SUPERGRAVITY, LINEAR MULTIPLETS, 
AND CHERN-SIMONS FORMS

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ABSTRACT

Some general features of locally supersymmetric theories (N=1 in four dimensions) involving Chern-Simons forms and antisymmetric tensors are sketched out. The relevance of the three-form multiplet both for the description of Chern-Simons forms and the supersymmetry properties of the gaugino condensate is pointed out.

1. Introduction

The supersymmetric standard model has a rather simple structure concerning the basic building blocks involved in its construction: only chiral and Yang-Mills multiplets are needed. On the other hand, when it comes to the discussion of low energy effective theories of superstrings one has to deal with more sophisticated ingredients. First of all the general Kähler structure, in particular the Kähler phase transformations, should be taken into account. This can be done in $U_K(1)$ superspace, a geometric framework which embodies at the same time supergravity and matter, with Kähler transformations appearing ab initio in the structural group, on the same footing as the local Lorentz transformations of supergravity.

Moreover, in superstring inspired scenarios, less familiar multiplet structures and new couplings appear, as for instance linear multiplets and Chern-Simons forms induced from the Green-Schwarz anomaly cancellation in the superstring. Again, $U_K(1)$ superspace provides an appropriate background for a geometric description of these new structures. In turn, supersymmetric Chern-Simons forms are closely related to the three-form multiplet; the three-form superspace geometry provides the relevant framework for the Chern-Simons forms, Yang-Mills as well as gravitational. In a similar line of reasoning it will be pointed out here that the three-form multiplet is the relevant object which accounts for the supersymmetry properties of the gaugino condensate supermultiplet. Finally, it might be conceivable that three-form multiplets enter the stage of supersymmetric theories in their own right.
2. $U_K(1)$ Superspace: Unification of Supergravity and Matter

The basic object in this geometric formulation is the frame $E^A = dz^ME^A_M(z)$, a differential one-form in superspace, which, as an extension of traditional general relativity, introduces the usual moving frame $e_m^a(x)$ together with the Rarita-Schwinger field $\psi_m^a$, its supersymmetry partner, in a unified manner. In distinction to the traditional approach, the frame is not only subject to local Lorentz transformations, but also to local chiral transformations, with chiral weights defined as

$$w(E^a) = 0, \quad w(E^-) = +1, \quad w(E_\dot{a}) = -1. \quad (1)$$

Correspondingly, in the definition of the torsion a new term appears, in addition to the familiar spin connection:

$$T^A = dE^A + E^B\Phi_B^A + w(E^A)E^A_A. \quad (2)$$

The crucial point is that the $U_K(1)$ gauge potential $A = E^A\Lambda_A$ is given in terms of the Kähler potential $K(\phi, \bar{\phi})$ of the matter sector - the traditional unconstrained prepotential of supersymmetric gauge theory has been consistently replaced by the Kähler potential, which is a function of the chiral and antichiral matter superfields, giving rise to a unified geometric description of the supergravity-matter system. In this construction Kähler transformations are built in from the very beginning, on the same footing as local Lorentz transformations. The transformation

$$K(\phi, \bar{\phi}) \mapsto K(\phi, \bar{\phi}) + F(\phi) + \bar{F}(\bar{\phi}), \quad (3)$$

of the Kähler potential itself induces, by construction, a transformation

$$A \mapsto A + \frac{i}{2}d\text{Im}F, \quad (4)$$

on the $U_K(1)$ gauge potential which in turn serves to covariantize the Kähler phase transformations

$$E^A \mapsto E^A\exp\left(-\frac{i}{2}w(E^A)\text{Im}F\right), \quad (5)$$

of the frame in superspace. Observe that these assignments determine completely the Kähler properties of the supergravity superfields. This holds in particular for the superfields $R, R^\dagger$ and $G_a$ of weights $w(R) = +2, w(R^\dagger) = -2$ and $w(G_a) = 0$, which are subject to the conditions

$$\mathcal{D}^\dagger R = 0, \quad \mathcal{D}_aR^\dagger = 0, \quad (6)$$

and

$$\mathcal{D}_a\mathcal{D}_aR - \mathcal{D}_\dagger\mathcal{D}^\dagger R^\dagger = 4i\mathcal{D}_aG^a, \quad (7)$$

with Lorentz and Kähler covariant derivatives. For a more exhaustive presentation of $U_K(1)$ superspace see the literature cited so far.
3. Yang-Mills in $U_K(1)$ Superspace and Chern-Simons Forms

Having set up the geometrical framework for the supergravity-matter system we shall now include gauge interactions. To this end we consider matter fields $\phi$ and $\bar{\phi}$ in some representation of the gauge group and with gauge transformations

$$g\phi = g^{-1}\phi, \quad g\bar{\phi} = \bar{\phi}g,$$

where $g$ is a superspace dependent group element, like $g(z) = \exp i\alpha^{(r)}(z)T_{(r)}$, with superfield gauge parameters $\alpha^{(r)}(z)$ and generators $T_{(r)}$. Exterior covariant derivatives

$$d\phi - A\phi = D\phi = E^A D_A \phi, \quad d\bar{\phi} + \bar{\phi}A = D\bar{\phi} = E^A D_A \bar{\phi},$$

are defined in terms of the superspace one-form Lie algebra valued gauge potential

$$A = E^A A_A^{(r)} T_{(r)}, \quad gA = g^{-1}Ag - g^{-1}dg,$$

and the matter fields are now constrained to be covariantly chiral, resp. antichiral:

$$D^\alpha \phi = 0, \quad D_{\dot{\alpha}} \phi = 0.$$

As is well known, the covariant field strength

$$dA + AA = F = \frac{1}{2} E^A E^B F_{BA},$$

is subject to constraints. Correspondingly, the gaugino superfields $W_\alpha$ and $W_{\dot{\alpha}}$ of Kähler weights $w(W_\alpha) = +1$ and $w(W_{\dot{\alpha}}) = -1$, respectively, are subject to

$$D_{\dot{\alpha}} W_\alpha = 0, \quad D^\alpha W_\alpha = 0,$$

$$D^\alpha W_{\dot{\alpha}} = D_{\dot{\alpha}} W_{\dot{\alpha}}.$$

In turn, as a consequence of this constrained superspace geometry, the gaugino-squared superfield $\text{tr} W^2$ and its complex conjugate are chiral, resp. antichiral superfields with the additional property

$$\left(D^\alpha D_\alpha - 24R^\alpha\right) \text{tr} W^2 - \left(D_{\dot{\alpha}} D_{\dot{\alpha}} - 24R^{\dot{\alpha}}\right) \text{tr} \bar{W}^2 = -2i \varepsilon^{dcba} \text{tr} (F_{da} F_{ba}).$$

This last equation has a very natural interpretation in relation with supersymmetric Chern-Simons forms built from the superspace gauge potential $A$ defined as

$$\text{tr} \left(AdA + \frac{2}{3} AAA\right) = Q = \frac{1}{3} E^A E^B E^C Q_{CBA},$$

and satisfying $dQ = \text{tr} (F F)$. We will come back to this issue in a short while after having introduced the linear multiplet and its superspace geometry.
4. Superfield Actions

Given the geometric structures of the previous two sections, we turn now to the invariant actions. In the geometric approach, invariance under general coordinate transformations and under supersymmetry means nothing else than invariance under general reparametrizations in superspace. In addition, the actions should be invariant under Lorentz, Kähler and Yang-Mills transformations. It turns out that already the simplest invariant, namely the basic volume density, is quite non-trivial: it provides at the same time the kinetic terms for supergravity and for the matter sector:

\[ \mathcal{L}_{\text{supergravity} + \text{matter}} = -3 \int E. \]  

(17)

Here the integration is performed over full superspace, the commuting and the anti-commuting directions. In the kinetic terms for the Yang-Mills sector,

\[ \mathcal{L}_{\text{Yang-Mills}} = \frac{1}{8} \int \frac{E}{R} f(r)(\phi) W^{(r)} W_{\alpha}^{(s)} + \frac{1}{8} \int \frac{E}{R^i} \tilde{f}(r)(\tilde{\phi}) W^{(r)}_{\bar{\alpha}} W^{(s)}_{\bar{\alpha}}, \]  

(18)

chiral and antichiral volume elements of non-trivial Kähler weights are used. In general, holomorphic gauge coupling functions can be present. In the potential terms,

\[ \mathcal{L}_{\text{pot}} = \frac{1}{2} \int \frac{E}{R} e^{K/2} W(\phi) + \frac{1}{2} \int \frac{E}{R^i} e^{K/2} \bar{W}(\bar{\phi}), \]  

(19)

the superpotential transforms as

\[ W(\phi) \mapsto e^{-F(\phi)} W(\phi), \quad \bar{W}(\bar{\phi}) \mapsto e^{-\bar{F}(\bar{\phi})} \bar{W}(\bar{\phi}), \]  

(20)

and Kähler invariance is established due to the factors \( e^{K/2} \). In other words, the combinations

\[ e^{K/2} W(\phi), \quad e^{K/2} \bar{W}(\bar{\phi}), \]  

(21)

have well-defined Kähler weights

\[ w\left( e^{K/2} W(\phi) \right) = +2, \quad w\left( e^{K/2} \bar{W}(\bar{\phi}) \right) = -2, \]  

(22)

which are compensated by those of \( R \) and \( R^i \), respectively.

The sum of these three separately invariant actions provides the dynamics of the complete traditional supergravity-matter and Yang-Mills system. In its explicit expansion in terms of component fields, which still requires some computational and book-keeping effort, the combinations

\[ \mathcal{D}^{\alpha} \mathcal{D}_\alpha R + \mathcal{D}_{\bar{\alpha}} \mathcal{D}^{\bar{\alpha}} R^\dagger, \]  

(23)

\[ \mathcal{D}^{\alpha} \mathcal{D}_\alpha \text{tr} W^2 + \mathcal{D}_{\bar{\alpha}} \mathcal{D}^{\bar{\alpha}} \text{tr} \bar{W}^2, \]  

(24)

orthogonal to those of Eq. (7) and Eq. (15), are of crucial importance.
5. Linear Multiplet and Chern-Simons Forms

The linear multiplet is another supermultiplet of helicity content \((0, 1/2)\). In distinction to the chiral multiplet which is composed of a complex scalar, a Majorana spinor and a complex scalar auxiliary field, the linear multiplet contains an antisymmetric tensor gauge potential, a real scalar and a Majorana spinor, no auxiliary field. The presence of the antisymmetric tensor

\[
b_{mn} = -b_{nm}, \quad b_{mn} \mapsto b_{mn} + \partial_m \xi_n - \partial_n \xi_m, \tag{25}\]

makes the linear multiplet a gauge multiplet. As an antisymmetric tensor should be viewed as a two-form gauge potential, the linear multiplet has a well-established geometric formulation based on the superspace two-form

\[
B = \frac{1}{2} E^A E^B B_{BA}(z). \tag{26}\]

As the corresponding field-strength, obtained from applying the exterior derivative, is a three-form, it may be combined with the Chern-Simons form \(Q\) encountered before in the Yang-Mills case, such that

\[
dB + kQ = H = \frac{1}{3!} E^A E^B E^C H_{CBA}, \tag{27}\]

with some constant \(k\). The Bianchi identity is then simply

\[
dH = k \text{tr}(\mathcal{F}\mathcal{F}). \tag{28}\]

At this point a detailed analysis of the superspace structure reveals that this provides indeed a compatible geometric system and the Bianchi identities correspond to the modified linearity conditions

\[
\left( \mathcal{D}^2 - 8R^\dagger \right) L = 2k \text{tr} \mathcal{W}^2, \tag{29}\]

\[
\left( \overline{\mathcal{D}}^2 - 8R \right) L = 2k \text{tr} \mathcal{W}^2. \tag{30}\]

These equations characterize the properties of the linear multiplet, coupled to Chern-Simons forms, in analogy to the chirality constraints of the usual matter superfields. They will become crucial in the evaluation of component field actions and the discussion of the ensuing interaction terms. Another information from the superspace Bianchi identities is the equation

\[
\left( [\mathcal{D}_\alpha, \mathcal{D}_\dot{\alpha}] - 4\sigma^{\alpha \dot{\alpha}} G_\alpha \right) L = -\frac{1}{3} \sigma_{\dot{\alpha}\alpha} \varepsilon^{deba} H_{cba} - 4k \text{tr} (\mathcal{W}_\alpha \mathcal{W}_{\dot{\alpha}}), \tag{31}\]

which identifies the field strength tensor \(H_{cba}\) in the superfield expansion of the linear superfield.
6. Invariant Actions with Linear Multiplets

The coupling of the linear multiplet (for simplicity, only one linear multiplet is considered here, in general an arbitrary number is possible) can be incorporated in promoting the superfield Kähler potential, which so far was a function of the chiral and antichiral matter superfields only, to a more general function

\[ K(\phi, \bar{\phi}, L), \]  

depending on the linear superfield \( L \) as well. In this case, the action obtained from the volume of superspace, Eq. (17), will now describe the kinetic terms for the linear multiplet as well. In addition, due to the modified linearity conditions, \( i.e. \) the gaugino superfield squared terms, it will also give rise to gauge kinetic terms with a gauge coupling function proportional to \( \partial K/\partial L \). Hence, the simple volume term of superspace, when expanded in terms of component fields reveals quite a lot of information.

On the other hand, in the explicit evaluation of the component field action one finds that the normalization of the curvature scalar acquires a field dependent contribution proportional to

\[ \left( 1 - \frac{1}{3} L \frac{\partial K}{\partial L} \right)^{-1}. \]  

In the geometric approach used here, the normalization of the Einstein term can easily be modified making use of the super-Weyl transformations adopted to \( U_K(1) \) superspace with linear superfield (whose proper rescalings must be taken into account too). Parametrizing the rescaling in terms of a superfield \( F(\phi, \bar{\phi}, L) \) (not to be confused with Kähler transformations denoted similarly), and requiring, for instance, canonical normalization for the curvature scalar, one finds that the corresponding action is given as

\[ \mathcal{L}_{\text{supergravity + chiral matter + linear + Yang–Mills}} = -3 \int F(\phi, \bar{\phi}, L), \]  

with the function \( F \) related to the modified Kähler potential through the equation

\[ F - L \frac{\partial F}{\partial L} = 1 - \frac{1}{3} L \frac{\partial K}{\partial L}, \]  

implying that \( F \) should be of the general form

\[ F(\phi, \bar{\phi}, L) = 1 + LV(\phi, \bar{\phi}) + \frac{1}{3} L \int \frac{dL}{L} \frac{\partial K}{\partial L}. \]  

Here, \( V(\phi, \bar{\phi}) \) is a new arbitrary function, relevant for supersymmetric theories with non-holomorphic gauge coupling functions. Also, it is precisely this superfield which appears in effective theories with Kähler anomaly cancellation mechanism.
The superfield appearance of the explicit Yang-Mills action, Eq. (18), and of $L_{pot}$, Eq. (19), remain unchanged.

### 7. Linear Multiplet vs. Chiral Multiplet

The modified linearity conditions, Eqs. (29,30), can be obtained from a variational principle in superspace. This goes as follows. First of all we express the gaugino-squared terms as derivatives of the Chern-Simons superfield,

$$\text{tr} \, \mathcal{W}^2 = \frac{1}{2} \left( \mathcal{D}^2 - 8 \mathcal{R}^\dagger \right) \Omega,$$

$$\text{tr} \, \mathcal{W}^2 = \frac{1}{2} \left( \mathcal{D}^2 - 8 \mathcal{R} \right) \Omega.$$

Then one writes down the first order action

$$\mathcal{L}_{(1)} = -3 \int \left( F(\phi, \bar{\phi}, L) + (L - k\Omega)(S + \bar{S}) \right).$$

In this action $L$ is understood to be unconstrained, while $S$ and $\bar{S}$ are chiral resp. antichiral. Variation of this action with respect to those chiral superfields, taking into account the chirality constraints and integration by parts in superspace, results in the modified linearity equations (29,30) and we get back the theory described in the previous section. On the other hand, variation of the first order action with respect to $L$ yields

$$\left( S + \bar{S} \right) \left( 1 - \frac{1}{3} L \frac{\partial K}{\partial L} \right) = \frac{1}{3} F \frac{\partial K}{\partial L} - \frac{\partial F}{\partial L}.$$

This equation should be read as an equation which serves to express $L$ in terms of $\phi$, $\bar{\phi}$ and of $S + \bar{S}$, giving rise to a theory entirely in terms of chiral multiplets with the special property that $S$ and $\bar{S}$ appear only through their sum.

One should, however, again keep track of the normalization of the curvature scalar: canonical normalization is established if one requires the condition

$$F(\phi, \bar{\phi}, L) + L(S + \bar{S}) = 1,$$

where $L$ is solution of the above equation. Combination of these two equations leads again to Eq. (35) of the previous section.

It is in this sense that a linear multiplet is said to be dual to a chiral multiplet. In this dual theory, $K$ is a true Kähler potential, it depends only on chiral superfields, and one might use this correspondence to give a geometric interpretation to the function $K(\phi, \bar{\phi}, L)$ in the previous theory. As an example consider

$$K(\phi, \bar{\phi}, L) = K_0(\phi, \bar{\phi}) + \alpha \log L,$$

$$F(\phi, \bar{\phi}, L) = 1 - \frac{1}{3} \alpha + LV(\phi, \bar{\phi}).$$
Eq. (40) is solved by \( \alpha/3L = S + \bar{S} + V(\phi, \bar{\phi}) \) yielding

\[
K(\phi, \bar{\phi}, S + \bar{S}) = K_0(\phi, \bar{\phi}) + \alpha \log \frac{\alpha}{3} - \alpha \log \left( S + \bar{S} + V(\phi, \bar{\phi}) \right).
\] (44)

8. Three-Form Multiplet

The three-form multiplet is yet another helicity \((0, 1/2)\) supermultiplet. It consists of a complex scalar, a Majorana spinor, an antisymmetric three-index tensor gauge potential and a real scalar auxiliary field. Again, it is a gauge multiplet, and its properties can be determined in superspace geometry. As a starting point consider

\[
C = \frac{1}{3!} E^A E^B E^C C_{CBA}(z),
\] (45)

a three-form in \( U_K(1) \) superspace with field strength

\[
dC = \Sigma = \frac{1}{4!} E^A E^B E^C E^D \Sigma_{DCBA},
\] (46)

and Bianchi identity \( d\Sigma = 0 \). A detailed superspace analysis allows to identify the three form multiplet in terms of a chiral superfield

\[
\mathcal{D}^\alpha T = 0, \quad \mathcal{D}_\alpha \bar{T} = 0,
\] (47)

with an additional constraint

\[
\left( \mathcal{D}^\alpha \mathcal{D}_\alpha - 24 R^f \right) T - \left( \mathcal{D}_\alpha \mathcal{D}^{\dot{\alpha}} - 24 R \right) \bar{T} = \frac{8i}{3} \varepsilon^{dcba} \Sigma_{dcba},
\] (48)

where the vectorial fieldstrength superfield

\[
\varepsilon^{dcba} \Sigma_{dcba} = \varepsilon^{dcba} \left( 4 \mathcal{D}_d C_{cba} + 6 T_{dc}^\alpha C_{\alpha ba} + 6 T_{dc} C_{\alpha ba} \right),
\] (49)

appears. The solution of these constraints is given in terms of an unconstrained prepotential superfield \( \Omega \) such that

\[
\bar{T} = (\mathcal{D}^2 - 8 R^f) \Omega, \quad T = (\mathcal{D}^2 - 8 R) \Omega.
\] (50)

As we are working in \( U_K(1) \) superspace the Kähler chiral weights are read off to be \( w(T) = +2 \) and \( w(\bar{T}) = -2 \). In coupling the three-form multiplet one may perfectly well include the superfields \( T \) and \( \bar{T} \) into the Kähler potential and the function \( F \), with appropriate care, however, to the normalization of the Einstein term. As to the superpotential, one should maintain the Kähler transformations defined in Eq. (20). Expanding the superpotential \( W(\phi, T) \) in powers of \( T \), this may be achieved with suitable insertions of exponentials of the Kähler potential

\[
W(\phi, T) = \sum_{n \geq 0} W_n(\phi) \left( e^{-K/2} T \right)^n,
\] (51)
and Kähler transformations

\[ W_n \mapsto e^{(n-1)F} W_n. \tag{52} \]

of the coefficient functions, thus establishing \( \mathcal{W} \mapsto e^{-F} \mathcal{W} \).

9. Comments

The investigation of the three-form multiplet is less academic as it might appear. First of all it seems that this multiplet structure applies to the description of the supercurrent multiplet and its anomaly structure. On the other hand it has been advantageously employed in the study of supersymmetric Chern-Simons forms, both Yang-Mills and gravitational.\[8,9]\] four-dimensional Chern-Simons forms are three-forms which change under gauge-transformations by the exterior derivative of a two-form.

In a similar line of reasoning the three-form multiplet should be relevant in gluino condensation: if the supersymmetry properties of the condensate are supposed to reflect those of the superfield \( tr \mathcal{W}^2 \) and its complex conjugate, the natural multiplet structure for an effective description of the gluino condensate is the three-form. This is related to the fact that the gaugino superfield is not just chiral, Eq. (13), but subject to the additional condition Eq.(14). As a consequence, the superfield \( tr \mathcal{W}^2 \) is not just chiral either, but subject to the same additional restrictions as the three-form (cf. Eq. (15) and Eq. (48)).

Apart from this possibility of parametrizing the gaugino condensate, the couplings of generic three-form multiplets may of course be investigated in their own right. Let me close with the description of a mechanism paraphrasing the Chern-Simons -antisymmetric tensor coupling on the level of the three form. To this end consider abelian one- and two-form gauge potentials \( A \) and \( B \) with fieldstrength \( F = dA \) and \( H = dB \). In addition, consider the three form gauge potential \( C \) with field strength \( \Sigma \) defined as

\[ \Sigma = dC + \tau H A. \tag{53} \]

Inspection of this geometric structure in superspace shows that the one-, two- and three-form geometries are indeed compatible with this definition of \( \Sigma \). Whereas in the one- and two-form sectors one has the usual equations for the gaugino and linear superfields, the chiral, antichiral superfields \( T, \bar{T} \) are now subject to a modified additional constraint

\[
\left( \mathcal{D}^{\alpha} \mathcal{D}^{\dot{\alpha}} - 24 R^{\dot{\alpha}} \right) T - \left( \mathcal{D}^{\dot{\alpha}} \mathcal{D}^{\alpha} - 24 R^{\alpha} \right) \bar{T} - \frac{8i}{3} \varepsilon_{dcba} \Sigma_{dcba} \\
+ 16 \tau \left( \mathcal{D}^{\alpha} \mathcal{W}_{\alpha} + \mathcal{D}_{\dot{\alpha}} \mathcal{W}^{\dot{\alpha}} \right) L + 64 \tau \left( \mathcal{W}^{\alpha} \mathcal{D}_{\alpha} L + \mathcal{W}_{\dot{\alpha}} \mathcal{D}^{\dot{\alpha}} L \right) = 0, \tag{54}
\]

reflecting the properties of the modified Bianchi-identities \( d\Sigma = \tau H F \). It is then a straightforward task to implement this geometrical structure in a supersymmetric dynamical context, which will be presented in a forthcoming publication.\[15]\)

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This list of references is by no means intended to be exhaustive, I apologize in advance for any undue omission.

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