New Models of Gauge Mediated Dynamical Supersymmetry Breaking

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Abstract
We propose a simple class of nonrenormalizable models of gauge mediated dynamical supersymmetry breaking. The models do not have gauge singlet fields. The Standard Model gauge group is embedded in the global symmetry of the SUSY breaking sector. At the renormalizable level the models possess a set of classical flat directions. Only one of those flat directions is unlifted by quantum effects, and requires nonrenormalizable term to stabilize the potential for the corresponding modulus. Large vacuum expectation value of this modulus at the minimum of the potential generates mass terms for the messenger fields. There are no light messengers, thus this class of models evades difficulties encountered in earlier constructions using nonrenormalizable models.

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Gauge mediated supersymmetry breaking (GMSB) [1] offers an attractive solution to the problem of the flavor changing neutral currents. While the original explicit models of GMSB [2] – [4] are phenomenologically viable, they are quite complicated. This is because the most elegant idea [5] of identifying Standard Model gauge group with the global symmetry of the supersymmetry breaking sector leads to the large increase in the number of fields with the Standard Model gauge quantum numbers and as a result QCD becomes non-asymptotically free and hits its Landau pole just a few decades above the weak scale. One possible solution to this problem suggested in [2] is to isolate the dynamical supersymmetry breaking (DSB) sector of the model from the Standard Model sector. This solution while leading to realistic models is not very appealing.

Recently a lot of effort has been devoted to simplifying the structure of the GMSB models [6]–[12]. Here we will follow an approach which attempts to identify the Standard Model with the (weakly gauged) subgroup of the global symmetry of the DSB sector. The asymptotic freedom problem mentioned above can be solved by making messenger fields very heavy so that they do not significantly affect running of the gauge couplings up to the unification scale and do not spoil perturbative gauge coupling unification. To generate large masses for the messengers one couples them to a modulus which acquires large vacuum expectation value (vev) at the minimum of the potential. Several classes of models have been constructed along these lines [6]–[11]. We will briefly review two of them here.

In the class of models suggested by Poppitz and Trivedi [6] the modulus parameterizes a D-flat direction which is only lifted by a non-renormalizable operator, and, therefore, obtains a large vev at the minimum of the potential. The serious problem encountered by Poppitz and Trivedi (which was also present in the analogous models of ref. [7]) is that there are light messenger fields with significant soft SUSY breaking scalar masses and positive supertrace. This leads to the negative mass squared for the squarks and sleptons through the two-loop RGE evolution [7, 13]

Another mechanism [8, 9] to generate large vev for the modulus is through a modification of the quantum moduli space models [14, 15] in which large vev is generated by the inverted hierarchy mechanism [16]. The most elegant models [8, 9] constructed along these lines suffer from the following problem (see [10] for the possible resolution). Since the Standard Model gauge group is identified with an unbroken diagonal subgroup of the product gauge group of the microscopic theory, models possess gauge messengers. As was shown in [17] this leads to the significant negative contribution to the superpartner masses.

Here we suggest a class of models which circumvent the difficulties mentioned above. This class of models can be thought of as a hybrid between the two approaches. In our models there will be a set of classical flat directions unlifted by the tree level superpotential at the renormalizable level. All but one of them will be lifted quantum mechanically. The quantum effects will lead to generation of a run-away scalar potential along remaining classical flat direction as in the models of refs. [6, 7]. The scalar potential will be stabilized by the nonrenormalizable operator in the tree level superpotential, ensuring that the corresponding
modulus will acquire a large vev and generate large masses for all messengers. Both modulus
and the messenger fields originate in a sector very similar to the $SU(5)^3$ model of ref. [9]. In
our case, however, the Standard Model matter fields and the modulus do not carry quantum
numbers under the same gauge groups and thus gauge messengers do not appear.

The simplest model in this class is based on $SU(5)_1 \times SU(5)_2 \times SU(5)_G$ gauge group with
a matter content given in the table 1. The Standard Model gauge group will be embedded
in $SU(5)_G$, but in our discussion of the supersymmetry breaking we will treat $SU(5)_G$ as a
global symmetry. As usual we will work in terms of the complete GUT multiplets although
this is not essential. We will choose to write the tree level superpotential in the form

$$W = XQ\bar{Q} + \frac{1}{M_{Pl}^2}X^5 + \cdots$$

(1)

We could also have added other nonrenormalizable terms, such as $Q^5$ and $\bar{Q}^5$. However, we
will be interested in the dynamics of the model for large $X$ where such terms are negligible. In
addition one could impose symmetries to exclude these terms.

Let us start by commenting on the matter content of the model. It clearly consists of two
distinct sectors. The first sector contains antisymmetric tensor $A$ and antifundamental $\bar{F}$
charged under $SU(5)_1$ group only. This sector has the matter content of the supersymmetry
breaking $SU(5)$ model [5]. Our goal is to construct the full model in such a way that the
low-energy effective theory describing SUSY breaking would contain $A$ and $\bar{F}$ as the light
fields with the addition of the modulus from the second sector\textsuperscript{2}. We will, therefore, loosely
refer to this sector as a DSB sector. The second sector is a model discussed in [18] with
an $SU(N)^2$ gauge group and $N_f = N$ flavors for each group. This sector has a run-away
direction\textsuperscript{3} parametrized by the vev of the light modulus $v = (\det X)^{1/5}$. All other classical
flat directions of this sector do not lead to supersymmetric vacua. This sector will provide
both messenger fields and the light modulus with non-vanishing vacuum expectation value
for both the scalar and auxiliary component and we will refer to it as a messenger sector.

\textsuperscript{2}This low energy matter content is analogous to the models of ref. [11]. In [11], however, the strong
$SU(5)$ dynamics served to stabilize modulus, while in our models it will push modulus to large vev.

\textsuperscript{3}This is exactly the direction we are interested in and it will persist in the full model at the renormaliz-
ablevel. The dynamics along this direction will, however, be somewhat modified by the presence of the
additional fields in the DSB sector.

Table 1: Quantum numbers of chiral superfields in $SU(5)^3$ model

<table>
<thead>
<tr>
<th></th>
<th>$SU(5)_1$</th>
<th>$SU(5)_2$</th>
<th>$SU(5)_G$</th>
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</thead>
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<td>$A$</td>
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<td>1</td>
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<tr>
<td>$\bar{F}$</td>
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<tr>
<td>$X$</td>
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<td>1</td>
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<tr>
<td>$\bar{Q}$</td>
<td></td>
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</tr>
<tr>
<td>$Q$</td>
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<td></td>
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</tbody>
</table>

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2

3
At the renormalizable level the superpotential (1) possesses a set of classical flat directions parametrized by the vev’s of the gauge invariant polynomials $S = v^5 = \det(X)$, $B = \det(Q)$, $\bar{B} = \det(\bar{Q})$, $P = A^2\bar{Q}$, $N = A\bar{Q}^3$ and $M = \bar{F}\bar{Q}$. As mentioned above we are interested in the dynamics for large $v$. In such a case all components of the $Q$ and $\bar{Q}$ become heavy. One, therefore, can hope that all gauge invariant polynomials involving $Q$ or $\bar{Q}$ will have vanishing vev’s. Still, let us show that all classical flat directions but $v$ are lifted quantum mechanically.

1. Along the $B$ direction the $SU(5)_2$ is completely broken while $SU(5)_1$ remains unbroken. All matter fields but $A$ and $\bar{F}$ become heavy. The low energy dynamics therefore breaks supersymmetry for every fixed value of $B$. By matching scales of microscopic and low-energy theories, we find the potential for $B$

$$V \sim \Lambda^4_L \sim (BA^8_1)^{4/13}$$

(2)

Clearly this stabilizes classical flat direction.

2. Along the $\bar{B}$ direction the gauge group $SU(5)_1$ is completely broken, while $SU(5)_2$ remains unbroken. There are no light matter fields charged under the unbroken gauge group. Gaugino condensation generates the superpotential. Using the scale matching conditions we can find the superpotential for $\bar{B}$:

$$W = \Lambda^3_L = \bar{B}^{1/5}\Lambda^2_2$$

(3)

which leads to a $\bar{B}$-independent non-vanishing potential\textsuperscript{4}. At one loop a potential for $\bar{B}$ is generated and theory is stabilized near the origin [8, 9, 19] (for certain range of parameters there is a local SUSY breaking vacuum for large but finite $\bar{B}$ due to the contributions of the dynamics in the broken $SU(5)_1$ group [8, 9]).

3. Along $P$ and $N$ flat directions unbroken gauge group is again $SU(5)_2$. In both cases there are 5 flavors transforming under the strong $SU(5)_2$ group. They are coupled to $\bar{Q}$ fields\textsuperscript{5} which are singlets of the $SU(5)_2$. As is well known all classical flat directions involving gauge singlet fields are lifted quantum mechanically in such a case.

4. $M$ direction is potentially the most dangerous. Along this direction $SU(5)_1$ is only broken to $SU(4)_1$ subgroup with a scale inversely proportional to a power of the vev. If the nonperturbative superpotential were generated by the strong $SU(4)_1$ dynamics, the interference effects could potentially lead to the restoration of the supersymmetry.

\textsuperscript{4}Remember that Kähler potential is nearly canonical in terms of elementary quark superfields for large $\bar{B}$.

\textsuperscript{5}Due to the large vev of the component(s) of $\bar{Q}$ one of the flavors is heavy along $P$ direction, and three flavors are heavy along $N$ direction. Thus we could have considered effective $SU(5)$ with $N_f = 4$ (or $N_f = 2$) and modulus-dependent scale. This would lead us to the same conclusions.
Fortunately, there are 5 flavors of fundamentals fields and antisymmetric tensor transforming under the effective $SU(4)_1$ group, and no superpotential can be generated. Therefore, $SU(4)_1$ dynamics can be neglected for large vev. Repeating the previous analysis of the $SU(5)_2$ dynamics we conclude that $M$ is lifted.

It is also easy to show that there is no SUSY minimum near the origin of the moduli space. Consider a limit $\Lambda_2 \gg \Lambda_1$. Below the scale $\Lambda_2$ the renormalizable Yukawa coupling in the superpotential turns into the mass term for $SU(5)_2$ mesons and $\bar{Q}$. At low energies the effective description is SUSY breaking $SU(5)$ model with the scale $\Lambda_L = \Lambda^8 \Lambda^5_2$. As a result there is no SUSY vacuum near the origin. Light spectrum also contains baryons $S = X^5$ and $B$ which are singlets under the low energy gauge group. For $S, B \ll \Lambda_2$ the Kähler potential is nearly canonical in terms of baryonic variables. The $B$ directions is lifted according to eqn. (2). Due to the quantum modified constrain in $SU(5)_2$ gauge group this leads to $S$ acquiring vev - thus leading the model towards the vacuum of interest.

Having established that all unwanted classical flat directions are lifted quantum mechanically and that there is no SUSY minimum near the origin of the moduli space, we are ready to consider the effective theory for large $v$. In this case the gauge group is broken to the diagonal $SU(5)_L$. In the effective theory only $A, F$, and $v$ remain light. For every fixed value of $v$ the potential is nonvanishing. The model is noncalculable and we can only give estimates of the vacuum energy and other parameters at the minimum of the scalar potential. Using the scale matching conditions we find

$$V \sim \Lambda_L^4 \sim \left(\frac{\Lambda^8 \Lambda_{10}^1}{v^5}\right)^{4/13}$$

This leads to run-away behavior. When we turn on nonrenormalizable coupling, the scalar potential is stabilized. Vacuum energy will be determined by the balance between the potential in (4) and $|F_v|^2 \sim \left|\frac{v^4}{M_{PL}}\right|^2$. At the minimum

$$v \sim \left(M_{PL}^{13} \Lambda^{18}\right)^{\frac{1}{31}} \quad V \sim \left(M_{PL}^{20} \Lambda^{144}\right)^{\frac{4}{31}} \quad F_v \sim \left(\frac{\Lambda_{72}^{72}}{M_{PL}^{10}}\right)^{\frac{1}{31}} \quad \frac{F_v}{v} \sim \left(\frac{\Lambda_{54}^{54}}{M_{PL}^{23}}\right)^{\frac{1}{31}}$$

where we used notation $\Lambda^9 = \Lambda^4 \Lambda^5_2$.

Upon identifying an $SU(3) \times SU(2) \times U(1)$ subgroup of the global $SU(5)_G$ symmetry with the Standard Model the heavy fields $Q$ and $\bar{Q}$ serve as messengers of the supersymmetry breaking. If we require that the scale of the supersymmetry breaking breaking in the Standard Model sector be $\Lambda_{SUSY} = \frac{F_v}{v} \sim 10^4$ GeV we find that

$$\Lambda \sim \text{few} \times 10^{10} \text{ GeV} \quad v \sim \text{few} \times 10^{13} \text{ GeV} \quad \sqrt{F} \sim \text{few} \times 10^{8} \text{ GeV}$$

\[\text{Note that despite this fact our model is quite predictive, since holomorphic SUSY breaking contributions to messenger masses dominate. The Standard Model superpartner spectrum can easily be calculated in terms of } \Lambda_{SUSY} = F_v/v \text{ and } \mu, \text{ assuming that dynamics generating } \mu \text{ term is not connected with supersymmetry breaking.}\]
It is easy to find several generalizations of the $SU(5)^3$ model described above. An almost trivial modification involves interchange of fundamental and antifundamental fields in the messenger sector. The set of mixed flat directions in such a model is different. Still only the $v$ direction is not stabilized at the renormalizable level, and the dynamics along this direction is the same as discussed above. More generally one can use a different DSB sector. Any DSB model without classical flat directions and a gauge group with $SU(5)$ factor can be a candidate. Such a modification clearly does not change our discussion of the $B$ and $\bar{B}$ classical flat directions. One should carefully check the stabilization of the potential along mixed flat directions involving vev’s of the fields of both sectors. In particular, it is possible that superpotential is generated in the unbroken subgroup of the DSB sector. If this is the case, it is necessary to verify that there are no interference effects leading to the supersymmetry restoration\textsuperscript{7}.

As an example consider a model based on the $U(1) \times SU(2) \times SU(5)_{1} \times SU(5)_{2} \times SU(5)_{G}$ group with matter content as given in table 2 and tree level superpotential

$$W = \gamma A \tilde{F}_{1} \tilde{F}_{2} + \eta S \phi_{1} \phi_{2} + \delta_{i} F \tilde{F}_{i} \phi_{i} + \lambda X Q \bar{Q} + \frac{1}{M_{Pl}^{2}} X^{5}$$ \hspace{1cm} (7)

The DSB sector of this model is described in ref. [4]. While the dynamics along mixed flat directions is much more complicated, it does not lead to the runaway behavior. For large $v$ the effective description is the $SU(5) \times SU(2) \times U(1)$ model of ref. [4] with the strong coupling scale given by $\Lambda^{11} = \Lambda_{1}^{6} \Lambda_{2}^{10} / v^{5}$. Thus we have an example in which low energy description is given by a calculable model.

For our models to lead to a realistic spectrum of the superpartner masses it is important for both the scalar component and $F$-term of the modulus $v$ to have a non-vanishing expectation value. In the $SU(5)^3$ model discussed above one can not calculate an $F$ term for the light modulus. We could only establish the order of magnitude of this term on dimensional grounds. While there are no symmetry reasons in this model for the $F$-term to vanish, it

\textsuperscript{7}Even when this happens there generically will be a local SUSY breaking minimum for large $v$. 

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<thead>
<tr>
<th></th>
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<th>$SU(2)$</th>
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Table 2: Quantum numbers of chiral superfields in a calculable model
Table 3: Quantum numbers of chiral superfields in toy model

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<td>¯Q</td>
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<td>3</td>
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would be satisfying to check the assertion in a calculable model. Our second example, an $U(1) \times SU(2) \times SU(5)₁ \times SU(5)₂$ model, is calculable and presents such a possibility. Instead of minimizing potential of this model we will work with a toy example^{8} based on the $SU(2) \times SU(3)₁ \times SU(3)₂ \times SU(3)₆$ model^{9} with a matter content given in the table 3. For large $v$ the effective description is the $3-2$ model of Affleck-Dine-Seiberg [5] with a modulus dependent scale and the effective superpotential (after integrating out heavy fields)

$$W = \frac{\Lambda^{10}}{v^3 \det(q\bar{q})} + \lambda_1 q\ell\bar{d} + \lambda_2 v^3$$

(8)

where $\Lambda^{10} = \Lambda^4 \Lambda^6$, $q = (\bar{u}, \bar{d})$, and $\lambda_2$ is small. We find that this model breaks SUSY and at the minimum

$$F_v = 0.3 \lambda_1^{4/15} \lambda_2^{8/15} \Lambda^2$$

(9)

Therefore, we have established that light modulus has non-vanishing $F$-term as desired for model-building.

Finally, let us comment on the $\mu$-problem. It is as severe in our models as in the most other GMSB models (see, however, ref. [10]). One could use a horizontal symmetry as suggested in [20] to generate $\mu$-term while a small (order $\alpha_2$) $B$-term would be generated at the two loop level.

To summarize, we have presented here a simple class of models with gauge mediated dynamical supersymmetry breaking. While implementing the idea of direct gauge mediation our models avoid some of the difficulties encountered in earlier attempts to realize this approach. In particular all messenger fields are heavy and there are no gauge messengers. Our models are completely chiral and do not contain gauge singlets, although gauge singlet fields may have to be introduced to generate $\mu$-term of the appropriate order of magnitude. Some of our models are calculable, but even noncalculable $SU(5)^3$ model is quite predictive.

^{8}We thank Yael Shadmi for suggesting this example.

^{9}This model has only $SU(3)₆$ global symmetry, and can not be used for model building.
Acknowledgements

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References


