

DIDIER ARNAL

HÁDI BENAMOR

BENJAMIN CAHEN

Minimal realizations of classical simple Lie algebras through deformations

Annales de la faculté des sciences de Toulouse 6^e série, tome 7, n^o 2 (1998), p. 169-184

http://www.numdam.org/item?id=AFST_1998_6_7_2_169_0

© Université Paul Sabatier, 1998, tous droits réservés.

L'accès aux archives de la revue « Annales de la faculté des sciences de Toulouse » (<http://picard.ups-tlse.fr/~annales/>) implique l'accord avec les conditions générales d'utilisation (<http://www.numdam.org/conditions>). Toute utilisation commerciale ou impression systématique est constitutive d'une infraction pénale. Toute copie ou impression de ce fichier doit contenir la présente mention de copyright.

NUMDAM

Article numérisé dans le cadre du programme
Numérisation de documents anciens mathématiques

<http://www.numdam.org/>

Minimal Realizations of Classical Simple Lie Algebras Through Deformations^(*)

DIDIER ARNAL⁽¹⁾, HÁDI BENAMOR⁽¹⁾
and BENJAMIN CAHEN⁽¹⁾

RÉSUMÉ. — Soit \mathfrak{g} une algèbre de Lie simple complexe et \mathcal{O}_{\min} son orbite coadjointe (non triviale) de dimension minimale. En utilisant un star-produit sur un revêtement de \mathcal{O}_{\min} (ou d'un ouvert dense de \mathcal{O}_{\min}), on donne une construction explicite des réalisations minimales de \mathfrak{g} .

ABSTRACT. — Let \mathfrak{g} be a complex simple Lie algebra and \mathcal{O}_{\min} be its minimal non trivial coadjoint orbit. Using a star product on a covering space of \mathcal{O}_{\min} (or an open subset of \mathcal{O}_{\min}), we give an explicit construction of the so called minimal realizations of \mathfrak{g} .

1. Introduction

The notion of star product was introduced by M. Flato and C. Fronsdal ([5], [7]) to give a new formulation for quantization of classical systems. In such a formulation, quantization is a deformation of the associative and Poisson structure of the algebra of classical observables. Applications of this notion to the theory of unitary representations of Lie groups were developed by many authors ([2], [3] and [4]).

The purpose of this paper is to give a new application of star products for the construction of the minimal realizations of a complex simple Lie algebra \mathfrak{g} from its non trivial minimal coadjoint orbit \mathcal{O}_{\min} . In particular, we construct by a very simple and natural way the minimal realizations given by A. Joseph ([8], [9]). Recall that a realization of \mathfrak{g} is a faithful

(*) Reçu le 16 janvier 1996, accepté le 17 juin 1996

(1) Département de Mathématiques et d'Informatique, U.R.A. C.N.R.S. 399, Université de Metz, Ile-du-Saulcy, F-57045 Metz Cedex (France)
e-mail : arnal@poncelet.univ-metz.fr

representation of \mathfrak{g} as differential operators on polynomial functions and it is minimal if the number of variables is minimal. Let us now describe our construction.

We first define a parametrization of an open subset of the minimal orbit \mathcal{O}_{\min} (Sect. 2). This subset is an orbit under a solvable subgroup of the group G associated to \mathfrak{g} . \mathfrak{g} is then embedded faithfully in a Poisson algebra \mathcal{P} (an algebra of polynomials, or an algebra of polynomials localized at one generator). We introduce the Moyal star product [5] on \mathcal{P} (Sect. 3). If the type of \mathfrak{g} is A_n , $n \geq 1$ (Sect. 4), the Moyal star product has the covariance property and we obtain a one complex parameter family of minimal realizations of \mathfrak{g} . If it is C_n , $n \geq 2$, we obtain the usual realization of the symplectic algebra by quadratic polynomials ([10], [11]; Sect. 5). Finally if \mathfrak{g} of type D_n , $n \geq 4$ (Sect. 6) or B_n , $n \geq 3$ (Sect. 7), the Moyal star product is not covariant thus we replace it by an equivalent star product which is covariant. This new star product leads us to the minimal realizations given in [8].

2. Parametrization of the minimal orbit

In section 2 and 3, we recall some properties of minimal orbits and star products and we describe the methods we shall use for each type of simple classical Lie algebra in section 4, 5, 6 and 7.

Let \mathfrak{g} be a simple complex Lie algebra. Fix a Cartan subalgebra \mathfrak{h} of \mathfrak{g} and a system of positive roots, we obtain the usual triangular decomposition:

$$\mathfrak{g} = \mathfrak{h} \oplus \mathfrak{n}^+ \oplus \mathfrak{n}^- .$$

If ψ is the highest root, we fix a weight vector X_ψ . Using the Killing form β of \mathfrak{g} , we identify \mathfrak{g} with its dual \mathfrak{g}^* . Let ξ_0 be the element of \mathfrak{g}^* corresponding to X_ψ . Let G be the adjoint group of \mathfrak{g} . The unique non trivial minimal nilpotent orbit for the adjoint action of G is $\mathcal{O}_{\min} = G \cdot \xi_0$.

PROPOSITION 1

1) *Let $\mathfrak{g}(X_\psi)$ be the centralizer of X_ψ in \mathfrak{g} . Let H_ψ be the covector associated to the highest root ψ . Then there exists a Heisenberg subalgebra \mathcal{H} of \mathfrak{g} with central element $X_{-\psi}$ such that:*

$$\mathfrak{g} = \mathfrak{g}(X_\psi) \oplus \mathbb{C}H_\psi \oplus \mathcal{H} .$$

2) Let $\mathfrak{t} = \mathbb{C}H_\psi \oplus \mathcal{H}$ and R be the analytic subgroup of G with Lie algebra \mathfrak{t} . Then $\tilde{\mathcal{O}} = R \cdot \xi_0$ is an open set of \mathcal{O}_{\min} . The coadjoint orbits $\mathcal{O}_{\min} = G \cdot \xi_0$ and $R \cdot (\xi_0|_{\mathfrak{t}})$ being equipped with their Kirillov's canonical 2-forms Ω and ω , the map $\xi \mapsto \xi|_{\mathfrak{t}}$ is a symplectomorphism from $\tilde{\mathcal{O}}$ onto $R \cdot (\xi_0|_{\mathfrak{t}})$.

Proof

- 1) See the following sections 4-7. See also [9].
- 2) Let us remark that Ω and ω are R -invariant. Now if X and Y are two elements of \mathfrak{g} , one can write $X = X_1 + X_2$, $Y = Y_1 + Y_2$, where X_1, Y_1 are in $\mathfrak{g}(X_\psi)$ and X_2, Y_2 in \mathfrak{t} . Then, since $[X_\psi, X_1] = [X_\psi, Y_1] = 0$, one has:

$$\begin{aligned} \Omega_{\xi_0}(X \cdot \xi_0, Y \cdot \xi_0) &= \langle \xi_0, [X, Y] \rangle = \beta(X_\psi, [X, Y]) = \beta(X_\psi, [X_2, Y_2]) \\ &= \langle \xi_0|_{\mathfrak{t}}, [X_2, Y_2] \rangle = \omega_{\xi_0|_{\mathfrak{t}}}(X_2, Y_2). \end{aligned}$$

This proves our proposition. \square

Now we obtain a parametrization of $\tilde{\mathcal{O}} \subset \mathcal{O}_{\min}$ by using the following facts.

- 1) It is easy to parametrize the coadjoint orbit of $\xi_0|_{\mathfrak{t}}$, under the action of the solvable group R by co-ordinates $(p_1, \dots, p_n, q_1, \dots, q_n)$ where $q_n \neq 0$ (here $n = 1/2 \dim \mathcal{O}_{\min}$). This is equivalent to define a symplectomorphism between $\mathbb{C}^{2n} \setminus \{q_n = 0\}$ (with the 2-form $dp_1 \wedge dq_1 \wedge \dots \wedge dp_n \wedge dq_n$) and $R \cdot (\xi_0|_{\mathfrak{t}})$ (see [2], [4]). We deduce by Proposition 1 a symplectomorphism:

$$\pi : \mathbb{C}^{2n} \setminus \{q_n = 0\} \longrightarrow \tilde{\mathcal{O}}.$$

- 2) For X in \mathfrak{g} and x in $\mathbb{C}^{2n} \setminus \{q_n = 0\}$, put $\tilde{X}(x) = \langle \pi(x), X \rangle$. Parametrizing the orbit $R \cdot (\xi_0|_{\mathfrak{t}})$ or giving the functions \tilde{X} , X in \mathfrak{t} , are of course equivalent. Now the explicit computation of the functions \tilde{X} (X in \mathfrak{g}), which define π , will become very easy in sections 4-7 because \mathfrak{g} will be an algebra of matrices and the elements of \mathcal{O}_{\min} are matrices of rank one or two.

3. Star products and minimal realizations

DEFINITION 1. — A star product on a Poisson manifold $(M, \{\cdot, \cdot\})$, defined on a subalgebra N of $C^\infty(M)$ stable by the Poisson bracket, is a

bilinear mapping \star from $N \times N$, into the space $N[[\nu]]$ of formal power series in the variable ν with coefficients in N :

$$(f, g) \mapsto f \star g = \sum_{n \geq 0} \nu^n c_n(f, g)$$

where c_n are bidifferential operators on M such that $c_n(N \times N) \subset N$ and

$$\begin{aligned} c_0(f, g) &= f \cdot g, & c_1(f, g) &= \{f, g\} \\ c_n(f, g) &= (-1)^n c_n(g, f), & c_n(1, f) &= 0 \quad \text{if } n > 0; \end{aligned}$$

furthermore, the star product satisfies, when extended to $N[[\nu]]$ by bilinearity, the associativity condition:

$$f \star (g \star h) = (f \star g) \star h, \quad f \in N, \quad g \in N, \quad h \in N.$$

Remark 1. — Such a star product gives simultaneously:

- 1) a deformation of the associative structure (for the usual pointwise product) of N ,
- 2) a deformation of the Poisson structure of N (called the \star bracket) namely, for f and g in N ,

$$[f, g]_{\star} = \frac{1}{2\nu} (f \star g - g \star f) = \sum_{r \geq 1} \nu^{2r} c_{2r+1}(f, g).$$

DEFINITION 2. — Two star products \star_1 and \star_2 on M are equivalent if there exists a formal power series $T = \text{Id} + \sum_{r \geq 1} \nu^r T_r$ where T_r , $r \geq 1$, are differential operators such that $T_r(N) \subset N$ and

$$T(f \star_1 g) = T(f) \star_2 T(g)$$

for each f, g in N .

DEFINITION 3. — Let M be the space \mathbb{C}^{2n} (or an open subset of \mathbb{C}^{2n}) endowed with the Poisson bracket defined in the co-ordinates $(p_1, \dots, p_n, q_1, \dots, q_n)$ by

$$P^1(f, g) = \{f, g\} = \sum_{i=1}^n \frac{\partial f}{\partial p_i} \frac{\partial g}{\partial q_i} - \frac{\partial g}{\partial p_i} \frac{\partial f}{\partial q_i}, \quad f, g \in C^\infty(M).$$

Minimal Realizations of Classical Simple Lie Algebras Through Deformations

We define on $N = C^\infty(M)$ (or on a subalgebra of $C^\infty(M)$ stable by the Poisson bracket) the Moyal star product \star_M by

$$f \star_M g = \sum_{r \geq 0} \nu^r \frac{1}{r!} P^r(f, g)$$

where P^r is the r th tensorial power of the Poisson bracket P^1 on \mathbb{C}^{2n} [5].

Remark 2. — When restricted to the localized algebra

$$N = \mathbb{C} \left[p_1, \dots, p_n, q_1, \dots, q_n, \frac{1}{q_n} \right]$$

of the polynomial algebra $\mathbb{C}[p_1, \dots, p_n, q_1, \dots, q_n]$ at q_n , the series $f \star_M g$ is always a finite sum. Fix the value of the deformation parameter $\nu = 1/2$, then the Moyal star product gives an associative product on N . Now, the Weyl's transform W is the linear mapping from N into the algebra of differential operators on \mathbb{C}^n endowed with the co-ordinates q_1, \dots, q_n defined by

$$\begin{aligned} W(p_i) &= \frac{\partial}{\partial q_i}, & W(q_i) &= q_i, & 1 \leq i \leq n \\ W(f \star g) &= W(f) \circ W(g), & f, g &\in N. \end{aligned}$$

W is a faithful representation of the algebra (N, \star) .

With the notations of Section 2, we shall see that the functions \tilde{X}, X in \mathfrak{g} , are elements of the algebra $N = \mathbb{C}[p_1, \dots, p_n, q_1, \dots, q_n, 1/q_n]$. Since $\pi : \mathbb{C}^{2n} \setminus \{q_n = 0\} \rightarrow \tilde{\mathcal{O}}$ is a symplectomorphism, the mapping $\varphi_0 : X \mapsto \tilde{X}$ is an injective morphism of Lie algebras from \mathfrak{g} to N endowed with the Poisson bracket.

DEFINITION 4. — *A star product \star defined on N is called covariant if:*

$$\tilde{X} \star \tilde{Y} - \tilde{Y} \star \tilde{X} = 2\nu \{\tilde{X}, \tilde{Y}\}, \quad X \in \mathfrak{g}, Y \in \mathfrak{g}.$$

When \mathfrak{g} is of type A_n or C_n we shall see in Sections 4 and 5 that the Moyal star product on $\tilde{\mathcal{O}}$ is covariant. The mapping $\varphi_0 : X \mapsto \tilde{X}$ leads to an injective morphism of Lie algebras from \mathfrak{g} to $N[[\nu]]$ endowed with the star bracket $[\cdot, \cdot]_{\star_M}$. Fixing the value of the deformation parameter one obtains a representation of \mathfrak{g} by considering the mapping $X \mapsto W(\tilde{X})$.

When \mathfrak{g} is of type B_n or D_n , the Moyal star product is not covariant (sects 6 and 7). φ_0 is not a Lie algebra morphism from \mathfrak{g} to $(N[[\nu]], [\cdot, \cdot]_{\star_M})$. But there exists a differential operator T_2 of N such that the mapping:

$$\varphi : X \mapsto \tilde{X} + \nu^2 T_2(\tilde{X})$$

is a Lie algebra morphism from \mathfrak{g} to $(N[[\nu]], [\cdot, \cdot]_{\star_M})$.

Replace φ_0 by φ means, in terms of star products, to replace the Moyal star product by an equivalent star product which is covariant. Fix $\nu = 1/2$, one obtains a representation of \mathfrak{g} (the minimal realization of \mathfrak{g}) by considering the mapping $X \mapsto W(\varphi(X))$.

All these considerations lead us to introduce the notion of star minimal realization.

DEFINITION 5

1) A star minimal realization of \mathfrak{g} is a morphism

$$\varphi : X \mapsto \tilde{X} + \sum_{r \geq 0} \nu^r \varphi_r(X) \quad \text{from } \mathfrak{g} \text{ into } (N, [\cdot, \cdot]_{\star_M}).$$

2) Two star minimal realizations φ_1 and φ_2 of \mathfrak{g} are equivalent if there exists an equivalence morphism

$$A = \text{Id} + \sum_{r \geq 0} \nu^r A_r \quad \text{of } (N, [\cdot, \cdot]_{\star_M})$$

such that $\varphi_2 = A \circ \varphi_1$.

4. Lie algebra of type A_n

In this section and the following, the notations corresponding to the classical simple Lie algebras are those of [12].

In this section $\mathfrak{g} = \mathfrak{sl}(n+1, \mathbb{C})$, $n \geq 1$, and \mathfrak{h} is the abelian subalgebra of \mathfrak{g} of diagonal matrices of \mathfrak{g} .

Let $\lambda_1, \dots, \lambda_{n+1}$ be the linear forms defined on \mathfrak{h} by

$$\lambda_i : \text{Diag}(a_1, \dots, a_n) \mapsto a_i.$$

Minimal Realizations of Classical Simple Lie Algebras Through Deformations

The system of roots is $\Delta = \{\lambda_i - \lambda_j \mid 1 \leq i \neq j \leq n+1\}$. Let $\Delta^+ = \{\lambda_i - \lambda_j \mid 1 \leq i < j \leq n+1\}$ be the set of positive roots. We denote by E_{ij} the usual matrix: the only non vanishing entries of E_{ij} has indices i and j and its value is 1. The eigensubspace corresponding to the root $\lambda_i - \lambda_j$ is $\mathfrak{g}_{\lambda_i - \lambda_j} = \mathbb{C}E_{ij}$. We identify \mathfrak{g} with \mathfrak{g}^* by the trace form:

$$\langle X, Y \rangle = \text{Tr}(XY).$$

With the notations of the Section 2, one has $\psi = \lambda_1 - \lambda_{n+1}$, the orbit \mathcal{O}_{\min} of $X_\psi = E_{1n+1}$ is the set of matrices of rank 1 and trace 0. We write $\mathfrak{g} = \mathfrak{g}(X_\psi) \oplus \mathbb{C}H_\psi \oplus \mathcal{H}$, where $H_\psi = E_{11} - E_{n+1n+1}$ and \mathcal{H} is the Heisenberg algebra generated by the $X_i = E_{n+1i+1}$, $Y_i = E_{i+11}$, $1 \leq i \leq n-1$ and $Z = E_{n+11}$.

Using the usual parametrization of coadjoint orbits of exponential group, we parametrize the orbit as follows:

$$\tilde{X}_i = p_i q_n, \quad \tilde{Y}_i = q_i, \quad 1 \leq i \leq n-1 \quad \text{and} \quad \tilde{Z} = q_n.$$

The commutation rules:

$$[H_\psi, X_i] = -X_i, \quad [H_\psi, Y_i] = -Y_i, \quad 1 \leq i \leq n-1,$$

and

$$[H_\psi, Z] = -2Z$$

give $\tilde{H}_\psi = -\sum_{i=1}^{n-1} p_i q_i - 2p_n q_n$.

By using the fact that the rank of the matrices in \mathcal{O}_{\min} is 1, one obtains

$$\pi : (p_1, \dots, p_n, q_1, \dots, q_n) \longmapsto \xi = (\xi_{ij})$$

where

$$\begin{aligned} \xi_{k+1\ell+1} &= p_k q_\ell, \quad 1 \leq k, \ell \leq n, \\ \xi_{11} &= -\sum_{i=1}^n p_i q_i, \quad \xi_{1\ell+1} = q_\ell, \quad 1 \leq \ell \leq n \end{aligned}$$

and

$$\xi_{k+11} = -p_k \sum_{i=1}^n p_i q_i.$$

Now, on the algebra $N = \mathbb{C}[p_1, \dots, p_n, q_1, \dots, q_n, 1/q_n]$ we define a structure of \mathfrak{g} -module by

$$X \cdot f = \{\tilde{X}, f\}, \quad X \in \mathfrak{g}, f \in N$$

and denote by $H^k(\mathfrak{g}, N)$ the corresponding k -th cohomological space.

PROPOSITION 2

- 1) *The Moyal star product \star_M defined on N is covariant.*
- 2) *The dimension of the space $H^1(\mathfrak{g}, N)$ is equal to 2. $H^1(\mathfrak{g}, N)$ is generated by the classes of φ_0 and φ_2 , defined by*

$$\begin{aligned} \varphi_0(E_{11} - E_{22}) &= 1 \\ \varphi_0(E_{ii} - E_{i+1, i+1}) &= 0, \quad 1 < i < n + 1 \\ \varphi_0(E_{k+1, 1}) &= p_k, \quad 0 \leq k \leq n \\ \varphi_0(E_{ij}) &= 0, \quad 1 < j, i \neq j. \end{aligned}$$

and

$$\varphi_1(X) = \frac{1}{q_n} \frac{\partial}{\partial p_n} \tilde{X}, \quad X \in \mathfrak{g}.$$

- 3) *Each minimal realization of \mathfrak{g} in $(N, [\cdot, \cdot]_\star)$ is equivalent to a minimal realization*

$$X \longmapsto \tilde{X} + \left(\sum_{n \geq 1} a_n \nu^n \right) \varphi_0(X)$$

where $a_n, n \geq 1$, are complex numbers.

- 4) *The family of linear mappings $W_\alpha : X \mapsto W(\tilde{X} + \alpha \varphi_0(X))$, $\alpha \in \mathbb{C}$, is a family of representations of \mathfrak{g} . It coincides with the family of minimal realizations given in [8].*

Proof

- 1) is obtained by a direct computation.
- 2) Let $\varphi : \mathfrak{g} \rightarrow N$ be a 1-cocycle, i.e.,

$$\varphi([X, Y]) - \{\tilde{X}, \varphi(Y)\} - \{\varphi(X), \tilde{Y}\} = 0$$

for X, Y in \mathfrak{g} . Modifying if necessary φ by a coboundary, i.e., by a mapping of the form $X \mapsto \{\tilde{X}, f\}$, $f \in N$, we can suppose that $\varphi(X) = 0$ for all X in \mathcal{H} and that $\varphi(E_{11} - E_{22})$ is a scalar. We deduce that φ is a linear combination of φ_0 and φ_1 .

3) is deduced from 2). \square

Remark 3. — The family of minimal realizations W_α of \mathfrak{g} can also be found by the method given by N. Conze in [6].

5. Lie algebra of type C_n

In this section, \mathfrak{g} is the Lie algebra $\mathfrak{sp}(2n, \mathbb{C})$, $n \geq 2$, of matrices of type

$$\begin{pmatrix} A & B \\ C & -A^t \end{pmatrix}$$

where A is a $n \times n$ matrix, B and C are two symmetric $n \times n$ matrices. We denote by (A, B, C) such a matrix. With the previous notations:

$$\mathfrak{h} = \left\{ (\text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mid a_i \in \mathbb{C} \right\}$$

$$\lambda_i : (\text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mapsto a_i, \quad i = 1, 2, \dots, n$$

$$\Delta^+ = \{ \lambda_i - \lambda_j \mid 1 \leq i < j \leq n \} \cup \{ \lambda_k + \lambda_\ell \mid 1 \leq k \leq \ell \leq n \}$$

$$\psi = 2\lambda_1, \quad X_\psi = (0, E_{11}, 0), \quad H_\psi = (E_{11}, 0, 0).$$

We identify \mathfrak{g}^* and \mathfrak{g} by the form $\langle X, Y \rangle = (1/2) \text{Tr}(XY)$. \mathcal{O}_{\min} is the orbit of $\xi_0 = X_\psi$ and the elements of \mathcal{O}_{\min} are matrices of $\mathfrak{sp}(2n, \mathbb{C})$ with rank 1. Here \mathcal{H} is the Heisenberg algebra generated by $X_i = (-E_{1\ i+1}, 0, 0)$, $Y_i = (0, 0, E_{1\ i+1} + E_{i+1\ 1})$, $1 \leq i \leq n-1$, and $Z = (0, 0, 2E_{11})$ (then $[X_i, Y_i] = \delta_{ij}Z$).

We parametrize the orbit as follows:

$$\tilde{X}_i = p_{n-i}q_n, \quad \tilde{Y}_i = q_{n-i}q_n, \quad 1 \leq i \leq n-1$$

and

$$\tilde{Z} = q_n^2.$$

As in Section 4, we deduce:

$$\tilde{H}_\psi = -p_nq_n.$$

Here $\pi : \mathbb{C}^{2n} \setminus \{0\} \rightarrow \mathcal{O}_{\min}$ is a twofold covering of the whole orbit \mathcal{O}_{\min} ([10], [11]), $\pi(p_1, \dots, p_n, q_1, \dots, q_n)$ is the matrix of rank 1 of \mathfrak{g} whose the first line is

$$(-p_n q_n, -p_{n-1} q_n, \dots, -p_1 q_n, q_n^2, q_{n-1} q_n, \dots, q_1 q_n)$$

and the $n + 1$ -th column is

$$(q_n^2, q_{n-1} q_n, \dots, q_1 q_n, p_n q_n, p_{n-1} q_n, \dots, p_1 q_n).$$

The mapping $\varphi_0 : X \mapsto \tilde{X}$ is the usual realization of \mathfrak{g} as a Poisson algebra of quadratic polynomials.

The Moyal star product defined on $N = \mathbb{C}[p_1, \dots, p_n, q_1, \dots, q_n]$ is covariant and the representation $X \mapsto W(\tilde{X})$ of \mathfrak{g} in the space $\mathbb{C}[q_1, \dots, q_n]$ is well known [10]. Its restriction to even polynomials of $\mathbb{C}[q_1, \dots, q_n]$ is an irreducible representation of \mathfrak{g} with dominant weight

$$\lambda : (\text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \rightarrow -\frac{1}{2}(a_1 + \dots + a_n) \quad [1].$$

Let us remark that $H^1(\mathfrak{g}, N)$ vanishes, by the first Whitehead lemma.

6. Lie algebra of type D_n

Here \mathfrak{g} is the Lie algebra $\mathfrak{so}(2n, \mathbb{C})$, $n \geq 4$, of complex matrices of type

$$\begin{pmatrix} A & B \\ C & -A^t \end{pmatrix}$$

where A , B and C are $n \times n$ matrices such that $B^t = -B$, $C^t = -C$. We denote by (A, B, C) such a matrix. With the notations of section 4 and 5, one has

$$\mathfrak{h} = \left\{ (\text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mid a_i \in \mathbb{C} \right\}$$

$$\lambda_i : (\text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mapsto a_i, \quad i = 1, 2, \dots, n$$

$$\Delta^+ = \{ \lambda_i - \lambda_j \mid 1 \leq i < j \leq n \} \cup \{ \lambda_k + \lambda_\ell \mid 1 \leq k < \ell \leq n \}$$

$$\psi = \lambda_1 + \lambda_2, \quad X_\psi = (0, E_{21} - E_{12}, 0), \quad H_\psi = (E_{11} + E_{22}, 0, 0).$$

Minimal Realizations of Classical Simple Lie Algebras Through Deformations

We identify \mathfrak{g}^* and \mathfrak{g} by the form $\langle X, Y \rangle = (1/2) \text{Tr}(XY)$. \mathcal{O}_{\min} is the orbit of $\xi_0 = X_\psi$ and the elements of \mathcal{O}_{\min} are matrices of \mathfrak{g} with rank 2. Here \mathcal{H} is the Heisenberg algebra generated by

$$\begin{aligned} X_i &= (-E_{i+2,2}, 0, 0), & Y_i &= (0, 0, E_{1i+2} - E_{i+2,1}), & 1 \leq i \leq n-2 \\ X_i &= (E_{i+2,1}, 0, 0), & Y_i &= (0, 0, E_{2i+2} - E_{i+2,2}), & n-1 \leq i \leq 2n-4 \\ Z &= (0, 0, E_{1,2} - E_{2,1}). \end{aligned}$$

We parametrize the orbit as follows:

$$\tilde{X}_i = p_i q_{2n-3}, \quad \tilde{Y}_i = q_i q_{2n-3}, \quad 1 \leq i \leq 2n-4$$

and

$$\tilde{Z} = q_{2n-3}^2, \quad \tilde{H} = -p_{2n-3} q_{2n-3}.$$

From the commutation rules we deduce

$$\tilde{H} = -\sum_{i=1}^{n-2} p_i q_i + \sum_{j=n-1}^{2n-4} p_j q_j \quad \text{if } H = (\text{Diag}(1, -1, 0, \dots, 0), 0, 0)$$

$$\tilde{X}_1 = -\sum_{i=1}^{n-2} p_i q_{i+n-2} \quad \text{if } X_1 = (E_{1,2}, 0, 0)$$

$$\tilde{X}_2 = -\sum_{i=1}^{n-2} p_{i+n-2} q_i \quad \text{if } X_2 = (E_{2,1}, 0, 0).$$

$\pi : \mathbb{C}^{2n} \setminus \{q_{2n-3} = 0\} \rightarrow \tilde{\mathcal{O}}$ is still a twofold covering of an open subset of \mathcal{O}_{\min} and $\pi(p_1, \dots, p_{2n-3}, q_1, \dots, q_{2n-3})$ is the matrix (ξ_{ij}) of \mathfrak{g} with rank 2 with first line

$$\begin{aligned} (\xi_{11}, \tilde{X}_2, p_{n-1} q_{2n-3}, \dots, \\ p_{2n-4} q_{2n-3}, 0, -q_{2n-3}^2, -q_1 q_{2n-3}, \dots, -q_{n-2} q_{2n-3}) \end{aligned}$$

and second line

$$\begin{aligned} (\tilde{X}_1, \xi_{22}, -p_1 q_{2n-3}, \dots, \\ -p_{n-2} q_{2n-3}, q_{2n-3}^2, 0, -q_{n-1} q_{2n-3}, \dots, -q_{2n-4} q_{2n-3}) \end{aligned}$$

where

$$\xi_{11} = \frac{1}{2} \left(- \sum_{i=1}^{n-2} p_i q_i + \sum_{i=n-1}^{2n-4} p_i q_i - p_{2n-3} q_{2n-3} \right)$$

$$\xi_{22} = \frac{1}{2} \left(\sum_{i=1}^{n-2} p_i q_i - \sum_{i=n-1}^{2n-4} p_i q_i - p_{2n-3} q_{2n-3} \right).$$

Let \star_M be the Moyal star product defined on

$$N = \mathbb{C} \left[p_1, \dots, p_{2n-3}, q_1, \dots, q_{2n-3}, \frac{1}{q_{2n-3}} \right] :$$

$$f \star_M g = \sum_{k \geq 0} \nu^k c_k(f, g), \quad f, g \in N.$$

An easy computation shows that \star_M is not covariant.

LEMMA 1. — *Let*

$$T_2 = \left(3n - \frac{15}{2} \right) \frac{1}{q_{2n-3}^2} \frac{\partial^2}{\partial p_{2n-3}^2}.$$

Then $T_2(N) \subset N$. Let $\theta : \mathfrak{g} \rightarrow N$ defined by

$$\theta(X) = T_2(\tilde{X}), \quad X \in \mathfrak{g}.$$

Then, for each X and Y in \mathfrak{g} ,

$$\partial\theta(X, Y) = \theta([X, Y]) - \{\tilde{X}, \theta(Y)\} - \{\theta(X), \tilde{Y}\} = c_3(\tilde{X}, \tilde{Y}).$$

Proof. — It is a direct consequence of the following results:

$$c_3(\xi_{2k+2}, \xi_{n+1k+2}) = -c_3(\xi_{1k+2}, \xi_{n+2k+2}) = \alpha \frac{1}{q_{2n-3}^2}$$

$$c_3(\xi_{2k+2}, \xi_{n+12}) = \alpha \frac{q_k}{q_{2n-3}^3}, \quad c_3(\xi_{n+1k+2}, \xi_{n+12}) = \alpha \frac{p_k}{q_{2n-3}^3}$$

$$c_3(\xi_{1k+2}, \xi_{n+12}) = -\alpha \frac{q_{n-2+k}}{q_{2n-3}^3}, \quad c_3(\xi_{n+2k+2}, \xi_{n+12}) = \alpha \frac{p_{n-2+k}}{q_{2n-3}^3}$$

where

$$\alpha = -\frac{3}{2}(n-2) + \frac{3}{4}$$

and $k = 1, 2, \dots, n-2$. All others $c_3(\tilde{X}, \tilde{Y})$ (for X and Y in a Chevalley basis of \mathfrak{g}) vanish. \square

PROPOSITION 3

1) The mapping $\Phi : X \mapsto \tilde{X} + \nu^2\theta(X)$ is a Lie algebra morphism from \mathfrak{g} into $(N[[\nu]], [\cdot, \cdot]_{\star_M})$ (i.e., Φ is a star minimal realization). If we fix $\nu = 1/2$, the mapping $X \mapsto W(\Phi(X))$ is a minimal realization of \mathfrak{g} .

2) Put $T = \text{id} + \nu^2 T_2$. Then the star product denoted by \star and defined by

$$T(f \star g) = T(f) \star_M T(g), \quad f, g \in N$$

is covariant.

Proof. — Let $r \geq 0$ and X, Y be in \mathfrak{g} , then

$$c_{2r+1}(\theta(X), \theta(Y)) = c_{2r+3}(\theta(X), \tilde{Y}) = c_{2r+5}(\tilde{X}, \tilde{Y}) = 0.$$

Now we deduce 1) from the previous lemma. 2) is a consequence of 1). \square

PROPOSITION 4

1) $H^1(\mathfrak{g}, N)$ is generated by the class of the mapping

$$X \mapsto \frac{1}{q_{2n-3}} \frac{\partial}{\partial p_{2n-3}} \tilde{X}.$$

2) Each star minimal realization is equivalent to the star minimal realization Φ .

Proof. — It is similar to the proof of Proposition 2. \square

7. Lie algebra of type B_n

Here \mathfrak{g} is the Lie algebra $\text{so}(2n+1, \mathbb{C})$, $n \geq 3$, of complex matrices of type

$$\begin{pmatrix} 0 & a & b \\ -b^t & A & B \\ -a_t & C & -A^t \end{pmatrix}$$

where A, B, C are $n \times n$ matrices, a and b are $1 \times n$ matrices and $B^t = -B$, $C^t = -C$. We denote by $(a, b; A, B, C)$ such a matrix. One has,

$$\mathfrak{h} = \left\{ (0, 0; \text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mid a_i \in \mathbb{C} \right\}$$

$$\lambda_i : (0, 0; \text{Diag}(a_1, \dots, a_n), 0, \dots, 0) \mapsto a_i, \quad i = 1, 2, \dots, n$$

$$\Delta^+ = \{ \lambda_i - \lambda_j \mid 1 \leq i < j \leq n \} \cup \{ \lambda_k + \lambda_\ell \mid 1 \leq k < \ell \leq n \}$$

$$\cup \{ \lambda_r \mid 1 \leq r \leq n \}$$

$$\psi = \lambda_1 + \lambda_2, \quad X_\psi = (0, 0; 0, E_{21} - E_{12}, 0), \quad H_\psi = (0, 0; E_{11} + E_{22}, 0, 0).$$

We identify \mathfrak{g}^* and \mathfrak{g} by the form $\langle X, Y \rangle = (1/2) \text{Tr}(XY)$. \mathcal{O}_{\min} is the orbit of $\xi_0 = X_\psi$. Here \mathcal{H} is the Heisenberg algebra generated by

$$\begin{cases} X_i = (0, 0; -E_{i+22}, 0, 0) \\ Y_i = (0, 0; 0, 0, E_{1i+2} - E_{i+21}), \end{cases} \quad 1 \leq i \leq n-2$$

$$\begin{cases} X_i = (0, 0; E_{i+21}, 0, 0) \\ Y_i = (0, 0; 0, 0, E_{2i+2} - E_{i+22}), \end{cases} \quad n-1 \leq i \leq 2n-4$$

$$X_{2n-3} = (0, (0, 1, 0, \dots, 0); 0, 0, 0)$$

$$Y_{2n-3} = (0, (1, 0, \dots, 0), 0, 0, 0)$$

$$Z = (0, 0; 0, 0, E_{12} - E_{21}).$$

Put $\tilde{X}_i = p_i q_{2n-2}$, $\tilde{Y}_i = q_i q_{2n-2}$, $1 \leq i \leq 2n-3$, and $\tilde{Z} = q_{2n-2}^2$. As in Section 6, we find that $\pi : \mathbb{C}^{2n} \setminus \{q_{2n-3} = 0\} \rightarrow \tilde{\mathcal{O}}$ is the 2-covering given by: $\pi(p_1, \dots, p_{2n-3}, q_1, \dots, q_{2n-3})$ is the matrix (ξ_{ij}) of \mathfrak{g} with rank 2 and second line:

$$(q_{2n-3} q_{2n-2}, \xi_{22}, \xi_{23}, p_{n-1} q_{2n-2}, \dots, p_{2n-4} q_{2n-2}, 0, -q_{2n-2}^2, -q_1 q_{2n-2}, \dots, -q_{n-2} q_{2n-2})$$

and third line

$$(p_{2n-3} q_{2n-2}, \xi_{32}, \xi_{33}, -p_1 q_{2n-2}, \dots, -p_{n-2} q_{2n-2}, q_{2n-2}^2, 0, -q_{n-1} q_{2n-2}, \dots, -q_{2n-4} q_{2n-2})$$

where

$$\xi_{22} = \frac{1}{2} \left(- \sum_{i=1}^{n-2} p_i q_i + \sum_{i=n-1}^{2n-4} p_i q_i - p_{2n-3} q_{2n-3} - p_{2n-2} q_{2n-2} \right)$$

$$\xi_{33} = \frac{1}{2} \left(\sum_{i=1}^{n-2} p_i q_i - \sum_{i=n-1}^{2n-4} p_i q_i + p_{2n-3} q_{2n-3} - p_{2n-2} q_{2n-2} \right)$$

$$\xi_{23} = \frac{1}{2} q_{2n-3}^2 - \sum_{i=1}^{n-2} p_{i+n-2} q_i$$

$$\xi_{32} = -\frac{1}{2} p_{2n-3}^2 - \sum_{i=1}^{n-2} p_i q_{i+n-2}.$$

Now we introduce the Moyal star product on the algebra

$$N = \mathbb{C} \left[p_1, \dots, p_{2n-2}, q_1, \dots, q_{2n-2}, \frac{1}{q_{2n-2}} \right]$$

and the operator

$$T_2 = 3(n-2) \frac{1}{q_{2n-2}^2} \frac{\partial^2}{\partial p_{2n-2}^2};$$

we obtain the same types of results of Proposition 3 and Proposition 4. \square

References

- [1] ARNAL (D.), BENAMOR (H) and CAHEN (B.) .— *Algebraic Deformation Program on Minimal Nilpotent Orbit*, Lett. Math. Phys. **30** (1994), pp. 241-250.
- [2] ARNAL (D.) and CORTET (J.-C.) .— *Nilpotent Fourier Transform and Applications*, Lett. Math. Phys. **9** (1985), pp. 25-34.
- [3] ARNAL (D.) and CORTET (J.-C.) .— *Représentations * des groupes exponentiels*, J. of Funct. Anal. **92** (1990), pp. 103-135.
- [4] ARNAL (D.), CORTET (J.-C.) and LUDWIG (J.) .— *Moyal Product and Representations of Solvable Lie Groups*, J. of Funct. Anal. **133** (1995), pp. 402-424.
- [5] BAYEN (F.), FLATO (M.), FRONSDAL (C.), LICHTNEROWICZ (A.) and STERNHEIMER (D.) .— *Deformation theory and Quantization*, Ann. Phys. **110** (1978), pp. 61-151.
- [6] CONZE (N.) .— *Algèbres d'opérateurs différentiels et quotient des algèbres enveloppantes*, Bull. Soc. Math. France **102** (1974), pp. 379-415.

- [7] FRONSDAL (C.) .— *Some ideas about Quantization*, Reports on Math. Phys. **15** (1978), pp. 111-145.
- [8] JOSEPH (A.) .— *Minimal Realizations and Spectrum Generating Algebras*, Comm. Math. Phys. **36** (1974), pp. 325-338.
- [9] JOSEPH (A.) .— *The minimal orbit in a simple Lie algebra and its associated maximal ideal*, Ann. Sci. Ecole Norm. Sup. **9** (1976), pp. 1-30.
- [10] STERNBERG (S.) and WOLF (J.) .— *Hermitian Lie algebras and metaplectic representations*, Trans. Math. Soc. **238** (1978), pp. 1-43.
- [11] WOLF (J.) .— *Representations associated to minimal coadjoint orbits*, in Lecture Notes in Math., Springer-Verlag, New York **676** (1978).
- [12] VARADARAJAN (V. S.) .— *Lie Groups, Lie Algebras and Their Representations*, Springer-Verlag, New York (1984).