University of Groningen

On the BRST operator of W-strings

Bergshoeff, E.; Roo, M. de; Panda, S.; Sevrin, A.; Boonstra, H.J.

Published in:
Physics Letters B

DOI:
[10.1016/0370-2693\(93\)90598-C](https://doi.org/10.1016/0370-2693(93)90598-C)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1993

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Bergshoeff, E., Roo, M. D., Panda, S., Sevrin, A., & Boonstra, H. J. (1993). On the BRST operator of W-strings. *Physics Letters B*, 308(1). [https://doi.org/10.1016/0370-2693\(93\)90598-C](https://doi.org/10.1016/0370-2693(93)90598-C)

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

On the BRST operator of W -strings

E. Bergshoeff^a, H.J. Boonstra^a, M. de Roo^a, S. Panda^a and A. Sevrin^b

^a *Institute for Theoretical Physics, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

^b *Theoretical Physics Group, Lawrence Berkeley Laboratory, 1 Cyclotron Rd and Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA*

Received 11 March 1993; revised manuscript received 26 April 1993

Editor: P.V. Landshoff

We discuss the conditions under which the BRST operator of a W -string can be written as the sum of two operators that are separately nilpotent and anticommute with each other. We illustrate our results with the example of the non-critical W_3 -string. Furthermore, we apply our results to make a conjecture about a relationship between the spectrum of a non-critical W_n -string and a W_{n-1} -string.

1. Introduction

In order to deal with a system of first-class constraints, it is convenient to use the BRST formalism [1]. In particular, this approach has turned out to be rather fruitful in the study of string theories [2,3] and, more recently, in the study of critical [4–6] and non-critical [7–10] W -string theories^{#1}. In the quantum case, the physical states are defined as the cohomology classes of a nilpotent BRST operator Q_B . In the case of strings and W -strings, the determination of these cohomology classes is a rather complicated task and, so far, has only been solved completely for critical [2] and non-critical [3] strings.

Recently, it has been pointed out [4] that, in the case of a critical W_3 -string, the relevant BRST operator can be written as the sum of two operators that are separately nilpotent and anticommute with each other, i.e.

$$Q_B = Q_0 + Q_1, \quad Q_0^2 = Q_1^2 = Q_0 Q_1 + Q_1 Q_0 = 0. \quad (1)$$

One thus ends up with a so-called *double complex* which leads to a double grading (m, n) such that Q_0 has grading $(1, 0)$ and Q_1 has grading $(0, 1)$. One would expect that, due to this additional structure, the determination of the cohomology of Q_B simplifies. For instance, each solution of the Q_0 and Q_1 cohomology can now be used to construct a solution of the full Q_B cohomology. In view of these expected simplifications, it is of interest to see whether the split-up of the BRST operator, as given in (1), also occurs under more general circumstances. It is the purpose of this paper to investigate this issue. Our strategy will be to first discuss the generic situation for classical systems. Next, we will consider the quantisation. We will illustrate our results with the example of the classical w_3 -algebra and the recently introduced modified w_3 -algebra [7,15]. At the end of this letter we will comment on the case of general w_n -algebras and make a conjecture about the spectrum of the non-critical W_n -string.

^{#1} The possibility of a W_3 -string was first discussed in [11]. The BRST-operator of the W_3 algebra has been constructed in [12], while in [13] the BRST-operator for general quadratically nonlinear algebras was obtained.

2. The classical case

In the classical BRST formalism, instead of imposing constraints, one first extends the standard phase space of coordinates and momenta with additional anticommuting ghost coordinates. To be more precise, let us assume that we have coordinates and momenta z_A with canonical Poisson brackets $\{z_A, z_B\} = \Omega_{AB}$. The matrix Ω defines a symplectic structure on the phase space. Furthermore, let $\Phi_\alpha(z_A)$ be a set of first-class constraints that form the following Poisson-bracket algebra

$$\{\Phi_\alpha, \Phi_\beta\} = f_{\alpha\beta}{}^\gamma(z_A) \Phi_\gamma. \quad (2)$$

To each of the constraints we associate a canonical pair of ghosts c^α, b_α with Poisson bracket $\{c^\alpha, b_\beta\} = -\delta^\alpha_\beta$. In the BRST approach one constructs, corresponding to this system, a nilpotent BRST charge Q_B , i.e. $\{Q_B, Q_B\} = 0$ (see e.g. [14]). The generic structure of this BRST charge is given by

$$Q_B = c^\alpha \Phi_\alpha - \frac{1}{2} f_{\alpha\beta}{}^\gamma c^\beta c^\alpha b_\gamma + \dots, \quad (3)$$

where the dots indicate terms of higher order in the ghosts. If we assume that the structure constants satisfy the condition

$$f_{[\alpha\beta}{}^\epsilon f_{\gamma]\epsilon}{}^\delta - \{f_{[\alpha\beta}{}^\delta, \Phi_{\gamma]}\} = 0, \quad (4)$$

then the BRST charge only contains terms linear and trilinear in the ghosts. For simplicity, we will restrict our discussion to algebras of this type. Let $\Phi_\alpha(z_A) = \{T_a(z_A), W_i(z_A)\}$, then we also assume that in terms of T_a and W_i the constraint algebra can be written as

$$\begin{aligned} \{T_a, T_b\} &= f_{ab}{}^c T_c, \\ \{T_a, W_i\} &= f_{ai}{}^j(z_A) W_j, \\ \{W_i, W_j\} &= f_{ij}{}^k(z_A) W_k, \end{aligned} \quad (5)$$

where $f_{ab}{}^c$ is independent of z_A . In particular, we note that both the T_a and the W_i form subalgebras of the constraint algebra. Corresponding to the split of the generators, it is natural to also split the ghosts as $c^\alpha = (c^a, \gamma^i)$ and $b_\alpha = (b_a, \beta_i)$. The following theorem can now be proved.

Theorem. The BRST charge Q_B corresponding to the constraint algebra (5) can be written in the form

$$Q_B = Q_0 + Q_1, \quad \{Q_0, Q_0\} = \{Q_1, Q_1\} = \{Q_0, Q_1\} = 0, \quad (6)$$

with

$$\begin{aligned} Q_0 &= c^a T_a - \frac{1}{2} f_{ab}{}^c c^b c^a b_c - f_{ai}{}^j \gamma^i c^a \beta_j, \\ Q_1 &= \gamma^i W_i - \frac{1}{2} f_{ij}{}^k \gamma^j \gamma^i \beta_k. \end{aligned} \quad (7)$$

The proof of this theorem is rather simple and relies on the fact that, due to the particular form of the constraint algebra (5), the Jacobi identity (4) decomposes into three independent sets of identities,

$$f_{[ab}{}^e f_{c]e}{}^d = 0,$$

$$f_{ab}{}^d f_{dJ}{}^I - 2f_{aI}{}^k f_{bk}{}^J + 2\{f_{aI}{}^J, T_b\} = 0, \quad (8)$$

$$f_{[IJ}{}^l f_{kl]}{}^m - \{f_{[IJ}{}^m, W_{k]}{}^l\} = 0, \quad (9)$$

$$2f_{aI}{}^k f_{jk}{}^l + f_{IJ}{}^k f_{ak}{}^l - 2\{f_{aI}{}^l, W_J\} - \{f_{IJ}{}^l, T_a\} = 0, \quad (10)$$

which can separately be used to show that $\{Q_0, Q_0\} = 0$, $\{Q_1, Q_1\} = 0$ and $\{Q_0, Q_1\} = 0$, respectively.

3. Examples

(1) As a first example we discuss the classical w_3 -algebra which has a spin-2 generator $T(z)$ and a spin-3 generator $W(z)$. In conformal OPE language the algebra takes the following form^{#2}:

$$\begin{aligned} T(z)T(w) &= \frac{2T(w)}{(z-w)^2} + \frac{\partial T(w)}{z-w} + \dots, \\ T(z)W(w) &= \frac{3W(w)}{(z-w)^2} + \frac{\partial W(w)}{z-w} + \dots, \\ W(z)W(w) &= \frac{2TT}{3(z-w)^2} + \frac{\partial(TT)}{3(z-w)} + \dots \end{aligned} \quad (11)$$

A multi-scalar realisation of the algebra is given by [16]

$$\begin{aligned} T &= -\frac{1}{2}(\partial\phi_1)^2 + T_X, \\ W &= \frac{i}{3\sqrt{6}}\{(\partial\phi_1)^3 + 6(\partial\phi_1)T_X\}. \end{aligned} \quad (12)$$

where T_X is a multi-scalar realisation of the Virasoro algebra. Note that the w_3 -algebra (11) is not yet of the form (5) and therefore we cannot apply our theorem. To bring the algebra in the desired form we make the following redefinition of the generators:

$$\begin{aligned} \tilde{T} &= T, \\ \tilde{W} &= W - \frac{2i}{\sqrt{6}}(\partial\phi_1)T = \frac{4i}{3\sqrt{6}}(\partial\phi_1)^3. \end{aligned} \quad (13)$$

The algebra then becomes

$$\begin{aligned} \tilde{T}(z)\tilde{T}(w) &= \frac{2\tilde{T}(w)}{(z-w)^2} + \frac{\partial\tilde{T}(w)}{z-w} + \dots, \\ \tilde{T}(z)\tilde{W}(w) &= \frac{3\tilde{W}(w)}{(z-w)^2} + \frac{\partial\tilde{W}(w)}{z-w} + \dots, \\ \tilde{W}(z)\tilde{W}(w) &= \frac{-2i\sqrt{6}\partial\phi_1\tilde{W}}{(z-w)^2} + \frac{-i\sqrt{6}\partial(\partial\phi_1\tilde{W})}{z-w} + \dots, \end{aligned} \quad (14)$$

^{#2} To facilitate the transition to the quantum case we represent from now on Poisson brackets by Operator Product Expansions where it is understood that at the l.h.s. of the equation only *single* contractions between the fundamental fields are taken. Later on, when we consider the quantum case, it is understood that *multiple* contractions are taken into account as well.

which is indeed of the form (5). Applying our theorem, we can now write the BRST charge $Q_B = \oint (dz/2\pi i) J_B$ in the form (6), (7) with the BRST currents J_0 and J_1 corresponding to Q_0 and Q_1 , respectively, given by

$$\begin{aligned} J_0 &= c\{\tilde{T} + T_{(\gamma,\beta)} + \frac{1}{2}T_{(c,b)}\}, \\ J_1 &= \gamma\{\tilde{W} - i\sqrt{6}\partial\phi_1\partial\gamma\beta\}. \end{aligned} \quad (15)$$

Here (c, b) and (γ, β) are the usual spin-2 and spin-3 ghost fields whose energy-momentum tensors are given by

$$T_{(c,b)} = -2b\partial c - \partial bc, \quad (16)$$

$$T_{(\gamma,\beta)} = -3\beta\partial\gamma - 2\partial\beta\gamma. \quad (17)$$

(2) As a second example we consider the modified w_3 -algebra of [7,15]. Let $\{T_M, W_M\}$ and $\{T_L, W_L\}$ be two commuting copies of the classical w_3 -algebra. For the matter sector we again use the realisation (12)^{#3}.

The matter and Liouville parts can be combined into a single modified w_3 -algebra by defining the new generators $T = T_M + T_L$ and $W = W_M + iW_L$ [7,15]. This algebra then takes the form of a modified w_3 -algebra where, instead of the third line of (11), we have

$$W(z)W(w) = \frac{2(T_M - T_L)T}{3(z-w)^2} + \frac{\partial\{(T_M - T_L)T\}}{3(z-w)} + \dots \quad (18)$$

Note that $T_M - T_L$ appears as a structure function, i.e. the algebra is of the so-called soft type.

Again, a redefinition of the generators can be made such that the algebra is of the form (5). In the present case, this redefinition is given by

$$\begin{aligned} \tilde{T} &= T, \\ \tilde{W} &= W - \frac{2i}{\sqrt{6}}(\partial\phi_1)T = \frac{4i}{3\sqrt{6}}(\partial\phi_1)^3 - \frac{2i}{\sqrt{6}}\partial\phi_1 T_L + iW_L \end{aligned} \quad (19)$$

In terms of the new generators the algebra is given by the same formula (14) which we already encountered in the case of the unmodified w_3 -algebra. The same applies to the BRST charge. It is again given by eq. (15).

As a byproduct of our manipulations, we see that, by allowing realization-dependent redefinitions of the generators, the classical w_3 -algebra and the modified w_3 -algebra can be brought into exactly the same form as given in (14). Of course, the *realization* of the generators is different in both cases. Obviously, the previous example is contained in this example as can be seen by putting $T_L = W_L = 0$.

4. Quantisation

To describe the quantisation, it is convenient to use the Batalin-Vilkovisky (BV) formalism [17]. This formalism enables one, under the condition that the theory has no anomalies, to derive from a given classical BRST charge a nilpotent BRST operator by means of an iterative procedure. This BV formalism has for instance been applied in [15] to derive the quantum BRST operator corresponding to the modified w_3 -algebra. A priori, it is not guaranteed by this procedure that a classical BRST charge with the property (6) carries over into a quantum

^{#3} Note that, instead of using realisation (12) of the matter sector, we could also use such a realisation for the Liouville sector. One could then perform the same analysis as given below leading to the same results with everywhere matter replaced by Liouville.

BRST operator with the property (1). However, in all cases we have investigated, the property (1) turns out to hold.

The expression for the quantum BRST operator corresponding to the redefined w_3 -algebra can be found in [4] so we will not repeat it here. In [4] it was noted that the quantum BRST operator corresponding to the redefined algebra (14) can be related to the quantum BRST operator corresponding to the unmodified w_3 -algebra by means of a field redefinition of the ghosts and the matter fields. In case of the redefined modified w_3 -algebra, instead of deriving the quantum BRST operator through the BV formalism, we found it much simpler to use the quantum BRST operator corresponding to the modified w_3 -algebra given in [7] and to apply a similar redefinition on it. Of course, the result is the same as what would follow from the BV formalism.

We have found that the quantum counterparts of the classical BRST currents (15) are given by

$$J_0 = c \{ T_{\phi_1} + T_X + T_L + T_{(\gamma,\beta)} + \frac{1}{2} T_{(c,b)} \}, \quad (20)$$

$$J_1 = \gamma \left[\frac{i}{3\sqrt{6}} \{ 4(\partial\phi_1)^3 - 12q_1\partial\phi_1\partial^2\phi_1 + (-15 + 4q_1^2)\partial^3\phi_1 \} + i \left\{ W_L - \frac{2}{\sqrt{6}}\partial\phi_1 T_L + \frac{1}{\sqrt{6}}q_1\partial T_L \right\} \right. \\ \left. - i\sqrt{6} \{ \partial\phi_1\partial\gamma\beta + \frac{1}{3}q_1\partial\beta\partial\gamma \} \right]. \quad (21)$$

The quantum energy-momentum tensor for the ϕ_1 scalar is given by

$$T_{\phi_1} = -\frac{1}{2}(\partial\phi_1)^2 + q_1\partial^2\phi_1 \quad (22)$$

This scalar contributes $c_{\phi_1} = 1 + 12q_1^2$ to the total central charge, while the additional matter scalars, with energy-momentum tensor T_X , contribute $c_X = 1 + 4q_1^2$ [16]. The total central charge contribution of the matter and Liouville sectors is thus given by $c_M = c_{\phi_1} + c_X = 2 + 16q_1^2$ and c_L , respectively. Furthermore, the energy-momentum tensors $T_{(c,b)}$ and $T_{(\gamma,\beta)}$ of the spin-2 and spin-3 ghosts satisfy a Virasoro algebra with central charge -26 and -74 , respectively. Finally, the generators (T_L, W_L) satisfy a quantum W_3 -algebra with central charge c_L . The nilpotency of the BRST operator requires that $c_M + c_L = 100$.

5. Comments

It has been suspected for a long time that various non-critical W_n strings are somehow related. Evidence supporting this can be found in the appearance of W_n constraints in the double scaling limit of multimatrix models and in the results for the spectrum of pure W_3 -gravity [18,19]. We believe that the present work strongly suggests a larger scheme which would enable one to establish relations across models.

In order to formulate our conjecture, we make two observations. In [18,20], it was shown that a set of W_{n-1} currents and one free scalar field with a fixed background charge allows one to construct the W_n currents. A second point is that the work in [7,15] very probably generalizes to arbitrary W_n models in the following way. Consider two mutually commuting copies of the W_n algebra, generated by $T_M^{(j)}$ and $T_L^{(j)}$ resp., where $2 \leq j \leq n$. The total currents $T^{(j)}$ are $T^{(j)} \equiv T_M^{(j)} + i^{j-2} T_L^{(j)}$ ^{#4}. We next write the Liouville currents in terms of a scalar field ϕ and W_{n-1} currents^{#5}. We conjecture that the BRST operator for this system can be written in the form (1) where Q_0 is the BRST operator for a W_{n-1} system. In Q_0 , the ghosts for the spin n symmetry together with the scalar ϕ have become “matter” for the W_{n-1} system. This conjecture can presumably be proven by combining the two observations above.

^{#4} This observation was made in collaboration with X. Shen.

^{#5} This is an alternative to what we did in example 2 of section 3 where we specified a realization of the matter sector. See also the footnote in that section

The following counting argument supports our conjecture. Consider W_n gravity coupled to (p, q) W_n minimal matter, i.e. non-critical W_n strings. The central charge c_M of the (p, q) minimal model is given by

$$c_M = (n-1)\{1 - n(n+1)Q_M^2\}, \quad (23)$$

where

$$Q_M = \sqrt{\frac{p}{q}} - \sqrt{\frac{q}{p}}. \quad (24)$$

The W_n gravity sector is an $Sl(n, \mathbb{R})$ Toda system with central charge c_T

$$c_T = (n-1)\{1 + n(n+1)Q_T^2\}, \quad (25)$$

where

$$Q_T = \sqrt{\frac{p}{q}} + \sqrt{\frac{q}{p}}. \quad (26)$$

The two central charges add up to

$$c_M + c_T = 2(n-1)(2n^2 + 2n + 1), \quad (27)$$

which gets precisely cancelled by the W_n ghost contributions to the total c . Following [18,20], the W_n Toda currents can now be rewritten in terms of W_{n-1} currents and one scalar field ϕ , with central charge $c_\phi = 1 + 3n(n-1)Q_T^2$. If our conjecture is true, the W_n minimal matter, together with ϕ and the ghost and the anti-ghost of the spin n symmetry (which has a central charge $c_{(c(n), b(n))} = -2(6n^2 - 6n + 1)$), combine to a matter sector with W_{n-1} symmetry. This matter has central charge

$$\tilde{c}_M = c_M + c_\phi + c_{(c(n), b(n))} = (n-2)\{1 - n(n-1)Q_M^2\}, \quad (28)$$

which is precisely what we expect for the (p, q) W_{n-1} minimal model. Our conjecture suggests novel realizations of (p, q) W_n minimal models in terms of $n+k-1$ scalar fields and k $b-c$ systems with $1 \leq k \leq n-2$.

If we restrict ourselves to unitary minimal models, i.e. choosing $q+1=p$, we get that the following relation across lines should exist:

pure W_2
gravity

Ising ($c = 1/2$) $\leftrightarrow$ pure W_3
+ W_2 gravity gravity

tricritical $\leftrightarrow$ 3-state $\leftrightarrow$ pure W_4
Ising ($c = 7/10$) Potts ($c = 4/5$) gravity
+ W_2 gravity + W_3 gravity

$\vdots$ $\vdots$ $\vdots$ $\ddots$

(29)

Our conjecture amounts to the claim that the spectrum of every model in the table contains as a subsector the spectrum of the model to its left. In other words, a (p, q) non-critical W_n string contains in its spectrum the spectrum of (p, q) non-critical W_{n-k} strings where $1 \leq k \leq n-2$.

Repeated applications of our conjecture would result in the factorization of Q into a Virasoro BRST charge and $n-2$ other, mutually anticommuting, nilpotent charges. This is supported by the fact that any classical w_n -algebra can be realised in terms of an arbitrary number of scalars X^μ and $n-2$ special scalars ϕ_i ($i = 1, 2, \dots, n-2$) as follows:

$$\begin{aligned}
 T &= T_X + \sum_{i=1}^{n-2} T_{\phi_i}, \\
 &\vdots \\
 W^{(n-3)} &\sim \sum_h (\partial \phi_{(n-3)})^{n-1-h} (\partial \phi_{(n-2)})^h, \\
 W^{(n-2)} &\sim (\partial \phi_{(n-2)})^n.
 \end{aligned} \tag{30}$$

The generic structure of a w_n -algebra in this basis is of the form

$$\begin{aligned}
 [T, T] &\rightarrow T, \\
 &\vdots \\
 [W^{(n-3)}, W^{(n-3)}] &\rightarrow W^{(n-3)}, W^{(n-2)}, \\
 [W^{(n-3)}, W^{(n-2)}] &\rightarrow W^{(n-3)}, W^{(n-2)}, \\
 [W^{(n-2)}, W^{(n-2)}] &\rightarrow W^{(n-2)}.
 \end{aligned} \tag{31}$$

This generalizes the structure given in (5). It would be interesting to see whether an algebra of the type (31) allows a multi-split of the corresponding BRST charge of the form

$$Q_B = \sum_{i=0}^{n-2} Q_i, \quad \{Q_i, Q_j\} = 0. \tag{32}$$

One could even consider taking the limit $n \rightarrow \infty$ and construct a W_∞ -string theory. More details on the generic case of classical w_n algebras and their quantisation will be given elsewhere [21].

Acknowledgement

The work of E.B. has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences (KNAW). The work of H.J.B. and S.P. was performed as part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM). The work of A.S. was supported in part by the Director Office of Energy Research and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098, and in part by the National Science Foundation under Grant PHY90-21139.

References

- [1] C. Becchi, A. Rouet and R. Stora, Phys. Lett. B 52 (1974) 344;
I.V. Tyutin, Lebedev preprint FIAN No. 39 (1975), unpublished.
- [2] M. Kato and K. Ogawa, Nucl. Phys. B 212 (1983) 443.
- [3] B. Lian and G. Zuckerman, Phys. Lett. B 254 (1991) 417; B 266 (1991) 21; Commun. Math. Phys. 145 (1992) 561.
- [4] H. Lu, C.N. Pope, S. Schrans and X.J. Wang, On the spectrum and scattering of W_3 -strings, preprint CTP TAMU-4/93, KUL-TF-93/2 (January 1993).
- [5] C.N. Pope, L.J. Romans and K.S. Stelle, Phys. Lett. B 268 (1991) 167;
C.N. Pope, E. Sezgin, K. Stelle and X.J. Wang, Discrete states in the W_3 string, preprint CTP TAMU-64/92;
C.N. Pope, Physical states in the W_3 string, preprint CTP TAMU-71/92;
H. Lu, B.E.W. Nilsson, C.N. Pope, K.S. Stelle and P.C. West, The low-level spectrum of the W_3 string, preprint CTP TAMU-70/92;
H. Lu, C.N. Pope, S. Schrans and X.J. Wang, The interacting W_3 string, preprint CTP TAMU-86/92.
- [6] M. Freeman and P. West, W_3 String scattering, preprint KCL-TH-92-4; The covariant scattering and cohomology of W_3 strings, preprint KCL-TH-93-2;
P. West, On the spectrum, no ghost theorem and modular invariance of W_3 strings, preprint KCL-TH-92-7.
- [7] M. Bershadsky, W. Lerche, D. Nemeschansky and N.P. Warner, Phys. Lett. B 292 (1992) 35, Extended $N = 2$ superconformal structure of gravity and W -gravity coupled to matter, preprint CERN-TH.6694/92;
W. Lerche, Chiral rings in topological (W -)gravity, preprint CERN-TH.6812/93.
- [8] H. Ooguri, K. Schoutens, A. Sevrin and P. van Nieuwenhuizen, Commun. Math. Phys. 145 (1992) 515;
K. Schoutens, A. Sevrin and P. van Nieuwenhuizen, Nucl. Phys. B 371 (1992) 315.
- [9] J. de Boer and J. Goeree, Covariant W -gravity and its moduli space from gauge theory, preprint THU-92/14;
J. Goeree, Higher-spin extensions of two-dimensional gravity, Ph.D. Thesis, Utrecht University.
- [10] P. Bouwknegt, J. McCarthy and K. Pilch, Semi-infinite cohomology of W -algebras, preprint USC-93/11.
- [11] A. Bilal and J.-L. Gervais, Nucl. Phys. B 326 (1989) 222.
- [12] J. Thierry-Mieg, Phys. Lett. B 197 (1987) 368.
- [13] K. Schoutens, A. Sevrin and P. van Nieuwenhuizen, Commun. Math. Phys. 124 (1989) 87.
- [14] M. Henneaux, Phys. Rep. 129 (1985) 1;
J. Govaerts, Hamiltonian quantisation and constrained dynamics, Vol. 4, series B: Theoretical Particle Physics (Leuven University Press).
- [15] E. Bergshoeff, A. Sevrin and X. Shen, Phys. Lett. B 296 (1992) 95.
- [16] L. Romans, Nucl. Phys. B 352 (1991) 829.
- [17] J.A. Batalin and G.A. Vilkovisky, Phys. Rev. D 28 (1983) 2567; D 30 (1984) 508; Nucl. Phys. B 234 (1984) 106.
- [18] S. Das, A. Dhar and S.K. Rama, Int. J. Mod. Phys. A 7 (1992) 2295.
- [19] S. K. Rama, Mod. Phys. Lett. 6 (1991) 3531.
- [20] H. Lu, C.N. Pope, S. Schrans and K.W. Xu, Nucl. Phys. B 385 (1992) 99;
H. Lu and C.N. Pope, Phys. Lett. B 286 (1992) 63.
- [21] E. Bergshoeff, H.J. Boonstra, M. de Roo, S. Panda, A. Sevrin and X. Shen, in preparation.