On M-Algebras, the Quantisation of Nambu-Mechanics, and Volume Preserving Diffeomorphisms[1]

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Dedicated to K. Hepp and W. Hunziker on the occasion of their 60th birthdays.

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Abstract: M-branes are related to theories on function spaces $\mathcal{A}$ involving M-linear non-commutative maps from $\mathcal{A} \times \cdots \times \mathcal{A}$ to $\mathcal{A}$. While the Lie-symmetry-algebra of volume preserving diffeomorphisms of T^M cannot be deformed when $M > 2$, the arising M-algebras naturally relate to Nambu's generalisation of Hamiltonian mechanics, e.g. by providing a representation of the canonical M-commutation relations, $[J_1, \cdots, J_M] = i\hbar$. Concerning multidimensional integrability, an important generalisation of Lax-pairs is given.

1. Introduction

Generalizing fundamental concepts, such as Lie algebras or Hamiltonian dynamics, may have quite divers merits; it can lead to new, interesting possibilities, – or reassure oneself of our present notions. While the result that volume preserving diffeomorphisms of toroidal M-branes, as a Lie-symmetry algebra, cannot be deformed (if $M > 2$) is of the latter nature – the following ideas appear to be worthwhile persueing:

— Using a $*M$-deformation of the algebra of functions on some M-dimensional manifold for representing the M-linear analogue to Heisenberg's commutation relations that Nambu [1] encountered in multi-Hamiltonian dynamics.

— Generalizing the Jacobi identity for Lie algebras to a (2-bracket) identity involving $2M - 1$ elements of a vectorspace V for which an antisymmetric M-linear map (M-commutator) from $V \times \cdots \times V$ to V is defined (in a dynamical context, an identity involving M, rather than 2, of the M-commutators, may be preferred).

— A potential relevance of M-algebras to the quantisation of space-time.

Perhaps most importantly (on a concrete, practical level), an explicit example is given (the multidimensional diffeomorphism-invariant integrable field theories found in [2]) for the usefulness (envisaged some time ago [3]) of generalizing Lax-pairs to -triples, ...

2. M-algebras from M-branes

A relativistic M-brane moving in D-dimensional space time may be described, in a light-cone gauge, by the VDiffΣ-invariant sector of ([4])

$$H = \frac{1}{2} \int_\Sigma \frac{d^M \varphi}{\rho(\varphi)} (\vec{p}^2 + g) \tag{1}$$

where g is the determinant of the M×M matrix $(g_{rs}) := (\nabla_r x^i \nabla_s x_i)_{r,s=1\cdots M}$, x^i and p_i ($i = 1, \cdots, D - 2 =: d$) are canonically conjugate fields, and ρ is a fixed non-dynamical density on the M-dimensional parameter-manifold Σ ($M = 1$ for strings, $M = 2$ for membranes,...). Generators of VDiffΣ, the group of volume-preserving diffeomorphisms of Σ (resp. the component connected to the identity), are represented by

$$K := \int_\Sigma f^r p_i \partial_r x^i d^M \varphi \tag{2}$$

with $\nabla_r f^r = 0$. g may be written as

$$g = \sum_{i_1 < i_2 < \cdots < i_M} \{x_{i_1}, \cdots, x_{i_M}\}\{x^{i_1}, \cdots, x^{i_M}\}, \tag{3}$$

where the 'Nambu-bracket' $\{\cdots\}$ is defined for functions $f_1, \cdots, f_M$ on Σ as

$$\{f_1, \cdots, f_M\} := \epsilon^{r_1 \cdots r_M} \partial_{r_1} f_1 \cdots \partial_{r_M} f_M. \tag{4}$$

This trivial, but important observation suggests to consider Hamiltonians

$$H_\lambda := \frac{1}{2} Tr\left(\vec{P}^{\,2} \pm \sum_{i_1 < \cdots < i_M} [X_{i_1}, \cdots, X_{i_M}]_\lambda^2\right), \tag{5}$$

resp.

$$H_\lambda = \frac{1}{2} \sum_{i=1}^{d} \beta\,(P_i, P_i) + \frac{1}{2} \sum_{i_1 < \cdots < i_M} \beta\,([X_{i_1}, \cdots, X_{i_M}]_\lambda, [X_{i_1}, \cdots X_{i_M}]_\lambda), \tag{6}$$

where X^i and P_i are elements of (possibly finite dimensional, λ-dependent) vectorspaces V on which antisymmetric M-linear maps $[,\cdots,]_\lambda : V \times \cdots \times V \to V$ are defined, and β a positive definite hermitean form, preferably invariant with respect to some analogue of volume preserving diffeomorphisms (cp. (2)).

With

$$[T_{a_1}, \cdots, T_{a_M}]_\lambda = f^a_{a_1 \cdots a_M}(\lambda)\, T_a \tag{7}$$

and

$$\beta(T_a, T_b) = \delta^a_b \tag{8}$$

for some (possibly λ-dependent) basis $\{T_a\}_{a=1}^{\dim V}$ of V, i.e.

$$f^a_{a_1 \cdots a_M}(\lambda) = \beta(T_a, [T_{a_1}, \cdots, T_{a_M}]_\lambda), \tag{9}$$

(6) reads

$$H_\lambda = \frac{1}{2}\, p^*_{ia} p_{ia} + \frac{1}{2}\, (f^a_{a_1 \cdots a_M}(\lambda))^* f^a_{b_1 \cdots b_M}(\lambda)$$
$$\frac{1}{M!}\, x^*_{i_1 a_1} \cdots x^*_{i_M a_M}\, x_{i_1 b_1} \cdots x_{i_M b_M}\,, \tag{10}$$

while (1) may be written as

$$H = \frac{1}{2}\, p^*_{i\alpha} p_{i\alpha} + \frac{1}{2}\, (g^\alpha_{\alpha_1 \cdots \alpha_M})^* g^\alpha_{\beta_1 \cdots \beta_M}$$
$$\frac{1}{M!}\, x^*_{i_1 \alpha_1} \cdots x_{i_M \beta_M}\,; \tag{11}$$

$$g^\alpha_{\alpha_1 \cdots \alpha_M} := \int_\Sigma Y^*_\alpha \{Y_{\alpha_1}, \cdots, Y_{\alpha_M}\}\, \rho\, d^M \varphi \tag{12}$$

is defined with respect to some orthonormal basis of functions (on Σ) satisfying

$$\int Y^*_\alpha\, Y_\beta\, \rho\, d^M \varphi = \delta^\alpha_\beta$$
$$\alpha, \beta = 1 \cdots \infty \tag{13}$$

(even for real x_i, it is often convenient to take a complex basis).
Obvious questions are:

1) Does there exist a 'natural' sequence of finite dimensional vectorspaces V_n with basis $\{T_a^{(n)}\}$ and antisymmetric maps $F_n : V_n \times \cdots \times V_n \to V_n$ such that for each $(M+1)$-tuple $(a\, a_1 \cdots a_M)$

$$\lim_{n\to\infty} f_{a_1\cdots a_M}^a (\lambda_n) \overset{?}{=} g_{a_1\cdots a_M}^a . \tag{14}$$

2) For which M do there exist finite dimensional analogues of (2), $K(n)$, leaving $(10)_{\lambda_n}$ invariant, such that, as $n \to \infty$, the full invariance under volume-preserving diffeomorphisms is recovered?

3) What about λ-deformations with infinite dimensional V's ?

Let us look at the case of a M-torus, $\Sigma = T^M$:
Choosing

$$Y_{\vec{m}} = e^{i\vec{m}\vec{\varphi}}, \vec{m} = (m_1, \cdots, m_M) \in \mathbb{Z}^M, \rho \equiv 1, \tag{15}$$

one gets

$$g_{\vec{m}_1\cdots\vec{m}_M}^{\vec{m}} = i^M(\vec{m}_1, \cdots, \vec{m}_M)\, \delta_{\vec{m}_1+\cdots+\vec{m}_M}^{\vec{m}} \tag{16}$$

where $(\vec{m}_1, \cdots, \vec{m}_M) \in \mathbb{Z}$ denotes the determinant of the corresponding $M \times M$ Matrix (an element of $GL(M, \mathbb{Z})$).

Consider now the following '$*M$-product' (a deformation of the ordinary commutative product of M functions $f_1, \cdots, f_M$ on Σ):

$$(f_1 \cdots f_M)_* := f_1 \cdots f_M + \sum_{m=1}^{\infty} \frac{(\frac{(-i)^{M+1}\lambda}{M!})^m}{m!} \begin{array}{c} \epsilon^{r_1 r_1' \cdots r_1^{(M)}} \\ \cdots \\ \epsilon^{r_m r_m' \cdots r_m^{(M)}} \end{array} \frac{\partial^m f_i}{\partial\varphi^{r_1} \cdots \partial\varphi_{r_m}} \cdots \frac{\partial^m f_M}{\partial\varphi^{r_1^{(M)}} \cdots \partial\varphi^{r_m^{(M)}}} . \tag{17}$$

One then finds that

$$(Y_{\vec{m}_1} \cdots Y_{\vec{m}_M})_* = \sqrt{\omega}^{-(\vec{m}_1,\cdots,\vec{m}_M)} Y_{\vec{m}_1+\cdots\vec{m}_M}$$
$$\sqrt{\omega} = e^{i\frac{\lambda}{M!}} . \tag{18}$$

Defining

$$[f_1, \cdots, f_M]_* := \sum_{\sigma \in S_M} (\text{sign }\sigma)\, (f_{\sigma 1} \cdots f_{\sigma M})_* \tag{19}$$

to simply be the antisymmetrized $*M$-product, one gets

$$[T_{\vec{m}_1}, \cdots, T_{\vec{m}_M}] = \frac{-i}{2\pi\Lambda} \sin\left(2\pi\Lambda\,(\vec{m}_1, \cdots, \vec{m}_M)\right) T_{\vec{m}_1+\cdots+\vec{m}_M} \tag{20}$$

$$\text{with } \Lambda := \frac{\lambda}{2\pi M!} \quad \text{and} \quad T_{\vec{m}} := \lambda^{-\frac{1}{M-1}} Y_{\vec{m}}.$$

For $M > 1$ arbitrary (but fixed), let V denote the vectorspace (over $\mathbb{C}$) generated by $\{T_{\vec{m}}\}_{\vec{m} \in \mathbb{Z}^M}$, $\mathbb{M}^\Lambda$ denote $(V, *)$ and $\mathbb{A}^\Lambda$ denote $(V, [\cdots]_*)$.

The hermitean form β (cp. (8),(9)),

$$\beta\,(T_{\vec{m}}, T_{\vec{n}}) \;=\; \delta_{\vec{n}}^{\vec{m}}, \quad \beta(c_i\,X_i, d_j\,X_j) \;=\; c_i^*\,d_j\;\beta(X_i, X_j),$$

will have the important property ('invariance') that (for $X_i = x_{i\vec{m}}T_{\vec{m}}$ with $x_{i\vec{m}}^* = x_{i-\vec{m}}$)

$$\beta\,(X, [X_{i_1}, \cdots X_{i_M}]) \;=\; -\,\beta\,(X_{i_r}, [X_{i_1}, \cdots, X_{i_{r-1}}, X, X_{i_{r+1}}, \cdots, X_{i_M}])\,,$$

as

$$\beta\,(T_{\vec{m}}, [T_{\vec{m}_1}, \cdots, T_{\vec{m}_M}]) \;=\; \frac{-i}{2\pi\Lambda}\;\delta_{\vec{m}_1+\cdots+\vec{m}_M}^{\vec{m}}\;\sin\,(2\pi\Lambda(\vec{m}_1, \cdots, \vec{m}_M))\,.$$

For rational $\Lambda = \frac{\widetilde{N}}{N}$ (assuming N and $\widetilde{N} < N$ having no common divisor > 1) both $\mathbb{A}^\Lambda$ and $\mathbb{M}^\Lambda$ may be divided by an ideal of finite codimension, namely (using the periodicity of the structure-constants) the vectorspace I generated by all elements of the form $T_{\vec{m}} - T_{\vec{m}+N \text{ (anything)}}$. One thus arrives at considering (for arbitrary odd N)

$$V^{(N)} \;:=\; \Big\langle T_{\vec{m}} \big|\, m_r = -\frac{N-1}{2}, \cdots, +\frac{N-1}{2} \Big\rangle_{\mathbb{C}} \qquad r = 1 \cdots M \qquad (21)$$

with a $*_M$ product on $V^{(N)}$ defined just as in (18):

$$(T_{\vec{m}_1} \cdots T_{\vec{m}_M})_* \;:=\; \frac{-\,i\,N}{2\pi\widetilde{N}M!}\;\omega^{-\frac{1}{2}\,(\vec{m}_1, \cdots, \vec{m}_M)}\;T_{\vec{m}_1+\cdots+\vec{m}_M \text{ (mod } N)}$$

$$\omega \;=\; e^{4\pi\,i\,\frac{\widetilde{N}}{N}}\,, \qquad\qquad\qquad\qquad\qquad\qquad\qquad (22)$$

and a corresponding alternating product,

$$[T_{\vec{m}_1}, \cdots, T_{\vec{m}_M}]_* \;=\; \frac{-\,i\,N}{2\pi\widetilde{N}}\;\sin\,\Big(2\pi\,\frac{\widetilde{N}}{N}\,(\vec{m}_1, \cdots, \vec{m}_M)\Big)\,T_{\vec{m}_1+\cdots+\vec{m}_M \text{ (mod } N)}$$

$$\vec{m}_r \in (\mathbb{Z}_N)^M\,. \qquad\qquad\qquad\qquad\qquad\qquad\qquad (23)$$

The 'structure constants' of the alternating finite dimensional M-algebras

$$\mathbb{A}_N \;:=\; (V^{(N)}, [,\cdots,]_*),$$

$$f_{\vec{m}_1 \cdots \vec{m}_M}^{(N)\,\vec{m}} \;:=\; \frac{-\,i\,N}{2\pi\widetilde{N}}\;\sin\,\Big(2\pi\,\frac{\widetilde{N}}{N}\,(\vec{m}_1, \cdots, \vec{m}_M)\Big)\cdot\delta_{\vec{m}_1+\cdots+\vec{m}_M \text{ (mod } N)}^{\vec{m}} \qquad (24)$$

satisfy (14) (up to an N and $\mathbb{Z}_N^M$-independent rescaling of the generators, resp. factors of i, which anyway drop out in (10) and (11); $n = N^M$, $f^{(N)} \stackrel{\Lambda}{=} f(\lambda_n)$, $\vec{m} \in \mathbb{Z}_N^M$ $V^{(N)} = V_{n=N^3}$, and $\displaystyle\lim_{N\to\infty} V^{(N)} = V$).

$$H_N \;=\; \frac{1}{2}\,p_{i-\vec{m}}\,p_{i\vec{m}}$$

$$+\;\frac{1}{2}\,\frac{N^2}{4\pi^2\,\widetilde{N}^2}\,\sin\,\Big(2\pi\,\frac{\widetilde{N}}{N}\,(\vec{m}_1 \cdots \vec{m}_M)\Big)\cdot\sin\,\Big(2\pi\,\frac{\widetilde{N}}{N}\,(\vec{n}_1 \cdots \vec{n}_M)\Big)$$

$$\frac{1}{M!}\cdot x_{i_1-\vec{m}_1}\cdots x_{i_M-\vec{m}_M}\,x_{i_1\vec{n}_1}\cdots x_{i_M\vec{n}_M}\,\delta_{\vec{n}_1+\cdots+\vec{n}_M}^{\vec{m}_1+\cdots+\vec{m}_M} \text{ (mod } N) \qquad (25)$$

could therefore be considered as a finite-dimensional analogue of (1).

3. Multidimensional Commutation Relations

Before turning to questions of symmetry, let me discuss in a little more detail the $*M$-algebras $\mathbb{M}^\Lambda$, with defining relations (cp. (18); note the slight change of notation/normalisation)

$$(T_{\vec{m}_1} \cdots T_{\vec{m}_M})_* = \omega^{-\frac{1}{2}(\vec{m}_1, \cdots, \vec{m}_M)} T_{\vec{m}_1 + \cdots + \vec{m}_M} \quad (*) \,,$$

and as vectorspaces generated by basis-elements $T_{\vec{m}}$, $\vec{m} \in S$ (where $S = \mathbb{Z}^M$, $S = (\mathbb{Z}_N)^M$, or any combination thereof – in the M-brane context, depending on whether $\Sigma = T^M$, resp. a fully, or partially, discretized M-torus).

First of all note, that for any M elements, $A_1, \cdots A_M \in V$, any even permutation $\sigma \in S_M$ (the symmetric group in M objects), and any choice of S (even $\mathbb{R}^M$),

$$(A_1 \cdots A_M)_* = (A_{\sigma(1)} \cdots A_{\sigma(M)}) \quad (\text{sign } \sigma = +) \,, \tag{26}$$

and that $E := T_{\vec{0}}$ acts as a 'unity' in the sense that if one of the A_r is equal to $T_{\vec{0}}$, the $*M$-product becomes commutative (i.e. independent of the order of its M entries).

Using E, one may identify $T_{(m=\pm|m|,0,\cdots,0)}$ with the $|m|$-th power of $E_{\pm 1} := T_{(\pm 1,0,\cdots,0)}$,

$$T_{(m,0,\cdots,0)} = ((((E \cdots E E_{\pm 1})_* \cdots E E_{\pm 1})_* \cdots)_* \cdots E E_{\pm 1})_* \,, \tag{27}$$
$$\uparrow$$
$$|m| \text{ brackets}$$

so that one may wonder whether $\mathbb{M}^\Lambda$ can be thought of as being generated by

$$E = T_{\vec{0}}, \; E_{\pm 1} = T_{(\pm 1 \, 0 \cdots 0)}, \cdots, \; E_{\pm M} = T_{(0 \cdots 0 \, \pm 1)} \,.$$

This is indeed the case: Let $\mathbb{F}^M$ be the free (non associative) M-algebra generated by $2M + 1$ elements $E, E_{\pm 1}, \cdots, E_{\pm M}$; define arbitrary powers $(E_r)^m$ of the generating elements as in (27) (from now on $E_{-r}^{|m|} =: E_r^{-|m|}$, a notation that will be justified via (29)), and let

$$E_{\vec{m}} := E_1^{m_1} E_2^{m_2} \cdots E_M^{m_M} \,. \tag{28}$$

Divide $\mathbb{F}^M$ by the ideal generated by elements

$$E_{\vec{m}'} E_{\vec{m}''} \cdots E_{\vec{m}^{(M)}} - \omega^{\gamma(\vec{m}', \vec{m}'', \cdots, \vec{m}^{(M)})} \cdot E_{\vec{m}' + \cdots + \vec{m}^{(M)}} \tag{29}$$

where $\omega = e^{4\pi i \Lambda}$ and

$$2\gamma(\vec{m}', \cdots, \vec{m}^{(M)}) := (m_1 \cdot m_2 \cdot \cdots \cdot m_M) - (\vec{m}', \vec{m}'', \cdots, \vec{m}^{(M)})$$
$$- \sum_{r=1}^{M} \left(\prod_{s=1}^{M} m_s^{(r)} \right) \tag{30}$$
$$(\vec{m} := \vec{m}' + \vec{m}'' + \cdots + \vec{m}^{(M)}) \,.$$

This quotient then is isomorphic to $\mathbb{M}^\Lambda$, as can be seen by defining

$$T_{\vec{m}} := \omega^{\frac{1}{2} m_1 m_2 \cdots m_M} E_1^{m_1} E_2^{m_2} \cdots E_M^{m_M} \,, \tag{31}$$

which (due to (29) being zero in $\mathbb{F}^\Lambda / I$) satisfies (18) (with Y standing for T).

Note that

$$E_2^{m_2}\, E_1^{m_1}\, E_3^{m_3}\, \cdots\, E_M^{m_M} \;=\; \omega^{m_1 m_2 \cdots m_M} \cdot E_1^{m_1}\, E_2^{m_2} \cdots E_M^{m_M}, \tag{32}$$

in particular:

$$E_2\, E_1\, E_3\, \cdots\, E_M \;=\; \omega\, E_1\, E_2\, \cdots\, E_M \tag{33}$$

(while any even permutation does not alter the product, cp. (26)).

In order to get a feeling for (29)/(30) it may be instructive to consider $M = 3$: due to (29),

$$
\begin{aligned}
&(E_1^{n_1}\, E_2^{n_2}\, E_3^{n_3})(E_1^{l_1}\, E_2^{l_2}\, E_3^{l_3})(E_1^{k_1}\, E_2^{k_2}\, E_3^{k_3}) \\
=\ & E_1^{n_1+l_1+k_1}\, E_2^{n_2+l_2+k_2}\, E_3^{n_3+l_3+k_3} \\
& \cdot\, \omega^{n_1 l_3 k_2 + n_2 l_1 k_3 + n_3 l_2 k_1} \\
& \cdot\, \sqrt{\omega}^{\,n_1(l_2 l_3 + k_2 k_3) + n_2(l_1 l_3 + k_1 k_3) + n_3(l_1 l_2 + k_1 k_2)} \\
& \cdot\, \sqrt{\omega}^{\,n_1 n_2(l_3 + k_3) + n_1 n_3(l_2 + k_2) + n_2 n_3(l_1 + k_1)}
\end{aligned}
\tag{34}
$$

The general rule (30) can hence be stated as follows:

Consider all possible triples (resp. M-tuples) containing powers of each of the $E_r (r = 1 \cdots M)$ exactly once. If the 'contraction' picks out exactly one factor from each of the 3 (resp. M) factors in (34) it does not contribute if they are already in the correct order, modulo even permutations (cp. 26), (like $E_1^{n_1}\, E_2^{l_2}\, E_3^{k_3}$, or $E_2^{n_2}\, E_3^{l_3}\, E_2^{k_1}$), while they contribute a factor $\omega^{(\text{product of the } E-\text{powers})}$, when they are not in the correct (modulo even permutation) order (like $E_2^{n_2}\, E_1^{l_1}\, E_3^{k_3}$). Contractions entirely within one of the factors don't contribute, while mixed contractions (involving at least 2, but not all, of the factors in (34)), all contribute a factor $\sqrt{\omega}^{(\text{product of the } E-\text{powers})}$, irrespective of their order.

Due to (32), all 'monomials' are proportional to one of the elements $E_{\vec{m}}$ (cp. (28)) – which therefore form a basis (with the convention $E_{\vec{0}} \equiv E$). Note that $2\pi M!\,\Lambda = \lambda \to 0$ is a 'classical limit' (resp. $\lambda \neq 0$ a 'quantisation' of the classical Nambu-structure) as, formally,

$$[\ln E_1, \ln E_2, \cdots, \ln E_M] \;=\; i\,\lambda\, E . \tag{35}$$

Having obtained this relation, one could of course start with objects $\ln E_r =: J_r$, $[J_1, J_2, \cdots, J_M] = i\,\lambda\, E$, and derive generalized 'Hausdorff-formulae' for products involving the $e^{i m_r J_r}$.

Of course, (35) cannot be true in any M-algebra containing only finite linear combinations of the basis-elements $E_{\vec{m}}$, as $T_{\vec{0}} = E$ never appears on the r.h.s. of (20); this is similar to the fact that the canonical commutation relations of ordinary quantum mechanics, $[q, p] = i\hbar\, \mathbf{1}$, cannot hold for trace-class operators. (35) may be justified by formally

expanding $\ln E_r \;=\; -\sum\limits_{n_r=1}^{\infty} \sum\limits_{k_r=0}^{n_r} \binom{n_r}{k_r} \dfrac{(-)^{k_r}}{n_r}\, E_r^k$, using

$$[E_1^{k_1}, E_2^{k_2}, \cdots, E_M^{k_M}] \;=\; \frac{M!}{2}\,(1 - \omega^{k_1 \cdots k_M})\, E_1^{k_1} \cdots E_M^{k_M}$$

and then resumming recursively, after the first step obtaining

$$\frac{M!}{2} \ln E_1 \cdots \ln E_M - \frac{M!}{2} \sum_{\substack{n_r, k_r \\ r>1}}{}' \cdots \ln(E_1 \omega^{k_2 \cdots k_M}) E_2^{k_2} \cdots E_M^{k_M} = \frac{M!}{2}(\ln \omega) \cdot E , \quad (36)$$

as formally,

$$\sum_{n_r=1}^{\infty} \sum_{k_r=1}^{n_r} \binom{n_r}{k_r} \frac{(-)^{k_r}}{n_r} k_r E_r^k = E_r \cdot \sum_{n'=0}^{\infty} (E - E_r)^{n'} = E .$$

4. Breakdown of Conventional Symmetries

Let us now discuss the question, whether theories like (5) or (6) can have symmetries reminiscent of volume preserving diffeomorphisms; in particular whether the generators (2) may be 'translated' to finite dimensional analogues. * For simplicity, consider again $\Sigma = T^M$.

As $f^r = \partial_s \omega^{rs} = \epsilon^{rsr_1 \cdots r_{M-2}} \partial_s \omega_{r_1 \cdots r_{M-2}}$ for non-constant (divergence-free) vector-fields on T^M, (2) may be written in the form

$$K_{r_1 \cdots r_{M-2}} = \int d^M \varphi \, \omega_{r_1 \cdots r_{M-2}} \{p_i, x^i, \varphi^{r_1}, \cdots, \varphi^{r_{M-2}}\} , \quad (37)$$

resp., in Fourier-components,

$$K_{r_1 \cdots r_{M-2}}^{\vec{l}} = \sum_{\substack{\vec{m}, \vec{n} \\ \in \mathbb{Z}^M}} \delta_{\vec{m}+\vec{n}}^{\vec{l}} \, p_{i\vec{m}} \, x_{i\vec{n}} \, (\vec{m}, \vec{n}, \vec{e}_{r_1}, \cdots, \vec{e}_{r_{M-2}}) \quad (38)$$

(where $\vec{e}_r$ denotes the unit vector in the r-direction).

Suppose the deformed theory was invariant under transformations that are still generated in a conventional way by phase-space functions of the form

$$K^{\vec{l}} = \sum_{\vec{m}, \vec{n} \in S} p_{i\vec{m}} x_{i\vec{n}} \, \delta_{\vec{m}+\vec{n}}^{\vec{l}} \, c_{\vec{m}\vec{n}} . \quad (39)$$

Using $[x_{i\vec{m}}, p_{j\vec{n}}] = \delta_{ij} \delta_{\vec{m}}^{-\vec{n}}$, while leaving open whether $S = \mathbb{Z}^M$ or $S = (\mathbb{Z}_N)^M$ as well as (independently) whether δ is defined mod N, or not, one has

$$[K^{\vec{l}}, \widetilde{K}^{\vec{l}'}] = \sum_{\substack{\vec{m}, \vec{n} \\ \in S}} p_{i\vec{m}} x_{i\vec{n}} \, \delta_{\vec{m}+\vec{n}}^{\vec{l}+\vec{l}'} \, \widetilde{\widetilde{c}}_{\vec{m}\vec{n}}$$

with   (40)

$$\widetilde{\widetilde{c}}_{\vec{m}\vec{n}} = \sum_{\vec{k} \in S} \left(\delta_{\vec{k}}^{\vec{l}-\vec{m}} \, \delta_{-\vec{k}}^{\vec{l}'-\vec{n}} \, c_{\vec{m}\vec{k}} \, \tilde{c}_{-\vec{k}\vec{n}} - \binom{\vec{l} \leftrightarrow \vec{l}'}{c \leftrightarrow \tilde{c}} \right) ,$$

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*For $M = 2$, this question was already considered in [4] and answered positively.

while $\dot{K}^{\vec{l}} = 0$ would require $c_{\vec{m}\vec{n}} = ----c_{\vec{n}\vec{m}}$ and

$$\sin\left(2\pi\Lambda(\vec{a}_1, \cdots, \vec{a}_M)\right) \sin\left(2\pi\Lambda(\vec{a}_1 + \cdots + \vec{a}_M, \vec{a}_2', \cdots, \vec{a}_M')\right)$$
$$\cdot c_{\vec{a}_1 + \cdots \vec{a}_1' + \cdots \vec{a}_M', \vec{a}_1'} \cdot x_{i_1 \vec{a}_1} x_{i_1 \vec{a}_1'} \cdots x_{i_M \vec{a}_M} x_{i_M \vec{a}_M'} = 0 \tag{41}$$

(where for (41) consistency of the δ-functions used in (39) and $(25)_\Lambda$ with the index set S was assumed).

The effect of the $x_{i\vec{m}}$-factors in (41) is to make the product $\sin \cdot \sin \cdot c$, symmetric under any interchange $\vec{a}_r \leftrightarrow \vec{a}_r'$, as well as any simultaneous interchange $\vec{a}_r \leftrightarrow \vec{a}_s$, $\vec{a}_r' \leftrightarrow \vec{a}_s'$. Choosing, e.g., $\vec{a}_r' = \vec{a}_r (r = 1 \cdots M)$, with $\sin(2\pi\Lambda(\vec{a}_1 \cdots \vec{a}_M)) \neq 0$, (41) requires that

$$\sum_{\sigma \in S_M} c_{\vec{a}_{\sigma 1} + 2(\vec{a}_{\sigma 2} + \cdots + \vec{a}_{\sigma M}), \vec{a}_{\sigma 1}} = 0. \tag{42}$$

This condition is insensitive to any alteration of the deformation: replacing the sine-function in (41) (resp. $(25)_\Lambda, \cdots$) by any other function of the determinant will still result in (42) as a necessary condition. Apart from $M = 2$ ($c_{\vec{a}_1 + 2\vec{a}_2, \vec{a}_1} + c_{\vec{a}_2 + 2\vec{a}_1, \vec{a}_2} = 0$ is trivially satisfied by any odd function) (42) is <u>not</u> satisfied by

$$c_{\vec{m}\vec{n}} = \sin(2\pi\Lambda(\vec{m}, \vec{n}, \vec{k}_1, \cdots, \vec{k}_{M-2})), \tag{43}$$

$----$ nor would (40) be a linear combination of the generators (39), for such a $c_{\vec{m}\vec{n}}$; for $M = 3$, e.g., one would obtain

$$\widetilde{\widetilde{c}}_{\vec{m}\vec{n}}(\vec{l}\,\vec{l}'; \vec{k}\,\vec{k}')$$
$$= \sin\left(2\pi\Lambda\left(\vec{l}, \vec{l}', \frac{\vec{k}+\vec{k}'}{2}\right)\right)$$
$$\cdot \sin\left(2\pi\Lambda\left(\left(\vec{m}, \vec{n}, \frac{\vec{k}+\vec{k}'}{2}\right) + \left(\vec{m}-\vec{n}, \frac{\vec{l}-\vec{l}'}{2}, \frac{\vec{k}-\vec{k}'}{2}\right)\right)\right) \tag{44}$$
$$- \sin\left(2\pi\Lambda\left(\vec{l}, \vec{l}', \frac{\vec{k}-\vec{k}'}{2}\right)\right)$$
$$\cdot \sin\left(2\pi\Lambda\left(\vec{m}, \vec{n}, \frac{\vec{k}-\vec{k}'}{2}\right) + \left(\vec{m}-\vec{n}, \frac{\vec{l}-\vec{l}'}{2}, \frac{\vec{k}+\vec{k}'}{2}\right)\right)$$

$----$ which means that the algebra closes only for $\vec{k}' = \vec{k}$ (for $\Lambda = \frac{1}{N}$ this would give N^3 closed Lie algebras, each of dimension N^3; in fact, each consisting of N copies of $gl(N)$). $-$ In any case, if $c_{\vec{m}\vec{n}}$ was a function of $(\vec{m}_1\vec{n}_1\vec{k}_1, \cdots, \vec{k}_{M-2})$, one could let $\vec{a}_2, \vec{a}_3, \cdots \vec{a}_M$ differ only in the ('irrelevant') $\vec{k}_1, \cdots \vec{k}_{M-2}$ directions and obtain

$$f\left(((2M-2)\vec{a}_2, \vec{a}_1, \cdots)\right) + (M-1)f\left((2\vec{a}_1, \vec{a}_2, \cdots)\right) = 0, \tag{45}$$

which eliminates all $c_{\vec{m}\vec{n}}$ that are non-linear functions of the determinant.

Interestingly, $c_{\vec{m}\vec{n}} = (\vec{m}, \vec{n}, \text{something})_{\text{if } M>2}$ is suggested by yet another consideration: replacing $\{p_i, x_i, \varphi^3, \cdots, \varphi^M\}$ (cp. (37); for notational simplicity taking $r_1 = 3, \cdots, r_{M-2} = M$) by

$$[P_i, X_i, \ln E_3, \cdots, \ln E_M], \tag{46}$$

(with $P_i = p_{i\vec{m}}T_{\vec{m}}, X_i = x_{i\vec{n}}T_{\vec{n}}$) formally expanding the logarithms in a power series, using (20), and then (formally) summing again, one obtains something proportional to

$$p_{i\vec{m}} \, x_{i\vec{n}} \, T_{\vec{m}+\vec{n}} \, \cdot \, (m_1 n_2 - m_2 n_1) \, . \tag{47}$$

$$[P_i, X_i, \ln E_3, \cdots, \ln E_M]$$

$$= \; p_{i\vec{m}} \, x_{i\vec{n}} \, (-)^{M-2} \sum_{n_3=1}^{\infty} \sum_{k_3=0}^{n_3} \cdots \sum_{n_M=1}^{\infty} \sum_{k_M=0}^{n_M} \binom{n_3}{k_3} \cdots \binom{n_M}{k_M} \frac{(-)^{k_3+\cdots+k_M}}{n_3 \cdots n_M}$$

$$\cdot \, [T_{\vec{m}}, \; T_{\vec{n}}, \; E_3^{k_3}, \cdots, E_M^{k_M}]$$

$$\sim \; \sum \cdots \sin \left(2\pi \Lambda \left(\vec{m}, \vec{n}, k_3 \, \vec{e}_3, \cdots, k_M \, \vec{e}_M \right) \right) \, \cdot \, T_{\vec{m}+\vec{n}+\vec{k}}$$

$$\sim \; \sum \cdots \left(\sqrt{\omega}^{\,k_3 \cdots k_M \, z} - \sqrt{\omega}^{\,-k_3 \cdots k_M \, z} \right) \, (\sqrt{\omega})^{\Pi_{r=1}^{M}(m_r+n_r+k_r)} \, .$$

$$\cdot \, E_1^{m_1+n_1} \, E_2^{m_2+n_2} \, E_3^{m_3+n_3+k_3} \, \cdots \, E_M^{m_M+n_M+k_M}$$

$$\sim \; {\sum}' \cdots \left(\ln \left(\sqrt{\omega}^{\,k_4 \cdots k_M \, z + \Pi_{r\neq3}(m_r+n_r+k_r)} \, E_3 \right) \right.$$

$$\left. - \ln \left(\sqrt{\omega}^{\,-k_4 \cdots k_M \, z + \Pi_{r\neq3}(\cdots)} \, E_3 \right) \right) \, \cdot \, \sqrt{\omega}^{\,(m_3+n_3)\cdot\Pi_{r\neq3}(\cdots)}$$

$$\cdot \, E_1^{m_1+n_1} \, E_2^{m_2+n_2} \, E_3^{m_3+n_3} \, E_4^{m_4+n_4+k_4} \, \cdots \, E_M^{m_M+n_M+k_M}$$

$$\begin{pmatrix} z \; := \; (\vec{m}, \vec{n}, \vec{e}_3, \cdots, \vec{e}_M) \; = \; m_1 n_2 - m_2 n_1 \\ \vec{k} \; = \; (0, \, 0, \, k_3, \cdots, k_M) \end{pmatrix}$$

$$= \; (\ln \omega) \, p_{i\vec{m}} \, x_{i\vec{n}} \, z \, (\vec{m}, \vec{n}) \, \sqrt{\omega}^{\,\Pi_1^M(m_r+n_r)} \, E_1^{m_1+n_1} \cdots E_M^{m_M+n_M}$$

$$= \; (m_1 n_2 - m_2 n_1) \, p_{i\vec{m}} \, x_{i\vec{n}} \, (\ln \omega) \, \cdot \, T_{\vec{m}+\vec{n}}$$

where (for $r > 3$) $-\sum_{n=1}^{\infty} \sum_{k=0}^{n} \binom{n}{k} \frac{(-)^k}{n} k \, \cdot \, E_r^k \, \cdot \, (\omega^{\cdots})^k \; = \; E$ was used.

However,

$$c_{\vec{m}\vec{n}} \; = \; (\vec{m}, \vec{n}, \text{anything}) \tag{48}$$

does <u>not</u> satisfy (41). Moreover, even if one considers more general deformations of the Hamiltonian, i.e. replacing the sine-function in (41) by an arbitrary odd (power-series) function f of the determinant, the corresponding condition,

$$f \, (\vec{a}_1, \cdots, \vec{a}_M) \, f \, (\vec{a}_1 + \cdots + \vec{a}_M, \; \vec{a}'_2, \cdots, \vec{a}'_M) \, \cdot (\vec{e}, \vec{a}'_1, \cdots) \; = \; 0$$
$$+ (M \, \cdot \, 2^M - 1) \text{ permutations} \, , \tag{49}$$

$\vec{e} = \sum_{r=1}^{M} (\vec{a}_r + \vec{a}'_r)$, can never be satisfied by any non-linear function f – as on can see, e.g., by choosing $\vec{a}'_r = \mu_r \vec{a}_r$. Supposing $f(x) = \alpha x + \beta x^{2n+1} = \cdots$, and denoting $(\vec{a}_1, \cdots, \vec{a}_M)$ by z, $\prod_{r=1}^{M} \mu_r$ by μ, the terms $\mu_1, \alpha \, z \, \beta \, (\mu \, z)^{2n+1}$, e.g., (occurring only twice, with the same sign) could never cancel.

The preceding arguments possibly suffice to prove that, independent of the above dynamical context, the Lie algebra of volume-preserving diffeomorphisms of $T^{M>2}$ does not possess any non-trivial deformations.*

5. Rigidity of Canonical Nambu-Poisson Manifolds

For the multilinear antisymmetric map (4), and $2M-1$ arbitrary functions $f_1, \cdots, f_{2M-1}$, one has (cp. [5]):

$$
\begin{aligned}
& \{\{f_M, f_1, \cdots, f_{M-1}\}, f_{M+1}, \cdots, f_{2M-1}\} \\
& + \{f_M, \{f_{M+1}, f_1, \cdots, f_{M-1}\}, f_{M+2}, \cdots, f_{2M-1}\} \\
& + \cdots + \{f_M, \cdots f_{2M-2}, \{f_{2M-1}, f_1, \cdots, f_{M-1}\}\} \\
& = \{\{f_M, \cdots, f_{2M-1}\}, f_1, \cdots, f_{M-1}\} .
\end{aligned}
\tag{50}
$$

Takhtajan [5], stressing its relevance for time-evolution in Nambu-mechanics [1], named (50) 'Fundamental Identity (FI)', and defined a 'Nambu-Poisson-manifold of order M' to be a manifold X together with a multilinear antisymmetric map $\{\cdots\}$ satisfying (50) and the Leibniz-rule

$$
\{f_1 \tilde{f}_1, f_2, \cdots, f_M\} = f_1\{\tilde{f}_1, f_2, \cdots, f_M\} + \{f_1, \cdots, f_M\} \tilde{f}_1
\tag{51}
$$

for functions $f_r : X \to \mathbb{R}$ (or $\mathbb{C}$).

Without (51), i.e. just demanding (50) for an antisymmetric M linear map: $V \times \cdots \times V \to V$, V some vectorspace, Takhtajan defines a 'Nambu-Lie-gebra' [5], – also called 'Fillipov [6] Lie algebra' [7]). I would like to point out various other identities satisfied by canonical Nambu-Poisson brackets (4), and show that all of them – including (50)! – do <u>not</u> allow deformations (of certain natural type), if $M > 2$.

At least from a non-dynamical point of view, all identities involving Nambu-brackets obtained from antisymmetrizing the product of two determinants formed from $2M$ M-vectors,

$$
(\vec{a}_1 \cdots \vec{a}_M)(\vec{a}_{M+1} \cdots \vec{a}_{2M})
\tag{52}
$$

with respect to $M+1$ of the $\vec{a}_\alpha (\alpha = 1 \cdots 2M)$ should be treated on an equal footing. For $M = 3$, e.g., one has – apart from

$$
\begin{aligned}
& (\vec{a}\,\vec{b}\,\vec{c}_1)(\vec{c}_2\,\vec{c}_3\,\vec{c}_4) - (\vec{a}\,\vec{b}\,\vec{c}_2)(\vec{c}_3\,\vec{c}_4\,\vec{c}_1) \\
& + (\vec{a}\,\vec{b}\,\vec{c}_3)(\vec{c}_4\,\vec{c}_1\,\vec{c}_2) - (\vec{a}\,\vec{b}\,\vec{c}_4)(\vec{c}_1\,\vec{c}_2\,\vec{c}_3) = 0 ,
\end{aligned}
\tag{53}
$$

which gives rise to $(50)_{M=3}$ for functions $f \in T^3$ – also

$$
(a\,\vec{c}_{[1}\,\vec{c}_2)(\vec{c}_3\,\vec{c}_{4]}\,\vec{b}) = 0 ,
\tag{54}
$$

*M. Bordemann has informed me that apparently an even more general statement of this nature has recently been proven in [19].

yielding the following 6-term identity $(FI)_6$ (which can of course also be proven by using just the definition (4), $\{f, g, h\} = \epsilon_{\alpha\beta\gamma} \, \partial_\alpha \, f \, \partial_\beta \, g \, \partial_\gamma \, h$, rather than (54); i.e. not necessarily specifying the manifold X):

$$\{\{f, f_{[1}, f_2\} \, f_3, f_{4]}\} = 0 \tag{55}$$

as well as the 4-term identity $(\widetilde{FI})$,

$$\begin{aligned}
&\{\{f, f_1, f_2\}, g, f_3\} \\
+ \; &\{\{f, f_2, f_3\}, g, f_1\} \\
+ \; &\{\{f, f_3, f_1\}, g, f_2\} \; = \; - \, \{f, g, \{f_1, f_2, f_3\}\}
\end{aligned} \tag{56}$$

- - - - each of which is independent of $(50)_{M=3}$ (while any 2 of the 3 identities yield the $3^{\rm rd}$).

Naively, one would think that (56) should follow from $(50)_3$ alone, as (54) follows from (53) (perhaps one should note that for general M, a theorem concerning vector invariants [8] states, that any (!) vector-bracket identity is an algebraic consequence of

$$(\vec{a}_{[1} \, \vec{a}_2 \, \cdots \, \vec{a}_M) \, (\vec{a}_{M+1]} \, \cdots \, \vec{a}_{2M}) \; = \; 0 \; ;$$

however, in the proof of (56) via vector-bracket identities, one in particular needs (54) for the special case $\vec{a} = \vec{b}$ – which cannot be stated as an identity between functions on X .) Curiously (with respect to a statistical approach to M-branes), vector-bracket identities ('Basis Exchange Properties' [9]) also play an important role in combinatorical geometry.

From an aesthetic point of view, the most natural quadratic identity for (4) is

$$\sum_{\sigma \in S_{2M-1}} (\text{sign } \sigma)\{\{f_{\sigma 1}, \cdots, f_{\sigma M}\} \, f_{\sigma M+1}, \cdots, f_{\sigma 2M-1}\} \; = \; 0 \; . \tag{57}$$

For $M = 3$, e.g., one could see this to be a consequence of $(50)_3$ and (56) by grouping the 10 distinct terms in (57) according to whether $\{f_{\sigma 1}, f_{\sigma 2}, f_{\sigma 3}\}$ contains both f_4 and f_5 (3 terms, 'type A'), only one of them (3 'B-terms' and 3 'C-terms') or none of them (1 term, 'type D'); for the B (resp. C)-terms one can use (56) while (50) for the A-terms, to get $\pm \, \{f_4, f_5, \{f_1 \, f_2 \, f_3\}\}$ for each of the 4 types, and for the B and C-terms with a sign opposite to the one obtained from the D (and A) term(s). (57) (taken without the derivation-requirement) is a beautiful generalisation of Lie-algebras ($M = 2$), and has recently started to attract the attention of mathematicians – mostly under the name of $(M - 1)$-ary Lie algebras [10 - 13]. *

Unfortunately, all identities (50), (55)–(57), can be shown to be rigid, in the following sense: assuming that

$$[T_{\vec{m}_1}, \cdots, T_{\vec{m}_M}]_\lambda \; = \; g_\lambda \, ((\vec{m}_1, \cdots, \vec{m}_M)) \, T_{\vec{m}_1 + \cdots + \vec{m}_M} \tag{58}$$

with $g_\lambda(x)$ a smooth odd function proportional to $x + \lambda^n \, c \, x^n$ as $\lambda \to 0$ $(n > 1)$ any of the above identities will require the constant c to be equal to zero (I have proved this

only for $M = 3$, and in the case of (57) – the a priori most promising case – for general $M > 2$).

Concerning

$$g_\lambda \left((\vec{a}, \vec{b}, \vec{c}_1) \right) \, g_\lambda \left((\vec{a} + \vec{b} + \vec{c}_1, \vec{c}_2, \vec{c}_3) \right)$$
$$+ \quad g_\lambda \left((\vec{a}, \vec{b}, \vec{c}_2) \right) \, g_\lambda \left((\vec{a} + \vec{b} + \vec{c}_2, \vec{c}_3, \vec{c}_1) \right)$$
$$+ \quad g_\lambda \left((\vec{a}, \vec{b}, \vec{c}_3) \right) \, g_\lambda \left((\vec{a} + \vec{b} + \vec{c}_3, \vec{c}_1, \vec{c}_2) \right)$$
$$\overset{!}{=} \quad g_\lambda ((\vec{c}_1, \vec{c}_2, \vec{c}_3)) \, g_\lambda \left((\vec{c}_1 + \vec{c}_2 + \vec{c}_3, \vec{a}, \vec{b}) \right) , \tag{59}$$

i.e. the deformation of $(50)_{M=3}$, one could assume $z := (\vec{c}_1, \vec{c}_2, \vec{c}_3) \neq 0$, $\vec{a} = \sum_1^3 \alpha_r \vec{c}_r$, $\vec{b} = \sum_1^3 \beta_r \vec{c}_r$, such that $g(y) := \bar{g}_\lambda(y) := g_\lambda(zy)$ must satisfy

$$g (\alpha_2 \beta_3 - \alpha_3 \beta_2) \cdot g (1 + \alpha_1 + \beta_1)$$
$$+ \text{ cyclic permutations} \tag{60}$$
$$= g (1) \cdot g (\alpha_2 \beta_3 - \alpha_3 \beta_2 + \text{cycl.})$$

for all α_r, β_r; which is clearly impossible for any nonlinear g of the required form. (e.g., as in next to lowest order in λ the terms $\alpha_1 (\alpha_2 \beta_3)^{n>1}$ appear only once).

Similarly, the deformation of (56) is impossible due to the analogous requirement

$$g (\alpha_3) \, g (\beta_2 - \beta_1 + (\alpha_1 \beta_2 - \alpha_2 \beta_1)) + \text{ cycl.}$$
$$\overset{!}{=} - g (1) \, g ((\alpha_1 \beta_2 - \alpha_2 \beta_1) + \text{cycl.}) . \tag{61}$$

Finally, concerning possible deformations of (57), let $(\vec{a}_1, \cdots, \vec{a}_M) \neq 0$, and

$$\vec{a}_{M+\bar{r}} = \sum_{s=1}^{M} \alpha_s^{(\bar{r})} \, \vec{a}_s \quad (\bar{r} = 1, \cdots, M - 1);$$

then $g \left(1 + \alpha_1^{(1)} + \cdots + \alpha_1^{(M-1)} \right) \cdot g \underbrace{\begin{pmatrix} 1 & & \\ 0 & \vec{\alpha}^{\,(1)} \cdots \vec{\alpha}^{\,(M-1)} \\ \vdots & \\ 0 & \end{pmatrix}}_{=: \, [1]}$,

e.g., contains (in next to lowest order in λ) a term $\alpha_1^{(1)} \cdot \alpha_1^{(2)} \cdot [1]$ (of total degree $(M + 1)$ in the $\alpha_s^{(\bar{r})}$), which cannot appear anywhere else (in the same order in λ), – in contradiction to the assumption that (57) should hold for $[\cdots]_\lambda$ (cp. (58)) replacing the curly bracket (4).

6. A Remark on Generalized Schild Actions

Consider

$$S := - \int d\varphi^0 \, d^M \varphi \, f(G) , \tag{62}$$

where $G := (-)^M \det (G_{\alpha\beta})$, $G_{\alpha\beta} := \frac{\partial x^\mu}{\partial \varphi^\alpha} \frac{\partial x^\nu}{\partial \varphi^\beta} \eta_{\mu\nu}$, $\eta_{\mu\nu} = \mathrm{diag} (1, -1, \cdots, -1)$, $\alpha, \beta = 0, \cdots, M$ and f some smooth monotonic function like G^γ ($\gamma = 1$ resp. $\frac{1}{2}$ corresponding to a generalized Schild-, resp. Nambu-Goto, action for M-branes). Apart from a few subtleties (like $\gamma = 1$ allowing for vanishing G, while $\gamma = \frac{1}{2}$ does not) actions with different f are equivalent, in the sense that the equations of motion,

$$\partial_\alpha \left(f'(G) G \, G^{\alpha\beta} \, \partial_\beta \, x^\mu \right) = 0 \qquad \mu = 0 \cdots D - 1 \tag{63}$$

are easily seen to imply

$$\partial_\alpha \, G = 0 \qquad \alpha = 0, \cdots, M \tag{64}$$

(just multiply (63) by $\partial_\epsilon x_\mu$ and sum) – unless $f(G) = \mathrm{const.} \sqrt{G}$, in which case (62) is fully reparametrisation invariant and a parametrisation may be assumed in which $G = \mathrm{const.}$ (such that (63) becomes proportional to $\partial_\alpha(G^{\alpha\beta} \, \partial_\beta x^\mu)$ also in this case). Due to

$$G = \sum_{\mu_1 < \cdots < \mu_{M+1}} \{x^{\mu_1}, \cdots, x^{\mu_{M+1}}\} \, \{x_{\mu_1}, \cdots, x_{\mu_{M+1}}\} \tag{65}$$

(63) may be written as (cp. [14] for strings, and [15] for membranes, in the case of $\gamma = 1$ resp. $\frac{1}{2}$)

$$\{f'(G)\{x^{\mu_1}, \cdots, x^{\mu_{M+1}}\}, \, x_{\mu_2}, \cdots, x_{\mu_{M+1}}\} = 0 , \tag{66}$$

whose deformed analogue (note the similarity between $G = \mathrm{const.}$ and condition (3.9) of [16])

$$\left[[x^{\mu_1}, \cdots, x^{\mu_{M+1}}], \, x_{\mu_2}, \cdots, x_{\mu_{M+1}}\right] = 0 \tag{67}$$

looks very suggestive when thinking about space-time quantization in M-brane theories.

7. Multidimensional Integrable Systems from M-algebras

Several ideas used in the context of integrable systems are based on bilinear operations. Our problems to extend results about low (especially 1+1) dimensional integrable field theories to higher dimensions may well rest on precisely this fact. Already some time ago, attempts were made to overcome this difficulty by generalizing Lax-pairs to -triples ([3], p. 72) and Hirota's bilinear equations for 'τ-functions' [17] to multilinear equations ([3], p. 107-111).

At that time, good examples were lacking, and – not being an exception to the rule that generalisations involving the number of dimensions (of one sort or an other) are usually hindered by implicitly low dimensional point(s) of view – the proposed generalisation of

Hirota-operators may have still been too naive; while hoping to come back to the question of multidimensional τ-functions in the near future, I would now like to give an example ($M > 3$ will then be obvious) for an equation of the form

$$\dot{\mathcal{L}} = \frac{1}{\rho} \{\mathcal{L}, \mathcal{M}_1, \mathcal{M}_2\} \tag{68}$$

being equivalent to the equations of motion of a compact 3 dimensional manifold $\widehat{\sum} \subset \mathbb{R}^4$ (described by a time-dependent 4-vector $x^i(\varphi^1, \varphi^2, \varphi^3, t)$), moving in such a way that its normal velocity is always equal to the induced volume density $\sqrt{g}$ (on $\widehat{\sum}$) devided by a fixed non-dynamical density $\rho(\varphi)$ ('the' volume density of the parameter manifold):

$$\dot{x}_1 = \frac{1}{\rho} \{x_2, x_3, x_4\}$$

$$\dot{x}_2 = -\frac{1}{\rho} \{x_3, x_4, x_1\}$$

$$\dot{x}_3 = \frac{1}{\rho} \{x_4, x_1, x_2\}$$

$$\dot{x}_4 = -\frac{1}{\rho} \{x_1, x_2, x_3\} . \tag{69}$$

With the curly bracket defined as before (cp. (4)), it will be an immediate consequence of (68) that

$$Q_n := \int_{\Sigma} d^3\varphi \, \rho(\varphi) \, \mathcal{L}^n \tag{70}$$

is time-independent (for any n).

In [2] evolution-equations of the form (69) (in any number of dimensions) were shown to correspond to the diffeomorphism invariant part of an integrable Hamiltonian field theory (as well as to a gradient flow); one way to solve such equations is to note ([18], [2]) that the time at which the hypersurface will pass a point $\vec{x}$ in space will simply be a harmonic function.

In any case, the (a) form of $(\mathcal{L}, \mathcal{M}_1, \mathcal{M}_2)$ that will yield the equivalence of (69) with (68) is:

$$\mathcal{L} = (x_1 + ix_2)\frac{1}{\lambda} + (x_3 + ix_4)\frac{1}{\mu} + \mu(x_3 - ix_4) - \lambda(x_1 - ix_2)$$

$$\mathcal{M}_1 = \frac{\mu}{2}(x_3 - ix_4) - \frac{1}{2\mu}(x_3 + ix_4) \tag{71}$$

$$\mathcal{M}_2 = \frac{\lambda}{2}(x_1 - ix_2) + \frac{1}{2\lambda}(x_1 + ix_2)$$

(involving two spectral parameters, λ and μ). Surely, this observation will have much more elegant formulations, and conclusions.

Acknowledgement

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