Flat directions, doublet-triplet splitting, the monopole problem, and all that

Borut Bajc\textsuperscript{(1)}, Ilia Gogoladze\textsuperscript{(2,3)}, Ramon Guevara\textsuperscript{(4)}, and Goran Senjanović\textsuperscript{(2)}

\textsuperscript{(1)} J. Stefan Institute, 1001 Ljubljana, Slovenia
\textsuperscript{(2)} International Center for Theoretical Physics, Trieste, Italy
\textsuperscript{(3)} Andronikashvili Institute of Physics, Georgian Academy of Sciences, 380077 Tbilisi, Georgia
\textsuperscript{(4)} Dept. of Physics, University of Trieste, 34100 Trieste, Italy

Abstract

We discuss a supersymmetric $SU(6)$ grand unified theory with the GUT flat direction being lifted by soft supersymmetry breaking, and the doublet-triplet splitting being achieved with Higgs as a pseudo-Goldstone boson. The theory offers a simple solution to the false vacuum and monopole problems.

I. INTRODUCTION

The doublet-triplet splitting (D-T) problem and the origin of the unification scale are the outstanding problems of grand-unification. Both of them seem to cry for low energy supersymmetry which, miraculously enough, leads automatically to the unification of couplings and the dynamical generation of electroweak scale.

Among various proposals to understand the lightness of the Higgs doublets, the mechanism that stands out is based on the beautiful idea of Higgs being pseudo-Goldstone boson\textsuperscript{(6–9)}. A particular simple realization of this scenario is realized in an $SU(6)$ GUT with an anomalous $U(1)_A$ symmetry\textsuperscript{(10)}.

On the other hand the most elegant mechanism for generating the GUT scale seems to be based on the idea of flat directions\textsuperscript{(11)}, often naturally present in supersymmetric gauge theories. These flat directions are lifted after supersymmetry breaking and their large vevs can be traced to the logarithmic running of coupling constants and masses.

In this paper we show how these appealing scenarios could be married in a realistic grand unified model. Our strategy is the following.

As in\textsuperscript{(10)} we separate various sectors of the theory through $U(1)_A$ in order to maintain the lightness of the Higgs doublets. Next, in order to guarantee the existence of flat directions we employ (an) additional global symmetries(y). This is the easiest way to achieve the right pattern of symmetry breaking.

On the other hand it is not so appealing to believe in global symmetries free from $1/M_{Pl}$ suppressed corrections. Thus we make an attempt to avoid completely global symmetries, i.e. to use only the local anomalous $U(1)_A$. While we cannot rigorously derive the correct symmetry breaking pattern in this case, we do believe that this is the most appealing possibility, worth pursuing further in future. If proven correct this would mean a realistic
grand unified theory with a natural doublet-triplet splitting and the GUT scale determined dynamically.

All this sounds nice. However, this program from its beginning suffered from a lack of phenomenological predictions and thus it becomes almost a question of semantics and not physics. Fortunately there is a possibility, as we show in this paper, that magnetic monopoles produced in the early universe are detectable in future experiments such as MACRO. The number of monopoles cannot be precisely calculated at this stage, but it could be comparable with the dark matter density of the universe.

Last, but not least, we briefly comment on various other cosmological issues such as the false vacuum, gravitino and moduli problems.

II. A PROTOTYPE MODEL

Before presenting a realistic theory we wish to discuss the generic features of the lifting of flat directions. The simplest GUT example is based on SU(6) gauge symmetry with the adjoint representation \( \Sigma \) and the following superpotential:

\[
W = \frac{\lambda}{3} Tr \Sigma^3.
\]  

(1)

The absence of the mass term is simply a desire to determine masses dynamically and can be accounted for by an appropriate R symmetry. It is clear that the direction

\[
\Sigma = \sigma \text{ diag}(1, 1, 1, -1, -1, -1)
\]  

(2)

is a flat direction since it disappears from the superpotential. It is also clear that this can only work in SU(2n) theories and thus not in SU(5). In this scenario one imagines the soft terms to originate at the Planck scale and to be positive as in the simplest models of supergravity. As in the MSSM the Higgs mass can change the sign \[5\] and due to the larger number of fields this can now happen close to the GUT scale \( M_{GUT} \) of the order \( 10^{16} \) GeV \[12-15\].

To complete the symmetry breaking down to the standard model the minimal set of Higgs scalars is a fundamental (\( H \)) and antifundamental (\( \bar{H} \)) representation. This can be achieved by nonrenormalizable terms in the superpotential or through D-terms. The latter case is preferred if one wants to avoid the introduction of arbitrary mass terms. An appealing possibility is to have \( H = \bar{H} \) as a flat direction, but the trouble is the absence of enough running to change the sign of the soft mass terms at high enough scale. The way out is to introduce an extra (anomalous) gauge \( U(1)_A \) symmetry, under which \( H \) and \( \bar{H} \) are charged. A nonzero Fayet-Iliopoulos D-term

\[
D_{U(1)_A} = q_H |H|^2 + q_{\bar{H}} |\bar{H}|^2 + \xi = 0
\]  

(3)

then forces nonvanishing (and equal) vevs for \( H \) and \( \bar{H} \):

\[
< H > = < \bar{H} > = \sqrt{\frac{-\xi}{q_H + q_{\bar{H}}}},
\]  

(4)
where from string theory

\[ \xi = \frac{g^2 Tr Q}{192 \pi^2 M_{Pl}^2}. \]  

(5)

What about the doublet-triplet splitting? Interestingly enough, it is achieved, but it ends up being a disaster: the SU(2) doublets are superheavy, while the colour triplets are light. Namely, if you do not couple \( H \) and \( \bar{H} \) to \( \Sigma \), the \( F \) part of the potential has enlarged global symmetry \( SU(6)_\Sigma \times SU(6)_H, \bar{H} \). Let us imagine that \( \Sigma \) first gets a vev, breaking the local \( SU(6) \rightarrow SU(3) \times SU(3) \times U(1) \). It is easy to see that all the particles of \( \Sigma \) (except the flat direction \( \sigma \)) become superheavy. Now, let us trigger the vevs of \( H \) and \( \bar{H} \) so that we break one of the two remaining \( SU(3) \)'s down to \( SU(2) \). The doublet components of \( H \) and \( \bar{H} \) are obviously eaten by the corresponding gauge bosons, so that only the triplet components of \( SU(3) \) may (and do) remain light. This is confirmed by the counting of Goldstone bosons:

(i) \( SU(6)_\Sigma \rightarrow SU(3) \times SU(3) \times U(1) \): \( 35 - (8 + 8 + 1) = 18 \);
(ii) \( SU(6)_H, \bar{H} \rightarrow SU(5) \): \( 35 - 24 = 11 \);
(iii) \( SU(6) \rightarrow SU(3) \times SU(2) \times U(1) \): \( 35 - (8 + 3 + 1) = 23 \);

\[ 18 + 11 - 23 = 6 = 3 + \bar{3}. \]

The above example shows that it seems to be easier to find flat directions than to achieve natural doublet-triplet splitting. Therefore we now focus our attention on the model of D-T splitting which works and look for the implementation of flat directions.

III. A REALISTIC THEORY

What we learned in the previous example is that is not good to break \( SU(3) \) down to \( SU(2) \) with \( H \) and \( \bar{H} \), since the doublets get eaten and the \( SU(3) \) triplets remain light. We need \( SU(3) \) triplets to be eaten, and this can happen naturally when \( SU(4) \) is broken down to \( SU(3) \). In fact this is what Dvali and Pokorski do: they break \( SU(6) \) down to \( SU(4) \times SU(2) \times U(1) \) through the vev of \( \Sigma \). At the next stage \( H \) and \( \bar{H} \) break \( SU(4) \), which as we said, makes the \( SU(3) \) triplets eaten and allows for the doublets to be light. A simple counting of Goldstone bosons demonstrates that the doublets are really light.

Of course, the order of symmetry breaking is irrelevant for the above arguments; if anything in supersymmetry one prefers to go through the \( SU(5) \) stage, i.e. to have first \( H \) and \( \bar{H} \) develop vevs (or simultaneously with \( \Sigma \)).

It is easy to achieve the desired symmetry breaking \[ \Sigma \]; it is enough to choose the complete superpotential for \( \Sigma \):

\[ W = \frac{\lambda}{3} Tr \Sigma^3 + \frac{m}{2} Tr \Sigma^2. \]  

(6)

One of the degenerate vacua is then

\[ \Sigma = \frac{m}{\lambda} diag(1, 1, 1, 1, -2, -2). \]  

(7)

The question of course is how to make it flat. The simplest possibility is to promote \( m \) into a dynamical variable, i.e. a singlet field \( S \). The trouble is that \( F_S = 0 \) will make \( \sigma \) vanish. Of course one can add a cubic self-interaction for \( S \), but the equations \( F_{\Sigma} = F_S = 0 \)
over determine the system, forcing again the vevs to vanish. Notice that we are not allowed
to introduce quadratic terms with our philosophy of generating masses dynamically.

We see then that unfortunately the prize for achieving both the flatness and D-T splitting
is to double the number of adjoints. Regarding the flat directions the situation here mimics
the one encountered in SU(5) [14]. It is the D-T splitting problem that points to the elegant
solution which requires SU(6) symmetry.

A. The model

A simple model that implements our program requires two adjoint superfields \( A, B \) and
two singlet ones \( S, S' \) with the following renormalizable superpotential

\[
W = \lambda_A Tr A^2 B + \lambda_S Str AB + \lambda_{S'} S'Tr B^2 .
\]

\( (8) \)

A physical minimum of the potential is given by

\[
< A > = \frac{\lambda_S}{\lambda_A} < S > \text{ diag}(1,1,1,1,-2,-2) , \quad < B > = 0 ,
\]

with \(< S > \) and \(< S' > \) undetermined.

The global symmetries of this superpotential are a U(1) R-symmetry and a U(1) global
symmetry with charges \((1,1,1,1)\) and \((1,-2,1,4)\), respectively, for \((A, B, S, S')\), which for-
bids all other terms to all orders in \(1/M_{Pl} \).

One is clearly tempted to get rid of one of the singlet superfields, for example \( S' \). This
is readily achieved with \( \lambda_{S'} = 0 \). This is a disaster for gauge coupling unification since both
\((4,2)\) and \((\bar{4},2)\) multiplets under SU(4)×SU(2) subgroup of SU(6) from \( B \) would remain
light. Of course you could add a term such as \( TrAB^2 \), but then no symmetry could forbid
the \( TrA^3 \) term, which spoils flatness.

Strictly speaking one can do without a U(1) R-symmetry. The reason is that only \( B \)
field carries a negative U(1) global charge and thus the nonrenormalizable terms will involve
at least two powers of \( B \). The vev of \( B \), as is readily seen, still remains zero and the flatness
is not spoiled.

The Higgs as a pseudogoldstone boson program requires, as we mentioned before and
as is well known, a separation in the superpotential of various sectors of the theory (for
a systematic and careful study of this issue as a perturbation in powers of \(1/M_{Pl} \) see for
example [19]). In particular \( H \) and \( \bar{H} \) must decouple from \( A, B, S \) and \( S' \). This can be
achieved simply by giving nonzero and not opposite U(1) \( A \) charges only to \( H \) and \( \bar{H} \) as in
\( [10] \).

B. Fixing the scales

A few words are in order regarding the determination of \(< A > \) which defines the GUT
scale. Since the couplings \( \lambda_A, S, S' \) are not known, the GUT scale cannot be determined from
the first principles. However, since the number of fields in \( A \) and \( B \) is large compared to
the situation in the MSSM, it is not surprising, that the running from \( M_{Pl} \) down may be
speeded up enough in order to flip the sign of the soft mass of the flat direction around the GUT scale. Furthermore, \( A \) is also coupled to matter fields \([17]\) and this can only help. For more details on similar models see \([12-15]\).

In summary, it appears, at least in the high energy sector of the theory, that everything works. The important ingredient though was at least one continuous global symmetry. Strictly speaking this is OK since we do not know the fate of global symmetries in the presence of quantum gravity. It is often suspected that only gauge symmetries are protected from gravitational, i.e. \(1/M_{Pl}\)-like effects. If one took this seriously it would be impossible to speak of Peccei-Quinn symmetry and the axion solution to the strong CP problem \([18-20]\).

C. No global symmetries?

Still, it would be reassuring to be able to get us rid of continuous global symmetries. It would also be much more elegant and physical to do so. The simplest and most appealing possibility is to use only the gauge (anomalous) U(1)\(_A\). Actually, this could work in principle. Namely, in this case the U(1)\(_A\) charges of \((A, B, S, S')\) would be \((1,-2,1,4)\) instead of zero, and the \(H, \bar{H}\) charges should be large enough and positive. As before, the fact that only \(B\) has negative charge guarantees that the mixing between the two sectors involves more powers of \(B\). For example, if the charges of \((H, \bar{H})\) are \((2,2)\), the lowest order mixing would be proportional to \(B^2 \bar{H} H\), which is not harmful, since the vev of \(B\) vanishes.

There is however a new potential problem. In the original version, since only \(H\) and \(\bar{H}\) has nonvanishing U(1)\(_A\) charges and since the SU(6) D-term has to be zero before supersymmetry breaking, both of these fields are forced to have nonvanishing and equal vevs (see \((3)-(4)\)). Now on the other hand the U(1)\(_A\) D-term takes the form

\[
D_{U(1)A} = Tr(AA^\dagger) - 2Tr(BB^\dagger) + |S|^2 + 4|S'|^2 + q_H|H|^2 + q_{\bar{H}}|\bar{H}|^2 + \xi = 0
\]

and the issue who and when gets a vev becomes somewhat tricky. In order to answer this question the RG improved effective potential should be calculated using the running from \(M_{Pl}\) to \(M_{GUT}\). This is a difficult task beyond the scope of this paper.

D. The matter sector

The theory can be made realistic with the proper inclusion of light matter superfields. A realistic theory can be shown to require three families of 15, \(\bar{6}\), and \(\bar{6}'\) (a minimal anomaly free set). Also, one needs a self-conjugate 20 of SU(6) in order to get a large top Yukawa coupling. This is discussed at length in \([17,21]\). A particular attention must be paid to neutrino mass as in general SU(6) models. Fortunately one has more than one option at disposal. Right-handed neutrinos can be the SU(5) singlet components of the 6 and \(\bar{6}'\) matter fields as for example in \([14]\) or additional SU(6) singlets as in \([21]\). In both cases one ends up with the usual mechanism for generation of small neutrino masses \([22]\).
IV. COSMOLOGICAL ISSUES: THE MONOPOLE PROBLEM AND THE PROBLEM OF THE FALSE VACUUM

Besides the well known monopole problem, SUSY GUTs are also plagued by the problem of the false vacuum. Namely, normally one gets a set of degenerate vacua which includes the unbroken one. At sufficiently high temperature the unbroken vacuum becomes the global minimum and the large barrier between the vacua prevents the tunneling to our world [23].

The theories with flat directions offer a natural solution to both of these problems. First, the monopole problem. The point is remarkably simple [24–27]: the critical temperature of the GUT phase transition becomes very small and the usual Kibble [28] mechanism production gets suppressed. On top of that, the phase transition is of the first order and the number of monopoles can get suppressed. For a small flat direction $\sigma$ ($<< T$) the one-loop high temperature correction to the effective potential is

$$\Delta V_T \approx -NT^4 + \alpha T^2 |\sigma|^2,$$

where $N$ is proportional to the degrees of freedom to which $\sigma$ is coupled and $\alpha$ is positive. In the opposite limit, when $\sigma >> T$, $\Delta V_T \approx \exp(-c|\sigma|/T)$ ($c > 0$), i.e. in this limit $\sigma$ is coupled only to superheavy fields ($>> T$) and is out of thermal equilibrium. Thus, for sufficiently high $T$ the $\sigma = 0$ minimum wins and the symmetry is restored just as in the case with no flat directions [29–31].

Since the energy difference between the $\sigma = 0$ and $\sigma = M_{GUT}$ vacua is only of order $m_{3/2}^2 M_{GUT}^2$, it is clear that the transition can take place not before the temperature drops down to at least $T_c \approx (m_{3/2} M_{GUT})^{1/2} \approx 10^9 - 10^{10}$ GeV. If the phase transition was of the second order, the ratio between the energy of monopoles and baryons today would be approximately

$$\left(\frac{\rho_M}{\rho_B}\right)_{\text{today}} \approx \frac{m_M(n_M/n_\gamma)}{m_B(n_B/n_\gamma)} \approx \left(\frac{T_c}{M_{Pl}}\right)^3 \times 10^{10} \times \frac{m_M}{m_B} \approx 10^{-3} - 1,$$

for the GUT monopoles with a mass of the order $10^{17}$ GeV. Clearly, even if this was true, the number of monopoles would be small enough not to be in conflict with cosmology. At first glance, the usual curse of grandunification would be turned into the blessing: monopoles could be the dark matter of the universe. Even more important, this is not far from the MACRO limit [32] and the old dream of detecting magnetic monopoles could be realized in not so far future.

In our case the phase transition is of first order and the monopole production could be suppressed, although not necessarily (see for example [33–35]).

Of course, all this is relevant if we do manage to tunnel into our world. In a sense, we are saying that the solution to the false vacuum problem automatically resolves the monopole problem. The quasi flat direction may imply no barrier at all and so no problem whatsoever. However, this is in principle model dependent. Also, it is conceivable that the production of monopoles happens only after the false vacuum stops being a local minimum, i.e. for $T \approx m_{3/2}$. Obviously, the number of monopoles could then be completely negligible, similar
to the case of inflation. A more careful study of these issues is on its way.

V. SUMMARY AND OUTLOOK

In short, the $SU(6) \times U(1)_A$ theory discussed here achieves the determination of the GUT scale through the lifting of the flat direction after supersymmetry breaking. Also, it allows for a simple solution of the doublet-triplet splitting problem with the Higgs being a pseudo-Goldstone boson of an accidental global symmetry.

Furthermore, independently of when the inflation takes place and what the reheating temperature is, the theory is free from the monopole and false vacuum problems. Of course, we believe that inflation did take place at some point for the usual reasons of horizon and flatness problems. By this we mean the usual inflationary scenario of at least 60 e-folds, but now with a reheating temperature higher than $M_{GUT}$.

For this reason one must face the gravitino problem. This is however easily solved by assuming a short inflation before the first order GUT phase transition discussed throughout this paper. It is enough to wash out the gravitinos thermally produced before it: the reaheating temperature will be smaller or at least equal to the critical temperature $T_C \approx 10^9$ GeV, which is safe.

The main physical implication of flat directions is the existence of moduli-like fields with masses of order $m_{3/2}$ and $1/M_{Pl}$ suppressed interactions. It is well known (for the original work see [36]) that it poses a serious cosmological problem. It can be solved with a short inflation (this time after the phase transition) as suggested in [37–39].

To be honest, both problems could be more severe through the non-thermal production of relics, as emphasized [40,41]. If so, one would need a low scale inflation at a later stage. The issue however is very subtle and recently an opposite point of view was raised [42], according to which the non-thermal production is suppressed in realistic models.

The reader may feel uneasy about this multi-inflation scenario. We do not believe one should worry about it, since inflation is a natural scenario and often it is more of a problem to get out of it [43] than to experience it. In our scenario there is an award of having a possibility of detecting magnetic monopoles. This is the major point of our work. Magnetic monopoles as much as proton decay, if not more, provide a test of the idea of grand unification. After all, these are the only generic properties of GUTs. Of course, the usual inflation with low reheating temperature solves the monopole problem, but at the tragic prize of implying no monopoles left in the whole universe.

ACKNOWLEDGMENTS

We are grateful to Lotfi Boubekeur for collaboration in the early stage of this work and to Gia Dvali for important comments regarding the monopole production in theories with first order phase transition. The work of B.B. is supported by the Ministry of Education, Science and Sport of the Republic of Slovenia; the work of I.G. and G.S. is partially supported by

---

1 We thank Gia Dvali for emphasizing this point.
EEC under the TMR contracts ERBFMRX-CT960090 and HPRN-CT-2000-00152. Both B.B. and R.G. thank ICTP for hospitality during the course of this work.
REFERENCES

[1] S. Dimopoulos, S. Raby and F. Wilczek, “Supersymmetry And The Scale Of Unification,” Phys. Rev. D 24 (1981) 1681.
[2] L. E. Ibanez and G. G. Ross, “Low-Energy Predictions In Supersymmetric Grand Unified Theories,” Phys. Lett. B 105 (1981) 439.
[3] M. B. Einhorn and D. R. Jones, “The Weak Mixing Angle And Unification Mass In Supersymmetric SU(5),” Nucl. Phys. B 196 (1982) 475.
[4] W. J. Marciano and G. Senjanović, “Predictions Of Supersymmetric Grand Unified Theories,” Phys. Rev. D 25 (1982) 3092.
[5] L. Alvarez-Gaume, J. Polchinski and M. B. Wise, “Minimal Low-Energy Supergravity,” Nucl. Phys. B 221 (1983) 495.
[6] K. Inoue, A. Kakuto and H. Takano, “Higgs As (Pseudo)Goldstone Particles,” Prog. Theor. Phys. 75 (1986) 664.
[7] A. A. Anselm and A. A. Johansen, “Susy GUT With Automatic Doublet - Triplet Hierarchy,” Phys. Lett. B 200 (1988) 331.
[8] A. A. Anselm, “A Supersymmetric Theory Of Grand Unification With Automatic Hierarchy And Low-Energy Physics,” Sov. Phys. JETP 67 (1988) 663 [Zh. Eksp. Teor. Fiz. 94 (1988) 26].
[9] Z. G. Berezhiani and G. R. Dvali, “Possible Solution Of The Hierarchy Problem In Supersymmetrical Grand Unification Theories,” Bull. Lebedev Phys. Inst. 5 (1989) 55 [Kratk. Soobshch. Fiz. 5 (1989) 42].
[10] G. Dvali and S. Pokorski, “Role of the anomalous U(1)A for the solution of the doublet-triplet splitting problem via the pseudo-Goldstone mechanism,” Phys. Rev. Lett. 78 (1997) 807 [hep-ph/9610431].
[11] E. Witten, “Mass Hierarchies In Supersymmetric Theories,” Phys. Lett. B 105 (1981) 267.
[12] K. Tabata, I. Umemura and K. Yamamoto, “Dynamical Generation Of Hierarchy In Guts With Softly Broken Supersymmetry,” Phys. Lett. B 127 (1983) 90.
[13] K. Tabata, I. Umemura and K. Yamamoto, “A Realistic SU(6) GUT With Dynamical Generation Of Gauge Hierarchy,” Prog. Theor. Phys. 71 (1984) 615.
[14] H. Goldberg, “From Planck to GUT via dimensional transmutation,” Phys. Lett. B 400 (1997) 301 [hep-ph/9704376].
[15] A. Dedes, C. Panagiotakopoulos and K. Tamvakis, “Radiative GUT symmetry breaking in a R-symmetric flipped SU(5) model,” Phys. Rev. D 57 (1998) 5493 [hep-ph/9710563].
[16] Z. Berezhiani, C. Csaki and L. Randall, “Could the supersymmetric Higgs particles naturally be pseudoGoldstone bosons?,” Nucl. Phys. B 444 (1995) 61 [arXiv:hep-ph/9501336].
[17] R. Barbieri, G. Dvali, A. Strumia, Z. Berezhiani and L. Hall, “Flavor in supersymmetric grand unification: A Democratic approach,” Nucl. Phys. B 432 (1994) 49 [hep-ph/9405428].
[18] M. Kamionkowski and J. March-Russell, “Planck scale physics and the Peccei-Quinn mechanism,” Phys. Lett. B 282 (1992) 137 [arXiv:hep-th/9202003].
[19] R. Holman, S. D. Hsu, T. W. Kephart, E. W. Kolb, R. Watkins and L. M. Widrow, “Solutions to the strong CP problem in a world with gravity,” Phys. Lett. B 282 (1992) 132 [arXiv:hep-ph/9203206].
[20] S. M. Barr and D. Seckel, “Planck scale corrections to axion models,” Phys. Rev. D 46 (1992) 539.
[21] Q. Shafi and Z. Tavartkiladze, “Proton decay, neutrino oscillations and other consequences from supersymmetric SU(6) with pseudo-Goldstone Higgs,” Nucl. Phys. B 573 (2000) 40 [arXiv:hep-ph/9905202].
[22] M. Gell-Mann, P. Ramond and R. Slansky, proceedings of the Supergravity Stony Brook Workshop, New York, 1979, eds. P. Van Nieuwenhuizen and D. Freeman (North-Holland, Amsterdam); T. Yanagida, proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, Japan 1979 (edited by A. Sawada and A. Sugamoto, KEK Report No. 79-18, Tsukuba); R. N. Mohapatra and G. Senjanović, “Neutrino Masses And Mixings In Gauge Models With Spontaneous Parity Violation,” Phys. Rev. D 23 (1981) 165.
[23] S. Weinberg, “Does Gravitation Resolve The Ambiguity Among Supersymmetry Vacua?,” Phys. Rev. Lett. 48 (1982) 1776.
[24] F. R. Klinkhamer, “Supersymmetric Unification And Cosmology,” Phys. Lett. B 110 (1982) 203.
[25] P. Ginsparg, “Finite Temperature Behavior Of Mass Hierarchies In Supersymmetric Theories,” Phys. Lett. B 112 (1982) 45.
[26] S. Pi, “Cosmological Consequences Of A Hierarchical Supersymmetric Model,” Phys. Lett. B 112 (1982) 441.
[27] K. Yamamoto, “Finite Temperature Behavior Of Gauge Hierarchy Models With Quantum Mechanical Resuscitation,” Phys. Lett. B 133 (1983) 315.
[28] T. W. Kibble, “Topology Of Cosmic Domains And Strings,” J. Phys. AA 9 (1976) 1387.
[29] H. E. Haber, “Baryon Asymmetry And The Scale Of Supersymmetry Breaking,” Phys. Rev. D 26 (1982) 1317.
[30] M. Mangano, “Global And Gauge Symmetries In Finite Temperature Supersymmetric Theories,” Phys. Lett. B 147 (1984) 307.
[31] B. Bajc, A. Melfo and G. Senjanović, “On supersymmetry at high temperature,” Phys. Lett. B 387 (1996) 796 [hep-ph/9607242].
[32] F. C. Adams, M. Fatuzzo, K. Freese, G. Tarle, R. Watkins and M. S. Turner, “Extension of the Parker bound on the flux of magnetic monopoles,” Phys. Rev. Lett. 70 (1993) 2511.
[33] A. H. Guth and S. H. Tye, “Phase Transitions And Magnetic Monopole Production In The Very Early Universe,” Phys. Rev. Lett. 44 (1980) 631 [Erratum-ibid. 44 (1980) 963].
[34] A. H. Guth and E. J. Weinberg, “Cosmological Consequences Of A First Order Phase Transition In The SU(5) Grand Unified Model,” Phys. Rev. D 23 (1981) 876.
[35] M. S. Turner, E. J. Weinberg and L. M. Widrow, “Bubble nucleation in first order inflation and other cosmological phase transitions,” Phys. Rev. D 46 (1992) 2384.
[36] G. D. Coughlan, W. Fischler, E. W. Kolb, S. Raby and G. G. Ross, “Cosmological Problems For The Polonyi Potential,” Phys. Lett. B 131 (1983) 59.
[37] L. Randall and S. Thomas, “Solving the cosmological moduli problem with weak scale inflation,” Nucl. Phys. B 449 (1995) 229 [arXiv:hep-ph/9407248].
[38] G. R. Dvali, “Inflation versus the cosmological moduli problem,” arXiv:hep-ph/9503259.
[39] M. Dine, L. Randall and S. Thomas, “Supersymmetry breaking in the early universe,”
[40] R. Kallosh, L. Kofman, A. D. Linde and A. Van Proeyen, “Gravitino production after inflation,” Phys. Rev. D 61 (2000) 103503 [arXiv:hep-th/9907124].

[41] G. F. Giudice, I. Tkachev and A. Riotto, “Non-thermal production of dangerous relics in the early universe,” JHEP 9908 (1999) 009 [arXiv:hep-ph/9907510].

[42] H. P. Nilles, M. Peloso and L. Sorbo, “Coupled fields in external background with application to nonthermal production of gravitinos,” JHEP 0104 (2001) 004 [arXiv:hep-th/0103202].

[43] A. H. Guth and E. J. Weinberg, “Could The Universe Have Recovered From A Slow First Order Phase Transition?,” Nucl. Phys. B 212 (1983) 321.