Moduli and Anomaly Mediation Combined

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Motivated by new developments in string theory, a new parametrization of soft supersymmetry breaking terms has been proposed. It is referred to as mirage mediation and assumes comparable contributions of moduli and anomaly mediation to the soft terms. We review certain phenomenological aspects of mirage mediation.

Phenomenology of supersymmetric models very much depends on the pattern of soft supersymmetry breaking terms. The minimal supersymmetric standard model (MSSM) includes all soft terms allowed by the symmetries, which results in a huge parameter space. For this reason, in phenomenological studies, the soft terms are parametrized in terms of a fewer number of variables. The existing parametrizations are usually inspired by some underlying model of supersymmetry breaking and its mediation to the observable sector. By far, the most popular choice is the constrained MSSM. It is motivated by supersymmetry breaking mediation in simple supergravity models and assumes that all scalar masses, all gaugino masses and all A-terms are universal at the unification scale. There also exist alternative parametrizations with non-universal boundary conditions at the high scale. The best known scenarios of that sort are based on gauge mediation and anomaly mediation.

The recent progress in string theory has prompted introducing a new parametrization, in which the soft terms receive comparable contributions from gravity mediation and anomaly mediation. Such parametrization was originally motivated by the string theoretical framework introduced by Kachru, Kallosh, Linde and Trivedi (KKLT).[1] These authors found a string scenario with a stable vacuum and a small positive cosmological constant. In refs. [2,3] it was pointed out that the KKLT scenario predicts a characteristic pattern of soft terms with comparable moduli and anomaly mediated contributions. Phenomenology of the MSSM with such soft terms was subsequently studied in refs.[4,5,6,7]. For the reasons that will become clear in the following, this scenario for the soft terms is often referred to as *mirage mediation*.[8] More recently, the pattern was found useful for relaxing the electroweak fine-tuning problem in the MSSM[9] although, most probably, the parameter space in which this can be achieved cannot be reached in string-inspired models.[10]

The usual assumption in supergravity models of soft terms is that supersymmetry breaking occurs in a hidden sector. The supersymmetry breaking is subsequently mediated to the observable sector via non-renormalizable interactions between the hidden sector and the MSSM fields. In order to describe such a mediation mechanism in full generality we introduce a set of *moduli* superfields T_n. These are chiral superfields that carry no charge under the SM gauge group and may acquire vevs both in their lowest components $\langle T_n \rangle$ and in their F-components F_n. The latter fully parametrize the supersymmetry breaking in our setup (we assume the D-term breaking is absent). The soft terms in the observable sector are then determined by the structure of interactions between the moduli and the MSSM fields. It turns out that the relevant interactions can be described in terms of three sets of functions: the matter kinetic functions $Y_i(T_n, T_n^\dagger)$, the gauge kinetic functions $f_a(T_n)$ (that also fix the gauge couplings $f_a(\langle T_n \rangle) = 1/g_a^2$) and by Yukawa functions $\lambda_{ijk}(T_n)$. The relevant interactions can be written in the superspace formalism as

$$\mathcal{L} = \int d^4\theta\, \Phi^\dagger \Phi Y_i(T_n, T_n^\dagger) Q_i^\dagger Q_i + \left\{ \int d^2\theta \left(\frac{1}{4} f_a(T_n) W^{a\alpha} W_\alpha^a + \Phi^3 \lambda_{ijk}(T_n) Q_i Q_j Q_k \right) + \text{h.c.} \right\} . \quad (1)$$

In the above Q_i denote the MSSM matter and Higgs superfields and W_α^a ($a = 1\ldots3$) are the field strength superfields for the three gauge group factors. The superfield $\Phi = 1 + \theta^2 F_\Phi$ is called the conformal compensator. Its F-component vev is related to the moduli vevs as $F_\Phi = m_{3/2} + \frac{\partial K}{\partial T_n} F_n$, where $m_{3/2}$ is the gravitino mass and K is the Kähler potential of the moduli fields.

Expanding the superfields in Eq 1 into components we can read off the soft term lagrangian, defined as[a]

$$\mathcal{L}_{soft} = -m_i^2 |Q_i|^2 - \left(\frac{1}{2} M_a \lambda^a \lambda^a + \frac{1}{6} A_{ijk} y_{ijk} Q_i Q_j Q_k + \text{h.c.} \right) . \quad (2)$$

The gaugino masses are given by

$$M_a = \frac{1}{f_a + \overline{f}_a} \frac{\partial f_a}{\partial T_n} F_n + \frac{1}{16\pi^2} b_a g_a^2 F_\Phi . \quad (3)$$

The first term is the usual moduli mediation that arises from tree-level interactions in the supergravity lagrangian. The second term is proportional to the respective beta function coefficient b_a in the MSSM. It is referred to as anomaly mediation. Similarly, the soft trilinear terms,

$$A_{ijk} = -\frac{\partial}{\partial T_n} \log \left(\frac{\lambda_{ijk}}{Y_i Y_j Y_k} \right) F_n - (\gamma_i + \gamma_j + \gamma_k) \frac{1}{16\pi^2} F_\Phi , \quad (4)$$

consist of the tree-level moduli mediated contribution and one-loop anomaly mediated contributon (proportional to the anomalous dimensions γ_i of the MSSM fields, $\gamma_i = -8\pi^2 \frac{\partial \log Y_i}{\partial \log \mu}$).

The scalar soft masses,

$$m_i^2 = -\frac{\partial^2 \log Y_i}{\partial T_n \partial T_m^\dagger} F_n F_m^\dagger - \dot{\gamma}_i \frac{1}{(16\pi^2)^2} |F_\Phi|^2 + \left(\frac{\partial \gamma_i}{\partial T_n} \frac{1}{16\pi^2} F_\Phi F_n^\dagger + \text{h.c.} \right) , \quad (5)$$

have a slightly more complicated structure. The tree-level moduli mediation depends on the kinetic functions Y_i. The anomaly mediated term arises at two loops and is proportional to the scale dependence of the anomalous dimensions, $\dot{\gamma}_i = 8\pi^2 \frac{\partial \gamma_i}{\partial \log \mu}$. The last term is a one-loop mixed anomaly-moduli mediated contribution.

[a] In our conventions the Yukawa couplings between gauginos and matter fields contain the i factor: $\mathcal{L} = -i\sqrt{2} Y_i Q_i^\dagger \chi \psi_i + \text{h.c.}$.

In typical supergravity models one expects $F_n \sim F_\Phi \sim m_{3/2}$. In such a case the moduli mediated contribution dominates over the loop suppressed anomaly mediation. This is the most frequently studied scenario. Here, however, we are interested in a situation in which moduli and anomaly mediation are comparable, which requires $F_\Phi \sim m_{3/2} \sim 4\pi^2 F_n$. An apparent obstacle to obtaining such a relation is the formula for the F-term contribution to the vacuum energy in supergravity:

$$V_F = M_{pl}^2 \left(\frac{\partial K}{\partial T_n \partial T_m^\dagger} F_n F_m^\dagger - 3m_{3/2}^2 \right) . \tag{6}$$

To arrive at $V_F = 0$ we need at least some of the F-terms to be of order $m_{3/2}$. However in certain models it is possible to arrange the moduli potential such that all the F-terms relevant for supersymmetry breaking mediation are suppressed with respect to the gravitino mass. This is the case in the original KKLT model, where there exists additional, non-supersymmetric contribution to the vacuum energy. In conventional supergravity comparable moduli and anomaly mediation can also be realized, if the dominant vacuum energy comes from a sector that is not coupled to the MSSM or from the D-term potential.[11]

In the following we describe the phenomenology of a specific model of mirage mediation studied in ref.[6], which is inspired by string theoretical constructions with the MSSM matter living on D7 branes. In this model only one modulus, denoted as T, plays a role in supersymmetry breaking. The kinetic terms are given by

$$Y_i = (T + \overline{T}) \qquad f_a = T \tag{7}$$

and the Yukawa terms λ_{ijk} are independent of T. We write the F-term component of the T superfield as

$$F_T/(T + \overline{T}) \equiv \alpha \frac{m_{3/2}}{16\pi^2} , \tag{8}$$

where α parametrizes the modulus to anomaly mediation ratio. It depends on the details of the moduli potential, therefore we keep it as a free parameter (in the original KKLT model $\alpha \approx 5 \div 6$). Using Eqs. 3, 5, 4 the soft terms can be written as

$$M_a = \frac{m_{3/2}}{16\pi^2} \left[\alpha + b_a g_a^2 \right] , \tag{9}$$

$$m_i^2 = \frac{m_{3/2}^2}{(16\pi^2)^2} \left[\alpha^2 - \dot{\gamma}_i + 2\alpha (T + \overline{T}) \partial_T \gamma_i \right] , \tag{10}$$

$$A_{ijk} = \frac{m_{3/2}}{16\pi^2} \left[3\alpha - \gamma_i - \gamma_j - \gamma_k \right] . \tag{11}$$

These soft terms contain two adjustable parameters: $m_{3/2}$ and α. Futhermore, the μ-term and the B term are also assumed to be free parameters (their values depend on the mechanism of solving the μ problem). The absolute value of μ is determined by requiring correct electroweak symmetry breaking, whereas its sign remains free. Further, it is conventional to trade B for the low energy parameter $\tan\beta$. The MSSM renormalization group (RG) parameters occuring in these formulas can be found, for example, in ref.[6]. Thus, the parameter space for phenomenological studies is

$$m_{3/2} , \quad \alpha , \quad \tan\beta , \quad \mathrm{sgn}(\mu) . \tag{12}$$

These are our input parameters at the GUT scale, which we take to be 2×10^{16} GeV. We assume that effective field theory is valid below this scale and use RG equations to derive the low energy SUSY spectrum.

Let us now overview main features of the resulting SUSY spectrum.

(i) Moduli/gravitino problem. A characteristic feature of the spectrum is a moderate hierarchy (a factor of 30 or so) between the MSSM soft masses and the gravitino mass. As discussed in ref.[4], this is advantageous from the cosmological perspective since the gravitino is heavy enough to decay before the nucleosynthesis and not to affect abundances of the light elements. The cosmological problems come back however if the early universe is dominated by the modulus T. In such a case T decays into the gravitino, which results in gravitino overabundance in a large portion of the parameter space.[12]

(ii) Tachyons. Pure anomaly mediation is notorious for its negative slepton mass squared problem. In mirage mediation, there is an additional moduli mediated contribution which rectifies the problem. The absence of tachyons imposes a lower bound on the parameter α. Indeed, the GUT scale boundary condition for the slepton masses of the first two generations reads

$$\begin{aligned} m_L^2 &\approx \left(-1-2\alpha+\alpha^2\right)\frac{m_{3/2}^2}{(16\pi^2)^2}, \\ m_E^2 &\approx \left(-2-\alpha+\alpha^2\right)\frac{m_{3/2}^2}{(16\pi^2)^2}. \end{aligned} \tag{13}$$

To avoid tachyonic sleptons, $\alpha > 2$ is required. For the squarks,

$$\begin{aligned} m_Q^2 &\approx \left(2-4\alpha+\alpha^2\right)\frac{m_{3/2}^2}{(16\pi^2)^2}, \\ m_U^2 &\approx \left(1-3\alpha+\alpha^2\right)\frac{m_{3/2}^2}{(16\pi^2)^2}, \\ m_D^2 &\approx \left(2-3\alpha+\alpha^2\right)\frac{m_{3/2}^2}{(16\pi^2)^2}. \end{aligned} \tag{14}$$

Although the squark masses are positive in pure anomaly mediation, they become tachyonic[b] for $0.5 < \alpha < 4$ due to the mixed anomaly–modulus contribution proportional to α. In conclusion, the tachyons which signify color or charge breaking minima are absent for $\alpha > 4$. This bound has important implications for phenomenology. In particular, most of the parameter space with characteristic signals of anomaly mediation such as a wino LSP is excluded. Curiously, $\alpha \sim 5$ predicted by the original KKLT model is on the safe side.

(iii) A-terms. Contrary to the constrained MSSM the magnitude of the A-terms is not a free parameter. In fact, the TeV scale A-terms are sizable in most of the parameter space. This results in a large mass splitting between the two stop eigenstates. For very large $\tan\beta$ the two sbottoms and staus also exhibit a large mass splitting.

(iv) LSP. In the non–tachyonic region, the bino is the lightest gaugino. For this reason a large portion of the parameter space is excluded because of dark matter overabundance. Furthermore, due to sizable A-terms certain parameter space regions contain the stop LSP or the stau LSP. In fact, for $\tan\beta \gtrsim 35$ all the parameter space is excluded due to existence of stau LSP. On the other hand, close to the boundary between the bino LSP and the stop LSP region, coannihilation reduces the bino abundance and allows to obtain the correct amount of dark matter.

(v) Mirage unification. An interesting feature of the scenario is the occurence of mirage unification.[5] That is, even though the gaugino and the scalar masses do not unify at the GUT scale, RG running of these quantities makes them unify at some intermediate scale. Indeed, the solutions to the 1–loop RG equations (neglecting Yukawa contributions) read

$$M_a(\mu) = \frac{m_{3/2}}{16\pi^2}\frac{\alpha + b_a g_{GUT}}{1-\frac{b_a g_{GUT}}{8\pi^2}\log\frac{\mu}{M_{GUT}}},$$

[b]For $\alpha > 2$, the squark masses squared are positive at the EW scale due to the RG running. However, $2 < \alpha < 4$ lead to tachyonic squarks at the GUT scale which signifies existence of color breaking minima in the effective potential.

$$m_i^2(\mu) \;=\; \frac{m_{3/2}^2}{(16\pi^2)^2}\alpha^2\left(1+2\frac{C_a(Q_i)}{b_a}\right)-2\frac{C_a(Q_i)}{b_a}M_a^2(\mu)\,. \tag{15}$$

At the mirage scale $\mu_{\rm mir}$,

$$\mu_{\rm mir} = M_{GUT}e^{-8\pi^2/\alpha}\,, \tag{16}$$

all gaugino and scalar masses of the first two generations unify,

$$M_a^2(\mu_{\rm mir}) = m_i^2(\mu_{\rm mir}) = \alpha^2\frac{m_{3/2}^2}{(16\pi^2)^2}\,. \tag{17}$$

This is truly a mirage scale as there is no physical threshold associated with it. Furthermore, the third generation scalar and the Higgs mass parameters do not unify at that scale. We note that for $\alpha \approx 5$ the mirage unification occurs at an intermediate scale, $\mu_{\rm mir} \sim 10^{11}$ GeV. In this case, the low energy spectroscopy is in some respects similar to that of pure moduli mediation with an intermediate string scale. In particular, the TeV scale superparticle spectrum is more squeezed, as compared to the constrained MSSM.

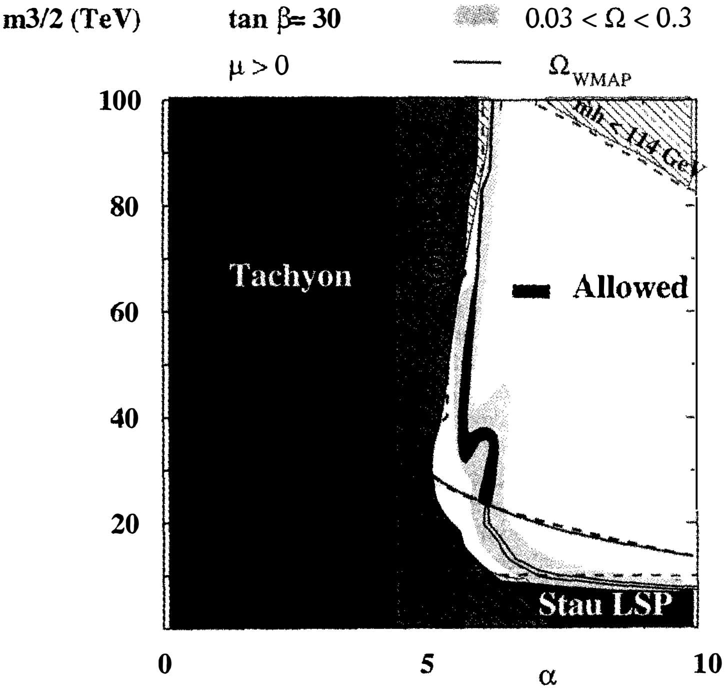

Figure 1: The parameter space of mirage mediation for $\tan\beta = 30$ and $\mathrm{sgn}(\mu) > 0$.

Fig. 1 shows the allowed $m_{3/2}$–α parameter space for $\tan\beta = 30$ and $\mathrm{sgn}(\mu) > 0$.[c] The region with small $\alpha \lesssim 4$ is excluded due to existence of tachyonic squark and/or leptons at the GUT scale. A consequence of sizable A-terms is the presence of the stop LSP region, which excludes $\alpha \lesssim 5$. The Higgs boson mass bound (green dashed line) excludes the region of small

[c]The shape of the allowed region differs from that presented in ref.[6]. The reason is the mistake made in ref.[6] concerning the relative sign between A terms and gaugino masses, which was pointed out in ref.[7].

gravitino mass (and thus small superpartner masses) with $m_{3/2} \lesssim 10\,\text{TeV}$. Even more stringent bound comes from $b \to s\gamma$ (magenta dashed line), which exludes $m_{3/2} \lesssim 20\,\text{TeV}$. Requiring neutralino dark matter abundance in agreement with the WMAP bound leaves a small strip of the parameter space between the two solid lines. The final allowed parameter space is marked in blue.

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