Deforming the Lie Superalgebra of Contact Vector Fields on $S^{1|1}$ inside the Lie Superalgebra of Superpseudodifferential operators on $S^{1|1}$

N BEN FRAJ † and S Omri ‡

† Institut Supérieur de Sciences Appliquées et Technologie, Sousse, Tunisie
E-mail: benfraj_nizar@yahoo.fr

‡ Département de Mathématiques, Faculté des Sciences de Sfax, Route de Soukra,
3018 Sfax BP 802, Tunisie
E-mail: omri_salem@yahoo.fr

Received Month *, 200*; Revised Month *, 200*; Accepted Month *, 200*

Abstract

We classify nontrivial deformations of the standard embedding of the Lie superalgebra $K(1)$ of contact vector fields on the (1,1)-dimensional supercircle into the Lie superalgebra of superpseudodifferential operators on the supercircle. This approach leads to the deformations of the central charge induced on $K(1)$ by the canonical central extension of $S\Psi DO$.

1 Introduction

The study of multi-parameter deformations of the standard embedding of the Lie algebra $\text{Vect}(S^1)$ of vector fields on the circle $S^1$ inside the Lie algebra $\Psi DO$ of pseudodifferential operators on $S^1$ was carried out in [10, 11]. In this paper we address the computation of the integrability conditions of infinitesimal deformations of the standard embedding of the Lie superalgebra $K(1)$ of contact vector fields on the supercircle $S^{1|1}$ inside the Lie superalgebra $S\Psi DO$ of superpseudodifferential operators on $S^{1|1}$. The infinitesimal deformations of this embedding are classified by $H^1(K(1), S\Psi DO)$. This space is four dimensional and it was calculated in [5]. The obstructions for integrability of infinitesimal deformations lie in $H^2(K(1), S\Psi DO)$. Our goal is to study these obstructions.

It turns out that there exist four even one-parameter families of nontrivial deformations. We will compute explicit formulas describing these families. A contraction procedure of those deformations leads to four one-parameter deformations of the standard embedding of $K(1)$ into the Poisson Lie superalgebra $SP$ of superpseudodifferential symbols on $S^{1|1}$. Each parameter describes an interesting algebraic curve in the space of parameters.

The well-known nontrivial central extension of $S\Psi DO$ induces a central extension of the subsuperalgebra $K(1)$ (see [3]). The restriction of the 2-cocycle generating this extension is the 2-cocycle defining the central extension of $K(1)$ known as the Neveu-Schwartz Lie superalgebra (see [3], [12]). As an application of our results, we obtain a “deformed” expression for the central charge induced by the deformations of the standard embedding we have constructed.

Copyright © 2005 by N Ben Fraj and S Omri
2 The main definitions

2.1 Superpseudodifferential operators on $S^{1|1}$

We first recall the definition of $\Psi DO$ (cf. [8, 12]). The supercircle $S^{1|1}$ is the superextension of the circle $S^1$ with local coordinates $(x, \theta)$, where $x \in S^1$ and $\theta$ is odd. A $C^\infty$-function on $S^{1|1}$ has the form $F = f(x) + 2g(x)\theta$, with $f, g \in C^\infty(S^1)$. The vector field $\eta = \frac{\partial}{\partial \theta} + \theta \frac{\partial}{\partial x}$ on $S^{1|1}$ sends $F$ to $\eta(F) = 2g(x) + f'(x)\theta$, so that $\eta^2 = \frac{1}{2}[\eta, \eta] = \frac{\partial}{\partial x}$.

The usual Leibniz rule: $\frac{\partial}{\partial x} \circ f = f' + f\frac{\partial}{\partial x}$ on $C^\infty(S^1)$, is replaced on $C^\infty(S^{1|1})$ by (p is for parity):

$$\eta \circ F = \eta(F) + \sigma(F)\eta,$$

where $\sigma(F) = (-1)^p F$.

Formula (2.1) generalizes by induction on $m$ to the graded Leibniz formula:

$$\eta^m \circ F = \sum_{k=0}^{\infty} \binom{m}{k}_s \eta_k \omega^{m-k} \sigma^{m-k}(F) \eta^{m-k}$$

for all integer $m$, where the super binomial coefficients $\binom{m}{k}_s$ are defined by:

$$\binom{m}{k}_s = \begin{cases} \binom{m}{k} & \text{if either } k \text{ is even or } m \text{ is odd} \\ 0 & \text{otherwise} \end{cases}$$

$[x]$ is the integer part of a real number $x$, and $\binom{x}{l} = \frac{x(x-1)\cdots(x-l+1)}{l!}$ for $l \in \mathbb{Z}_{\geq 0}$. Set:

$$\Psi DO = \left\{ \sum_{k \in \mathbb{Z}_{\geq 0}} F_k \eta^k \omega^{-k} \mid w \in \mathbb{Z}, F_k \in C^\infty(S^{1|1}) \right\},$$

where the composition of superpseudodifferential operators is given by (2.2):

$$F \eta^m \circ G \eta^n = \sum_{k=0}^{\infty} \binom{m+n}{k}_s F \eta^k \omega^{-k} \sigma^{m-k}(G) \eta^{m+n-k} \text{ for any } m, n \in \mathbb{Z} \text{ and } F, G \in C^\infty(S^{1|1}).$$

Denote by $\Psi DO_{SL}$ the Lie superalgebra with the same superspace as $\Psi DO$ and the supercommutator defined on homogeneous elements by:

$$[A, B] = A \circ B - (-1)^{p(A)p(B)} B \circ A.$$

The space $S\mathcal{P}$ of superpseudodifferential symbols on $S^{1|1}$ has the following form:

$$S\mathcal{P} = C^\infty(S^{1|1}) \otimes (\mathbb{C}[\xi][[\xi^{-1}]] \oplus \mathbb{C}[\xi][[\xi^{-1}]]\zeta),$$

where $\mathbb{C}[\xi][[\xi^{-1}]]$ is the space of (formal) Laurent series of finite order in $\xi$.

Any element of $S\mathcal{P}$ can be expressed in the following form:

$$S(x, \xi, \zeta) = \sum_{-\infty}^{n} F_k(x) \xi^k + \left( \sum_{-\infty}^{n} G_k(x) \zeta^k \right)\zeta,$$
where \( F_k, G_k \in C^\infty(S^{1|1}) \), the symbol \( \zeta = \overline{\theta} + \theta \xi \) corresponds to \( \eta \), \( \xi \) corresponds to \( \frac{\partial}{\partial x} \) and \( \overline{\theta} \) corresponds to \( \frac{\partial}{\partial \theta} \) (hence \( \overline{\theta}^2 = \zeta^2 = 0 \)).

For \( F \in C^\infty(S^{1|1}) \), one has \( \zeta F^m = \sigma(F) \xi^m \zeta \), so then, the multiplication in \( \mathcal{SP} \) is obvious. On \( \mathcal{SP} \), there is a super Poisson bracket given by (cf. [9]):

\[
\{S, T\} = \frac{\partial S}{\partial \xi} \frac{\partial T}{\partial x} - \frac{\partial S}{\partial x} \frac{\partial T}{\partial \xi} - (-1)^{p(S)} \left( \frac{\partial S}{\partial \theta} \frac{\partial T}{\partial \theta} + \frac{\partial S}{\partial \overline{\theta}} \frac{\partial T}{\partial \overline{\theta}} \right)
\]

for any \( S, T \in \mathcal{SP} \). (2.4)

Consider a family of associative laws on \( \Psi \mathcal{DO} \) depending on one parameter \( h \in [0,1] \) by:

\[
F \eta^m \circ_h G \eta^n = \left\{ \begin{array}{ll}
\sum_{k=0}^{\infty} \binom{m}{k} F h^{\left(\frac{k}{2}\right)} \eta^k (\sigma^{m-k}(G)) \eta^{m+n-k} & \text{if } m \text{ and } n \text{ are odd}, \\
\sum_{k=0}^{\infty} \binom{m}{k} F h^{\left(\frac{k}{2}\right)} \eta^k (\sigma^{m-k}(G)) \eta^{m+n-k} & \text{otherwise}.
\end{array} \right.
\]

Denote by \( \Psi \mathcal{DO}_h \) the associative superalgebra of superpseudodifferential operators on \( S^{1|1} \) equipped with the multiplication \( \circ_h \). It is clear that all the associative superalgebras \( \Psi \mathcal{DO}_h \) are isomorphic to each other.

For the supercommutator \( [A,B]_h := \frac{1}{h}(A \circ_h B - (-1)^{p(A)p(B)} B \circ_h A) \), one has:

\[
[A,B]_h = \{A,B\} + O(h)
\]

and therefore \( \lim_{h \to 0} [A,B]_h = \{A,B\} \), where we identify \( \mathcal{SP} \) with \( \Psi \mathcal{DO} \) as vector spaces. Hence the Lie superalgebra \( \Psi \mathcal{DO}_{SL} \) contracts to the Poisson superalgebra \( \mathcal{SP} \) (cf. [4]).

Furthermore, \( \Psi \mathcal{DO}_{SL} \) admits an analogue of the Adler trace defined on the Lie algebra \( \Psi \mathcal{DO} \) of pseudodifferential operators on \( S^1 \) (cf. [12] [3]): let \( A = \sum_{k \in \mathbb{Z}} F_k \eta^k \) be a superpseudodifferential operator. Its super residue \( Sres(A) \) is the coefficient \( F_{-1} \in C^\infty(S^{1|1}) \) and the Adler supertrace (which vanishes on the brackets) is

\[
Str(A) = \int_{S^{1|1}} Sres(A) \ vol(x,\theta) = \int_{S^1} \frac{\partial F_{-1}}{\partial \theta} dx.
\]

(2.5)

Recall that the Lie superalgebra \( \mathcal{K}(1) \) (also known as the Neveu-Schwartz superalgebra without central charge, cf. [3] [3]) consists of vector fields on \( S^{1|1} \) preserving the Pfaff equation given by the contact 1-form \( \alpha = dx + \theta d\theta \). Explicitly \( \mathcal{K}(1) \) consists of vector fields of the form:

\[
v_F = F \eta^2 + \frac{1}{2} \eta(F) \bar{\eta}, \quad \text{where } \bar{\eta} = \frac{\partial}{\partial \theta} - \theta \frac{\partial}{\partial x}.
\]

3 Statement of the problem

The main purpose of this paper is to study deformations of the canonical embedding \( \rho : \mathcal{K}(1) \to \Psi \mathcal{DO}_{SL} \) defined by

\[
\rho(v_F) = F \eta^2 + \frac{1}{2} \eta(F) \bar{\eta}
\]

(3.1)

into a one-parameter family of Lie superalgebra homomorphisms.
3.1 Formal deformations

Let \( \rho : K(1) \to S\Psi DO_{SL} \) be an embedding of Lie superalgebras,

\[
\tilde{\rho}_t = \rho + \sum_{k=1}^{\infty} t^k \rho_k : K(1) \to S\Psi DO_{SL}, \quad \text{satisfying } \tilde{\rho}_t([X,Y]) = [\tilde{\rho}_t(X), \tilde{\rho}_t(Y)],
\]

where \( \rho_k : K(1) \to S\Psi DO \) are even linear maps, a formal deformation of \( \rho \).

The bracket in the right hand side in (3.2) is a natural extension of the Lie bracket in \( S\Psi DO_{SL} \) to \( S\Psi DO_{SL}[[t]] \). Two formal deformations \( \tilde{\rho}_t \) and \( \tilde{\rho}'_t \) are said to be equivalent if there exists an inner automorphism \( I_t : S\Psi DO[[t]] \to S\Psi DO[[t]] \)

\[
I_t = \exp(t \text{ad} F_1 + t^2 \text{ad} F_2 + \cdots),
\]

where \( F_i \in S\Psi DO \) such that \( \tilde{\rho}'_t = I_t \circ \tilde{\rho}_t \).

3.2 Polynomial deformations

Observe that a polynomial deformation defined in this section is NOT a particular case of a formal definition. Recall that a deformation \( \tilde{\pi} \) of a homomorphism \( \pi : \text{Vect}(S^1) \to \Psi DO \) defined by

\[
\tilde{\pi}(f(x) \partial_x) = f(x) \xi
\]

is (after [10]) said to be polynomial if it is an homomorphism of the following form

\[
\tilde{\pi}(c) = \pi + \sum_{k \in \mathbb{Z}} \tilde{\pi}_k(c) \xi^k,
\]

where \( c \in \mathbb{R}^n \) are parameters of deformation, each linear map \( \tilde{\pi}_k(c) : \text{Vect}(S^1) \to C^\infty(S^1) \) being polynomial in \( c \), \( \tilde{\pi}_k \equiv 0 \) for sufficiently large \( k \) and \( \tilde{\pi}_k(0) = 0 \).

Now, consider a Lie superalgebra homomorphism \( \tilde{\rho}(c) : K(1) \to S\Psi DO_{SL} \) of the following form:

\[
\tilde{\rho}(c) = \rho + \sum_{k \in \mathbb{Z}} \tilde{\rho}_k(c),
\]

where \( \tilde{\rho}_k(c) : K(1) \to SP_k \) are even linear maps, polynomial in \( c \in \mathbb{R}^n \) and such that \( \tilde{\rho}_k \equiv 0 \) for sufficiently large \( k \) and \( \tilde{\rho}_k(0) = 0 \).

To define the notion of equivalence in the case of polynomial deformations, one simply replaces the formal automorphism \( I_t \) in (3.3) by an automorphism

\[
I(c) : S\Psi DO_{SL} \to S\Psi DO_{SL}
\]

depending on \( c \in \mathbb{R}^n \) in the following way :

\[
I(c) = \exp \left( \sum_{i=1}^{n} c_i \text{ad} F_i + \sum_{i,j=1}^{n} c_i c_j \text{ad} F_{i,j} + \cdots \right),
\]

where \( F_i, F_{i,j}, \cdots F_{i_1 \cdots i_k} \) are even elements of \( S\Psi DO \).

**Remark 1.** Theory of polynomial deformations seems to be richer than that of formal ones. The equivalence problem for polynomial deformations has additional interesting aspects related to parameter transformations.
4 Deformations and cohomology

In this section, we will give a relationship between formal and polynomial deformations of Lie superalgebra homomorphisms and cohomology, cf. Nijenhuis and Richardson [2].

4.1 Infinitesimal deformations and the first cohomology

If $\rho: g \rightarrow b$ is a Lie superalgebra homomorphism, then $b$ is naturally a $g$-module. A map $\rho_t + t\rho_1: g \rightarrow b$, where $\rho_1 \in Z^1(g, b)$ is a Lie superalgebra homomorphism up to quadratic terms in $t$, it is said to be an infinitesimal deformation.

The problem is now to find higher order prolongations of these infinitesimal deformations. Setting $\phi_t = \tilde{\rho}_t - \rho$, one can rewrite the relation (3.2) in the following way:

$$[\phi_t(X), \rho(Y)] + [\rho(X), \phi_t(Y)] - \phi_t([X, Y]) + \sum_{i,j>0} [\rho_i(X), \rho_j(Y)]t^{i+j} = 0.$$  \hspace{1cm} (4.1)

The first three terms are $\delta\phi_t(X, Y)$, where $\delta$ stands for the coboundary. For arbitrary linear maps $\phi, \phi': g \rightarrow b$, define:

$$[[\phi, \phi']] : g \otimes g \rightarrow b$$
$$[[\phi, \phi']](X, Y) = [\phi(X), \phi'(Y)] + [\phi'(X), \phi(Y)].$$  \hspace{1cm} (4.2)

The relation (4.1) becomes now equivalent to:

$$\delta\phi_t + \frac{1}{2}[[\phi_t, \phi_t]] = 0.$$  \hspace{1cm} (4.3)

Expanding (4.3) in power series in $t$, we obtain the following equation for $\rho_k$:

$$\delta\rho_k + \frac{1}{2} \sum_{i+j=k} [[\rho_i, \rho_j]] = 0.$$  \hspace{1cm} (4.4)

The first nontrivial relation is $\delta\rho_2 + \frac{1}{2}[[\rho_1, \rho_1]] = 0$ gives the first obstruction to integration of an infinitesimal deformation. Indeed, it is easy to check that for any two 1-cocycles $\gamma_1$ and $\gamma_2 \in Z^1(g, b)$, the bilinear map $[[\gamma_1, \gamma_2]]$ is a 2-cocycle. The first nontrivial relation (4.3) is precisely the condition for this cocycle to be a coboundary. Moreover, if one of the cocycles $\gamma_1$ or $\gamma_2$ is a coboundary, then $[[\gamma_1, \gamma_2]]$ is a 2-coboundary. We therefore, naturally deduce that the operation (4.2) defines a bilinear map:

$$H^1(g, b) \otimes H^1(g, b) \rightarrow H^2(g, b),$$  \hspace{1cm} (4.5)

called the cup-product.

All the obstructions lie in $H^2(g, b)$ and they are in the image of $H^1(g, b)$ under the cup-product. So, in our case, we have to compute $H^1(K(1), S\Psi DO)$ and the product classes in $H^2(K(1), S\Psi DO)$. 

5 The space $H^1(\mathcal{K}(1), S\Psi DO)$

5.1 A filtration on $S\Psi DO$

The natural embedding of $\mathcal{K}(1)$ into $S\Psi DO$ given by the expression (5.1) induces a $\mathcal{K}(1)$-module structure on $S\Psi DO$. Analogously, we have a $\mathcal{K}(1)$-module structure on $S\mathcal{P}$ given by the natural embedding of $\mathcal{K}(1)$:

$$\pi : v_F \mapsto F\xi + \frac{1}{2}\eta(F)\bar{\zeta}, \quad (5.1)$$

where $\bar{\zeta} = \bar{\theta} - \theta\xi$.

Setting the degree of $x, \theta$ be zero and the degree of $\xi, \zeta$ be 1 we introduce a $\mathbb{Z}$-grading in the Poisson superalgebra $S\mathcal{P}$. Then we have

$$S\mathcal{P} = \bigoplus_{n \in \mathbb{Z}} S\mathcal{P}_n := \bigoplus_{n < 0} S\mathcal{P}_n \bigoplus \left( \prod_{n \geq 0} S\mathcal{P}_n \right), \quad (5.2)$$

where $S\mathcal{P}_n = \{ F\xi^{-n} + G\xi^{-n-1}\zeta \mid F, G \in C^\infty(S^{1|1}) \}$ is the homogeneous subspace of degree $-n$. Each element of $S\Psi DO$ can be expressed as

$$A = \sum_{k \in \mathbb{Z}} (F_k + G_k\eta^{-1})\eta^{2k}, \quad \text{where} \quad F_k, G_k \in C^\infty(S^{1|1}).$$

We define the order of $A$ to be

$$\text{ord}(A) = \text{sup}\{ k \mid F_k \neq 0 \text{ or } G_k \neq 0 \}.$$  

This definition of order equips $S\Psi DO$ with a decreasing filtration as follows: set

$$F_n = \{ A \in S\Psi DO \mid \text{ord}(A) \leq -n \}, \quad \text{where} \quad n \in \mathbb{Z}.$$  

So one has

$$\ldots \subset F_{n+1} \subset F_n \subset \ldots. \quad (5.3)$$

This filtration is compatible with the multiplication and the super Poisson bracket, that is, for $A \in F_n$ and $B \in F_m$, one has $A \circ B \in F_{n+m}$ and $\{ A, B \} \in F_{n+m-1}$, after we identify $S\mathcal{P}$ with $S\Psi DO$. This filtration makes $S\Psi DO$ an associative filtered superalgebra. Moreover, this filtration is compatible with the natural action of $\mathcal{K}(1)$ on $S\Psi DO$. Indeed, if $v_F \in \mathcal{K}(1)$ and $A \in F_n$, then

$$v_F \cdot A = [v_F, A] \in F_n.$$  

The induced $\mathcal{K}(1)$-action on the quotient $F_n/F_{n+1}$ is isomorphic to the $\mathcal{K}(1)$-action on $S\mathcal{P}_n$. Therefore, the $\mathcal{K}(1)$-action on the associated graded space of the filtration (5.3), is isomorphic to the graded $\mathcal{K}(1)$-module $S\mathcal{P}$, that is

$$S\mathcal{P} \simeq \bigoplus_{n \in \mathbb{Z}} F_n/F_{n+1}.$$  

Now we can deduce the cohomology of the filtered module from the cohomology of the associated graded module.
5.2 $H^1(\mathcal{K}(1), S\mathcal{P})$

Observe that $H^1(\mathcal{K}(1), S\mathcal{P}) = \bigoplus_{n \in \mathbb{Z}} H^1(\mathcal{K}(1), S\mathcal{P}_n)$. These spaces are known (see [5]). They are nontrivial if and only if $n = 0, 1$ and the corresponding dimensions are 3 and 1, respectively. Therefore, $H^1(\mathcal{K}(1), S\mathcal{P}) \cong \mathbb{R}^4$. The nontrivial cocycles generating the space $H^1(\mathcal{K}(1), S\mathcal{P})$ are $(\text{ad}_\zeta(\pi(v_F))) = \{\zeta, \pi(v_F)\}$ with $\pi$ as in (5.1):

$$C_0(v_F) = \frac{1}{4}(F + \sigma(F)) + \frac{1}{2}F,$$

(5.4)

$$C_1(v_F) = \eta^2(F),$$

(5.5)

$$C_2(v_F) = \text{ad}^3(\pi(v_F))\xi^{-2}\bar{\eta}$$

(5.6)

with values in $S\mathcal{P}_0$, and

$$C_3(v_F) = \text{ad}^5(\pi(v_F))\xi^{-3}\bar{\eta}$$

(5.7)

with values in $S\mathcal{P}_1$.

5.3 $H^1(\mathcal{K}(1), S\Psi DO)$ ([5])

The result of [5] is a specialization at $h = 1$ of the following theorem obtained as in [3]:

**Theorem 1.** The space $H^1(\mathcal{K}(1), S\Psi DO_\hbar)$ is purely even. It is spanned by the classes of the following nontrivial 1-cocycles

$$\Theta_0(v_F) = \frac{1}{4}(F + \sigma(F)) + \frac{1}{2}F,$$

$$\Theta_1(v_F) = \eta^2(F),$$

$$\Theta_2,h(v_F) = \sum_{n=1}^{\infty} (-1)^n h^{n-1} \frac{n - 2}{n} \sigma(\bar{\eta}^{2n+1}(F))\bar{\eta}^{-2n+1} + \sum_{n=1}^{\infty} (-1)^n h^{n} \frac{n-3}{n+1} \bar{\eta}^{2n+2}(F)\bar{\eta}^{-2n},$$

$$\Theta_3,h(v_F) = \sum_{n=2}^{\infty} (-1)^n h^{n-2} \frac{n - 1}{n} \sigma(\bar{\eta}^{2n+1}(F))\bar{\eta}^{-2n+1} + \sum_{n=2}^{\infty} (-1)^n h^{n-1} \frac{n-1}{n+2} \bar{\eta}^{2n+2}(F)\bar{\eta}^{-2n}.$$

6 Integrability of infinitesimal deformations

The space $H^1(\mathcal{K}(1), S\Psi DO)$ classifies infinitesimal deformations of the standard embedding $\mathcal{K}(1) \hookrightarrow S\Psi DO_{SL}$ given by (3.1). In this section we will calculate the integrability conditions of infinitesimal deformations into polynomial ones. Any nontrivial infinitesimal deformation can be expressed in the following form:

$$\rho_1 = \rho + \sum_{0 \leq i \leq 3} c_i \Theta_i,$$

(6.1)

where $c_0, c_1, c_2, c_3 \in \mathbb{R}$.

The integrability condition (below) imply that either $c_0 = 0$ or $c_2 = c_3 = 0$. 
6.1 Deformations generated by $\Theta_0$ and $\Theta_1$

Since zero-order operators commute in $S\Psi DO$, it is evident that the cup-products $[[\Theta_0, \Theta_0]]$, $[[\Theta_0, \Theta_1]]$ and $[[\Theta_1, \Theta_1]]$ vanish identically, and therefore the map

$$\rho_{\nu, \lambda} : K(1) \to S\Psi DO, \ v_F \mapsto \rho_{\nu, \lambda}(v_F) = \rho(v_F) + \nu \Theta_0(v_F) + \lambda \Theta_1(v_F) \quad (6.2)$$

is indeed, a nontrivial deformation of the standard embedding. This deformation is polynomial since it is of order 1.

**Proposition 1.** Any nontrivial formal deformation of the embedding (3.1) generated by $\Theta_0$ and $\Theta_1$ is equivalent to a deformation of order 1, that is, to a deformation given by (6.2).

**Proof.** Consider a formal deformation of the embedding (3.1) generated by $\Theta_0$ and $\Theta_1$:

$$\tilde{\rho}_t = \rho + t_0 \Theta_0 + t_1 \Theta_1 + \sum_{m \geq 2} \sum_{i+j=m} t_i^j \rho_{i,j}^{(m)}, \quad (6.3)$$

where the highest-order terms $\rho_{ij}^{(m)}$ are even linear maps from $K(1)$ to $S\Psi DO$. The solution $\rho_{ij}^{(2)}$ of (4.4) is defined up to a 1-cocycle and it has been shown in [4] that different choices of solutions of (4.4) correspond to equivalent deformations. Thus, one can always kill $\rho_{ij}^{(2)}$. Then, by recurrence, the highest-order terms satisfy the equation $\delta \rho_{ij}^{(m)} = 0$ and can also be killed. $\blacksquare$

**Remark 2.** Recall that, in the classical case (cf. [10]), there exists an analogous deformation $\pi_{\nu, \lambda}$ of $\pi$. Then, one can easily check that the following diagram commutes:

$$\begin{array}{ccc}
K(1) & \xrightarrow{\rho_{\nu, \lambda}} & S\Psi DO \\
\uparrow i & & \uparrow j \\
Vect(S^1) & \xrightarrow{\pi_{\nu, \lambda}} & \Psi DO
\end{array}$$

where

$$i(f(x)\partial_x) = v_f(x),$$
$$\pi_{\nu, \lambda}(f(x)\partial_x) = f(x)\xi + \nu f(x) + \lambda f'(x),$$
$$j(A) = A + \frac{1}{2} \eta^2(\partial_x A) \theta \eta .$$

Real difficulties begin when we deal with polynomial or formal integrability of the infinitesimal deformations corresponding to the cocycles $\Theta_1, \Theta_2$ and $\Theta_3$.

6.2 Deformations generated by $\Theta_1, \Theta_2$ and $\Theta_3$

Consider an infinitesimal deformation of the standard embedding of $K(1)$ into $S\Psi DO_{SL}$ defined by the cocycles $\Theta_1, \Theta_2, \Theta_3$ and depending on the real parameters $c_1, c_2, c_3$

$$\tilde{\rho}(v_F) = \rho(v_F) + c_1 \Theta_1(v_F) + c_2 \Theta_2(v_F) + c_3 \Theta_3(v_F). \quad (6.4)$$
Theorem 2. The infinitesimal deformation (6.4) corresponds to a polynomial deformation, if and only if the following relations are satisfied:

\[
\begin{align*}
3c_1c_3 - 2c_1^2 - 2c_1^2c_3 + c_2^2 + 2c_3^2 &= 0 \\
c_1 &= c_2
\end{align*}
\] (6.5)

or

\[
\begin{align*}
c_3c_1 - 2c_3c_1^2 - 2c_3^2 &= 0 \\
c_2 &= 0
\end{align*}
\] (6.6)

To prove Theorem 2, we first introduce the notion of homogeneity for a deformation given by differentiable maps, then we will prove that the conditions (6.5–6.6) are necessary for integrability of infinitesimal deformations. In the end of this section we will show that these relations are sufficient by exhibiting explicit deformations.

### 6.2.1 Homogeneous deformation

Consider an arbitrary polynomial deformation of the standard embedding, corresponding to the infinitesimal deformation (6.4):

\[
\bar{\rho}(c)(v_F) = \rho(v_F) + c_1\eta^2(F) + c_2(\bar{\eta}^3(F)\eta^{-1} + \bar{\eta}^4(F)\eta^{-2}) + c_3(\bar{\eta}^5(F)\eta^{-3}) + \sum_{k \in \mathbb{Z}} P_k(c)\rho_k(v_F),
\] (6.7)

where \(c = (c_1, c_2, c_3) \in \mathbb{R}^3\), \(P_k\) are polynomial functions of degree \(\geq 2\) and \(\rho_k\) are some differentiable even linear maps from \(K(1)\) to \(SP_k\).

Note that, since the cocycles \(\Theta_1, \Theta_2, \Theta_3\) are defined by differentiable maps, an arbitrary solution of the deformation problem is also defined via differentiable maps. This follows from the Gelfand-Fuchs formalism of differentiable (or local) cohomology (see [3]).

Now, let us introduce a notion of homogeneity for deformation given by differentiable maps. A deformation (6.7) is said to be homogeneous of degree \(m\) if \(\bar{\rho}(c)(v_F)\) is of the form:

\[
\bar{\rho}(c)(v_F) = \sum_{k \in \mathbb{Z}} P_k(c)(\sigma^k(\bar{\eta}^{k+m}(F)))\eta^{-k}.
\]

Since the cocycles \(\Theta_1, \Theta_2\) and \(\Theta_3\) are of degree 2, every homogeneous deformation (6.7) corresponding to a nontrivial infinitesimal deformation is of degree 2:

\[
\bar{\rho}(c)(v_F) = \rho(v_F) + c_1\eta^2(F) + c_2(\bar{\eta}^3(F)\eta^{-1} + \bar{\eta}^4(F)\eta^{-2}) + c_3(\bar{\eta}^5(F)\eta^{-3}) + \sum_{k \geq 4} P_k(c)(\sigma^k(\bar{\eta}^{k+2}(F)))\eta^{-k}.
\] (6.8)

**Proposition 2.** Every deformation (6.7) is equivalent to a homogeneous deformation (6.8).

**Proof.** It is easy to see that any homomorphism preserves homogeneity. This means that the first term in (6.7) (the term of the lowest degree in \(c\)) which is not homogeneous of degree 2 must lie in \(H^1(K(1), SP)\). Such a 1-cocycle is cohomologous to a linear combination of the 1-cocycles \(C_1, C_2\) and \(C_3\), see (5.5)–(5.7) which are homogeneous of degree 2. Thus, one can add (or remove) a coboundary in the term of the polynomial deformation (6.7) to obtain an equivalent one. 

\[\square\]
6.2.2 Integrability conditions are necessary

The infinitesimal deformation (6.4) is clearly of the form
\[ \tilde{\rho}(c)(v_F) = \rho(v_F) + c_1 \eta^2(F) + c_2(\sigma(\tilde{\eta}^3(F))\tilde{\eta}^{-1} + \tilde{\eta}^4(F)\tilde{\eta}^{-2}) + c_3 \sigma(\tilde{\eta}^5(F))\tilde{\eta}^{-3} + \cdots, \]
where \( \cdots \) means the terms in \( \tilde{\eta}^{-4}, \tilde{\eta}^{-5} \). To compute the obstructions for integrability of the infinitesimal deformation (6.4), one has to add the first nontrivial terms and impose the homomorphism condition. So, put

\[ \tilde{\rho}(c)(v_F) = \rho(c)(v_F) + P_4(c)\eta^6(F)\tilde{\eta}^{-4} + P_5(c)\sigma(\tilde{\eta}^7(F))\tilde{\eta}^{-5}, \]

where \( P_4(c) \) and \( P_5(c) \) are some polynomials in \( c = (c_1, c_2, c_3) \) and compute the difference \([\tilde{\rho}(c)(v_F), \tilde{\rho}(c)(v_G)] - \tilde{\rho}(c)([v_F, v_G])\).

A straightforward but boring computation leads to the following equations:
\[
\begin{align*}
  c_2c_1 &= c_2^2, \\
  3P_4 &= 2c_3 - c_2 - 2c_3c_1 + 4c_3c_2 + c_2c_1, \\
  3P_5 &= -c_2 - 4c_3 + 2c_2^2 - 2c_3c_2 + 4c_3c_1.
\end{align*}
\]

Let us go one step further, expand our deformation up to \( \tilde{\eta}^{-7} \), that is, put

\[ \tilde{\rho}(c)(v_F) = \rho(c)(v_F) + P_6(c)\eta^8(F)\tilde{\eta}^{-6} + P_7(c)\sigma(\tilde{\eta}^9(F))\tilde{\eta}^{-7}. \]

The homomorphism condition leads to a nontrivial relations for the parameters. For \( c_1 = c_2 \), the relations are:
\[
\begin{align*}
  2P_6 &= -c_1 + c_1^2 + P_4(-3 + 2c_1), \\
  2P_7 &= 5c_3 - 2c_2^2 - 6c_3c_1 - 3P_4 + 4c_1P_4, \\
  5P_7 &= c_1 - 2c_1^2 + c_1P_4 + (3c_1 - \frac{9}{2})P_5 - \frac{3}{2}P_6.
\end{align*}
\]

Substituting expressions (6.11), and (6.12) for \( P_4, P_5, P_6 \) and \( P_7 \) in (6.13), one gets formula (6.5).

For \( c_2 = 0 \), the relations are:
\[
\begin{align*}
  P_6 &= (\frac{3}{2} - c_1)(P_4 + P_5), \\
  2P_7 &= 3c_3 - 4c_3c_1 - 2c_2^2, \\
  4(P_6 + P_7) &= (-3 + 2c_1)(P_4 + P_5).
\end{align*}
\]

Substituting expressions (6.11), and (6.14) for \( P_4, P_5, P_6 \) and \( P_7 \) in (6.15), we get formula (6.6). We have thus shown that the conditions (6.5) are necessary for integrability of infinitesimal deformations.

Remark 3. The obstructions to integrability of an infinitesimal deformation (6.4), which does not satisfy the conditions (6.5), corresponds to a nontrivial class of \( H^2(K(1), SP_3) \).
6.3 Introducing the parameter $h$

One can now modify the relations in order to get a deformation in $S\Psi\mathcal{DO}_h$, the scalar $h$ then appears with different powers according to the “weight” of the respective terms in formulas $[6.5] \, [6.6]$. One finally gets

$$\begin{cases}
  h^2 c_1^2 + h(3c_1 c_3 - 2c_1^3) + 2c_2^2 - 2c_1^2 c_3 = 0 \\
  c_1 = c_2
\end{cases} \quad \text{or} \quad \begin{cases}
  hc_3 c_1 - 2c_3 c_1^2 - 2c_3^2 = 0 \\
  c_2 = 0.
\end{cases} \tag{6.16}
$$

These relations are necessary for the integrability of the infinitesimal deformation $[6.4]$ in $S\Psi\mathcal{DO}_h$.

**Remark 4.** By setting weights: $\text{wht}(c_1) = \text{wht}(h) = 1$ and $\text{wht}(c_3) = 2$, we make the polynomials $[6.16]$ homogeneous of weight 4. Moreover, setting $h = 0$, one gets the necessary conditions to have a polynomial deformation of the standard embedding $[5.1]$ corresponding to a given infinitesimal one generated by the cocycles $C_1, C_2$ and $C_3$ given by $[5.5] \, [5.7]$.

Now, we will give a natural description of the curves defined by equations $[6.16]$ in order to unveil their algebraic nature.

6.3.1 A rational parameterization

There exists a rational parameterization of the curves $[6.16]$: 

**Proposition 3.** i) For all $\lambda \in \mathbb{R}$, the constants

$$(6.17) \quad \begin{cases}
  c_1 = -\lambda \\
  c_2 = -\lambda \\
  c_3 = h\lambda
\end{cases} \quad \text{or} \quad \begin{cases}
  c_1 = -\lambda \\
  c_2 = -\lambda \\
  c_3 = \lambda^2 + \frac{1}{2} h\lambda
\end{cases}$$

satisfy the first of relations $[6.16]$.

ii) For all $\lambda \in \mathbb{R}$, the constants

$$(6.18) \quad \begin{cases}
  c_1 = -\lambda \\
  c_2 = c_3 = 0
\end{cases} \quad \text{or} \quad \begin{cases}
  c_1 = -\lambda \\
  c_2 = 0 \\
  c_3 = -\lambda^2 - \frac{1}{2} h\lambda
\end{cases}$$

satisfy the second of relations $[6.16]$.

iii) Any triple $c_1, c_2, c_3 \in \mathbb{R}$ satisfying $[6.16]$ is of the form $[6.17]$ or $[6.18]$ for same $\lambda$.

**Proof.** By direct computations. ■

**Remark 5.** Geometrically, the curves $[6.5]$ and $[6.6]$ are just lines and parabolas.

Now, the analogue of Richardson-Nijenhuis theory in supergeometry (cf. $[4.5]$) prescribes us to compute $H^2(\mathcal{K}(1), S\Psi\mathcal{DO})$ in order to obtain the complete information concerning the cohomological obstructions. This, however, seems to be a quite difficult problem. We shall not do that; an explicit construction of deformations will allow to avoid the standard obstruction framework.
6.3.2 Construction of deformations

Now, to complete the proof of our main result (Theorem 2), we construct a polynomial deformation corresponding to any infinitesimal deformation (6.4) satisfying the condition (6.16). This implies that these conditions are not only necessary, but also sufficient for integrability of infinitesimal deformations (6.4).

The space $H_0(S\Psi DO, S\Psi DO)$ of even outer superderivations of the Lie superalgebra $S\Psi DO$ contains the linear operator $\text{ad log} \xi$ on $S\Psi DO$ (cf. [3]). This outer superderivation can be integrated to a one-parameter family of outer automorphisms denoted by $\Psi_\nu$ and defined by

$$\Psi_\nu(F) = \xi^{\nu} \circ F \circ \xi^{-\nu},$$

(6.19)

which should be understood as a Laurent series in $\eta$ (depending on the parameter $\nu$).

Let us apply the automorphism (6.19) to the elementary deformation $\rho_{0,\lambda}$ (6.2):

$$\tilde{\rho}_1^\lambda(v_F) = \Psi_{-\frac{\lambda}{h}}(\rho(v_F) + \lambda \eta^2(F))$$

$$= \rho(v_F) - \lambda \eta^2(F)$$

$$- \lambda \sigma(\tilde{\eta}^5(F))\tilde{\eta}^{-1} + \tilde{\eta}^4(F)\tilde{\eta}^{-2}$$

$$+ (\lambda^2 + \frac{1}{2} \lambda h)(\sigma(\tilde{\eta}^5(F))\tilde{\eta}^{-3}) + \cdots$$

(6.20)

Since $\Psi_{-\frac{\lambda}{h}}$ is an automorphism, it is, indeed, a polynomial deformation of embedding (3.1) for any $\lambda \in \mathbb{R}$, corresponding to any infinitesimal deformation (6.4) satisfying the second of conditions (6.17).

**Proposition 4.** The map

$$\tilde{\rho}_2^\lambda : v_F \rightarrow \rho(v_F) + \lambda \tilde{\Theta}_h(v_F),$$

(6.21)

where $\tilde{\Theta}_h = 2h\Theta_3 - \Theta_2 - \Theta_1$, is both a polynomial and a formal deformation of embedding (3.1) for any $\lambda \in \mathbb{R}$, corresponding to any infinitesimal deformation (6.4) satisfying the first of conditions (6.17).

**Proof.** Since $\tilde{\Theta}_h$ is an even 1-cocycle, the map $\tilde{\rho}_2^\lambda$ is a polynomial deformation if the supercommutator $[\tilde{\Theta}_h, \tilde{\Theta}_h]$ vanishes. So put

$$\tilde{\Theta}_h(v_F) = \sum_{n \geq 1} (-1)^n h^{-1} a^{(n+1)} \xi^{-n} \theta \frac{\partial}{\partial \theta} + \sum_{n \geq 0} (-1)^{n+1} h^n a^{(n+1)} \xi^{-n}$$

$$+ 2 \sum_{n \geq 1} (-1)^n h^{n-1} b^{(n)} \xi^{-n} \frac{\partial}{\partial \theta},$$

where $F = a + 2b \theta$ with $a, b \in C^\infty(S^1)$ and compute $[\tilde{\Theta}_h(v_F), \tilde{\Theta}_h(v_G)]$, where $G = c + 2d \theta$ with $c, d \in C^\infty(S^1)$. Collect the terms with $a^{(\alpha+1)} c^{(\beta+1)} \xi^{-\alpha-\beta}$ for $\alpha, \beta \in \mathbb{N}$:

$$\begin{cases}
    H(\alpha, \beta) & \text{if } \alpha \geq 2 \text{ and } \beta \geq 2, \\
    0 & \text{otherwise},
\end{cases}$$

(6.22)
where

\[ H(\alpha, \beta) = -(-h)^{\alpha + \beta - 1} \times \left( \frac{\alpha + \beta - 1}{\alpha - 1} - \frac{\alpha + \beta - 1}{\beta - 1} + \sum_{n=1}^{\beta - 1} \left( \frac{\alpha + n - 1}{\alpha - 1} - \frac{\alpha + n - 1}{\beta - 1} \right) \right). \] (6.23)

It is now easy to check that the expression (6.23) vanishes for \( \beta = 2 \) and \( \alpha \geq 2 \). We will prove by recurrence that this expression vanishes for \( \alpha \geq 2 \) and \( \beta \geq 2 \).

Assume that, for \( \beta \geq 2 \), one has

\[ \left( \frac{\alpha + \beta - 1}{\beta - 1} \right) - \left( \frac{\alpha + \beta - 1}{\alpha - 1} \right) \sum_{n=1}^{\beta - 1} \left( \frac{\alpha + n - 1}{\alpha - 1} \right) + \sum_{n=1}^{\beta - 1} \left( \frac{\beta + n - 1}{\beta - 1} \right) = 0. \] (6.24)

Using

\[ \sum_{k=1}^{\alpha} \left( \frac{\beta + k - 1}{\beta} \right) = \frac{\alpha + \beta}{\alpha - 1}, \quad \frac{\alpha + \beta}{\beta} = \frac{\alpha + \beta}{\beta - 1}, \]
and equation (6.21), one obtains

\[ \left( \frac{\alpha + \beta}{\alpha} \right) - \left( \frac{\alpha + \beta}{\alpha - 1} \right) \sum_{n=1}^{\beta} \left( \frac{\alpha + n - 1}{\alpha - 1} \right) + \sum_{n=1}^{\beta} \left( \frac{\beta + n}{\beta - 1} \right) = 0 \]

which implies that the expression (6.24) vanishes.

Note that the term with \( a^{(\alpha + 1)} c^{(\beta + 1)} \xi^{-\alpha - \beta} \eta^\beta \xi^\alpha \), where \( \alpha, \beta \in \mathbb{N} \), vanishes since it has the same expression as (6.22). Finally, one can easily see that the coefficients of \( a^{(\alpha + 1)} d^{(\beta)} \xi^{-\alpha - \beta} \eta^\beta \xi^\alpha \) and of \( c^{(\alpha + 1)} b^{(\beta)} \xi^{-\alpha - \beta} \eta^\beta \xi^\alpha \) are the same, and hence

\[ \left\{ \begin{array}{ll}
L(\alpha, \beta) & \text{if } \alpha \geq 1 \text{ and } \beta \geq 2, \\
0 & \text{otherwise},
\end{array} \right. \] (6.25)

where

\[ L(\alpha, \beta) = -(-h)^{\alpha + \beta - 2} \left( 1 - \left( \frac{\alpha + \beta - 1}{\beta - 1} \right) + \sum_{n=1}^{\beta - 1} \left( \frac{\alpha + n - 1}{\alpha - 1} \right) \right). \] (6.26)

The same arguments show that expression (6.26) vanishes. We have proved thus that \([\Theta_h, \Theta_h] = 0\). Hence, the map \( \widetilde{\rho}_2^\alpha \) is both a polynomial and formal deformation. To complete the proof of Proposition 10, observe that every infinitesimal deformation \( \tilde{\rho}_2^\alpha \) satisfying the first of conditions (6.17) can be realized as the infinitesimal part of the polynomial deformation \( \widetilde{\rho}_2^\alpha \).

Finally, we will construct a polynomial deformation corresponding to any infinitesimal deformation \( \tilde{\rho}_2^\alpha \) satisfying the second of conditions (6.18). We apply the automorphism (6.19) to the polynomial deformation (6.21):

\[ \widetilde{\rho}_2^\alpha(v_F) = \Psi \frac{\lambda}{h} \circ \rho_2^\alpha(v_F) = \lambda \eta^2(F) - (\lambda^2 + \frac{1}{2} \lambda h)(\sigma(\eta^5(F)\eta^{-3}) + \cdots, \] (6.27)
so we obtain a polynomial deformation corresponding to any infinitesimal deformation \((6.4)\) satisfying the second of conditions \((6.18)\).

**Remark 6.** Under the first of conditions \((6.18)\), any infinitesimal deformation \((6.4)\) becomes a polynomial deformation.

Applying the contraction procedure as \(h \to 0\) to the deformations \((6.20), (6.21)\) and \((6.27)\), we get polynomial deformations of the infinitesimal deformation of the standard embedding \((5.1)\) generated by the 1-cocycles \(C_1, C_2\) and \(C_3\) corresponding to the conditions \((6.16)\) at \(h = 0\). More precisely, we get:

**Theorem 3.** Every nontrivial polynomial deformation of the standard embedding \((5.1)\) is equivalent to one of the four following deformations:

\[
\begin{align*}
\rho_1^\lambda(v_F) & = \frac{1}{2} ((F + \sigma(F)) \xi + \eta(F) \zeta) + \lambda \eta^2(F), \\
\rho_2^\lambda(v_F) & = \frac{1}{2} ((F + \sigma(F)) \xi + \eta(F) \zeta) + \lambda (\eta^2(F) - \sigma(\eta^3(F)) \xi^{-1} \zeta), \\
\rho_3^\lambda(v_F) & = \frac{1}{2} ((F(x - \frac{2a}{\xi})) + \sigma(F(x - \frac{2a}{\xi}))) \xi + \eta(F(x - \frac{2a}{\xi})) \zeta) + \lambda \eta^2(F(x - \frac{2a}{\xi})), \\
\rho_4^\lambda(v_F) & = \frac{1}{2} ((F(x - \frac{2a}{\xi})) + \sigma(F(x - \frac{2a}{\xi}))) \xi + \eta(F(x - \frac{2a}{\xi})) \zeta) + \lambda (\eta^2(F(x - \frac{2a}{\xi}) \\
& - \sigma(\eta^3(F(x - \frac{2a}{\xi})))) \xi^{-1} \zeta),
\end{align*}
\]

where \(\lambda \in \mathbb{R}\) is parameter of the deformation.

### 7 A variation of the central charge

The outer superderivation \(\text{ad} \log \xi \in H^0(S\Psi DO, S\Psi DO)\) defines a nontrivial 2-cocycle with scalar values by the formula \((7.1)\)

\[
\tilde{C}_1(A, B) = \text{Str}(\text{ad} \log \xi, A \circ B).
\]

It is known that \(\dim H^2(K(1), \mathbb{C}) = 1\) \((9)\) and \(H^2(K(1), \mathbb{C})\) is spanned by the Neveu-Schwarz cocycle:

\[
C(v_F, v_G) = -\frac{1}{4} \int_{S^1} F \eta^5(G) \text{vol}(x, \theta) = -\frac{1}{4} \int_{S^1} (4bd'' + ac''')dx,
\]

where \(F = a + 2b\theta\) and \(G = c + 2d\theta\) with \(a, b, c, d \in C^\infty(S^1)\).

**Remark 7.** The restriction of the 2-cocycle \((7.1)\) to the Lie superalgebra \(K(1)\) coincides with the Neveu-Schwarz cocycle.

**Proposition 5.** The restriction of the cocycle \(\tilde{C}_1\) to \(K(1) \hookrightarrow S\Psi DO_h\) with respect to the embedding \((6.20), (6.21)\) or \((6.27)\) is

\[
\rho^{\lambda}(\tilde{C}_1) = (h - 4\lambda)C.
\]

**Proof.** By direct computations. ■

**Acknowledgements** It is a pleasure to thank Valentin Ovsienko who introduced us to the question of deforming the Lie superalgebra of contact vector fields on \(S^{1\mid 1}\) inside the Lie superalgebra of superpseudodifferential operators on \(S^{1\mid 1}\). We also thank Claude Roger, M. Ben Ammar, B. Agrebaoui, and F. Ammar for helpful discussions.
Deforming the Lie Superalgebra of Contact Vector Fields on $S^{1|1}$

References

[1] A. Fialowski, D. B. Fuchs, Construction of miniversal deformations of Lie algebras J. Func. Anal. 161:1 (1999) 76–110.

[2] A. Nijenhuis, R. W. Richardson Jr., Deformations of homomorphisms of Lie groups and Lie algebras, Bull. Amer. Math. Soc. 73 (1967), 175–179.

[3] A.O. Radul, Non-trivial central extensions of Lie algebras of differential operators in two higher dimensions, Phys. Letters B265(1991)86–91.

[4] B. Agrebaoui, F. Ammar, P. Lecomte, V. Ovsienko, Multi-parameter deformations of the module of symbols of differential operators, Internat. Mathem. Research Notices, 2002, N. 16, 847–869.

[5] B. Agrebaoui, N. Ben Fraj, On the cohomology of the Lie superalgebra of contact vector fields on $S^{1|1}$, Belletin de la Société Royale des Sciences de Liège, vol.72, 6, 2004, pp.365-375.

[6] D. B. Fuchs, Cohomology of infinite-dimensional Lie algebras, Plenum Publ. New York, 1986.

[7] E. Poletaeva, A spinor-Like representation of the contact superconformal algebra $K'(4)$, J. Math. Phys. vol. 42(2001) nu.1, 526–540.

[8] P. Cohen, Yu. I. Manin, D. Zagier, Automorphic pseudodifferential operators, Algebraic aspects of integrable systems, 17–47, Progr. Nonlinear Differential Equations Appl., 26, Birkhäuser Boston, Boston, MA, 1997.

[9] P. Grozman, D. Leites, and I. Shchepochkina, Lie superalgebras of string theories, Acta Mathematica Vietnamica, v. 26, 2001, no. 1, 27–63; hep-th/9702120

[10] V. Ovsienko, C. Roger, Deforming the Lie algebra of vector fields on $S^1$ inside the Lie algebra of pseudodifferential operators on $S^1$, AMS Transl. Ser. 2, (Adv. Math. Sci.) vol. 194 (1999) 211–227.

[11] V. Ovsienko, C. Roger, Deforming the Lie algebra of vector fields on $S^1$ inside the Poisson algebra on $T^*S^1$, Comm. Math. Phys., 198 (1998) 97–110.

[12] Yu.I. Manin and A. O. Radul, A Supersymmetric extension of Kadomtsev-Petviashvili hierarchy, Commun. Math. Phys. 98(1985), 65-77.