Poisson brackets on rational functions and multi-Hamiltonian structure for integrable lattices

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Abstract

We introduce a family of compatible Poisson brackets on the space of rational functions with denominator of a fixed degree and use it to derive a multi-Hamiltonian structure for a family of integrable lattice equations that includes both the standard and the relativistic Toda lattices.

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1

It has been known since Moser’s work on finite non-periodic Toda lattice ([19]) that the space of rational functions plays an important role in solving integrable lattice and constructing action-angle variables. The Moser map that sends the space of $n \times n$ tri-diagonal matrices (the phase space for the Toda lattice) into a space of proper rational functions with a denominator of degree $n$ was later utilized in a more general context (see, e.g. [10], [4], [11]) and generalized in [18] for an arbitrary semisimple Lie algebra to be used, mainly, as a tool for linearization for a class of finite systems of differential-difference equations.

The goal of this paper is to show that the Moser map also serves as an effective tool in establishing a multi-Hamiltonian nature of a class of integrable lattices that includes, in particular, the standard and the relativistic Toda lattices. This class was studied in our recent paper [12]. Our approach is in contrast to those of [8], [9], [22], where the search for compatible Poisson structures was conducted in terms of the matrix entries of the Lax operator. Instead, we introduce explicitly the family of compatible Poisson brackets on the space of rational functions and then pull them back to a phase space of a lattice in question via the Moser map. Note that the linear Poisson structure on the phase space then corresponds to the Atiyah-Hitchin Poisson structure on rational functions [2]. (In the case of the finite non-periodic Toda lattice, this correspondence was first explicitly pointed out in [1].)

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In sect. 2 we review the construction of the family of integrable systems introduced in [12] as restrictions of the full Kostant-Toda flows in \( \mathfrak{sl}(n) \) to elements of a certain family of symplectic leaves. A construction of compatible Poisson structures on rational functions and a consequent description of multi-Hamiltonian structure for lattices of sect. 2 is given in sect. 3. In the last section we give explicit formulae in terms of the corresponding Lax operators for master symmetries that generate these multi-Hamiltonian structure. In the case of the symmetric Toda lattice such master symmetries were implicitly defined via recursive relations in [8].

We conclude this introduction with two natural questions that we would like to address in the future. First, it would be interesting to extend our approach to more general (e.g. generic) symplectic leaves of the full Kostant-Toda flows. Second, we would like to understand how results of this paper can be translated into a geometric language for bi-Hamiltonian systems advocated in [15].

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2

Let us first recall the definition of the Kostant-Toda flows. Denote by \( e_j \) \((j = 0, \ldots, n)\) vectors of the standard basis in \( \mathbb{R}^{n+1} \), by \( E_{ij} \) an elementary matrix \((\delta^\alpha_i \delta^\beta_j)_{\alpha, \beta=0}^n\) and by \( J \) an \((n + 1) \times (n + 1)\) matrix with 1s on the first sub-diagonal and 0s everywhere else. Let \( \mathfrak{b}_+, \mathfrak{n}_+, \mathfrak{b}_-, \mathfrak{n}_- \) be, resp., algebras of upper triangular, strictly upper triangular, lower triangular and strictly lower triangular \((n + 1) \times (n + 1)\) matrices. Denote by \( \mathcal{H} \) the set \( J + \mathfrak{b}_+ \) of upper Hessenberg matrices.

For any matrix \( A \) we write its decomposition into a sum of lower triangular and strictly upper triangular matrices as

\[
A = A_- + A_0 + A_+
\]

and define \( A_{\geq 0} = A_0 + A_+ \), \( A_{\leq 0} = A_0 + A_- \).

The hierarchy of commuting Kostant-Toda flows on \( \mathcal{H} \) is given by the family of Lax equations

\[
\dot{X} = [X, (X^m)_{\leq 0}] \ (m = 1, \ldots, n). \tag{2.1}
\]

Each of the flows defined by (2.1) is Hamiltonian with respect to a linear Poisson structure on \( \mathcal{H} \) obtained as a pull-back of the Kirillov-Kostant structure on \( \mathfrak{b}_+^* \), the dual of \( \mathfrak{b}_- \), if one identifies \( \mathfrak{b}_-^* \) and \( \mathcal{H} \) via the trace form. Then a Poisson bracket of two functions \( f_1, f_2 \) on \( \mathcal{H} \) is

\[
\{f_1, f_2\}(X) = \langle X, [(\nabla f_1(X))_{\leq 0}, (\nabla f_2(X))_{\leq 0}] \rangle, \tag{2.2}
\]

where we denote by \( \langle X, Y \rangle \) the trace form \( \text{Trace}(XY) \) and gradients are computed w.r.t. this form. The \( m \)-th flow of the hierarchy (2.1) is generated by the Hamiltonian

\[
H_{m+1}(X) = \frac{1}{m + 1} \text{Tr}(X^{m+1}) = \frac{1}{m + 1} \sum_{i=0}^{n} \lambda_i^{m+1}, \tag{2.3}
\]

where \( \lambda_i(i = 0, \ldots, n) \) are the eigenvalues of \( X \).

The Weyl function

\[
M(\lambda) = M(\lambda, X) = ((\lambda 1 - X)^{-1} e_0, e_0) = \sum_{j=0}^{\infty} \frac{s_j(X)}{\lambda^{j+1}} \tag{2.4}
\]
is an important tool in the study of the Toda flows (2.1) (see, e.g., [4], [7], [10], [11], [19]). Here  
\( s_j(X) = (X^j e_0, e_0) \).

If \( X \in \mathcal{H}_0 \), where \( \mathcal{H}_0 \subset \mathcal{H} \) consists of elements with simple real spectrum \( \lambda_1 < \ldots < \lambda_n \), one can write (2.4) as

\[
M(\lambda) = \sum_{i=0}^{n} \frac{\rho_i(X)}{\lambda - \lambda_i(X)} \quad \text{and} \quad \sum_{i=0}^{n} \rho_i(X) = 1 .
\]  

(2.5)

The Lax equation (2.1) implies the following evolution for \( \rho_i(X), \lambda_i(X) \)

\[
\dot{\rho}_i(X) = (\lambda_i(X)^m - s_m)\rho_i(X), \quad \dot{\lambda}_i(X) = 0 .
\]  

(2.6)

An identity

\[
s_m = \sum_{j=0}^{n} \lambda_j^m \rho_j(X)
\]  

(2.7)

allows one to write the system (2.6) in a closed form. The solution of (2.6) is given by

\[
\rho_i(X(t)) = e^{\lambda_i^m t} \rho_i(X(0)) \quad \text{and} \quad \sum_{j=0}^{n} e^{\lambda_j^m t} \rho_j(X(0)) = 1 .
\]  

(2.8)

As is well-known, symplectic leaves of the bracket (2.2) are orbits of the coadjoint action of the group \( B_- \) of lower triangular invertible matrices:

\[
\mathcal{D}_X = \{ J + (\text{Ad}_n X)_{\geq 0} : n \in B_- \} .
\]  

(2.9)

In [12] we described a family of integrable lattices associated with orbits \( \mathcal{D}_X \) of a special kind. This family contains both the standard and relativistic Toda lattices. Its members are parameterized by increasing sequences of natural numbers \( I = \{ i_1, \ldots, i_k : 0 < i_1 < \ldots < i_k = n \} \). To each sequence \( I \) there corresponds a 1-parameter family of 2n-dimensional coadjoint orbits

\[
M_I = \mathcal{D}_{X_{I+n+1}} \in \mathcal{H},
\]

where

\[
X_I = e_{0i_1} + \sum_{j=1}^{k-1} e_{ij+1} .
\]  

(2.10)

Two Darboux parametrizations for \( M_I \) were found in [12]. Each of them allows us to lift the first \( (m = 1) \) of the Kostant-Toda flows (2.1) on \( M_I \) to an integrable flow on \( \mathbb{R}^{2n+2} \) equipped with the standard symplectic structure. In one of these parametrizations the Toda Hamiltonian \( H_1(X) \) has a form

\[
\tilde{H}_1(Q, P) = \frac{1}{2} \sum_{i=0}^{n} P_i^2 + \sum_{0 \leq i < n; j \neq i_1, \ldots, i_{k-1}} P_i e^{Q_{i+1} - Q_i} + \sum_{j=1}^{k-1} e^{Q_{i+1} - Q_j} .
\]  

(2.11)

The set \( M'_I \) of elements of the form

\[
X = (J + D)(1 - C_k)^{-1}(1 - C_{k-1})^{-1} \cdots (1 - C_1)^{-1},
\]  

(2.12)
where \( D = \text{diag}(d_0, \ldots, d_n) \)

\[
C_j = \sum_{\alpha=i_{j-1}}^{i_j-1} c_\alpha e_{\alpha,\alpha+1},
\]

is dense in \( M_I \).

Then the first \((m = 1)\) of the Kostant-Toda flows \((2.1)\) on \( M'_I \) is equivalent to the following system

\[
\dot{d}_i = d_i(c_i - c_{i-1}),
\]

\[
\dot{c}_i = c_i(d_{i+1} - d_i + c_{i+1} - c_{i-1}) \quad (i < i < i_{j+1}, j = 0, \ldots, k-1)
\]

\[
\dot{c}_{ij} = c_{ij}(d_{ij+1} - d_{ij} + (1 - \delta_{ij+1,i_{j+1}})c_{ij+1}) \quad (j = 0, \ldots, k-1).
\]

Equations \((2.14)\) can be viewed as particular cases of the constrained KP lattice introduced and discretized in \([23]\). In fact, all the minimal indecomposable invariant submanifolds for the latter system can be obtained this way. To emphasize a connection to Toda flows and the dependence on \( I \) we will denote the lattice \((2.14)\) by \( TL_I \). If \( I = \{n\} \), we recover the relativistic Toda lattice

\[
\dot{c}_i = c_i(d_{i+1} - d_i + c_{i+1} - c_{i-1}), \quad \dot{d}_i = d_i(c_i - c_{i-1}).
\]

If, on the other hand, \( I = \{1, 2, \ldots, n\} \), then \( M_I \) is the set \( \text{Jac} \) of tri-diagonal matrices in \( \mathcal{H} \) with non-zero entries on the super-diagonal and thus, one obtains the standard Toda lattice. In coordinates \( c_i, d_i \) equations of motion form a system

\[
\dot{d}_i = d_i(c_i - c_{i-1}), \quad \dot{c}_i = c_i(d_{i+1} - d_i),
\]

which, after relabeling \( d_i = u_{2i-1}, c_i = u_{2i} \), becomes the Volterra lattice

\[
\dot{u}_i = u_i(u_{i+1} - u_{i-1}).
\]

In \([12]\) we proved the following

**Proposition 2.1** For any \( I \), there exists a unique birational transformation of the form \( X \to Ad_{n(X)}X \) from \( M_I \) to \( \text{Jac} \), that preserves the Weyl function \( M(\lambda, X) \) and, for \( k = 1, \ldots, n \), sends the \( k \)-th Toda flow \((2.4)\) on \( M_I \) into the \( k \)-th Toda flow on \( \text{Jac} \). Here \( n(X) \) is a unipotent upper triangular matrix, whose off-diagonal elements in the first row are all equal to zero.

One of the consequences of Proposition \(2.1\) is that, for any \( I \), on the open dense set in \( M_I \), an element \( X \in M_I \) can be uniquely determined by its Weyl function \( M(\lambda, X) \). (This, of course, is well-known in the case of the tri-diagonal and relativistic Toda lattices, see, e.g., \([19]\), \([4]\), \([7]\), \([17]\).) In the next section, we use this fact to derive the multi-Hamiltonian structure for systems \( TL_I \).

3

Let \( \text{Rat}_{n+1} \) denote a space of rational functions of the form

\[
m(\lambda) = \frac{q(\lambda)}{p(\lambda)} = \sum_{i=0}^{\infty} \frac{h_i}{\lambda^{i+1}},
\]

(3.1)
where $p(\lambda)$ is a monic polynomial of degree $n+1$ and $q(\lambda)$ is a polynomial of degree less than $n+1$. To define a Poisson bracket on $\text{Rat}_{n+1}$, it is sufficient to specify pairwise brackets for $p(\lambda), q(\lambda), p(\mu), q(\mu)$, where $\lambda$ and $\mu$ are arbitrary.

For fixed $p(\lambda), q(\lambda)$ and $k = 0, \ldots, n$, let us denote

$$q^{[k]}(\lambda) = \lambda^k q(\lambda) \pmod{p(\lambda)} \quad (3.2)$$

and define a skew-symmetric bracket $\{ , \}_k$ on coefficients of $p(\lambda), q(\lambda)$ by setting

$$\{p(\lambda), p(\mu)\}_k = \{q(\lambda), q(\mu)\}_k = 0 \quad (3.3)$$

and

$$\{p(\lambda), q(\mu)\}_k = \frac{p(\lambda)q^{[k]}(\mu) - p(\mu)q^{[k]}(\lambda)}{\lambda - \mu}. \quad (3.4)$$

**Proposition 3.1** $\{ , \}_k \ (k = 0, \ldots, n)$ are compatible Poisson structures on $\text{Rat}_{n+1}$.

**Proof.** It is sufficient to check the statement on an open dense subset of $\text{Rat}_{n+1}$ defined by the assumption that $p(\lambda)$ and $q(\lambda)$ are co-prime and all roots $\lambda_0, \ldots \lambda_n$ of $p(\lambda)$ are distinct. On this subset

$$m(\lambda) = \frac{q(\lambda)}{p(\lambda)} = \sum_{i=0}^{n} \frac{r_i}{\lambda - \lambda_i}$$

and the data $\{\lambda_i, q(\lambda_i), i = 0, \ldots, n\}$ determines $p(\lambda)$ and $q(\lambda)$ completely. In particular,

$$r_k = q(\lambda_i) \prod_{j \neq i} \frac{1}{\lambda_i - \lambda_j} = \frac{q(\lambda_i)}{p'(\lambda_i)} \quad (3.5)$$

By (3.3),

$$\{\lambda_i, \lambda_j\}_k = 0 \quad (3.6)$$

Since

$$0 = \{p(\lambda_i), q(\mu)\}_k = p'(\lambda_i)\{\lambda_i, q(\mu)\}_k + \{p(\lambda), q(\mu)\}_k \mid_{\lambda = \lambda_i},$$

one obtains from (3.4)

$$\{\lambda_i, q(\mu)\}_k = \frac{p(\mu)q^{[k]}(\lambda_i)}{p'(\lambda_i)(\lambda_i - \mu)} = \frac{p(\mu)\lambda_i^k q(\lambda_i)}{p'(\lambda_i)(\lambda_i - \mu)} = -\lambda_i^k q(\lambda_i) \prod_{j \neq i} \frac{\mu - \lambda_j}{\lambda_i - \lambda_j}, \quad (3.7)$$

which, together with (3.6), implies

$$\{\lambda_i, q(\lambda_j)\}_k = -\lambda_i^k q(\lambda_i) \delta_{ij}, \quad (3.8)$$

and, consequently,

$$\{q(\lambda_i), q(\lambda_j)\}_k = 0. \quad (3.9)$$
It follows from (3.6), (3.8), (3.9), that in coordinates \( \lambda_i, q_i = q(\lambda_i) \), any linear combination \( \{ , \}_c = \sum_{k=0}^n c_k \{ , \}_k \) has a form

\[
\begin{align*}
\{ \lambda_i, \lambda_j \}_c &= \{ q_i, q_j \}_c = 0 , \\
\{ \lambda_i, q_j \}_c &= -c(\lambda_i)q_i\delta^j_i ,
\end{align*}
\]  

(3.10)

where \( c(\lambda) = \sum_{k=0}^n c_k \lambda^k \). It is easy to see that the bracket defined by (3.10) satisfies the Jacobi identity, with canonical coordinates given by

\[
x_i = \int \frac{d\lambda_i}{c(\lambda_i)} , \quad y_i = \ln q_i \; (i = 0, \ldots , n) .
\]  

(3.11)

Thus, any linear combination of \( \{ , \}_k \) is a Poisson bracket, which finishes the proof. \( \square \)

Remarks. 1. The expression in the right hand side of (3.4) is called a Bezoutian of polynomials \( p(\lambda) \) and \( q[k]\lambda) \). For more information on bezoutians and the role they in the control theory we refer the reader to a survey [14].

2. When \( k = 0 \), brackets (3.3), (3.4) give Atiyah-Hitchin Poisson structure on \( \text{Rat}_{n+1} \) [2].

Poisson structure (3.3), (3.4) can be re-written directly in terms of the elements \( m(\lambda) \in \text{Rat}_{n+1} \) as follows

\[
\{ m(\lambda), m(\mu) \}_k = \left( (\lambda^k m(\lambda))_+ - (\mu^k m(\mu))_+ \right) \frac{m(\lambda) - m(\mu)}{\lambda - \mu} ,
\]  

(3.12)

where, for a rational function \( r(\lambda) \), \( (r(\lambda))_+ \) denotes the polynomial part of its Laurent decomposition and \( (r(\lambda))_- = r(\lambda) - (r(\lambda))_+ \). It follows from (3.12) that, in terms of coefficients \( h_i \) of the Laurent expansion (3.1) of \( m(\lambda) \), \( \{ , \}_k \) has a form

\[
\{ h_i, h_j \}_k = \sum_{\alpha=i}^j h_{k+\alpha} h_{i+j-1-\alpha} \; (i < j)
\]  

(3.13)

Now we can restrict brackets \( \{ , \}_k \) to a subset of \( \text{Rat}_{n+1} \) that contains the image of the map \( M(\lambda, \cdot) : \mathcal{H} \to \text{Rat}_{n+1} \) described by (2.4). This subset, denoted by \( \text{Rat}'_{n+1} \) is the set of all \( M(\lambda) = \frac{q(\lambda)}{p(\lambda)} \in \text{Rat}_{n+1} \) with both polynomials \( q(\lambda) \) and \( p(\lambda) \) monic. To compute a Poisson bracket induced by \( \{ , \}_k \) on \( \text{Rat}'_{n+1} \), we first note that, by (3.4), the bracket between \( h_0 \), the leading coefficient of \( q(\lambda) \), and \( p(\lambda) \) is \( \{ p(\lambda), h_0 \}_k = q[k](\lambda) \). Then, since \( M(\lambda) = \frac{1}{h_0} m(\lambda) \) defines a surjective map from \( \text{Rat}_{n+1} \) to \( \text{Rat}'_{n+1} \), a straightforward computation leads to the following

Proposition 3.2 The family of compatible Poisson structures on \( \text{Rat}'_{n+1} \) is given by

\[
\{ M(\lambda), M(\mu) \}_k = \left( (\lambda^k M(\lambda))_+ - (\mu^k M(\mu))_+ \right) \left( \frac{M(\lambda) - M(\mu)}{\lambda - \mu} \right) + M(\lambda) M(\mu) .
\]  

(3.14)

Any linear combination \( \{ , \}_c = \sum_{k=0}^n c_k \{ , \}_k \) of brackets (3.14) is degenerate. Indeed, it follows from (3.7), that

\[
\{ \lambda_i, h_0 \}_k = -\frac{\lambda^k q_i}{p'(\lambda_i)} .
\]  

(3.15)
Let \( F = \sum_{i=0}^{n} x_i \), where \( x_i \) are defined in (3.11). Then, clearly, \( \{ p(\lambda), F \}_c = 0 \) and

\[
\{ q(\lambda), F \}_c = \sum_{i=0}^{n} q(\lambda_i) \prod_{j \neq i} \frac{\lambda - \lambda_j}{\lambda_i - \lambda_j} - q(\lambda_i) \sum_{i=0}^{n} h_0 q_i p(\lambda_i) \]

But, by (3.5), \( \sum_{i=0}^{n} \frac{q(\lambda_i)}{h_0 q_i p(\lambda_i)} = 1 \) and so \( \{ q(\lambda), F \}_c = 0 \) by the Lagrange interpolation formula. Thus, \( F = \sum_{i=0}^{n} x_i \) is a Casimir for \( \{ , \}_c \) on \( \text{Rat}_{n+1}' \), while canonical coordinates coordinates for this bracket can be easily derived from (3.11):

\[
x_i = \int \frac{d\lambda_i}{c(\lambda_i)}, \quad y_i = \ln \frac{q_i}{q_0} \quad (i = 0, \ldots, n-1). \tag{3.16}
\]

Denote \( \rho_i = \frac{r_i}{h_0} = \frac{q_i}{h_0 p(\lambda_i)} \) and define \( H_j = \frac{1}{2} \sum_{l=0}^{n} \lambda_l^j (j = \pm 1, \pm 2, \ldots) \) and \( H_0 = \sum_{i=0}^{n} \ln \lambda_i \). Then (3.8), (3.13) imply

\[
\{ \rho_i, H_j \}_k = (\lambda_i^{k+j-1} - \sum_{l=0}^{n} \lambda_l^{k+j-1} \rho_l) \rho_i.
\]

Comparing the last equation with (2.6), (2.7), one sees that equations of motion induced on \( \text{Rat}_{n+1}' \) via the map (2.4) by the m-th Toda flow (2.4) coincide with Hamilton equations generated in the Poisson structure \( \{ , \}_k \) by the Hamiltonian \( H_{m+1-k} \). Now, by Proposition 2.1, for any index set \( I, (2.4) \) defines an almost everywhere invertible map from \( M_I \) to \( \text{Rat}_{n+1}' \). Moreover, the bracket (3.14) is polynomial in terms of the coefficients of the Laurent expansion \( M(\lambda, X) = \sum_{j=0}^{\infty} h_j \lambda^{-j-1} = \sum_{l=0}^{\infty} (L^l c_0, e_0) \lambda^{-l-1} \), the well-known determinantal formulae, expressing the entries of the element of \( \text{Jac} \) via \( h_j \) are rational in \( h_j \) (\( \text{[1]} \)), and, by Proposition 2.1, so are formulae expressing matrix entries of elements of \( M_I \) in terms of \( h_j \). Thus each of the brackets in (3.14) uniquely defines a Poisson bracket on \( M_I \) which is rational if written in terms of either matrix entries of elements of \( M_I \) or in terms of the parameters \( c_i, d_i \) defined on \( M_I' \) by (2.12), (2.13). We obtain

**Theorem 3.3** For any \( I \), the restriction of the hierarchy (2.4) to \( M_I \subset \mathcal{H} \) possesses a multi-Hamiltonian structure. Compatible Poisson brackets \( \{ , \}_k \) (\( k = 0, \ldots, n \)) for this structure are obtained as a pull-back of the Poisson brackets (3.14) via the restriction of the map (2.4) to \( M_I \). The m-th flow of the hierarchy (2.4) is generated in the Poisson structure \( \{ , \}_k \) by the Hamiltonian \( H_{m+1-k}(X) \), where

\[
H_j = \begin{cases} \frac{1}{2} \text{Tr}(X^j) & j \neq 0 \\ \ln \det(X) & j = 0 \end{cases} \tag{3.17}
\]

Theorem 3.3 provides a uniform way of constructing a multi-Hamiltonian structure for both standard and relativistic Toda lattices, as well as all lattices \( TL_I \). Furthermore, since the relativistic Toda hierarchy is connected to the Ablowitz-Ladik one (\( \text{[3]} \)) via a birational transformation (cf., e.g. (II), (II)), one can use Theorem 3.3 to construct a multi-Hamiltonian structure for the latter hierarchy too. Note also, that for any \( I \), \( \{ , \}_0 \) is the restriction of the bracket (2.2) to \( M_I \).

We shall now derive a formula that, for fixed \( \lambda \) and \( \mu \), expresses \( \{ M(\lambda, X), M(\mu, X) \}_k \) in terms of \( X \), that agrees with the formula conjectured (and proved for \( k = 0, 1, 2 \)) in (III) for compatible Poisson brackets for the symmetric Toda lattice. First, recall the definition of the \( R \)-matrix associated with the Lax equation (2.7). It is defined by \( R(A) = (A)_{\leq 0} - (A)_{>0} \) (see, e.g. (2)).
\textbf{Proposition 3.4}

\[ \{ M(\lambda, X), M(\mu, X) \}_{k} = \frac{1}{4} \left< X, \left[ R(X^{k} \nabla_{\lambda} + \nabla_{\lambda} X^{k}), \nabla_{\mu} \right] + \left[ \nabla_{\lambda}, R(\nabla_{\lambda} X^{k} + \nabla_{\mu} X^{k}) \right] \right> , \]  

(3.18)

where \( \nabla_{\lambda} = \nabla M(\lambda, X) \).

\textbf{Proof.} Denote \( R_{\lambda} = (\lambda I - X)^{-1} \). It follows from (2.4) that \( \nabla_{\lambda} = \nabla M(\lambda, X) = R_{\lambda} E_{00} R_{\lambda} \). The following identities are easily checked:

\[ \frac{1}{\lambda - \mu} (R_{\lambda} - R_{\mu}) = -R_{\lambda} R_{\mu} , \quad [X, \nabla_{\lambda}] = [R_{\lambda}, E_{00}] . \]  

(3.19)

Note also that \( (\lambda^{k} M(\lambda))_{-} = (X^{k} R_{\lambda} e_{0}, e_{0}) \). Taking (3.19) into an account, one sees that the second factor in the right-hand side of (3.14) is equal to \( (R_{\lambda} e_{0}, e_{0})(R_{\mu} e_{0}, e_{0}) - (R_{\lambda} R_{\mu} e_{0}, e_{0}) = e_{0} R_{\lambda}(E_{00} - 1) R_{\mu} e_{0} \), while the first factor is equal to \( ((X^{k} (R_{\lambda} - R_{\mu}) e_{0}, e_{0}) = e_{0}^{T} X^{k} (R_{\lambda} - R_{\mu}) e_{0} \).

Thus,

\[ \{ M(\lambda, X), M(\mu, X) \}_{k} = Tr \left( X^{k} \nabla_{\lambda} (E_{00} - 1) R_{\mu} e_{0} \right) \]

\[ = Tr \left( X^{k} \nabla_{\lambda} (E_{00} - 1) R_{\mu} e_{0} - E_{00} R_{\lambda} (E_{00} - 1) \nabla_{\mu} X^{k} \right) \]

\[ = Tr \left( X^{k} \nabla_{\lambda} [E_{00}, R_{\mu}] e_{0} - E_{00} [E_{00}, R_{\lambda}] \nabla_{\mu} X^{k} \right) \]

(3.19)

\[ = Tr \left( E_{00} X^{k} \nabla_{\lambda} \left[ \nabla_{\mu}, X \right] - \left[ \nabla_{\lambda}, X \right] \nabla_{\mu} X^{k} E_{00} \right) \]  

(3.20)

Since the Weyl function \( M(\lambda, X) \) is invariant under the adjoint action of a subgroup of \( GL(n + 1) \) that consists of matrices whose off-diagonal entries in the first row and column are zero, one concludes that for any \((n + 1) \times (n + 1)\) matrix \( A \), that satisfies this property, \( Tr ([\nabla_{\lambda}, X] A) = \langle ([\nabla_{\lambda}, X], A) = 0. \) Then (3.20) can be re-written as

\[ \{ M(\lambda, X), M(\mu, X) \}_{k} = \langle (X^{k} \nabla_{\lambda})_{>0}, [\nabla_{\mu}, X] \rangle - \langle [\nabla_{\lambda}, X], (\nabla_{\mu} X^{k})_{\leq 0} \rangle \]

\[ = \langle X, [(X^{k} \nabla_{\lambda})_{>0}, \nabla_{\mu}] - [\nabla_{\lambda}, (\nabla_{\mu} X^{k})_{\leq 0}] \rangle . \]  

(3.21)

Next, since (3.14) defines a skew-symmetric bracket on \( Rat'_{n+1} \) and, hence, \( \{ M(\lambda, X), M(\mu, X) \}_{k} = \frac{1}{2} \{ M(\lambda, X), M(\mu, X) \}_{k} \), (3.21) implies

\[ \{ M(\lambda, X), M(\mu, X) \}_{k} = \frac{1}{2} \langle X, ((X^{k} \nabla_{\lambda})_{>0} - (\nabla_{\lambda} X^{k})_{\leq 0}, \nabla_{\mu}] + [\nabla_{\lambda}, (X^{k} \nabla_{\mu})_{>0} - (\nabla_{\mu} X^{k})_{\leq 0}] \rangle \]

\[ = \frac{1}{2} \langle X, [(X^{k} \nabla_{\lambda} + \nabla_{\lambda} X^{k})_{>0}, \nabla_{\mu}] + [\nabla_{\lambda}, (X^{k} \nabla_{\mu} + \nabla_{\mu} X^{k})_{>0}] - [\nabla_{\lambda} X^{k}, \nabla_{\mu}] - [\nabla_{\lambda}, \nabla_{\mu} X^{k}] \rangle \]

\[ = \frac{1}{2} \langle X, (X^{k} \nabla_{\lambda} + \nabla_{\lambda} X^{k})_{\leq 0}, \nabla_{\mu}] - [\nabla_{\lambda}, (X^{k} \nabla_{\mu} + \nabla_{\mu} X^{k})_{\leq 0}] + [X^{k} \nabla_{\lambda}, \nabla_{\mu}] + [\nabla_{\lambda}, X^{k} \nabla_{\mu}] \rangle \]

Taking the average of the last two lines and observing that, due to the Jacobi identity,

\[ \langle X, [(X^{k}, \nabla_{\lambda}), \nabla_{\mu}] \rangle = \langle X, [\nabla_{\lambda}, (X^{k}, X^{k})] \rangle = 0, \]  

one obtains (3.18). \( \Box \)

4

In \cite{8}, master symmetries were used to establish a multi-Hamiltonian structure of the symmetric finite non-periodic Toda lattice. (For a definition and examples of master symmetries see, e.g., \cite{13}.) Namely, a family of vector fields \( Y_{m}, m \geq 1 \) was constructed, that satisfies the properties, that, in the context of the non-symmetric Toda lattice, can be described as follows. Let \( \mathcal{L}_{Y} \) denote the Lie derivative in the direction of the vector field \( Y, \nu_{m} \) be the Hamiltonian vector field on
where an auxiliary matrix $B_l(X)$ was chosen in such a way, that the right-hand side of (4.1) is tridiagonal (such choice is not unique). For $l > 2$, vector fields $Y_l$ were defined recursively as $Y_l = \frac{1}{l-2}[Y_1, Y_{l-1}]$. Various extensions of the results of [8] can be found in [9].

Using results from the previous section, we shall give explicit formulae for master symmetries (Proposition 4.1) satisfying a condition rank$([X, Z]) = 1$. This class plays an important role in study of classical and quantum solvable models, see, e.g. [24], where it was studied in connection with the Calogero-Moser model, and [16] where it was used to derive a discrete time integrable system for the energies certain solvable quantum models.

First, we need to modify the results of [8, 4] to describe nonisospectral flows on $\text{Jac}$. Recall that for any $X \in \text{Jac}, \lambda \in \mathbb{C}$ there exist uniquely defined vectors $P(\lambda) = (p_i(\lambda))_{i=0}^n$, $\tilde{P}(\lambda) = (\tilde{p}_i(\lambda))_{i=0}^n$, such that $p_0(\lambda) = \tilde{p}_0(\lambda) = 1$ and

$$XP(\lambda) = \lambda P(\lambda) - p_{n+1}(\lambda)e_n, \quad \tilde{P}(\lambda)^T X = \lambda \tilde{P}(\lambda)^T - \tilde{p}_{n+1}(\lambda)e_n^T.$$  \hspace{1cm} (4.2)

Necessarily, $p_i(\lambda), \tilde{p}_i(\lambda)$, $i = 1, \ldots, n + 1$ are polynomials of degree $i$ (moreover, $\tilde{p}_i(\lambda)$ are monic). Furthermore, $p_{n+1}(\lambda)$ is equal to and $\tilde{p}_{n+1}(\lambda)$ is a scalar multiple of the characteristic polynomial of $X$. Consequently,

$$\frac{d}{d\lambda} P(\lambda) = \mathcal{D} P(\lambda), \quad \frac{d}{d\lambda} \tilde{P}(\lambda)^T = \tilde{P}(\lambda)^T \tilde{\mathcal{D}},$$  \hspace{1cm} (4.3)

where $\mathcal{D}$ (resp. $\tilde{\mathcal{D}}$) is a uniquely defined strictly lower (resp. upper) triangular matrix independent of $\lambda$. Then a differentiation of equalities (4.2) w.r.t. $\lambda$ leads to the following relations

$$[X, \mathcal{D}] = 1 + e_n v^T, \quad [X, \tilde{\mathcal{D}}] = -1 + \tilde{v} e_n^T,$$  \hspace{1cm} (4.4)

where $v_r, v_t$ are vectors that depend on $X$.

Remark. It is worth mentioning that pairs $(X, -\mathcal{D})$ and $X, \tilde{\mathcal{D}}$ belong to a class matrix pairs $(X, Z)$ satisfying a condition rank$([X, Z] + 1) = 1$. This class plays an important role in study of classical and quantum solvable models, see, e.g. [24], where it was studied in connection with the Calogero-Moser model, and [16] where it was used to derive a discrete time integrable system for the energies certain solvable quantum models.

For any polynomial $Q(\lambda) = \sum_{k=0}^m Q_k \lambda^k$, consider now a differential equation

$$\dot{X} = Q(X) + \left[ X, (Q(X) \tilde{\mathcal{D}})_{\leq 0} - (\mathcal{D} Q(X))_{> 0} \right],$$  \hspace{1cm} (4.5)

**Proposition 4.1** The vector field defined by (4.3) is tangent to $\text{Jac}$. If $X(t)$ evolves according to (4.3), then the evolution of functions $\rho_i = \rho_i(X(t)), \lambda_i = \lambda_i(X(t)), i = 0, \ldots, n$ and $s_j = s_j(X(t)), j = 0, \ldots$ defined in (4.4), (4.3) is given by equations

$$\dot{\rho}_i = 0, \quad \dot{\lambda}_i = Q(\lambda_i).$$  \hspace{1cm} (4.6)

and

$$\dot{s}_j = j \sum_{k=0}^{m} Q_k s_{k+j-1}$$  \hspace{1cm} (4.7)
Due to the second equality in (4.4). Similarly, if 

\[ A \]

the super-diagonal, then \((4.5)\) follows. By (2.7), \(s_j = \sum_{i=0}^{n} \lambda_i^m \rho_i(X)\). Then it is easily seen, that \((4.6)\) is consistent with \((4.7)\) and therefore is satisfied by \(\rho_i, \lambda_i\) due to the well-known fact that \(\rho_i, \lambda_i\) are determined uniquely by \(s_j(j \geq 0)\).

Next, \((4.8)\) implies

\[ \dot{X}j = jXj^{-1}Q(X) + [Xj, (Q(X)\dot{D})] \leq 0 - (Q(X)\dot{D}) > 0 \]  

(4.8)

Since \(\dot{D}\) and \(\dot{\mathcal{D}}\) are, resp., strictly lower and upper triangular, both \((Q(X)\dot{D}) \leq 0\) and \((Q(X)\dot{D}) > 0\) have zero first row and zero first column. Thus, it follows from (4.8) that \(s_j = (\dot{X}j)e_0, e_0) = j(Xj^{-1}Q(X)e_0, e_0)\) and \((4.7)\) follows. By (2.7), \(s_j = \sum_{i=0}^{n} \lambda_i^m \rho_i(X)\). Then it is easily seen, that \((4.6)\) is consistent with \((4.7)\) and therefore is satisfied by \(\rho_i, \lambda_i\) due to the well-known fact that \(\rho_i, \lambda_i\) are determined uniquely by \(s_j(j \geq 0)\).

Consider now vector fields \(V_l\) \((l = 1, 2, \ldots)\) on \(\text{Rat}_{n+1}\) defined, in coordinates \(\lambda_i, q_i = q(\lambda_i)\), by

\[ V_l = \sum_{i=0}^{n} \lambda_i^{i+1} \frac{\partial}{\partial\lambda_i} \]  

(4.9)

and let, as before, \(H_j = \frac{1}{2} \sum_{i=0}^{n} \lambda_i^j (j = \pm 1, \pm 2, \ldots)\) and \(H_0 = \sum_{i=0}^{n} \ln \lambda_i\) and \(\{ , \}k\) be the Poisson brackets \((3.3), (3.4)\).

**Proposition 4.2** Vector fields \(V_l\) satisfy the following properties:

(i) \(\mathcal{L}_{V_l}H_j = (l + j)H_{l+j}\)

(ii) \(\mathcal{L}_{V_l}\{ , \}k = (k - l - 1)\{ , \}_{k+l}\)

(iii) \(\mathcal{L}_{V_l}h_j = (j + l - n)h_{j+l} - \sum_{\beta=1}^{l}H_{\beta}h_{j+l-\beta}\)

**Proof.** (i) is obvious. To prove (ii), it suffices to use \((3.6), (3.8), (3.8)\) and an identity \((\mathcal{L}_{V}\{ , \})(f, g) = \mathcal{L}_{V}\{( f, g) - \{ f, \mathcal{L}_{V}g\}\}\).

To prove (iii), recall from \((3.1), (3.5)\) that

\[ h_j = \sum_{i=0}^{n} r_i \lambda_i^j = \sum_{i=0}^{n} \frac{q_i}{p'(\lambda_i)} \lambda_i^j \]  

(4.10)

Since

\[ \mathcal{L}_{V_l} \ln p'(\lambda_i) = \sum_{\alpha \neq i} \mathcal{L}_{V_i} \ln(\lambda_i - \lambda_\alpha) = \sum_{\alpha \neq i} \frac{\lambda_i^{i+1} - \lambda_i^{i+1}}{\lambda_i - \lambda_\alpha} \]  

\[ = \sum_{\alpha \neq i} \sum_{\beta=0}^{l} \lambda_i^\beta \lambda_i^{l-\beta} = (n - l)\lambda_i^l + \sum_{\beta=1}^{l} \lambda_i^{l-\beta}H_\beta, \]

one obtains from \((1.5), (4.10)\)

\[ \mathcal{L}_{V_l}h_j = \sum_{i=0}^{n} r_i((j + l - n)\lambda_i^{j+l} - \sum_{\beta=1}^{l} \lambda_i^{j+l-\beta}H_\beta) = (j + l - n)h_{j+l} - \sum_{\beta=1}^{l} H_{\beta}h_{j+l-\beta}. \Box \]

We are now ready to prove the following
Theorem 4.3 Let functions $H_j$ on $Jac$ be defined as in (3.17) and, for $l = 1, 2, \ldots$, let $B_l(X) = (X^{l+1}D)_{\leq 0} - (DX^{l+1})_{> 0} + \sum_{\beta=1}^{l} H_{\beta} (X^{l-\beta})_{\leq 0}$. Then vector fields $Y_l$ on $Jac$ defined by (4.1) satisfy

(i) $\mathcal{L}_{Y_l} H_j = (l + j) H_{l+j}$

(ii) $\mathcal{L}_{Y_l} \{ , \}_{k} = (k - l - 1) \{ , \}_{k+l}$, where $\{ , \}_{k}$ are compatible Poisson brackets on $Jac$ described by Theorem 3.3.

Proof. All we need to show is that evolution equations induced by vector fields $Y_l$ on the Weyl function $M(\lambda)$ defined in (2.4) coincide with evolution equations on $Rat_{n+1}'$ induced by vector fields $\nu_l$ on $Rat_{n+1}$ via the map $m(\lambda) \rightarrow M(\lambda) = \frac{m(\lambda)}{m_0}$. To this end, it suffices to compare equations for Laurent coefficients $s_j$ of $M(\lambda)$. The latter equations do coincide, which drops out immediately from equations (2.6) and Propositions 4.1 and 4.2. $\blacksquare$

Combined with Proposition 2.1, Theorem 4.3 allows us to construct master symmetries for the Toda flows on $M_I$ for any $I$ and gives an alternative description of the multi-Hamiltonian structure for integrable lattices $TL_I$.

References


