

\mathcal{R}^2 supergravity

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ABSTRACT: We formulate R^2 pure supergravity as a scale invariant theory built only in terms of superfields describing the geometry of curved superspace. The standard supergravity duals are obtained in both “old” and “new” minimal formulations of auxiliary fields. These theories have massless fields in de Sitter space as they do in their non supersymmetric counterpart. Remarkably, the dual theory of R^2 supergravity in the new minimal formulation is an extension of the Freedman model, describing a massless gauge field and a massless chiral multiplet in de Sitter space, with inverse radius proportional to the Fayet-Iliopoulos term. This model can be interpreted as the “de-Higgsed” phase of the dual companion theory of $R + R^2$ supergravity.

KEYWORDS: Superspaces, Supergravity Models

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1 Introduction

Recently, various authors [1–3] considered pure R^2 theories of gravity coupled to matter. These theories are particularly interesting also in regard to cosmology because they naturally accommodate for de Sitter universes. While demanding conformal invariance (Weyl local gauge symmetry) would require spin two ghosts arising from the Weyl square term [4, 5], the rigid scale invariant R^2 theory propagates only physical massless modes in de Sitter space, in contrast with the $R + R^2$ theory, which has in addition a Minkowski phase with a massive scalar, the inflaton. An Einstein term is then obtained through quantum effects as substantiated by the analysis of [1]. Further restrictions that follow from the supersymmetric extensions of these theories are the aim of the present investigation. In particular, in this note we implement the analysis of [1] by requiring that pure R^2 supergravity be effectively derived solely in terms of the geometry of curved superspace. This poses severe restrictions on the dual standard supergravity theory which, in fact, cannot be an arbitrary scale invariant theory of supergravity. For example, we find that only certain cases are possible among the ones worked out in [1]. Moreover, one conformally coupled chiral superfield (that we call S) and another one that we call the chiral superfield T , are not matter fields but have a pure gravitational origin. In fact, out of the three (unique) suggested forms of superpotential in [1], only a certain linear combination of TS and S^3 can arise; $T^{3/2}$ alone is also possible. This result parallels the same analysis made in the $R + R^2$ theory [6, 7]. Also, the $T^{3/2}$ theory, where only the T field is present, is not an R^2 completion but a particular (scale invariant) case of the super $F(R) = R^3$ chiral theory originally investigated in [8–13]. The latter has in fact an anti-de Sitter rather than a de Sitter phase. All these theories have instabilities in some scalar direction and the problem caused by these instabilities is similar to the one found in the context of $R + R^2$ supergravity [13–16, 18–38], which was solved in [15]. Even more interesting is the analysis in the new minimal formulation [39, 40]. Here the dual supergravity $R + R^2$ theory is a gauge theory in the Higgs phase [17–20]. The de-Higgsed phase corresponds to the pure

R^2 theory in the limit that $HM_P = gM_P^2$ is kept fixed (H is the Hubble constant) while the gauge coupling goes to zero. This theory is in fact the extension of the Freedman model [41], where a massless vector multiplet with a Fayet-Iliopoulos (FI) term gives rise to a positive cosmological constant. Here there is an additional massless chiral field, dual to the antisymmetric tensor auxiliary field that has become dynamical.

The paper is organized as follows. In section 2 we present the superconformal rules needed for our analysis and we discuss the pure R^2 in the old minimal formulation of the $\mathcal{N} = 1$ supergravity. We also present the corresponding scale invariant matter couplings. In section 3 we describe pure R^2 supergravity in the new minimal formulation; we conclude in section 4.

2 R^2 supergravity in the old minimal formulation

For our convenience we report here some rules of superconformal tensor calculus that will be useful in order to go from the R^2 theory to its standard supergravity form. These rules are explained in [42], and also in [13, 21].

Superconformal fields are denoted by their Weyl weight w and chiral weight n . So we will use the notation $X_{w,n}$ and we will only consider scalar superfields. The basic operator is the Σ operator, which is the curved superspace analog of \bar{D}^2 . The Σ operator has weights $(1, 3)$ and it can be applied to a superconformal field $X_{w,w-2}$ so that $\Sigma X_{w,w-2}$ is a chiral superfield of weights $(w+1, w+1)$. X can be (anti)chiral only if $w = 1$, in which case $\Sigma \bar{X}_{(1,-1)}$ is a chiral superfield of weight $(2, 2)$. The basic identity between F and D densities of a chiral superfield f of weight $(0, 0)$ is

$$[f\mathcal{R}S_0^2]_F = [(f + \bar{f})S_0\bar{S}_0]_D, \quad (2.1)$$

where $\mathcal{R} = (\Sigma(\bar{S}_0)/S_0)_{(1,1)}$ is the chiral scalar curvature multiplet. The notation $[O]_{D,F}$ denotes, as usual, the standard D- and F-term density formulae of conformal supergravity, for a real superfield O with scaling weight 2 and vanishing chiral weight or a chiral superfield with Weyl (and chiral) weight 3. In particular, the bosonic components of the curvature chiral scalar multiplet \mathcal{R} are

$$\mathcal{R} = \frac{1}{3}\bar{u} + \dots + \theta^2\mathcal{F}_R, \quad (2.2)$$

where

$$\mathcal{F}_R = -\frac{1}{2}R - 3A_\mu^2 + 3iD^\mu A_\mu. \quad (2.3)$$

and u, A_μ are the supergravity auxiliary fields [43, 44].

2.1 Scale invariant supergravity

It can easily be seen from the chiral curvature superfield \mathcal{R} that we can write the following scale-invariant supergravity action

$$\mathcal{L}_{\text{scal.inv}} = \alpha[\mathcal{R}\bar{\mathcal{R}}]_D - \beta[\mathcal{R}^3]_F, \quad (2.4)$$

where α, β are dimensionless couplings. We may write eq. (2.4) in a dual form by introducing Lagrange multiplier superfields T, S so that

$$\mathcal{L}_D = \alpha [S_0 \bar{S}_0 S \bar{S}]_D - \beta [S_0^3 S^3]_F - 3 \left[T \left(\frac{\mathcal{R}}{S_0} - S \right) S_0^3 \right]_F, \quad (2.5)$$

It is easy to check that by integrating out the Lagrange multiplier superfield T in (2.5), we get back the original theory (2.4). However, by using the identity in eq. (2.1), we may write (2.5) as

$$\mathcal{L}_D = -[(3T + 3\bar{T} - \alpha S \bar{S}) S_0 \bar{S}_0]_D + [(-\beta S^3 + 3TS) S_0^3]_F, \quad (2.6)$$

which describes standard supergravity with Kähler potential ($\alpha \geq 0$)

$$K = -3 \log \left(T + \bar{T} - \frac{\alpha}{3} S \bar{S} \right), \quad (2.7)$$

and superpotential

$$W(T, S) = 3TS - \beta S^3. \quad (2.8)$$

The case $\alpha = 0$. In this particular case, the scale invariant supergravity action turns out to be

$$\mathcal{L}_D = -\beta [\mathcal{R}^3]_F, \quad (2.9)$$

which can be written in a dual form as

$$\mathcal{L}_D = -[3(T + \bar{T}) S_0 \bar{S}_0]_D + [(-\beta S^3 + 3TS) S_0^3]_F. \quad (2.10)$$

We see that S appears now as a Lagrange multiplier superfield and it can be integrated out. As a result, we find that $S = (T/\beta)^{1/2}$ and eq. (2.10) is written as

$$\mathcal{L}_D = -[3(T + \bar{T}) S_0 \bar{S}_0]_D + [2\beta^{-1/2} T^{3/2} S_0^3]_F, \quad (2.11)$$

so that the Kähler potential and the superpotential are given by

$$K = -3 \log(T + \bar{T}), \quad (2.12)$$

$$W = \frac{2}{\beta^{1/2}} T^{3/2}. \quad (2.13)$$

This is one of the models used in [1] to describe a supergravity dual of pure R^2 supergravity. However, its origin is not from the scale invariant $\mathcal{R}\bar{\mathcal{R}}$ term but rather from the other scale invariant \mathcal{R}^3 term. As observed in [1], it has a negative cosmological constant and so it cannot be the dual of an R^2 theory [13, 14].

2.2 Scale invariant matter couplings

Pure R^2 supergravity (in its dual formulation) is invariant under scale symmetry under

$$T \rightarrow Te^\lambda, \quad S \rightarrow Se^{\lambda/2}, \quad S_0 \rightarrow S_0 e^{-\lambda/2}, \quad (2.14)$$

which is inherited from the scale symmetry of the gravitational R^2 theory

$$\frac{\mathcal{R}}{S_0} \rightarrow \frac{\mathcal{R}}{S_0} e^{\lambda/2}, \quad S_0 \rightarrow S_0 e^{-\lambda/2}. \quad (2.15)$$

Let us add n superconformal chiral multiplets A^i with scaling $A^i \rightarrow A^i e^{\lambda/2}$ (but $(0,0)$ superfield weights). Then as in [1], we can have conformally coupled matter $C_{\bar{j}}^{\bar{i}} A^j \bar{A}_{\bar{i}} S_0 \bar{S}_0$ but also chiral F terms coupling to the curvature R ,¹

$$RC_{ij} A^i A^j S_0^2, \quad \frac{R^2}{2} C_i A^i S_0, \quad C_{ijk} A^i A^j A^k S_0^3, \quad (2.16)$$

with some constant coefficient $C_{\bar{j}}^{\bar{i}}$, C_{ij} , C_i , C_{ijk} . In this case, the dual theory takes the form

$$-3 \left[\left(T + \bar{T} - \frac{\alpha}{3} S \bar{S} - \frac{C_{\bar{j}}^{\bar{i}}}{3} A^i \bar{A}_{\bar{j}} \right) S_0 \bar{S}_0 \right]_D + [W(T, S, A^i) S_0^3]_F \quad (2.17)$$

with²

$$W(T, S, A^i) = 3TS - \beta S^3 + \frac{S^2}{2} C_i A^i + SC_{ij} A^i A^j + C_{ijk} A^i A^j A^k. \quad (2.18)$$

This is a restricted superpotential which does not have a $T^{3/2}$ term, neither other direct coupling to matter. Note that the scaling symmetry weight is not the same as the superconformal weight, that in our notation is always $(0,0)$ for all chiral fields with the exception of S_0 $(1,1)$ and \mathcal{R} $(1,1)$. \mathcal{R} is actually scale inert as it is obvious from eq. (2.15). So the scale symmetry in the pure gravitational theory is only dictated by the compensator S_0 .

3 R^2 supergravity in the new minimal formulation

In new-minimal supergravity, the appropriate gauging is implemented by a real linear multiplet L with scaling weight $w = 2$ and vanishing chiral weight $n = 0$ [39, 45]. In particular, the pure R^2 new minimal supergravity Lagrangian can be written as

$$\mathcal{L} = \frac{1}{4g^2} \left([W^\alpha(V_R) W_\alpha(V_R)]_F + \text{h.c.} \right), \quad (3.1)$$

where

$$V_R = \ln \left(\frac{L}{S_0 \bar{S}_0} \right), \quad (3.2)$$

$$W_\alpha(V_R) = -\frac{1}{4} \bar{\nabla}^2 \nabla_\alpha(V_R). \quad (3.3)$$

¹A term $d_i R \bar{A}^{\bar{i}}$ that generates a mixing $d_i S \bar{A}^{\bar{i}} + \text{h.c.}$ in the Kähler potential is also possible.

²Note that the terms containing S in W can be transferred to the Kähler potential by a T redefinition.

The Lagrangian in eq. (3.1) is superconformally invariant and the superconformal symmetry can be fixed by choosing $L = 1$. Then, the superspace geometry is described by the new-minimal formulation, [39, 40], where the graviton multiplet $(e_\mu^a, \psi_\mu, A_\mu, B_\mu)$ consists of: the graviton e_μ^a , the gravitino ψ_μ and two auxiliary gauge fields A_μ , and $B_{\mu\nu}$ possessing the gauge symmetry

$$\delta A_\mu = \partial_\mu b, \quad \delta B_{\mu\nu} = \partial_\mu b_\nu - \partial_\nu b_\mu. \quad (3.4)$$

In fact, the superconformal gauge fixing respects the $U(1)_R$ R -symmetry of the superconformal algebra, which is gauged by the vector A_μ . Then, V_R is the gauge multiplet of the supersymmetry algebra with components (in the Wess-Zumino gauge)

$$V_R = \left(A_\mu - 3H_\mu, -\gamma_5 \gamma^\nu r_\nu, -\frac{1}{2} \hat{\mathcal{R}} - 3H_\mu H^\mu \right), \quad (3.5)$$

where r_ν is the supercovariant gravitino field strength, $\hat{\mathcal{R}}$ is the (supercovariant) Ricci scalar and H^μ the Hodge dual of the (supercovariant) field strength for the auxiliary two-form [40]

$$H_\mu = -\frac{1}{3!} \epsilon_{\mu\nu\rho\sigma} H^{\nu\rho\sigma}, \quad H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \text{cyclic perm.} \quad (3.6)$$

Obviously, H_μ is divergenceless

$$\nabla^\mu H_\mu = 0. \quad (3.7)$$

In other words, the bosonic content of the gauge multiplet V_R is

$$V_R = \left(A_\mu^-, 0, -\frac{1}{2} R - 3H_\mu H^\mu \right), \quad A_\mu^- = A_\mu - 3H_\mu. \quad (3.8)$$

Clearly, the F-term in eq. (3.1) will produce the usual D_R^2 term in the bosonic action, where D_R is the highest component of the gauge multiplet. Since the latter contains the scalar curvature R as can be seen from eq. (3.8), it is obvious that eq. (3.1) describes an R^2 theory [17–20]. Indeed, by employing eqs. (3.3), (3.5), we find that the bosonic part of (3.1), is written as

$$e^{-1} \mathcal{L} = \frac{1}{8g^2} \left(R + 6H_\mu H^\mu \right)^2 - \frac{1}{4g^2} F_{\mu\nu}(A_\rho^-) F^{\mu\nu}(A_\rho^-). \quad (3.9)$$

We can integrate out H_μ after introducing the Lagrange multipliers Λ, a such that

$$e^{-1} \mathcal{L} = \frac{1}{8g^2} \Lambda (R + 6H_\mu H^\mu) - \frac{1}{32g^2} \Lambda^2 - \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} + \frac{1}{g^2} a \nabla_\mu H^\mu. \quad (3.10)$$

Integrating out Λ gives back (3.9), whereas the field a enforces the constraint (3.7). The auxiliary field H_μ appears now quadratically and it can easily be integrated out leading to

$$H_\mu = \frac{2}{3\Lambda} \partial_\mu a; \quad (3.11)$$

therefore, eq. (3.10) is equivalent to

$$e^{-1}\mathcal{L} = \frac{1}{8g^2}\Lambda R - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{32g^2}\Lambda^2 - \frac{1}{3g^2\Lambda}\partial_\mu a\partial^\mu a. \quad (3.12)$$

The theory in eq. (3.12) is in a Jordan frame and it can be expressed in the Einstein frame after the conformal transformation

$$g_{\mu\nu} \rightarrow e^{-\sqrt{\frac{2}{3}}\phi} g_{\mu\nu}, \quad (3.13)$$

where

$$\phi = \sqrt{\frac{3}{2}} \ln \frac{\Lambda}{4g^2}. \quad (3.14)$$

Then, eq. (3.12), after rescaling $A_\mu^- \rightarrow gA_\mu^-$ and $a \rightarrow g^2\sqrt{6}a$, is written in the Einstein frame as

$$e^{-1}\mathcal{L} = \frac{1}{2}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\phi}\partial_\mu a\partial^\mu a - \frac{1}{2}g^2. \quad (3.15)$$

Therefore, R^2 in new minimal supergravity is described by a standard supergravity coupled to a massless vector field and a massless complex scalar

$$T = \frac{1}{2}e^{\sqrt{\frac{2}{3}}\phi} + i\frac{a}{\sqrt{6}}. \quad (3.16)$$

The field T parametrizes the symmetric space $SU(1,1)/U(1)$ of scalar curvature $R = -2/3$. In fact, in new minimal supergravity, the R^2 theory and its dual form, can both be described by a unique Lagrangian of the form [17–19]

$$\mathcal{L} = [B(L - S_0\bar{S}_0e^U)]_D + \frac{1}{4g^2}W^\alpha(U)W_\alpha(U)]_F + c.c., \quad (3.17)$$

where U is an unconstrained vector superfield, $W_\alpha(U) = -\frac{1}{4}\bar{\nabla}^2\nabla_\alpha(U)$ and B is a real-multiplet Lagrange multiplier. It is easy to see that by integrating out B we find that

$$U = V_R. \quad (3.18)$$

Substituting (3.18) into (3.17), we get back the new minimal supergravity action (3.1). On the other hand, integrating out L we get

$$B = T + \bar{T}, \quad (3.19)$$

where T is chiral. Hence, eq. (3.17) can be written in standard old minimal form as

$$\mathcal{L} = -[S_0\bar{S}_0e^U(T + \bar{T})]_D + \frac{1}{4g^2}W^\alpha(U)W_\alpha(U)]_F + c.c. \quad (3.20)$$

We see that the Kähler potential is

$$K = -3\ln[(T + \bar{T})], \quad (3.21)$$

whereas the term e^U will give rise a FI term [46, 47]. Indeed, in component form, Lagrangian (3.20) is

$$e^{-1}\mathcal{L} = \frac{1}{2}R - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{3}{(T+\bar{T})^2}\partial_\mu T\partial_\mu\bar{T} - \frac{1}{2}g^2. \quad (3.22)$$

In fact the pure R^2 theory can be seen already from the $R+R^2$ theory in the new minimal supergravity, which is described in ref. [33], by taking an appropriate limit. Restoring dimensions in the FI term $\xi = gM_P^2$, the limit is $g \rightarrow 0$ with ξ fixed, which corresponds to a de-Higgsed phase. The $R+R^2$ theory is described by the master action [33]

$$\mathcal{L} = -[S_0\bar{S}_0e^U U]_D + [B(S_0\bar{S}_0e^U - L)]_D + \frac{1}{4g^2}([W^\alpha(V_R)W_\alpha(V_R)]_F + \text{h.c.}). \quad (3.23)$$

The rescaling

$$S_0 \rightarrow S_0 e^{-\lambda/2}, \quad B \rightarrow B e^\lambda, \quad L \rightarrow L e^{-\lambda} \quad (3.24)$$

clearly gives eq. (3.1) in the $\lambda \rightarrow \infty$ limit. Therefore, the dual R^2 theory in new minimal supergravity can be described as standard supergravity coupled to a massless chiral superfield and a massless vector superfield with a FI term. This theory is an extension of the Freedman model [41] by a massless chiral multiplet. The latter describes a massless vector coupled to supergravity with a positive cosmological constant.

4 Conclusions

Prompted by the interesting proposal of [1–3], we have discussed here the supersymmetric completion of pure R^2 gravity. The latter is rigidly scale invariant and propagates a massless graviton and a massless scalar on a de Sitter background [3], contrary to the $R+R^2$ theory which has an additional Minkowski phase with a massive scalar (the inflaton). In $\mathcal{N} = 1$ supergravity, one can write two scale invariant superspace densities, an $\mathcal{R}\bar{\mathcal{R}}$ (D-term) and an \mathcal{R}^3 (F-term). If both terms are present, the dual theory in old-minimal formulation contains the usual scalaron field T together with a conformally coupled scalar S of gravitational origin. In this case the most general superpotential turns out to be a linear combination of ST and S^3 . However, when only the \mathcal{R}^3 term is present, it turns out that S is auxiliary and after integrating it out, a superpotential of the form $T^{3/2}$ arises. This theory has an anti-de Sitter rather than a de Sitter phase [1, 13, 14]. When matter fields with definite scaling are introduced, it is possible to couple them to supergravity either by a D-term or an F-term coupling to the chiral curvature multiplet \mathcal{R} . In this case, it turns out that the matter fields mix with S but not with T in the superpotential.

A similar analysis can be done in the new minimal formulation of $\mathcal{N} = 1$ supergravity, which reveals that the dual theory of the R^2 theory is described by a massless chiral multiplet together with a massless vector multiplet with a FI term. The dual theory is thus an extension by a chiral multiplet of the Freedman model.

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