Cosmological moduli problem, supersymmetry breaking, and stability in postinflationary cosmology

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We review scenarios that have been proposed to solve the cosmological problem caused by moduli in string theory, the postmodern Polonyi problem (PPP). In particular, we discuss the difficulties encountered by the apparently "trivial" solution of this problem, in which moduli masses are assumed to arise from nonperturbative, SUSY-preserving, dynamics at a scale higher than that of SUSY breaking. This suggests a powerful *cosmological vacuum selection principle* in superstring theory. However, we argue that if one eschews the possibility of cancellations between different exponentials of the inverse string coupling, the mechanism described above cannot stabilize the dilaton. Thus, even if supersymmetric dynamics gives mass to the other moduli in string theory, the dilaton mass must be generated by SUSY breaking, and dilaton domination of the energy density of the Universe cannot be avoided. We conclude that the only proposal for solving the PPP that works is the intermediate scale inflation scenario of Randall and Thomas. However, we point out that all extent models have ignored unavoidably large inhomogeneities in the cosmological moduli density at very early times, and speculate that the effects associated with nonlinear gravitational collapse of these inhomogeneities may serve as an efficient mechanism for converting moduli into ordinary matter. As an important by-product of this investigation we show that in a postinflationary universe minima of the effective potential with a negative cosmological constant are not stationary points of the classical equations of scalar field cosmology. Instead, such points lead to catastrophic gravitational collapse of that part of the Universe which is attracted to them. Thus postinflationary cosmology dynamically chooses non-negative values of the cosmological constant. This implies that supersymmetry *must* be broken in any sensible inflationary cosmology. We suggest that further study of the cosmology of moduli will lead to additional important insight about cosmology, SUSY breaking, and the choice of the vacuum in superstring theory.

PACS number(s): 98.80.Cq, 11.27.+d, 12.60.Jv

I. INTRODUCTION

The modular problem of string cosmology [1,2] is a modern version of the cosmology difficulties created by the Polonyi field in the earliest versions of spontaneously broken supergravity [3]. One may call it the postmodern Polonyi problem (PPP). Briefly, in hidden sector models of supersymmetry (SUSY) breaking (with gravitational strength forces playing the role of messenger [4]) there often exist scalar fields with masses on the order of the weak scale and gravitational strength coupling to ordinary matter. Even in inflationary cosmologies these fields behave like nonrelativistic matter just after inflation and dominate the energy density of the Universe until it is too low for nucleosynthesis to occur.

In generic hidden sector supergravity models, such fields are needed to generate gaugino masses of order the weak scale. One can eliminate them by choosing a model in which SUSY is broken at low energies. In string the-

ory we have no such luxury. Massless moduli fields exist in all known string ground states. They parametrize the continuous ground-state degeneracies characteristic of supersymmetric theories. Even if one were to find a ground state with no *geometrical* moduli[1] one would still have the model-independent dilaton superfield. If these moduli fields, which are massless to all orders in perturbation theory, get their mass from the same nonperturbative mechanism which breaks SUSY, and if the SUSY-breaking F term is $< 10^{10}$–10^{11} GeV, as it is in all known models of SUSY breaking,[2] then the moduli pose

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[1] We use this phrase to describe moduli associated with the internal conformal field theory of a string ground state which is the tensor product of four flat spacetime dimensions and a conformal field theory with a discrete spectrum of conformal dimensions.

[2] ... with the possible exception of models with continuous noncompact global symmetries that have been discussed by Binetruy and Gaillard [5]. These models cannot be exact consequences of string theory, but is possible that discrete remnants of the noncompact symmetries used by these authors are sufficient to obtain their results.

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a cosmological problem.

In this paper we will survey attempts that have been made to resolve this problem. In our opinion, no completely satisfactory resolution of the cosmological moduli problem has been discovered, although the proposal of Randall and Thomas seems promising. Nonetheless, all extent models require new and interesting phenomena to occur, both in the realm of cosmology and in the theory of SUSY breaking. We view this as an indication that a correct theory of the cosmology of moduli will have important, and probably testable, consequences.

In Sec. II of this paper we review existing proposals for solving the cosmological moduli problem, including an unpublished (because unworkable) proposal by Cohen, Nir, Moore, and one of the present authors [6]. The proposal of Randall and Thomas [7] is reviewed. It seems to solve successfully the PPP and can be made technically natural by imposing a certain discrete R symmetry on their model. Louis and Nir [8] have investigated models which incorporate at tree level the mechanism proposed by Binetruy and Gaillard [5]. They show that, in generic vacuum states, radiative corrections drastically limit the separation that one can achieve between the moduli masses and the weak scale. The allowed separation is marginally satisfactory from the cosmological point of view but all of these models have flavor-changing neutral currents that are too large to be compatible with experiment. We briefly discuss the question of whether there are specific vacuum states in which radiative corrections to the Binetruy-Gaillard mechanism are hierarchically small.

We then turn to proposals for giving mass to the moduli at a scale higher than that of nonperturbative SUSY breaking. This turns out to be more difficult than it sounds. In supergravity the manifold of chiral superfields must be a Kahler manifold, and the effective potential has the form

$$V = e^{K}[D_i W D_{\bar{j}} \bar{W} K^{i\bar{j}} - 3|W|^2] \, . \qquad (1.1)$$

Here K is the Kahler potential, D_i the corresponding Kahler covariant derivative, and W the superpotential. In order to have a supersymmetric ground state with vanishing cosmological constant, the superpotential and all of its first derivatives must vanish at the minimum of the effective potential. This is a nongeneric condition, involving $n + 1$ equations for n unknowns. It can be satisfied "naturally" if both supersymmetry (which requires the Kahler derivatives of W to vanish) and a complex R symmetry (which requires the superpotential to vanish) are preserved. We argue that in the context of the conventional gaugino condensation description of nonperturbative effects in string theory[3] the vanishing of the superpotential can only occur at points in moduli space where chiral multiplets charged under the hidden sector group become massless. No such points have been

found on any of the submanifolds of moduli space yet explored.

Thus, while there are examples of nonperturbatively generated superpotentials which give rise to stable, supersymmetric ground states, these ground states generically break all R symmetries. The superpotential is nonvanishing at the potential minimum. As a consequence such a state will exhibit a large negative cosmological constant.

In Sec. III, probably the most important section of this paper, we show that a negative cosmological constant is more than just a phenomenological embarrassment. A universe that has undergone inflation cannot settle into a minimum of the potential with negative vacuum energy. Instead, it undergoes a violent recontraction on microscopic time scales. Thus, if a system has several minima of its effective potential, some of which have negative energy, cosmological evolution will favor those with non-negative energy.

The argument described above is based on the classical equations of cosmological evolution. States with non-negative vacuum energy are potentially unstable to decay into negative energy states via quantum tunneling. We show that in theories of moduli, and more generally in "natural" models of inflation, the tunneling amplitudes are less than $e^{-10^{10}}$ per unit space time volume, and might be identically zero. A zero energy ground state in such a theory has a lifetime for decay into hypothetical negative energy states, which is much longer than the age of the Universe. This implies that even though our own universe might be unstable in such a model, we have no need to worry about living in such an unstable world.

In Sec. IV we return to an examination of supersymmetric ground states which can freeze the moduli in string theory. We argue that the restriction to states with vanishing cosmological constant is indeed very strong in this context. As mentioned above, the requirement appears to force us to sit at a point in moduli space where extra chiral multiplets charged under the hidden sector gauge group become massless. There are no known points where this occurs. We discuss the implications, and provide a favorable interpretation, of this negative result. It suggests that the search for supersymmetric ground states with nonperturbatively vanishing cosmological constant may lead to isolated points in string moduli space. Thus, the cosmological selection of such states becomes a dynamical vacuum selection principle for string theory.

We point out that the mechanism under discussion can probably not give mass to the dilaton. Finally, we examine the generation of a dilaton mass by SUSY-violating phenomena, and confirm that all known mechanisms for SUSY breaking still lead to cosmological disaster.

In passing, we provide a mechanism for cancellation of the cosmological constant in scenarios of low energy SUSY breaking. We show that it requires the existence of a light weakly coupled field (the dilaton in our case) with a mass of order 10^{-2}–10^{-3} eV. In the presence of such a field, the cancellation of the cosmological constant in theories with low-energy SUSY breaking is no more unnatural than it is in hidden sector models. In addition,

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[3]The arguments are definitely more general than this, and probably apply to a wide range of nonperturbatively generated superpotentials in SUSY-gauge theories.

the dynamics of a field with such a small mass might conceivably explain the fine-tuning of the cosmological constant to levels consistent with observation. Unfortunately, it is precisely this light field which dominates the energy density of the Universe in these models, leading to a PPP. In this case, the ideas of [6] can be made to work, saving nucleosynthesis. However, the ratio of nonrelativistic matter to radiation in the present era is predicted to be many orders of magnitude larger than it actually is.

In Sec. V we present a highly speculative scenario which might resolve the cosmological moduli problem in a novel way. We point out that in all extant models, moduli do dominate the energy density of the Universe for a long time after inflation. Since they behave like nonrelativistic matter, inhomogeneities in the moduli fields grow with the expansion. We show that they go nonlinear long before the moduli decay. This leads us to speculate that nonlinear processes associated with gravitational collapse (e.g., the formation of stable, gravitationally bound *modular stars*) could lead to an enhancement in the decay of moduli into ordinary matter, thus eliminating the moduli before the era of nucleosynthesis. At present, we do not know how to calculate in this complicated nonlinear regime, so we cannot assess the viability of this proposal.

Finally let us note the recent paper of Bento and Bertolami, which also treats the Polonyi problem in string theory [9].

II. SOME MODEST PROPOSALS

The general argument that moduli fields dominate the energy density of the Universe has a number of loopholes, and proposals to avoid the problem have tried to exploit most of them.

A. Intermediate scale inflation as a solution to the PPP?

We begin by reviewing the work of Randall and Thomas (RT) [7], who suggested inflation with a weak scale Hubble parameter as a mechanism for diluting the moduli. If the Hubble parameter is of the order of the modular masses then their energy density indeed redshifts away exponentially during inflation. Randall and Thomas estimate that 7 to 10 e-foldings are sufficient to reduce the modular energy density to an acceptable level. They call their proposal weak scale inflation, but we prefer the name intermediate scale inflation (ISI), because the intermediate scale $\sqrt{M_W M_P}$ is the fourth root of the inflationary vacuum energy in this model.

RT note that intermediate scale inflation produces density fluctuations many orders of magnitude smaller than those required by observations of inhomogeneities in the cosmic microwave background. To resolve this, they invoke a previous era of inflation, with a higher vacuum energy density. They claim that the requirement that the primordial fluctuations responsible for the observed microwave background distribution not be blown up larger than our horizon volume by the second stage of inflation,

is that there be fewer than 25–30 e-foldings of ISI. This is compatible with the amount of inflation necessary to eliminate the moduli.

Unfortunately, the RT proposal appears to have a naturalness problem. Indeed, such proposals were considered and telegraphically dismissed by Nelson in a cryptic footnote in [1]. The problem is that in order to obtain sufficient reheating (i.e., in order for the Randall-Thomas inflaton *not* to pose the same kind of problem as the moduli), one must couple the inflaton to ordinary matter via renormalizable couplings. Generically, this would lead to a renormalized effective potential for the inflaton field which varied when the inflaton field changes by an amount of order the weak scale. Such a potential cannot lead to inflation.

Randall and Thomas propose to deal with this problem by invoking SUSY nonrenormalization theorems. They would like to have a term in the superpotential coupling the inflaton I to low-energy fields in a renormalizable way, but no terms in the superpotential that depend only on I. Neither can they afford to have soft SUSY-breaking terms containing only a single power of the SUSY-breaking F term multiplied by a function of I/M_P. Any superpotential term or soft SUSY-breaking term of this type will generate a potential much larger than the fourth power of the intermediate scale. If no such terms occur, then the potential for I can vanish up to linear order in F, at the minimum for the other fields.

The solution they find to this infinite set of conditions is clever and probably unique. A discrete R symmetry under which I is neutral forbids all the relevant terms. In addition one must assume no elementary fields, Φ_2 with R charge 2, to prevent the appearance of terms of the form $\Phi_2 G(I/M_P)$ in the superpotential. Finally one must worry about the necessary breaking of the R symmetry.

Surprisingly, this does not pose any problems. Generic nonrenormalizable hidden sector (NRHS) [1] models contain a strongly interacting sector which breaks all complex R symmetries at a scale M_R related to the SUSY-breaking scale by $M_R \sim (F M_P)^{1/3}$. This is necessary in order for the cosmological constant to be zero. The field whose F term breaks SUSY carries R charge zero (and so its F term carries R charge -2) because it is a flat direction of the tree level potential, whose vacuum expectation value (VEV) is being fixed by nonperturbative physics at scale M_R. The R symmetry is a valid symmetry along this flat direction only if the superfield carries R charge zero.

In any such model, all R breaking terms in the action of the field I will have their origin in its coupling to the strongly interacting sector at M_R. If all such couplings are nonrenormalizable (which is automatically the case if the strongly coupled theory is a pure SUSY-gauge theory or one with matter in purely chiral representations), the R breaking superpotential induced for I will have the form $M_R^3 w(I/M_P)$ and will give an intermediate scale potential (remember that in such theories $M_f^2 \sim M_R^3/M_P$).

Renormalization of the Kahler potential of I by weak scale loops will modify this potential in the regime where I is much smaller than the Planck scale and inflation will not occur when I is in this regime. However, the

asymptotic behavior of these corrections for large I will be of the form

$$\delta V \sim \frac{\lambda^2}{8\pi^2} \ln\left(\frac{I^2}{M_P^2}\right) V \,, \qquad (2.1)$$

where λ is the renormalizable Yukawa coupling of I to weak scale matter. For a reasonable range of small values of λ, these corrections are negligible compared to V itself, even when I is a few times the Planck scale.

Thus, the imposition of a discrete R symmetry makes the Randall-Thomas proposal technically natural within the framework of NRHS theories. It remains to be seen if one can actually find a string vacuum state with a field with the properties of I. One must further study the effect on this proposal of the early gravitational clumping of moduli that we will discuss in the final section. With these caveats in mind, however, one can conclude that intermediate scale inflation is an acceptable solution of the PPP. It remains to be seen whether such a model can be derived from string theory and whether the double inflation scenario invoked by Randall and Thomas truly emerges naturally from the dynamics of a specific model.

B. Can one have a hierarchy between squark and moduli masses?

A second loophole in the argument that moduli dominate the energy density of the universe is the assumption that the highest scale of SUSY breaking F is related to the squark masses by $F \leq M_P M_{\rm sq}$. The motivation for this assumption is the fact that one can write dimension-6 operators invariant under any compact symmetry which couple the superfield whose F term breaks SUSY, to the quark superfields. These terms generate squark masses when SUSY is broken. It is reasonable to assume that the relevant scale for these nonrenormalizable couplings is not larger than the Planck mass, whence the bound. Binetruy and Gaillard [5] have suggested that noncompact global symmetries can suppress squark masses by higher powers of the Planck scale. The continuous global symmetries that they invoke cannot be exact symmetries of string theory, but one might hope that some discrete remnant of these symmetries could do the job.

One cannot hope for such a mechanism to be stable under radiative corrections in a theory in which SUSY solves the hierarchy problem. Stability of scalar masses under gravitational radiative corrections bounds the gravitino mass by about 10^{11} GeV. Louis and Nir [8] have studied the one-loop radiative corrections to vanishing scalar masses around conventional string vacua. They find that generically, the one-loop corrections due to light fields with gauge charge are nonvanishing. Thus, in the vacuum states they studied, the inequality relating the high scale of SUSY breaking to the squark masses can only be weakened by a single factor of α_3/π. This may allow us to raise the moduli masses high enough to allow for nucleosynthesis. It is certainly not enough to allow the temperature to which the Universe is reheated after modular decay to be high enough to ignite weak scale baryogenesis. We will see below that this may not be too much of a problem.

Unfortunately, Louis and Nir also showed that models of this type have large flavor-changing neutral currents as a consequence of string loop corrections. They are unlikely to be compatible with experiment. We note, however, that Louis and Nir studied generic vacuum states which have noncompact continuous symmetries at the tree level. We know that these symmetries are broken by loop corrections, but some discrete noncompact subgroup might be preserved in *particular vacuum states*. It is conceivable that in such special vacuum states the radiative corrections to squark masses are hierarchically small, as suggested by Binetruy and Gaillard. Perhaps the flavor problems are also mitigated in vacuum states invariant under noncompact discrete groups.

C. Saviors of the Universe?

We now turn to the proposal of [6] for solving the reheating problem. Although unsuccessful, it illustrates some interesting features that may reappear in a more robust theory of moduli. The value we have been using for moduli masses is an order of magnitude estimate. Let us assume that for one or more of the moduli fields, this estimate is off by the rather large factor of 30. Then some of the moduli will have a reheat temperature[4] of order a few MeV, hot enough for nucleosynthesis.[5] More importantly, until the energy density falls to this value, the heavy moduli (which we will dub the *saviors*) behave just like the light ones. The ratio of energy densities in heavy and light moduli is of order 1 at the end of inflation,[6] and remains constant until the saviors decay. Thus, if the initial ratio is somewhat larger than 1, we will have a radiation-dominated universe at the energy density relevant for nucleosynthesis.

Of course, the temperature will never be high enough for even weak scale baryogenesis, but this is unnecessary. All of the moduli have only Planck scale couplings to ordinary matter, and it is perfectly consistent with all data on baryon number conservation to assume that these couplings violate baryon number and CP. Thus, baryogenesis could arise from the (obviously out of equilibrium) decay of the saviors.[7] The baryon to photon ratio produced in this decay process would be the inverse savior mass, measured in MeV, times the asymmetry in a given decay. Thus, a factor of 10^{-7}–10^{-8} in the baryon

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[4]We use the phrase *reheat temperature of the moduli* to refer to the temperature of the gas of light particles produced by thermalization of the products of modular decay.

[5]The proposal to solve the Polonyi problem by raising the Polonyi mass above the weak scale was apparently first made by the authors of [10]. Recently Yamaguchi *et al.* investigated a similar suggestion for solving the Polonyi problem in a more general context [11].

[6]Actually it is more like the ratio of the number of fields of each type. This leads one to search for string ground states with a small total number of moduli, something that may be called *the minimum modulus principle*.

[7]Making them the creators of all matter as well as its saviors.

to entropy ratio just represents the small ratio between the reheat temperature and the mass of the saviors. The rest of the observed suppression of the baryon-to-photon ratio could come from a weak-coupling factor. The decay of the heavy savior into conventional matter can be computed in the parton model in terms of the matrix elements of the leading operator which causes the decay. In order to see a CP-violating phase and obtain an asymmetry one must interfere tree level and higher-order diagrams and pay the price of a loop factor. It is not implausible then that such a model could reproduce the observed baryon asymmetry.

The problem of this model comes with the decay of the light moduli. Although the entropy produced in their decay does not wash out the baryon asymmetry, the details of the decay process completely change the element abundances produced in the (presumed successful) nucleosynthesis that followed savior decay. Moduli are very heavy, and their decays will produce hard photons and hard hadron jets. These will thermalize their energy, initially through hardonic collisions, but in the process will first produce large numbers of photons capable of disintegrating deuterium. Dimopoulos *et al.* [12] have studied this problem in great detail for gravitinos, and have come to the conclusion that the fraction of energy density in heavy decaying particles in such a situation cannot be larger than 10^{-6}. In the model of [6] we cannot reasonably expect this fraction to be smaller than one-tenth.

To summarize, although several ideas have been proposed for resolving the cosmological moduli problem, only intermediate scale inflation appears to hold out any promise. The models discussed so far retained the assumption that the physics responsible for moduli masses was also the agent of dynamical SUSY breaking. At first sight, the most reasonable resolution of the whole problem would seem to be decoupling these two nonperturbative effects. Moduli get their mass from dynamics at a higher scale than SUSY breaking. This seems particularly plausible in view of the fact that we have two hints in the present data of the existence of a new scale of physics at 10^{16} –10^{17} GeV. These are the "observed" unification of couplings, and the vacuum energy density required to explain the Cosmic Background Explorer (COBE) microwave background anisotropy data in inflationary cosmology. If physics at such a scale generated moduli masses, the moduli would decay long before the beginning of the classical period of cosmic history.

It is somewhat surprising to find that this simple solution does not really work. More precisely, we show below that the nonperturbatively generated superpotential for moduli must vanish in the vacuum in order to have an acceptable cosmology. This nongeneric condition is not satisfied by any know superstring vacuum. Further, we argue that a SUSY-preserving superpotential cannot stabilize the dilaton unless we are willing to imagine the cancellation of two effects which are of different order in the weak-coupling expansion.

Before proceeding to demonstrate these facts, we must pause for an act of iconoclasm. Our discussion will hinge on the fact that typical supersymmetric minima of the potential have negative vacuum energy. Everyone would agree that this is not good for phenomenology. What we will demonstrate is that in the context of inflationary cosmology, such minima do not even correspond to stationary states of the system. This will lead to a powerful cosmological selection principle for superstring vacua.

III. THE IMPORTANCE OF BEING NON-NEGATIVE

All systems seek their state of lowest energy, is a maxim that physicists learn sometime in their preschool years. Like most convenient aphorisms, it summarizes the behavior of an often complicated set of rules in a way that is easy to remember and easy to apply. The utility of this principle in physics has been so great that it is somewhat shocking to find that there are systems, such as spin glasses, to which it does not apply. It is little wonder than that most discussions of fundamental cosmology assume that the Universe is tending towards a stable vacuum state as time goes on, and that this state has the lowest energy density allowed by the basic Lagrangian.

Andrei Linde pointed out long ago that observations do not require such absolute stability [13]. If one wants to place a rigorous theoretical lower bound on the mass of the Higgs boson by requiring that the standard model vacuum be stable, the most one can honestly ask for is that its lifetime be longer than the observed "age of the Universe."[8] Linde's calculations referred to a tunneling instability, in which weak couplings can easily explain a very long lifetime.

Despite these observations, there has been a certain amount of unease in the astroparticle community about the prospect that the state of the Universe in which we find ourselves is not absolutely stable. Perhaps the strongest concrete reason for this unease has to do with the genericness of initial conditions. We know that our Universe once had a much larger energy density than it does today. If the barrier that prevents the classical decay of our hypothetically false vacuum was smaller than the available energy density in thermal motions *at any time in the phase history of the Universe*, it is very hard to understand how we came to rest at this false minimum. The Universe should "overshoot" the false vacuum and end up in the true minimum of the potential. This expectation is based on the maxim with which we began this section.

The main thing that we wish to demonstrate in this section is that this argument is false, if we assume certain natural conditions.

(1) The present history of the Universe was preceded by a period of inflation, during which all spatial curvatures and scalar field inhomogeneities were washed out.

(2) The cosmological constant in the hypothetical false vacuum in which we live is zero. Our results are not

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[8]More precisely, "the age of our current horizon volume according to conventional cosmology."

changed very much if we assume a positive cosmological constant.

Assume that the scalar field potential of our model has a locally stable minimum with zero cosmological constant and one or more minima with negative cosmological constant. Then we will show below that the only stable fixed point of the equations of motion is one in which the scalar field sits at its zero energy minimum and the Universe is flat and static. Solutions with generic initial conditions are not attracted to this fixed point. Instead, they lead to a situation in which the Universe contracts irreversibly (we assume it is initially expanding). No solution comes to rest in the minimum energy density state. This means that if we assume some probability distribution for the initial conditions, the only solutions which lead to a stable evolution of a large Universe are those which asymptote to the false vacuum.[9] The criterion for classical stability in a postinflationary expanding Universe is very different than that in flat space.

Our observations do not change the considerations of Coleman and DeLucia about the quantum-mechanical instability of the false vacuum. However, if we restrict attention to the class of models of modular dynamics which we have been studying, then the tunneling amplitudes are very small. In these models the dynamics of the early Universe is dominated by a set of scalar fields which have only string scale nonrenormalizable couplings in the fundamental Lagrangian and to all orders in perturbation theory. At an exponentially lower scale M nonperturbative dynamics gives these fields a potential of order M^6/M_P^2.

In this general class of models, a simple scaling argument shows that the instanton action which controls the instability of the false vacuum is of order $(M_P/M)^6$, where M_P is the string scale. Thus for all reasonable values of M^{10} the lifetime of the false vacuum is enormously longer than the age of our horizon volume.

A. Scalar fields in a postinflationary era

The equations of motion for a set of scalar fields in a postinflationary cosmology with Robertson-Walker scale factor R are

$$\frac{d}{dt}[M_P G_{ij}(z)\dot{z}^i] + 3H M_P G_{ij}(z)\dot{z}^j + \frac{1}{M_P}\partial V/\partial z^i = 0 ,$$

$$(3.1)$$

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \left(\frac{1}{M_P^2}\right)[\tfrac{1}{2}M_P^2(G_{ij}\dot{z}^i\dot{z}^j) + V] . \quad (3.2)$$

Here $z^i \equiv \phi^i/M_P$ are dimensionless scalar fields, and G_{ij} is the metric on the space of fields . Note the absence of a spatial curvature term in Einstein's equation, which signals that we have undergone a period of inflation. From the second of these equations it follows immediately that there are no solutions with ϕ_i coming to rest at a minimum with negative value of the potential. What then is the typical behavior if the potential has a local zero energy minimum and a global minimum with negative energy?

Combining the two equations we obtain

$$\dot{E} \equiv \dot{H}^2 = 2H\dot{H} = -3G_{ij}\dot{Z}^i\dot{Z}^j \quad (3.3)$$

In an expanding Universe, H is positive. Equation (3.3) says that it decreases in magnitude as the Universe expands. What happens when H reaches zero? Equation (3.2) says that this can only happen at a place where the potential is less than or equal to zero. In particular, H vanishes if we are sitting at rest in the zero-energy false vacuum. It is easy to see that this is an exact solution to the equations of motion. Since, in an expanding Universe, we are dealing with a system which has *friction*, a finite volume in phase space will be attracted to this fixed point. Generically, solutions with initial conditions outside this volume will stop expanding when H hits zero, as long as any field velocity is nonvanishing. Equation (3.3) shows that H will then change sign and the Universe will begin to contract. H^2 increases without bound, and the Universe rapidly contracts back to a singular state. In effect, for initial conditions which lie in the basin of attraction of the negative energy minimum, inflation is never successfully completed. If different regions of the Universe exit inflation with different initial conditions for the scalar fields, only those regions which are attracted to the zero-energy minimum will remain large for any substantial period of time.

There are solutions with finely tuned initial conditions for which all velocities vanish at a nonstationary point on the potential surface with $V = 0$. The system then enters a limit cycle, moving on the negative part of the potential surface, with total energy equal to zero. This limit cycle is an exact solution of the full equations of the system, but an unstable one. Generic small perturbations of it drive one to a collapsing state.

We see that in a postinflationary Universe, minimizing the energy is not the way to achieve classical stability. It should be emphasized that there is nothing in this argument that depends strongly on the fact that the energy in the false vacuum is zero. If it is positive there will be an abstractive "fixed point" solution in which the fields are at rest in the false vacuum and the metric is de Sitter type. Our arguments explain the classical stability of a flat vacuum state relative to one with negative cosmological constant, but do not provide any obvious clue as to why the cosmological constant must vanish.

The foregoing line of reasoning does not imply the

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[9] As a consequence of the friction in an expanding Universe, this is a set of nonzero measure in the space of all initial conditions, with respect to a flat probability distribution.

[10] It seems to us that the maximum reasonable value for M is that which leads to the vacuum energy scale (10^{16}–10^{17} GeV) required by the inflationary explanation of the observed fluctuations in the microwave background. This gives a tunneling amplitude of order $e^{-10^{12}}$ per unit Planck volume.

quantum-mechanical stability of the false vacuum state. Indeed, decay of the false vacuum proceeds by quantum tunneling in a finite-sized bubble. A prior era of inflation does nothing to erase the spatial curvature inside this bubble, and a local, anti–de Sitter metric is still the proper geometry of the bubble interior after its formation. The analysis of Coleman and DeLuccia [14] remains valid, and their generically gloomy prediction of the consequent fate of the world is unaltered.

The probability of tunneling is of course highly model dependent. If we restrict attention to Lagrangians for string theory moduli, the characteristic form of the effective potential is

$$V_{\text{eff}} = \frac{M^6}{M_P^2} V(z^i) \,, \qquad (3.4)$$

where M_P is the string scale. The fields z^i are assumed to be canonically normalized at $z^i = 0$. At other points in field space they have a kinetic term

$$\mathcal{L}_{\text{kin}} = \tfrac{1}{2} M_P^2 G_{ij}(z^i) \nabla z^i \nabla z^j \,. \qquad (3.5)$$

These formulas follow from the fact that the potential is generated by a strongly interacting supersymmetric gauge theory with scale M and the moduli are coupled to the strongly interacting fields only through irrelevant operators scaled by the Planck mass.

Assume now that the effective potential has a zero energy minimum at $z^i = 0$, and another one with negative energy. If we assume that the potential contains no particularly large or small dimensionless constants, the second minimum is at $z^i \sim 1$ and the negative vacuum energy of order M^6/M_P^2.

The equation for the flat space instanton which controls the tunneling rate from the false to true vacuum is

$$\nabla^2 (G_{ij}(z)z^j) = -M^6/M_P^4 V_i(z) \,. \qquad (3.6)$$

The solutions will have the form

$$z^i = f^i \left(x \frac{M^3}{M_P^4} \right) \,, \qquad (3.7)$$

where the functions $f^i(x)$ do not depend on either M or M_P. As a consequence, it is easy to see that the instanton action is of the order of

$$S_{\text{inst}} = O\left(\left(\frac{M_P}{M} \right)^6 \right) \,. \qquad (3.8)$$

In the class of models in which M is the scale of nonperturbative physics which is responsible for inflation, $M_P/M \geq 10^{5/3}$ and the vacuum tunneling probability per unit space time volume is of the order of

$$P \sim \frac{M_P^{16}}{M^{12}} e^{-(M_P/M)^6} \leq 10^{24} e^{-10^{10}} M_P^4 \,. \qquad (3.9)$$

This is so small that it is of no conceivable relevance to physics as measured by local observers in our Universe. The false vacuum is essentially stable. Moduli-dominated

cosmological models that undergo inflation can thus live happily in a false vacuum, with no fear of instability.

In fact, it is possible that the false vacua in these models are absolutely stable. Coleman and DeLucia showed that in many cases no instanton exists for tunneling from a space with a non-negative cosmological constant into anti–de Sitter space [15]. Heuristically this occurs because the spatial sections of anti–de Sitter space have constant negative curvature. Thus, an anti–de Sitter bubble has constant surface-to-volume ratio as it grows, and energy balance does not automatically induce the growth of large enough bubbles.

It is easy to see that even in the presence of gravity, all small parameters scale out of the equations of motion which determines the existence of instanton solutions. Thus, the existence of instantons depends on dimensionless numerical constants in the Lagrangian. It is conceivable that in the modular Lagrangians determined by string theory these constants are such that no instanton exists, and the zero-energy vacuum is absolutely stable. We emphasize, however, that this hypothetical possibility is in no way necessary to our argument. Even if modular instantons exist, the tunneling rates which they predict are too small to be of interest on time scales of the order of the age of our Universe.

We believe that the instability of negative energy minima of the potential in postinflationary cosmology is an important clue about the nature of the Universe. In the next section we will show that it can be the basis of a powerful vacuum selection criterion in superstring theory.

IV. MASSLESS MULTIPLETS AND MASSIVE MODULI

The results of the preceding section put strong constraints on the idea that supersymmetric nonperturbative dynamics gives mass to the moduli. Mass generation for the moduli can only occur if a nonperturbative superpotential is generated. If SUSY is preserved, the stationary point of the supergravity potential will have a negative cosmological constant of the form $-3/M_P^2 |W_{\text{min}}|^2$. We have seen that fields lying at rest in the minimum of the potential will not be a stationary solution of the postinflationary cosmological equations unless $W_{\text{min}} = 0$. We can phrase this important result in terms of symmetries: *In postinflationary cosmology, breakdown of R symmetry*[11] *implies that SUSY must be broken in a stable (Minkowski or de Sitter) vacuum state.*

Now consider the form of the nonperturbatively generated superpotential in a string theory ground state. We will assume for simplicity that at generic points in moduli space, the strongly coupled gauge theory which generates the superpotential is a pure, $N = 1$, SUSY-gauge theory.

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[11] To be precise, of any R symmetry larger than a Z_2 R parity. We remind the reader that any R symmetry larger than Z_2 implies the vanishing of the superpotential at a symmetric minimum of the potential.

We believe that our results are more general than this, but it would take us too far afield to delineate the precise class of theories for which our discussion is valid. For pure gauge theory, the exact form of the superpotential is known to be

$$W_{\text{NP}} = M_P^4 e^{-bS - \Pi(\Phi_i)} . \qquad (4.1)$$

Here, $S (= 8\pi^2/g^2 + i\theta)$ is the dilaton superfield, Φ_i are the moduli, and b is related to the one-loop β function for generic values of the moduli. Π is the moduli-dependent one-loop renormalization of the coupling coming from (generically) massive modes. At nonzero values of g, (4.1) will only vanish if, at some point in moduli space, Π diverges. This means that extra massless fields appear at this point. If we want to reduce the value of the superpotential, then these must be matter fields rather than gauge fields. Indeed, the example of SUSY QCD shows us that an increase in the number of massless chiral multiplets can lead to vanishing of the nonperturbative superpotential. This theory has a nonperturbative superpotential for $N_C > N_F$, but not for $N_F \geq N_C$. We will assume that there are points in string moduli space where such an increase in the number of matter multiplets in the hidden sector occurs. We do not know of an example of such a point, but, as we will see, this fact may be interpreted in a positive manner.

At these points, Φ^0, the superpotential will vanish like a power of $\Phi_i - \Phi_i^0$ (Π will blow up logarithmically as a consequence of the existence of new massless states). If this power is greater than 1, then $\partial_{\Phi_i} W$ will also vanish and SUSY will be preserved. Under these conditions, string theory will have a locally stable supersymmetric ground state. (Of course, SUSY can be broken by dynamics at a lower scale.) If the point in moduli space where extra massless nonsinglet chiral multiplets appear is isolated, then the fluctuations in all of the moduli fields apart from the dilaton will be massive, with masses of order $e^{-bS} M_P$. It would appear desirable then that the special points where massless chiral multiplets are present are dimension zero submanifolds of moduli space, so that we can give mass to all the moduli. This might explain why a survey of known ground states, which explores a submanifold of moduli space with large codimension, fails to reveal such a point.[12]

The paragraph above is the promised vacuum selection principle for superstrings. Four-dimensional classical ground states for string theory, with non-Abelian low-energy gauge fields, will often lead to nonperturbative superpotentials for the moduli fields, and to spontaneous violation of all complex R symmetries. Supersymmetric "ground" states will generically have a negative vacuum energy and will, as we have seen, not be stationary states of a postinflationary Universe. The hypothetical points in moduli space where the superpotential vanishes will

be dynamically chosen by the equations of cosmology.

The above discussion assumed that SUSY was not spontaneously broken by the nonperturbative dynamics. We note in passing that the above arguments may also provide a hint of the explanation of why SUSY is broken in the real world. The minimization of the potential and the vanishing of the superpotential are $n + 1$ complex equations for n unknowns. It may be that for the full low-energy superpotential, they have no common solution. This would mean that R symmetry is spontaneously broken. A successful inflationary cosmology would then require that SUSY be broken as well.

As an example of how this could happen, imagine a class of string ground states for which the low-energy hidden sector gauge theory was (at generic points in moduli space) a pure gauge theory with a product of two groups $SU(N)$ and $SU(L)$ with $N > L$. Suppose that, for $SU(N)$ there exists an isolated "magical" point in moduli space, at which $N_F > N$ massless chiral multiplets in the $\mathbf{N} + \bar{\mathbf{N}}$ appear. Assume that these are singlets under the second factor in the gauge group. The argument above implies that the theory will have a supersymmetric ground state at this point, and that it will be cosmologically chosen in preference to other possible supersymmetric minima of the potential for moduli.

Apart from the dilaton, the moduli will all be massive at this point. Thus, below the first "confinement" scale, the low-energy theory will consist of a dilaton, a pure SUSY $SU(L)$ gauge theory, and some massless fields associates with the chiral symmetries of the massless matter in the first factor of the gauge group. The superpotential for these $SU(L)$ singlet fields will have a supersymmetric minimum, at which the superpotential vanishes. Gaugino condensation in $SU(L)$ will now generate a superpotential $e^{-S/L}$ for the dilaton below the $SU(L)$ confinement scale. The structure of the dilaton potential will be

$$V = e^{K - (S + \bar{S})/L} \left[K_{SS}^{-1} \left| \frac{1}{L} - K_S \right|^2 - 3 \right] . \qquad (4.2)$$

In the present state of our knowledge of string theory we can give only the first term, $-\ln(S + \bar{S})$ of the large S asymptotic expansion of the Kahler potential K. Thus we can only speculate about the existence of possible stable cosmological solutions of the equations of gravity coupled to the dilaton in this model. However, we can be sure that no such solution is supersymmetric. Hypothetical supersymmetric vacua at finite S will have negative vacuum energy and suffer from the instability described above. The state at infinite S suffers from the Dine-Seiberg instability. Any stable solution of this system violates SUSY.

This example teaches us another lesson about our attempt to freeze the moduli. Even if our hypothetical points in moduli space exist, the superpotential given above cannot completely finish the job of giving mass to the moduli at a supersymmetric minimum, for the superpotential vanishes for all values of the dilaton field if it vanishes at all. This result is quite general and could only be averted if the superpotential had a complicated dependence on the dilaton, which seems unlikely in the

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[12]We are well aware that this argument is at best a good excuse. The program that we are outlining requires us to at least prove the existence of these special points in moduli space. We have so far failed to do so.

weak-coupling region.[13] The dilaton mass must come from SUSY-breaking dynamics, and we are not yet out of the modular woods.[14]

A. The dilaton mass and the mechanism for SUSY breaking

Perhaps the simplest way to break SUSY and give the dilaton a mass is the one described in the preceding section. The moduli are frozen by supersymmetric dynamics at a high scale, and we assume another gaugino condensate at a scale $e^{-c/3}M_P$. Since the other moduli are assumed to be frozen out at the higher scale $e^{-b/e}M_P$, this would give rise to a dilaton potential

$$V_D = e^{-c(S+S^*)}[K^{SS^*}|c - \partial_S K|^2 - 3] \ . \qquad (4.3)$$

Note that the minimum of this potential is not the same as that of V_I defined in the previous footnote. If we accept the assertion [17] that we do not currently know how to calculate K for the relevant values of S, then it is not implausible that V_D has a stable minimum with zero cosmological constant (we disregard the fine-tuning of the cosmological constant). This can only happen if SUSY is spontaneously broken, and hypothetical supersymmetric minima of V_D would not be stationary points of the equation of motion after inflation.

Variations on this scheme are possible in which dynamics more complicated than gaugino condensation generate the dilaton potential. All one needs is a supersymmetric gauge theory which in the absence of the dilaton (i.e., when the coupling constant is a constant) generates a nonvanishing, nonperturbative superpotential, and is characterized by a single energy scale. All such theories give rise to what were referred to in [1] as nonrenormalizable hidden sector (NRHS) models. In such models SUSY breaking will be communicated to the standard model by gravitational scale dynamics, and the nonperturbative scale $e^{-c\mathrm{Re}S_0/3}M_P$ must be of order $10^{13.5}$ GeV. As a consequence, the dilaton will get a mass of order 1 TeV and the cosmology of the model will suffer from the PPP. One is led to consider the possibility of low-energy SUSY breaking.

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[13]Many popular models of the dilaton potential assume cancellations between different exponentially small terms in the string coupling. While no definitive argument that such models are incorrect exists, we find them unpalatable.

[14]Note that, during inflation when W_0 is nonzero, the dilaton may be quickly driven to a "minimum" of the potential $V_I = W_0 e^{K-(S+S^*)/N}[K^{SS^*}|-1/N + \partial_S K|^2 + K^{ij^*}\partial_i(\ln W_0 + K)\partial_{j^*}(\ln W_0^* + K) - 3$ [16]. This is unlikely to be the true minimum of the full dilaton potential and so the dilaton will generally start out its postinflationary motion a distance of order M_P from the minimum. Dine, Randall, and Thomas suggested this temporary inflation-generated potential as a way to solve the problem of moduli, but no one has come up with a plausible way to ensure that the minimum of the potential during inflation is the same as that in the vacuum state.

B. A digression on the cosmological constant in theories with low energy SUSY breaking

One serious problem with low-energy breaking of SUSY is the cosmological constant. In NRHS models the cancellation of the cosmological constant is "natural in order of magnitude" [1]. That is, the two terms which must cancel in order to give a zero cosmological constant naturally have the same order of magnitude. This is because the breaking of R symmetry responsible for the negative term in the potential is the trigger for the breaking of SUSY which gives rise to the positive term. The latter is a gravitational strength reaction to the former.

In theories with low-energy SUSY breaking, this is not the case. The breaking of SUSY is a flat space effect and the negative term in the supergravity potential is nominally subleading by two powers of the low-energy scale over the Planck mass. Conventionally this is "fixed up" by adding an appropriate constant to the superpotential, but this is a very suspicious procedure in string theory. According to the rules of perturbative string theory, the constant term in the superpotential is quantized in units of the cube of the inverse compactification radius, which is itself close to the string scale. All other terms in the superpotential are field dependent.

In the present context, in which the low-energy theory contains a dilaton in addition to the low-energy degrees of freedom which break SUSY, this problem may be solved. Let us suppose that the low-energy theory has a nonperturbative scale μ, given in terms of the dilaton by $\mu = e^{-S/b}M_S$. μ is the scale of dynamical SUSY breaking. The effective action for the Goldstino has the form

$$\mathcal{S}_{\mathrm{Goldstino}} = \int d^4\theta^K(X, X^*)$$

$$+\mu^2 \int d^2\theta X + \mathrm{H.c.} \qquad (4.4)$$

The Kahler potential is chosen so that the scalar partners of the Goldstino all have mass of order μ. It has the form $XX^*k(X/\mu, X^*/\mu)$. In the absence of a dilaton, this Lagrangian would give a positive cosmological constant of order μ^4 when plugged into the supergravity formula for the potential. The negative term in the formula is smaller than the positive term by a factor of order μ^2/M_P^2. In the presence of a dilaton coupled to X via the S dependence of μ however, we are free to add a purely S-dependent term to the superpotential. This would come from, for example, gaugino condensation in some strongly coupled gauge theory with a scale higher than μ.

The dilaton will also control the coupling of this second gauge theory. If we assume that the second theory has a β function one and a half times as large as that of the low-energy SUSY-breaking theory, then the (positive and negative) contributions to the dilaton potential from the more strongly coupled theory will be of the same order of magnitude as the SUSY-breaking F term. The cancellation of the cosmological constant will no longer require the introduction of a constant superpotential with un-

explained (and in string theory, unexplainable) order of magnitude. The $\frac{3}{2}$ ratio between β functions that is required in this approach could naturally arise from group theory. The search for pairs of theories with the required properties might be an interesting constraint on string vacua.

We emphasize that our considerations do not explain the precise fine tuning of the cosmological constant, but are only order of magnitude predictions. However, models of low-energy SUSY breaking lead to an interesting range of dilaton masses. Depending on the mechanism for transmitting SUSY breaking to the standard model, the scale μ can range from 1000 to 1 TeV. This leads to dilaton masses between 100 and 10^{-4} eV. The lower end of this range is of considerable interest. General renormalization group arguments[15] suggest that a local field theoretic explanation of the vanishing of the cosmological constant could only make sense if there existed a scalar with mass less than or equal to (the fourth root of) the observational bound on the cosmological constant, or about 10^{-2} eV. This could arise in the present context from a SUSY-breaking scale less than about 10 TeV. While we have not demonstrated a mechanism by which such a light dilaton could cancel the cosmological constant, at least the possibility is not ruled out by general renormalization-group arguments.

C. After the digression, the problem remains

Unfortunately, the entire range of dilaton masses compatible with low-energy SUSY breaking appears to be ruled out by conventional cosmology. In this mass range, the dilaton lifetime is longer than the age of the Universe and it leads to a postmodern Polonyi problem. We can try to resolve this problem by invoking the "savior" field of [6], although we would now have to complicate the theory in order to explain the origin of a savior field with the right mass. Now the nuclei produced in the aftermath of savior decay will not be destroyed by the subsequent decay of dilatons. However, the dilatons will come to dominate the energy density of the Universe shortly after nucleosynthesis, at an energy scale of order 0.1 MeV. They would be a form of dark matter. In such a cosmology the ratio between dark matter and radiation energy densities at the present epoch would be 10^8, while measurements of the present temperature and density of the Universe bound this ratio by something of order 10^4. One would have to invoke the generation of large amounts of entropy after nucleosynthesis to make the model consistent with this observation, but that would also dilute the baryon content of the Universe, and would again make the model inconsistent with the data.

Indeed, the "savior" idea seems to run into either the nucleodestruction problem or the above dark matter domination problem, for any values of the moduli masses. Nucleodestruction will be a problem if the mass

is significantly higher than an MeV. Particles with mass lighter than an MeV and gravitational couplings will have lifetimes of order 10^{24} sec or more. This is seven orders of magnitude longer than the age of the Universe. Such particles will dominate the energy density at the present era to an extent ruled out by our knowledge of the dark matter content of the Universe.

Intermediate scale inflation cannot remove a light dilaton from the Universe either, since the weak scale is much larger than the dilaton mass. Thus, the RT solution to the cosmological moduli problem is an argument in favor of hidden sector models for SUSY breaking.

V. A SPECULATIVE PROPOSAL

All the models that we have considered were based on the standard equations of homogeneous isotropic cosmology. We would now like to show that in the context of modular physics, the standard assumptions of homogeneity and isotropy are untenable. The moduli may or may not dominate the energy density of the Universe just after inflation. However, they certainly dominate it from about the time that the energy density is M^6/M_P^2 (the moduli masses are $\sim M^3/M_P^2$) until they decay. During this period the Universe is matter dominated, and fluctuations can grow. $\delta\rho/\rho$ will grow like the scale factor R on all scales inside the horizon. It would not be sensible to take the initial value of $\delta\rho/\rho$ in modular energy to be less than the 10^{-5} value of primordial fluctuations. This means that modular inhomogeneities will go nonlinear when the scale factor has increased by a factor of 10^5 from its value when the Universe became dominated by moduli. At this time, the energy density will have decreased by a factor of 10^{-15}. On the other hand, the energy density at the time of modular decay is m_{mod}^6/M_P^2, which is a factor of $(m_{\mathrm{mod}}/M_P)^4$ times the energy density when the moduli begin to dominate. This is less than 10^{-64}. Thus the modular energy density fluctuations go nonlinear long before moduli decay. We have been, for the most part, conservative in these estimates. In fact, the moduli could dominate the energy density right after inflation, as they would in models in which the moduli themselves are the inflatons. Furthermore, in models with low-energy SUSY breaking, the modular lifetime is longer than the age of the Universe, and modular energy density surely goes nonlinear before the moduli decay. The only place in which we may have made an overestimate, is in our "sensible" estimate of the initial inhomogeneity in the moduli. However, the discrepancy between the scale at which moduli gravitationally collapse and that at which they decay is so large that we do not believe that initial conditions could substantially alter our qualitative conclusion.

All discussions of modular cosmology must face up to the prediction of a very early stage of the formation of collapsed objects. We emphasize, however, that the scale of these inhomogeneities is extremely small, and that if we successfully get rid of moduli before nucleosynthesis, they will have no effect whatsoever on large-scale measurements of the structure of the microwave background.

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[15]These arguments are due to L. Susskind, and have not been published.

We have only the most preliminary remarks to make about what appears to be a very complicated dynamical problem. The two most likely results of gravitational collapse of moduli are the formation of stable *modular stars*, and the formation of black holes. The formation of modular stars could possibly alleviate the problem of modular domination of the Universe. The modular field strengths inside such objects could well be very large, and lead to a substantial enhancement of the decay probability of modular matter into ordinary particles. We may expect moduli to have (for example) couplings to photons of the form $(\phi/M_P)F_{\mu\nu}^2$. In the core of a modular star, the modular field amplitude Φ might be much larger than the Planck scale, enhancing the coupling of this field to photons. A modular star could well explode into a burst of photons, quarks, and leptons, soon after it forms.

Stable gravitationally bound configurations of moduli may not exist, or may not be the fate of all large-density fluctuations. An alternative would be collapse towards a black hole. However, the work of [18] suggests that if the spectral index of primordial density fluctuations is near 1 (as it is expected to be if the fluctuations originate from inflation), then very few black holes will form. We do not understand what the evolution of the system would be if local analysis were to preclude the existence of localized stationary solutions of the coupled gravity-moduli system, while the global analysis of [18] rules out the formation of black holes.

Thus, nonlinear gravitational effects in the modular medium might provide a mechanism for solving the modular dominance problem, but our understanding of this complicated nonlinear regime is sketchy. It seems clear then that all conclusions about the viability of a cosmology which includes moduli must await the resolution of the complicated dynamical problem of modular collapse.

VI. SUMMARY AND CONCLUSIONS

In summary, our investigation of the modular cosmological problem has taught us a number of interesting things about cosmology and SUSY breaking. The intermediate scale inflation scenario of Randall and Thomas seems to solve the problem if SUSY is broken by a nonrenormalizable hidden sector mechanism. Attempts to solve the problem by attributing moduli masses to SUSY preserving high-scale dynamics led to a number of interesting conclusions: Generic supersymmetric stationary points of the effective potential are not stationary points of the equations of cosmology in a postinflationary Universe. Inflation can create large long-lived smooth regions of the Universe only if the cosmological constant is greater than or equal to zero, which means that either SUSY is broken or R symmetry is preserved.[16] R-symmetry preservation is a very strong constraint on the strongly coupled dynamics which is supposed to give mass to the moduli. If, at a generic point in string moduli space, the strongly coupled sector is a pure gauge theory, then R symmetry can only be preserved at special

points in moduli space where massless chiral multiplets with hidden sector gauge charge appear. There are no known points in moduli space where this happens. Even if one could be found, strongly coupled SUSY-preserving dynamics cannot give mass to the dilaton.

The postmodern Polonyi problem posed by string theory moduli seems to us to be a serious but potentially exciting crisis for string theory. Although attempts to solve this problem have led to a number of interesting ideas about string vacuum selection, SUSY breaking, and the notion of stability in postinflationary cosmology, the only acceptable solution in sight is intermediate scale inflation (ISI). It is important to investigate the consequences of this scenario and to search for its origins in an explicit string vacuum solution.

We note, however, that extant attempts to resolve the PPP have completely ignored the gravitational collapse of modular energy-density fluctuations which we demonstrated to be important in the very early Universe (according to string theory). It is not clear whether the dynamics during this era eliminates moduli without ISI, or whether it instead leads to further problems that cannot be solved even by ISI. Clearly, closer investigation of this primordial matter-dominated era is called for. We hope to return to it in a future paper.

Finally, we wish to emphasize that although we have posed the PPP in the context of inflationary cosmology, it is equally serious in any big bang cosmology. Inflation with a Hubble constant higher than the weak scale gives us specific predictions about the initial conditions of moduli fields, but any model in which the energy density is of order $(10^{11}\text{ GeV})^4$ at some period in cosmic history will also predict that the moduli start the conventional Robertson-Walker era displaced from the minimum of their potential. The postmodern Polonyi problem cannot be evaded by rejecting inflation.

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[16]We use this symmetry statement as a synonym for the vanishing of the superpotential since without R symmetry the superpotential could only vanish by fine-tuning.

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