}{2b_0}) \gg 1, F_T = \sqrt{\frac{3T^2}{4\pi^2}} \tilde{G}_2(T)$ and $\delta \equiv \frac{n_g b_0}{144\pi^2} \ll 1$.

We recover the tree level potential by setting $\delta = 0$.

**Results**

Let us now compare the results obtained by minimizing the scalar potential in the case of two gaugino condensates (I) and for the case of one gaugino condensate (II). In both cases a large hierarchy can be obtained.

| (I) 2 gaugino condensates | (II) 1 gaugino condensate |
|---------------------------|---------------------------|
| $< S > \simeq 0.17 \frac{N_2 M_1 - N_1 M_2}{(3N_2 - M_2)(3N_1 - M_1)}$ | $< S > \simeq \frac{4\pi}{\sqrt{n_g}}$ |
| $< T > \simeq 1.2$ | $< T > \simeq \frac{3S_r}{2\pi b_0 (1 - \alpha_0)} \simeq O(10 - 20)$ |
| $m_{3/2} = O(1)TeV$ | $m_{3/2} = O(1)TeV$ |
| $G_S = 0, \; G_T \neq 0$ | $G_S \gg G_T$ |

where $b_i = \frac{1}{16\pi^2} (3N_i - M_i)$, $\alpha_0$ is related to the number and weight of the hidden sector fields (for an orbifold with untwisted fields only $\alpha_0 = -1/3$) and $G_S, G_T$ are the auxiliary fields of the dilaton and moduli fields respectively. All the parameters are related to the normalization and number of fields of the hidden sector and are fixed for a given compactification scheme. Note that the v.e.v. of the moduli in case (II) are much larger than in case (I).

The phenomenology depends strongly on which auxiliary field breaks SUSY and in case (I) SUSY is broken due to the auxiliary field of the moduli $G_T$ while in case (II) it is mainly due to the auxiliary field of the dilaton $G_S \gg G_T$. The soft supersymmetric breaking terms are universal if SUSY is broken via $G_S$ while they differ if SUSY is broken via $G_T$ and they have been calculated in
Experimental evidence on the neutron dipole momenta show that the scalar masses must be almost degenerated \(((m_1^2 - m_2^2)/m^2 < 10^{-2} - 10^{-3})\).

**UNIFICATION SCALE AND COUPLING**

We will, now, discuss the unification scale and coupling. The fine structure constant at the unification scale is \(\alpha^{-1}_X \simeq \frac{4\pi}{g_{\text{gut}}} \simeq 4\pi \text{Re } S\) and using the solutions of minimization for case (II) we have \([8]\)

\[
\alpha^{-1}_X \simeq \frac{16\pi^2}{\sqrt{n_g}}. \tag{2}
\]

Consistency with MSSM unification \([9]\) requires then \(33 < n_g < 44\) and this is satisfied only for the gauge groups \(SU(6)\) or \(SO(9)\). In case (I) there are more possibilities to obtain a fine structure constant required by MSSM unification and the gauge group is therefore not constraint. However, MSSM unification also imposes constraint on the value of the unification scale. The unification scale \(M_X\) is a moduli dependent function with the property to be close to the string scale for \(T \simeq 1\). On the other hand if \(T\) is larger then there is the possibility of having \(M_X \simeq 10^{16}\) as required \([9]\). As an example we can take an \(SU(6)\) with \(b_0 = 15/16 \pi^2\) for which \(T = 22\), the unification fine structure constant and scale are \(\alpha^{-1}_X = 26.1, M_X = 2.8 \times 10^{16} \text{GeV}\).

**COSMOLOGICAL CONSTANT**

The vanishing of the cosmological constant is an important and still open problem. Experimental evidence shows that the cosmological constant is very small and it is not clear how to implement it a natural scheme. Another approach, is to study the possibility of having a potential with vanishing cosmological constant by introducing new terms and fine tuning them. In non-supersymmetric models this represents no problem. However, in SUSY potentials the possible terms are constraint. In fact, for global supersymmetry it is not possible, if one requires

\(^4\text{Considering only } SU(N) \text{ and } SO(N) \text{ gauge groups.}\)
SUSY to be broken (spontaneously or explicitly). On the other hand, in sugra models one has, in principle, the possibility of having $V=0$ and SUSY spontaneously broken (SB). The breaking of SUSY is a necessary condition but for the simplest potentials if a symmetry is SB the vacuum energy will then be proportional to the symmetry breaking scale ($\Lambda$), $V = -O(\Lambda^4)$. For realistic hierarchy solution $V \simeq -(10^{-12})^4$ which is many orders of magnitude larger than the observational upper limit $|V| < 10^{-120}$. In the context of supergravity models, the canceling of the cosmological constant must come through a non-vanishing value of an auxiliary field $G_i \neq 0$.

The condition of zero cosmological constant, considering the tree level potential only, is $G_a(K^{-1})^a_b G^b = 3|W|^2$ but it is hard to satisfy dynamically. Imposing $T$-duality symmetry and assuming, for simplicity, that the $T$ dependent part of the superpotential can be factorized we have $W = \eta(T)^{-6} \Omega(S, \phi)$ with $\Omega = \Omega_0(S) + \Omega_{ch}(\phi)$ and $\Omega_0$ the contribution from the gaugino condensates while $\Omega_{ch}$ the contribution from the chiral matter fields. The scalar potential becomes

$$V_0 = e^K|\eta|^{-12} \left[ |h|^2 + |k|^2 + |\Omega|^2 \left( \frac{3T^2}{4\pi^2} |\hat{G}_2(T)|^2 - 3 \right) \right]$$

(3)

where $\hat{G}_2$ is the Eisenstein function of modular weight 2, $h = S_r \Omega_S - \Omega$ and $k \equiv K_s \Omega + \Omega_i$.

To find the vacuum state with zero cosmological constant one needs to solve the eqs. $|V| = V_S| = V_T| = V_i| = 0$ where “$|$” denotes that the quantities should be evaluated at the minimum. $|V| = V_T| = 0$ is satisfied for $T$ at the dual invariant points ($T = 1, e^{-\pi/6}$) where $\hat{G}_2 = 0$. This implies that the auxiliary field of the moduli is zero, $G_T = 0$, and it does not break SUSY contrary to case (I) where the condition $V| = 0$ was not imposed. The cancelation of the cosmological constant must then be due to $h$ or $k$. In the absence of $k$, for the two gaugino condensates case, the solution to $V_S = 0$ is $h = 0$ and therefore the condition $V| = 0$ must be due to $k$. However, if all superpotential terms $\Omega_{ch}$ are at least quadratic in $\phi_i$ then $k = 0$ for $\phi_i = 0$. The only possibility to have $k \neq 0$ is with a linear superpotential $\Omega_{ch} = c\phi$, where $c$ is an arbitrary constant to be fine
tuned to give $V| = 0$. Let us take the example $N_1 = 6, M_1 = 0, N_2 = 7, M_2 = 6$. For this example one obtains a large hierarchy and $S = 2.16$ if $k = 0$. The numerical solution to $V| = V_S| = V_\phi| = 0$ is $S = 2.15$, $c = 1.2 \times 10^{-15}$, $\phi = -0.5$ corresponding to a stable solution. We note that the variation of $S$ is quite small.

We have thus seen that it is possible to cancel the cosmological constant using the tree level sugra scalar potential. SUSY is also broken but mainly due to the auxiliary field $k = G_\phi$ since $G_T = 0$ and $G_S \approx 0$. Unfortunately, most phenomenological terms depend on how SUSY is broken and in this case it is broken via the term which we now least and was introduced with the only motivation of rendering $V| = 0$.

If SUSY is broken via a single gaugino condensate, i.e. case (II), one can use the same linear superpotential and the cosmological constant may be arranged to vanish at the minimum. The welcome difference in this case is that SUSY is mainly broken by the auxiliary field of the dilaton $G_S$.

**INFLATION**

String models are valid below the Planck scale and it should therefore describe the evolution of the universe. The standard big bang theory has some shortcomings like the horizon and flatness problems. An inflationary epoch, where the universe expanded in an accelerated way, may solve this problems. For arbitrary values of the different fields one expects $V$ to be positive and to evolve to its minimum. In this evolution one would hope for an inflationary period. However, it is difficult to obtain an inflationary potential in string models due to the dynamics of the dilaton field $S$.

The interaction of the dilaton field is very much constraint and the superpotential $W$ is independent of $S$ perturbatively but it may acquire a non-trivial superpotential non-perturbatively like when gauginos condense. Even in the presence of the non-perturbative superpotential when the scalar potential $V$ evolves to the minimum of the dilaton field, the universe, keeping all other fields fixed, does not
go through an inflationary period. At the minimum, SUSY is broken and for vanishing v.e.v. of the chiral fields, the vacuum energy is negative and of the order of $\Lambda^4$ but as we have seen in the previous section it is possible to have SUSY broken with vanishing cosmological constant. However, in string theory there are many chiral matter fields and its potential may drive an inflationary potential \[3\]. The condition that these potential terms do not destabilize the dilaton field yields some strong constraint on the magnitude of these terms. Nevertheless, it is still possible to have a potential that inflates enough to solve the horizon and flatness problem. The constraint on the magnitude of these potential terms sets un upper limit on the density fluctuations which is of the order of magnitude as the observed by COBE \[3\].

A possible picture is that of a universe that starts with random values of the different fields (dilaton, moduli, chiral matter fields). The universe cools down and it evolves in a standard non-inflationary way until $S$ and $T$ are stabilized. Below this scale, other fields, like the chiral matter fields, could drive an exponentially fast expansion of the universe as long as its potential does not destabilize $S$ and $T$. So, we expect that the universe arrives at an inflationary period naturally when the fields roll down to their minimum and the inflationary conditions are first met.

ACKNOWLEDGMENTS

I would like thank G.G. Ross and S. Lola for many useful discussions and comments.

References

[1] For a review see D. Amati, K. Konishi, Y. Meurice, G. Rossi and G. Veneziano, Phys. Rep 162 (1988) 169; J.P.Derendinger, L.E.Ibanez and H.P.Nilles, Phys. Lett. B155 (1985) 65; M.Dine, R.Rohm, N.Seiberg and E.Witten, Phys. Lett. B156 (1985) 55; A. Font, L. Ibanez, D. Lust and F. Quevedo, Phys. Lett. B245 (1990) 401.
[2] R. Brustein and P. J. Steinhardt, Phys. Lett. B302 (1993) 196; P. Binetruy and M. K. Gaillard, Phys. Rev. D34 (1986) 3069.

[3] A. de la Macorra and S. Lola, hep-ph/9411443, IFUNAM -FT-94-63 Mexico preprint, HD-THEP-94-45 Heidelberg preprint.

[4] A. Font, L. E. Ibanez, D. Lüst and F. Quevedo, Phys. Lett. B249 (1990) 35.

[5] B. de Carlos, J. A. Casas and C. Munoz, Phys. Lett. B263 (1991) 248 and ref. therein.

[6] A. De La Macorra and G. G. Ross, Nucl. Phys. B404 (1993) 321; Phys. Lett. B325 (1994) 85.

[7] B. de Carlos, J. A. Casas and C. Munoz, Phys. Lett. B 299 (1993) 234.

[8] A. de la Macorra, Unification Scale in String Theory, Oxford preprint OUTP-93-33P, hep-ph/9401230, to appear in Phys. Lett B.

[9] J. Ellis, S. Kelley and D.V. Nanopoulos, Phys. Lett. B249 (1990) 441; Phys. Lett. B260 (1991) 131; U. Amaldi, W. de Boer and H. Fürstenau, Phys. Lett. B260 (1991) 447; P. Langacker and M. Luo, Phys. Rev. D44 (1991) 817.

[10] A. de la Macorra "Vanishing of the Cosmological Constant, Stability of the Dilaton and Inflation" Mexico preprint IFUNAM-FT-94-64 hep-ph/9501250; A. de la Macorra and G.G. Ross, “Supersymmetry Breaking in 4D String Theory”, (preprint OUTP-31P);