THE GEOMETRY OF SUPERSYMMETRIC $\sigma$-MODELS

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ABSTRACT

We review non-linear $\sigma$-models with (2,1) and (2,2) supersymmetry. We focus on off-shell closure of the supersymmetry algebra and give a complete list of (2,2) superfields. We provide evidence to support the conjecture that all $N = (2,2)$ non-linear $\sigma$-models can be described by these fields. This in its turn leads to interesting consequences about the geometry of the target manifolds. One immediate corollary of this conjecture is the existence of a potential for hyper-Kähler manifolds, different from the Kähler potential, which does not only allow for the computation of the metric, but of the three fundamental two-forms as well. Several examples are provided: WZW models on $SU(2) \times U(1)$ and $SU(2) \times SU(2)$ and four-dimensional special hyper-Kähler manifolds.

2. Introduction and conclusions

Non-linear $\sigma$-models with more than one supersymmetry are the building blocks for stringtheories. For $N \geq (2,2)$ no complete off-shell formulation of these models has been given. An off-shell realization is desirable as it gives a manifest model independent description of the supersymmetry, facilitates computations, makes the geometry (more) obvious and finally it allows for the construction of the T-duals, keeping the extended supersymmetry manifest. In this paper, which is in part a review \footnote{Contribution to the proceedings of the workshop Gauge Theories, Applied Supersymmetry and Quantum Gravity, Imperial College, London, July 5-10, 1996}, we investigate the (2,2) case. A complete classification of (2,2) superfields exists: there are no other superfields than chiral, twisted chiral \footnote{Aspirant NFWO} and semi-chiral \footnote{Contribution to the proceedings of the workshop Gauge Theories, Applied Supersymmetry and Quantum Gravity, Imperial College, London, July 5-10, 1996} ones. We provide several arguments to support the claim that this is sufficient to describe all (2,2) $\sigma$-models. The central object is the commutator of the left and right complex structures. Its kernel is parametrized by chiral and twisted chiral coordinates and correspond to “Kähler-like” directions. The complement of the kernel is parametrized using semi-chiral coordinates and can be viewed as a deformation of a hyper-Kähler manifold.

If this conjecture turns out to be true, then one gets that the geometry of a large class of complex manifolds is encoded in a potential, which allows for the computation...
of the metric, torsion and complex structures. An immediate corollary of this would be that for hyper-Kähler manifolds there should exist a potential, not necessarily equivalent to the Kähler potential which allows not only for the computation of the metric but of the three complex structures as well!

Our results open several potentially interesting applications. A systematic study of the T-duals along the lines of [11] should be done. Another point which deserves interest is the systematic study of (2,2), (2,1) and (2,0) strings. Up to now, the only $N = 2$ strings studied are those described solely by chiral fields [3] and those described by chiral and twisted chiral fields [4]. As will be shown in this paper, very different choices can be made for the complex structures and it would be interesting to know how the geometry of (2,2) strings depends on this. We presently investigate the geometry of $N = 2$ strings with semi-chiral fields. Such a study could be relevant for the recent proposals in [7] relating the $D = 11$ membrane to type IIB stringtheory.

3. $N = (2,1)$ non-linear $\sigma$-models in superspace

Omitting the dilaton term, a supersymmetric non-linear $\sigma$-model in $N = (1,1)$ superspace is given by

$$S = \int d^2x d^2\theta \left( g_{ab} + b_{ab} \right) D\phi^a \bar{D}\phi^b. \quad (3.1)$$

The metric on the target manifold is $g_{ab}$ and $b_{ab} = -b_{ba}$ is a potential for the torsion, $T_{abc} \equiv -\frac{3}{2}b_{[ab,c]}$. A second, left-handed supersymmetry is of the form

$$\delta\phi^a = \varepsilon J^a_b D\phi^b. \quad (3.2)$$

The action, eq. (3.1), is invariant provided $\nabla^{\pm} J^a_b = 0$ and $J_{ab} = -J_{ba}$ hold. One obtains the standard supersymmetry algebra if $J$ obeys $J^2 = -1$ and $N^a_{bc}[J] = 0$, with the Nijenhuis tensor given by

$$N^a_{bc}[J] \equiv J^a_{[b} J^c_{a],d} + J^a_{d} J^c_{[b,d]} \quad (3.3)$$

In other words $J$ is a complex structure which is covariantly constant and for which the metric is hermitean. This can easily be put in (2,1) superspace. We choose a coordinate system such that the non-vanishing components of $J$ are $J^{\alpha\beta} = g^{\alpha\beta} = 0$. The constancy of $J$ implies

$$\Gamma^{\bar{\alpha}}_{\alpha\beta,c} = 0 \Rightarrow T_{\alpha\beta\gamma} = 0, \quad (g_{\bar{\gamma}[\alpha} - b_{\bar{\gamma}[\alpha},\beta\gamma] = 0, \quad (3.4)$$

where we used that one can always gauge $b_{\alpha\beta}$ to zero. Eq. (3.4) implies that locally, metric and torsion can be expressed in terms of a vector potential $k$:

$$g_{\alpha\beta} = \frac{1}{2}(k_{\alpha\beta} + k_{\beta\alpha}), \quad b_{\alpha\beta} = -\frac{1}{4} k_{[\alpha}\beta]) \Rightarrow T_{\alpha\beta\gamma} = -\frac{1}{4}(k_{\alpha\beta} - k_{\beta\alpha}),\gamma \quad (3.5)$$

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3 We take $D \equiv \frac{\partial}{\partial \phi} + \theta \partial \theta$ and $\bar{D} \equiv \frac{\partial}{\partial \bar{\phi}} + \bar{\theta} \partial \bar{\phi}$, with $\partial \equiv \frac{\partial}{\partial z}$ and $\bar{\partial} \equiv \frac{\partial}{\partial \bar{z}}$.

4 By $\nabla^{\pm}$ we denote covariant differentiation using the $\Gamma^{\pm}_{abc} \equiv \{a_{bc} \pm T^a_{bc} \text{ connection.}$

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The vectorfield \( k_a \) is determined modulo \( k_a \simeq k_a + f_\alpha + i g_\alpha \), where \( f_{\alpha,\beta} = 0 \) and \( g \) is a real function. Introducing now a second Grassman coordinate \( \theta \) and denoting the derivatives by \( \theta D \equiv \frac{\partial}{\partial \theta} - i \partial D \), we get the action in \((2,1)\) superspace:

\[
S = \frac{1}{2} \int d^2z d^2\theta d\bar{\theta} \left( k_\alpha \theta D \phi^\alpha - k_\alpha \theta D \bar{\phi}^\bar{\alpha} \right),
\]

(3.6)

where \( \phi \) are \((2,1)\) chiral fields: \( \theta D \phi^\alpha = -\bar{\phi}^\alpha \), \( \theta D \bar{\phi}^\bar{\alpha} = \phi^\bar{\alpha} \).

4. \( N = (2,2) \) non-linear \( \sigma \)-models in superspace

4.1. \((2,2)\) supersymmetry

We turn back to the action eq. \((3.1)\) and consider a second, non-chiral supersymmetry:

\[
\delta \phi^a = \varepsilon J^{ab} D \phi^b + \bar{\varepsilon} \bar{J}^{ab} D \bar{\phi}^b.
\]

Requiring invariance and a standard on-shell \( N = (2,2) \) supersymmetry algebra gives that both \( J \) and \( \bar{J} \) are covariantly constant (\( J \) w.r.t. the \( \Gamma_+ \) and \( \bar{J} \) w.r.t. the \( \Gamma_- \) connection) complex structures such that the metric is hermitean for both. The only off-shell non-closure comes from the commutator of the right-handed with the left-handed supersymmetry:

\[
[\delta(\varepsilon), \delta(\bar{\varepsilon})] \phi^a = \varepsilon \bar{\varepsilon} [J, \bar{J}]^a_b (D \bar{\phi}^b + \Gamma^b_{-cd} D \phi^d \bar{D} \phi^c).
\]

(4.1)

One recognizes the equation of motion for \( \phi \) preceeded by the commutator of \( J \) and \( \bar{J} \). This leads to the important observation that the algebra closes off-shell in the direction of \( \ker [J, \bar{J}] \), which hints towards the possibility that \( \ker [J, \bar{J}] \) can be described without the introduction of additional auxiliary fields while the complement of \( \ker [J, \bar{J}] \) will need auxiliary fields.

4.2. \( N=(2,2) \) superfields

In addition to the \((1,1)\) superspace coordinates, we introduce two new fermionic coordinates, \( \hat{\theta} \) and \( \hat{\bar{\theta}} \). The derivatives are given by

\[
\hat{D} \equiv \frac{\partial}{\partial \hat{\theta}} - \hat{\theta} \partial, \quad \hat{\bar{D}} \equiv \frac{\partial}{\partial \hat{\bar{\theta}}} - \hat{\bar{\theta}} \partial.
\]

(4.2)

The lagrange density in \((2,2)\) superspace can only be a function of scalar fields, so the dynamics will be largely determined by the choice of superfields. Constraints on a set of general superfields \( \phi^a, a \in \{1, \ldots, n\} \), are of the form \( \hat{D} \phi^a = i J(\phi)^a_b D \phi^b \).

Integrability \( (\hat{D}^2 = -\partial) \) of this requires \( J \) to be a complex structure. Imposing additional constraints of opposite chirality \( \hat{D} \phi^a = i \bar{J}(\phi)^a_b \bar{D} \phi^b \) require not only that \( \bar{J} \) is a complex structures but from \( \{\hat{D}, \hat{D}\} = 0 \), impose that \( J \) and \( \bar{J} \) commute as well. Constraining both chiralities reduces the degrees of freedom of a general superfield to those of an \( N = (1,1) \) field. One shows that through an appropriate coordinate transformation, \( J \) and \( \bar{J} \) can be diagonalized simultaneously. The eigenvalues, \( \pm i \), can be combined in four different ways, yielding the basic superfields:

\[\text{In the literature, one often finds the coordinates } \theta^+ \text{ and } \theta^- \text{. They are related to our coordinates by } \theta^\pm = \frac{1}{\sqrt{2}} (\theta \pm \bar{\theta})\]
1. chiral field $\Phi$ and anti-chiral field $\bar{\Phi}$:

\[
\begin{align*}
\hat{D} \Phi &= -D \Phi, & \hat{D} \bar{\Phi} &= +D \bar{\Phi}, \\
\hat{D} \bar{\Phi} &= -D \bar{\Phi}, & \hat{D} \Phi &= +D \Phi.
\end{align*}
\]

(4.3)

2. twisted chiral field $\Phi$ and twisted anti-chiral field $\bar{\Phi}$ [2]:

\[
\begin{align*}
\hat{D} \Phi &= -D \Phi, & \hat{D} \bar{\Phi} &= +\bar{D} \bar{\Phi}, \\
\hat{D} \bar{\Phi} &= +D \bar{\Phi}, & \hat{D} \Phi &= -D \Phi.
\end{align*}
\]

(4.4)

There is only one other type of superfield, the semi-chiral superfield [3], in which only one chirality is constrained. An analysis of the integrability conditions and the requirement that in the end we want a $\sigma$-model forces us to take them in pairs, such that the constraints on each member are of opposite chirality. So contrary to the previous fields which correspond to two real dimensions, a semi-chiral multiplet describes four real dimensions. Each member of the pair contains now two $N = (1,1)$ superfields, one of which will be auxiliary. We come back to a detailed study of this in the following section.

4.3. $N = (2,2)$ non-linear $\sigma$-models in superspace

An obvious question is whether all non-linear $\sigma$-models can be described using the fields mentioned above. When $[J, \bar{J}] = 0$, the model can be described using chiral and twisted chiral fields [2], which parametrize ker$(J - \bar{J})$ and ker$(J + \bar{J})$ resp., where ker$[J, \bar{J}] = \ker(J - \bar{J}) \oplus \ker(J + \bar{J})$. Such manifolds have a product structure: $\Pi \equiv J\bar{J}$ with $\Pi^2 = 1$. The projection operators $P_\pm \equiv \frac{1}{2}(1 \pm \Pi)$ project on ker$(J \pm \bar{J})$, where each of the subspaces is Kähler. Introducing a real potential $K$, function of these fields and denoting the chiral and twisted chiral directions by indices $\alpha$ and $\mu$ resp., one easily computes the vector $k$ introduced in eq. (3.5): $k_\alpha = -K_\alpha$ and $k_\mu = K_\mu$. If we write the potential with subindices, we mean the derivatives of the potential w.r.t. those fields.

Remains the case where $[J, \bar{J}] \neq 0$. An important result [8] states that ker$(J - \bar{J})$ and ker$(J + \bar{J})$ are always integrable to chiral and twisted chiral fields resp. This leaves us with the subspace where ker$[J, \bar{J}]$ is non-degenerate, which we expect to be parametrized by semi-chiral fields. As one semi-chiral multiplet corresponds to four real dimensions, the complement of ker$[J, \bar{J}]$ needs to have a dimension which is a multiple of four. One can show [1] that this is indeed the case. Let us restrict our attention to manifolds where ker$[J, \bar{J}] = \emptyset$. If we diagonalize one of the complex structures, then we get the following structure:

\[
J = i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \bar{J} = \begin{pmatrix} a & b \\ -b^{-1}(1 + a^2) & -b^{-1}ab \end{pmatrix},
\]

(4.5)

and $a^2 \neq -1$. Both $a$ and $b$ have to satisfy several requirements [1]. It remains to be shown that the general solution to these equations is indeed provided by a semi-chiral parametrization. However, the previous and following arguments, together with
several explicitly worked out examples, support this claim. Before turning to the semi-chiral parametrization, we point out an interesting feature: \( a = 0 \) corresponds to hyper-Kähler manifolds. In this way one can view a generic manifold with \( \ker[J, \bar{J}] = \emptyset \) as a deformation of a hyper-Kähler manifold.

We take \( n \) semi-chiral multiplets \( \{\phi^\alpha, \phi^\bar{\alpha}, \eta^\beta, \eta^{\bar{\beta}}\} \). Through a coordinate transformation, one can always reduce the defining relations of a semi-chiral multiplet \[ \square \] to:

\[
\widehat{D}\phi^\alpha = -D\phi^\alpha, \quad \widehat{D}\phi^{\bar{\alpha}} = D\phi^{\bar{\alpha}}, \quad \widehat{D}\eta^\beta = \bar{D}\eta^{\bar{\beta}}, \quad \widehat{D}\eta^{\bar{\beta}} = -\bar{D}\eta^\beta. \tag{4.6}
\]

Taking an arbitrary real potential \( K(\phi, \eta, \phi, \bar{\eta}) \), which is determined modulo a generalized Kähler transformation \( K \approx K + f(\phi) + g(\eta) + \bar{f}(\phi) + \bar{g}(\eta) \), we pass to (1,1) superspace:

\[
S = \int d^2z d^2\theta d^2\bar{\theta} K = \int d^2z d^2\theta \left\{ \chi^T L\psi - \bar{D}\eta^T PLPD\phi - \chi^T (L\psi - PL\bar{D}\phi - 2PM\bar{D}\eta) - (\chi^T L + D\eta^T LP - 2D\phi^T PM)\psi \right\}, \tag{4.7}
\]

where \( L, M \) and \( \bar{M} \) are \( 2n \times 2n \) matrices

\[
L \equiv \begin{pmatrix} K_{\bar{\alpha}\beta} & K_{\bar{\alpha}\bar{\beta}} \\ K_{\alpha\bar{\beta}} & K_{\alpha\bar{\beta}} \end{pmatrix}, \quad \bar{M} \equiv \begin{pmatrix} 0 & K_{\alpha\bar{\beta}} \\ K_{\bar{\alpha}\bar{\beta}} & 0 \end{pmatrix}, \quad M \equiv \begin{pmatrix} 0 & K_{\bar{\alpha}\beta} \\ K_{\alpha\beta} & 0 \end{pmatrix}, \tag{4.8}
\]

and \( \phi \) and \( \eta \) are \( 2n \times 1 \) matrices while \( P \) is a constant \( 2n \times 2n \) matrix:

\[
\phi \equiv \begin{pmatrix} \phi^\alpha \\ \phi^{\bar{\alpha}} \end{pmatrix}, \quad \eta \equiv \begin{pmatrix} \eta^\beta \\ \eta^{\bar{\beta}} \end{pmatrix}, \quad P \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{4.9}
\]

Assuming that \( L \) is invertible, one can eliminate the auxiliary fields \( \chi \equiv \bar{D}\eta \) and \( \psi \equiv \bar{D}\phi \) through their e.o.m. and one gets the second order action,

\[
S = \int d^2z d^2\theta \left\{ -D\phi^T PL^T P\bar{D}\eta + (D\eta^T L + 2D\phi^T M)PL^{-1} P(L\bar{D}\phi + 2M\bar{D}\eta) \right\}, \tag{4.10}
\]

from which both the metric and the torsion potential can be read off. \( J \) can be diagonalized through the coordinate transformation \( \phi^\alpha \to \varphi^a = \phi^\alpha, \eta^a \to \varphi_a = K_a \).

Using this, we get \( k \) defined in eq. \( \square \). In the original semi-chiral coordinates we have \( \bar{k} = LPL^{-1}P\bar{K} \) and \( k = 2ML^{-1}\bar{k} \), where

\[
\bar{K} \equiv \begin{pmatrix} K_{\bar{\alpha}}^\alpha \\ K_{\alpha}^{\bar{\alpha}} \end{pmatrix}, \quad \bar{k} \equiv \begin{pmatrix} k_{\bar{\alpha}}^\alpha \\ k_{\alpha}^{\bar{\alpha}} \end{pmatrix}, \quad k \equiv \begin{pmatrix} k_{\alpha} \alpha \\ k_{\bar{\alpha}} \bar{\alpha} \end{pmatrix}. \tag{4.11}
\]

Parmetrizing rows as \( (\phi, \eta) \), one also gets the complex structures:

\[
J = \begin{pmatrix} iP & 0 \\ 2iL^{-1}TPM & iP \end{pmatrix}, \quad \bar{J} = \begin{pmatrix} -iL^{-1}PL & 2iL^{-1}\bar{M}P \\ 0 & -iP \end{pmatrix}. \tag{4.12}
\]
Requiring the metric to be non-degenerate implies that \( \ker [J, \bar{J}] = \emptyset \).

The necessary and sufficient conditions to have a semi-chiral description of a hyper-Kähler manifold are

\[
L^{-1} P L P + P L^{-1} L = 4 L^{-1} P \bar{M} L^{-1} T M P
\]

\[
\{ P, L^{-1} T M P L^{-1} \} = \{ P, L^{-1} P \bar{M} L^{-1} T \} = 0. \tag{4.13}
\]

Restricting ourselves to \( d = 4 \), we find that the two latter eqs. are trivially satisfied while the former becomes: \( |K_{\phi\eta}|^2 + |K_{\phi\bar{\eta}}|^2 = 2K_{\eta\bar{\eta}}K_{\phi\bar{\phi}} \). It is known that a 4-dimensional Kähler manifold is hyper-Kähler iff. the Kähler potential satisfies the Monge-Ampère equation. So a concrete way to test our hypothesis would be to show that somehow the previous equation is equivalent to the Monge-Ampère equation. Looking at arbitrary dimensions, we see that we get a full set of equations similar to those obtained in [9]. The problem in proving our conjecture is essentially that while it is very easy to pass from semi-chiral coordinates to coordinates where one of the complex structures is diagonal, the reverse is not true. We are presently studying this particular point.

5. Examples

5.1. Wess-Zumino-Witten models

WZW-models on even dimensional groups are particular examples of \((2,2)\) \(\sigma\)-models [10]. The complex structures are easily characterized by their action on the Lie algebra: they are almost completely determined by a Cartan decomposition. The complex structure has eigenvalue \(+i\) and \(-i\) on generators corresponding with positive and negative roots resp. The only freedom left is the action of the complex structure on the Cartan subalgebra (CSA). Except for the requirement that the structure maps the CSA bijectively to itself, no further conditions have to be imposed. One has that, except for \(SU(2) \times U(1)\), \([J, \bar{J}] \neq 0\) [11]. Choosing for \(SU(2) \times U(1)\) the left and right complex structures so that they differ by a sign on the CSA, the complex structures commute and the model can be parametrized by a chiral \(\phi\), and a twisted chiral field \(\chi\). The potential is given by [11]

\[
K = -\int \frac{|\chi|^2}{|\phi|} \, d\zeta \ln(1 + \zeta) + \frac{1}{2} \left( \ln(\phi \bar{\phi}) \right)^2. \tag{5.1}
\]

If on the other hand we choose left and right complex structures to be equal on the Lie algebra, then \(\ker [J, \bar{J}] = \emptyset\) and we can describe the model with one semi-chiral multiplet with potential [1, 8]

\[
K = -\phi \bar{\phi} + \bar{\phi} \bar{\eta} + \phi \eta - 2i \int (x - y) \ln(1 + \exp \frac{i}{2} x). \quad \tag{5.2}
\]

Finally, an interesting example where different multiplets occur, is \(SU(2) \times SU(2)\) [1]. Choosing both complex structures to be equal on the Lie algebra we get that
ker$[J, \bar{J}]$ is two-dimensional. The manifold can be parametrized by one chiral field $\zeta$ and a semi-chiral multiplet. The potential is explicitly given by:

$$K = -\zeta \bar{\zeta} + \zeta \bar{\phi} + \bar{\zeta} \phi + i\eta \zeta - i\bar{\eta} \bar{\zeta} + i\bar{\eta} \bar{\phi} - i\eta \phi$$

$$-i \int^{\phi - \bar{\phi}} dy \ln(1 - \exp iy) - i \int^{\eta - \bar{\eta}} dy \ln(1 - \exp iy). \quad (5.3)$$

### 5.2. Special hyper-Kähler manifolds

As already mentioned, hyper-Kähler manifolds are an interesting class of manifolds to test our conjecture. We present here the particular example of four-dimensional special hyper-Kähler manifolds. They arise as the scalar subsector of hypermultiplets in rigid $N = 2, d = 4$. The full structure of these manifolds is explained elsewhere [12] and we provide here just what is needed. The manifolds are parametrized by coordinates $x$ and $v$ and the Kähler potential is given by $K_K = 2(i(F_x \bar{x} - \bar{F}_x x) + i(\bar{v} - v)^2(F_{xx} - \bar{F}_{\bar{x}x})^{-1}$, where $F(x)$ is a holomorphic prepotential. The first fundamental 2-form is just the standard Kähler two form while the two other ones are simply $\omega_2 = 2(dx \wedge dv + d\bar{x} \wedge d\bar{v})$ and $\omega_3 = 2i(dx \wedge dv - d\bar{x} \wedge d\bar{v})$. The semi-chiral parametrization is obtained through the coordinate transformation:

$$x \rightarrow \phi = x, \quad v \rightarrow \eta = -2i(F_x + \bar{F}_{\bar{x}}) + x + \bar{x} + \frac{1}{N} - 2i\bar{F}_{\bar{x}x} v - \frac{1}{N} - 2iF_{xx} \bar{v}, \quad (5.4)$$

with $N \equiv i(F_{xx} - \bar{F}_{\bar{x}x})$. The semi-chiral potential is

$$K_{SC} = \frac{1}{2} \eta \bar{\eta} + (\phi + \bar{\phi})^2 + 4(F_{\phi} + \bar{F}_{\bar{\phi}})^2 - (2i(F_\phi + \bar{F}_{\bar{\phi}}) + \phi + \bar{\phi}) \eta +$$

$$(2i(F_\phi + \bar{F}_{\bar{\phi}}) - \phi - \bar{\phi}) \bar{\eta}. \quad (5.5)$$

Using the formulas given in section (3.3), one computes from the potential not only the metric but the three complex structures as well.

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