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A Remark on the Hankel Determinant Formula for Solutions of the Toda Equation

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Abstract. We consider the Hankel determinant formula of the τ functions of the Toda equation. We present a relationship between the determinant formula and the auxiliary linear problem, which is characterized by a compact formula for the τ functions in the framework of the KP theory. Similar phenomena that have been observed for the Painlevé II and IV equations are recovered. The case of finite lattice is also discussed.

AMS classification scheme numbers: 37K10, 37K30, 34M55, 34M25, 34E05

1. Introduction

The Toda equation[24]

$$\frac{d^2 y_n}{dt^2} = e^{y_{n-1}-y_n} - e^{y_n-y_{n+1}}, \quad (1.1)$$

where $n \in \mathbb{Z}$, is one of the most important integrable systems. It can be expressed in various forms such as

$$\frac{dV_n}{dt} = V_n(I_n - I_{n+1}), \quad \frac{dI_n}{dt} = V_{n-1} - V_n, \quad (1.2)$$

$$\frac{d\alpha_n}{dt} = \alpha_n(\beta_{n+1} - \beta_n), \quad \frac{d\beta_n}{dt} = 2(\alpha_n^2 - \alpha_{n-1}^2), \quad (1.3)$$

where the dependent variables are related to y_n as

$$V_n = e^{y_n - y_{n+1}}, \quad I_n = \frac{dy_n}{dt}, \quad \alpha_n = \frac{1}{2} e^{\frac{y_n - y_{n+1}}{2}}, \quad \beta_n = -\frac{1}{2} \frac{dy_n}{dt}. \quad (1.4)$$

The Toda equation can be reduced to the bilinear equation

$$\tau_n'' \tau_n - (\tau_n')^2 = \tau_{n+1} \tau_{n-1}, \quad (1.5)$$

by the dependent variable transformation

$$y_n = \log \frac{\tau_{n-1}}{\tau_n}, \quad V_n = \frac{\tau_{n+1} \tau_{n-1}}{\tau_n^2}, \quad I_n = \frac{d}{dt} \log \frac{\tau_{n-1}}{\tau_n}. \quad (1.6)$$

In general, the determinant structure of the τ function (dependent variable of bilinear equation) is the characteristic property of integrable systems. For example, the Casorati determinant formula of the N-soliton solution of the Toda equation (see, for example, [25, 4])

$$\tau_n = e^{\frac{t^2}{2}} \det(f_{n+j-1}^{(i)})_{i,j=1,\dots,N}, \quad f_n^{(k)} = p_k^n e^{p_k t + \eta_{k0}} + p_k^{-n} e^{\frac{1}{p_k} t + \xi_{k0}}, \quad (1.7)$$

where p_k , η_{k0} and ξ_{k0} ($k = 1, \dots, N$) are constants, is a direct consequence of the Sato theory; the solution space of soliton equations is the universal Grassman manifold, on which infinite dimensional Lie algebras are acting [9, 15, 25].

If we consider the Toda equation on semi-infinite or finite lattice, the soliton solutions do not exist but another determinantal solution arises. For the semi-infinite case we impose the boundary condition as

$$\tau_{-1} = 0, \quad \tau_0 = 1, \quad V_0 = 0, \quad n \geq 0. \quad (1.8)$$

Then τ_n admits the Hankel determinant formula[13, 5, 6]

$$\tau_n = \det(a_{i+j-2})_{i,j=1,\dots,n}, \quad a_0 = \tau_1, \quad a_i = a'_{i-1}, \quad n \in \mathbb{Z}_{\geq 0}. \quad (1.9)$$

The important feature of this determinant formula is that the lattice site n appears as the determinant size, while for the soliton solutions the determinant size describes the number of solitons. This type of determinant formula is actually a special case of the determinant formula for the infinite lattice[12]. However the meaning of the formula has not been yet fully understood.

The purpose of this article is to establish a characterization of the Hankel determinant formula of the Toda equation; entries of the matrices in the determinant formula are closely related to the solution of auxiliary linear problem. Moreover, this relationship can be described by a compact formula in the framework of the theory of KP hierarchy.

In section 2, we discuss the Hankel determinant formula of the infinite Toda equation and present the relationship between the determinant formula and auxiliary linear problem. In section 3, we apply the results to the Painlevé II equation. We consider the case of finite lattice in section 4.

2. Hankel determinant formula of the solution of the Toda equation

2.1. Determinant formula and auxiliary linear problem

The Hankel determinant formula for τ_n satisfying the infinite Toda equation (1.5) is given by as follows:

Proposition 2.1 [12] *For fixed $k \in \mathbb{Z}$, we have:*

$$\frac{\tau_{k+n}}{\tau_k} = \begin{cases} \det(a_{i+j-2}^{(k)})_{i,j=1,\dots,n} & n > 0, \\ 1 & n = 0, \\ \det(b_{i+j-2}^{(k)})_{i,j=1,\dots,|n|} & n < 0, \end{cases} \quad (2.1)$$

$$\begin{cases} a_i^{(k)} = a_{i-1}^{(k)'} + \frac{\tau_{k-1}}{\tau_k} \sum_{l=0}^{i-2} a_l^{(k)} a_{i-2-l}^{(k)}, & a_0^{(k)} = \frac{\tau_{k+1}}{\tau_k}, \\ b_i^{(k)} = b_{i-1}^{(k)'} + \frac{\tau_{k+1}}{\tau_k} \sum_{l=0}^{i-2} b_l^{(k)} b_{i-2-l}^{(k)}, & b_0^{(k)} = \frac{\tau_{k-1}}{\tau_k}. \end{cases} \quad (2.2)$$

We shall now relate the determinant formula to the auxiliary linear problem of the Toda equation (1.2) given by

$$\begin{cases} V_{n-1}\Psi_{n-1} + I_n\Psi_n + \Psi_{n+1} = \lambda\Psi_n, \\ \frac{d\Psi_n}{dt} = V_{n-1}\Psi_{n-1}, \end{cases} \quad (2.3)$$

or

$$\begin{cases} L_n\Psi_n = \lambda\Psi_n, \\ \frac{d\Psi_n}{dt} = B_n\Psi_n, \end{cases} \quad (2.4)$$

where

$$L_n = V_{n-1}e^{-\partial_n} + I_n + e^{\partial_n}, \quad B_n = V_{n-1}e^{-\partial_n}. \quad (2.5)$$

The adjoint linear problem associated with the linear problem (2.3) is given by

$$\begin{cases} \Psi_{n-1}^* + I_n\Psi_n^* + V_n\Psi_{n+1}^* = \lambda\Psi_n^*, \\ \frac{d\Psi_n^*}{dt} = -V_n\Psi_{n+1}^*, \end{cases} \quad (2.6)$$

or

$$\begin{cases} L_n^*\Psi_n^* = \lambda\Psi_n^*, \\ -\frac{d\Psi_n^*}{dt} = B_n^*\Psi_n^*, \end{cases} \quad (2.7)$$

where

$$L_n^* = V_n e^{\partial_n} + I_n + e^{-\partial_n}, \quad B_n^* = V_n e^{\partial_n}. \quad (2.8)$$

The compatibility condition for each problem

$$\frac{dL_n}{dt} = [B_n, L_n], \quad \frac{dL_n^*}{dt} = [-B_n^*, L_n^*] \quad (2.9)$$

yields the Toda equation (1.2), respectively.

One of our main results is that the entries of the determinants in the Hankel determinant formula arise as the coefficients of asymptotic expansions at $\lambda = \infty$ of

the ratio of solutions of the linear and adjoint linear problems. To state the result more precisely, we define

$$\Xi_k(t, \lambda) = \frac{\Psi_k(t, \lambda)}{\Psi_{k+1}(t, \lambda)}, \quad \Omega_k(t, \lambda) = \frac{\Psi_{k+1}^*(t, \lambda)}{\Psi_k^*(t, \lambda)}. \quad (2.10)$$

Theorem 2.2 (i) *The ratios $\Xi_k(t, \lambda)$ and $\Omega_k(t, \lambda)$ admits two kinds of asymptotic expansions as functions of λ as $\lambda \rightarrow \infty$*

$$\Xi_k^{(-1)}(t, \lambda) = u_{-1}\lambda^{-1} + u_{-2}\lambda^{-2} + \dots, \quad (2.11)$$

$$\Xi_k^{(1)}(t, \lambda) = v_1\lambda + v_0 + v_{-1}\lambda^{-1} + \dots, \quad (2.12)$$

and

$$\Omega_k^{(-1)}(t, \lambda) = u_{-1}\lambda^{-1} + u_{-2}\lambda^{-2} + \dots, \quad (2.13)$$

$$\Omega_k^{(1)}(t, \lambda) = v_1\lambda + v_0 + v_{-1}\lambda^{-1} + \dots, \quad (2.14)$$

respectively.

(ii) *The above asymptotic expansions are related to the Hankel determinants entries $a_i^{(k)}$ and $b_i^{(k)}$ as follows:*

$$\Xi_k^{(-1)}(t, \lambda) = \frac{1}{\lambda} \frac{\tau_k}{\tau_{k-1}} \sum_{i=0}^{\infty} b_i^{(k)} \lambda^{-i}, \quad (2.15)$$

$$\Xi_k^{(1)}(t, \lambda) = \frac{\tau_k^2}{\tau_{k+1}\tau_{k-1}} \left[\lambda - \frac{\left(\frac{\tau_k}{\tau_{k+1}}\right)'}{\frac{\tau_k}{\tau_{k+1}}} - \frac{1}{\lambda} \frac{\tau_k}{\tau_{k+1}} \sum_{i=0}^{\infty} a_i^{(k+1)} (-\lambda)^{-i} \right], \quad (2.16)$$

and

$$\Omega_k^{(-1)}(t, \lambda) = \frac{1}{\lambda} \frac{\tau_k}{\tau_{k+1}} \sum_{i=0}^{\infty} a_i^{(k)} (-\lambda)^{-i}, \quad (2.17)$$

$$\Omega_k^{(1)}(t, \lambda) = \frac{\tau_k^2}{\tau_{k+1}\tau_{k-1}} \left[\lambda - \frac{\left(\frac{\tau_{k-1}}{\tau_k}\right)'}{\frac{\tau_{k-1}}{\tau_k}} - \frac{1}{\lambda} \frac{\tau_k}{\tau_{k-1}} \sum_{i=0}^{\infty} b_i^{(k-1)} \lambda^{-i} \right]. \quad (2.18)$$

(iii) $\Xi_k^{(\pm 1)}$ and $\Omega_k^{(\pm 1)}$ are related as follows:

$$\Omega_k^{(1)}(t, \lambda) \Xi_k^{(-1)}(t, \lambda) = \frac{\tau_k^2}{\tau_{k+1}\tau_{k-1}}, \quad \Omega_k^{(-1)}(t, \lambda) \Xi_k^{(1)}(t, \lambda) = \frac{\tau_k^2}{\tau_{k+1}\tau_{k-1}}. \quad (2.19)$$

Brief sketch of the proof of Theorem 2.2. One can prove Theorem 2.2 by direct calculation. From the linear problem (2.3) and (2.10), we see that $\Xi_k(t, \lambda)$ satisfies the Riccati equation

$$\frac{\partial \Xi_k}{\partial t} = -V_k \Xi_k^2 + (\lambda - I_k) \Xi_k - 1. \quad (2.20)$$

Plugging series expansion $\Xi_k = \lambda^\rho \sum_{i=0}^{\infty} h_i \lambda^{-i}$ into (2.20) and considering the balance of leading terms, we find that ρ must be $\rho = 1, -1$, which proves (2.11) and (2.12). Moreover, it is possible to verify (2.15) and (2.16) by deriving recursion relations of coefficients for each case and comparing them with (2.2). Similarly, from the Riccati equation for Ω

$$\frac{\partial \Omega_k}{\partial t} = V_k \Omega_k^2 + (-\lambda + I_{k+1}) \Omega_k + 1, \quad (2.21)$$

one can prove the statements for Ω . For (iii), putting $X_k = \frac{\tau_k^2}{\tau_{k+1}\tau_{k-1}} \frac{1}{\Xi_k^{(-1)}} = \frac{1}{V_k \Xi_k^{(-1)}}$, plugging this expression into the Riccati equation (2.21) and using (1.2), we find that X_k satisfies (2.20). Since the expansion of $\Xi_k^{(-1)}$ starts from λ^{-1} , the leading order of X_k is λ and thus $X_k = \Omega^{(1)}$. The second equation of (2.19) can be proved in a similar manner. \square

2.2. KP theory

The results in the previous section can be characterized by a compact formula in terms of the language of the KP theory[9, 15, 19].

We introduce infinitely many independent variables $x = (x_1, x_2, x_3, \dots)$, $x_1 = t$, and let $\tau_n(x)$ be the τ function of the one-dimensional Toda lattice hierarchy[25, 9] and the first modified KP hierarchy[9]. Namely, τ_n , $n \in \mathbb{Z}$, satisfy the following bilinear equations

$$D_{x_1} p_{j+1} \left(\frac{1}{2} \tilde{D} \right) \tau_n \cdot \tau_n = p_j \left(\frac{1}{2} \tilde{D} \right) \tau_{n+1} \cdot \tau_{n-1}, \quad j = 0, 1, 2, \dots, \quad (2.22)$$

$$\left[D_{x_1} p_j \left(\frac{1}{2} \tilde{D} \right) - p_{j+1} \left(\frac{1}{2} \tilde{D} \right) + p_{j+1} \left(-\frac{1}{2} \tilde{D} \right) \right] \tau_{n+1} \cdot \tau_n = 0, \quad j = 0, 1, 2, \dots, \quad (2.23)$$

where $p_0(x), p_1(x), \dots$ are the elementary Schur functions

$$\sum_{n=0}^{\infty} p_n(x) \kappa^n = \exp \sum_{i=1}^{\infty} x_i \kappa^i, \quad (2.24)$$

and

$$\tilde{D} = (D_{x_1}, \frac{1}{2} D_{x_2}, \dots, \frac{1}{n} D_{x_n}, \dots), \quad (2.25)$$

D_{x_i} ($i = 1, 2, \dots$) being the Hirota's D -operator. Then we have the following formula:

Proposition 2.3 *For fixed $k \in \mathbb{Z}$, we have*

$$\frac{\tau_{k+n}}{\tau_k} = \begin{cases} \det(a_{i+j-2}^{(k)})_{i,j=1,\dots,n} & n > 0, \\ 1 & n = 0, \\ \det(b_{i+j-2}^{(k)})_{i,j=1,\dots,|n|} & n < 0, \end{cases} \quad (2.26)$$

where

$$a_i^{(k)} = p_i(\tilde{\partial}) \frac{\tau_{k+1}}{\tau_k}, \quad b_i^{(k)} = (-1)^i p_i(-\tilde{\partial}) \frac{\tau_{k-1}}{\tau_k}, \quad (2.27)$$

and

$$\tilde{\partial} = (\partial_{x_1}, \frac{1}{2} \partial_{x_2}, \dots, \frac{1}{n} \partial_{x_n}, \dots). \quad (2.28)$$

Remark 2.4 *It might be interesting to remark here that $a_0^{(k)} = \frac{\tau_{k+1}}{\tau_k}$ and $b_0^{(k)} = \frac{\tau_{k-1}}{\tau_k}$ satisfy the nonlinear Schrödinger hierarchy. In fact, Equations (2.2) and (2.27) with $i = 2$ imply for $a = a_0^{(k)}$ and $b = b_0^{(k)}$*

$$a_{x_2} = a_{x_1 x_1} + 2a^2 b, \quad b_{x_2} = -(b_{x_1 x_1} + 2a^2 b). \quad (2.29)$$

Similarly, for $i = 3$ we have

$$a_{x_3} = a_{x_1 x_1 x_1} + 6aba_{x_1}, \quad b_{x_3} = b_{x_1 x_1 x_1} + 6abb_{x_1}. \quad (2.30)$$

Before proceeding to the proof, we note that the auxiliary linear problem (2.3) and its adjoint problem (2.6) are recovered from the bilinear equations (2.22) and (2.23). In fact, suppose that τ_n depends on a discrete independent variable l and satisfies the discrete modified KP equation

$$D_{x_1} \tau_n(l+1) \cdot \tau_n(l) = -\frac{1}{\lambda} \tau_{n+1}(l+1) \tau_{n-1}(l), \quad (2.31)$$

$$\left(\frac{1}{\lambda} D_{x_1} + 1\right) \tau_{n+1}(l+1) \cdot \tau_n(l) - \tau_n(l+1) \tau_{n+1}(l) = 0, \quad (2.32)$$

then one can show that Equations (2.22) and (2.23) are equivalent to (2.31) and (2.32), respectively, through the Miwa transformation [14, 9]

$$x_n = \frac{l}{n(-\lambda)^n} \quad \text{or} \quad \frac{\partial}{\partial l} = -\frac{1}{\lambda} \frac{\partial}{\partial x_1} + \frac{1}{2\lambda^2} \frac{\partial}{\partial x_2} + \cdots + \frac{1}{j(-\lambda)^j} \frac{\partial}{\partial x_j} + \cdots. \quad (2.33)$$

Putting

$$\Psi_n^* = \lambda^{-n} \frac{\tau_n(l+1)}{\tau_n(l)}, \quad (2.34)$$

$$V_n = \frac{\tau_{n+1}(l) \tau_{n-1}(l)}{\tau_n(l)^2}, \quad I_n = \frac{d}{dt} \log \frac{\tau_{n-1}(l)}{\tau_n(l)}, \quad (2.35)$$

and noticing $t = x_1$, the bilinear equations (2.31) and (2.32) are rewritten as

$$\begin{aligned} \Psi_n^{*'} &= -V_{n+1} \Psi_{n+1}^*, \\ \Psi_n^* + I_{n+1} \Psi_{n+1}^* + V_{n+2} \Psi_{n+2}^* &= \lambda \Psi_{n+1}^*, \end{aligned} \quad (2.36)$$

which are equivalent to the adjoint linear problem (2.6). Similarly, shifting $l \rightarrow l-1$ in (2.31) and (2.32) and putting

$$\Psi_{n+1} = \lambda^n \frac{\tau_n(l-1)}{\tau_n(l)}, \quad (2.37)$$

we obtain

$$\begin{aligned} \Psi_{n+1}' &= V_n \Psi_n, \\ V_n \Psi_n + I_{n+1} \Psi_{n+1} + \Psi_{n+2} &= \lambda \Psi_{n+1}, \end{aligned} \quad (2.38)$$

which is also equivalent to the linear problem (2.3).

Proof of Proposition 2.3. From (2.37), (2.33) and (2.24) we have

$$\begin{aligned} \frac{\Psi_k(t, \lambda)}{\Psi_{k+1}(t, \lambda)} &= \frac{1}{\lambda} \frac{\tau_{k-1}(l-1) \tau_k(l)}{\tau_k(l-1) \tau_{k-1}(l)} = \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k-1}(l)} e^{-\frac{\partial}{\partial t} \frac{\tau_{k-1}(l)}{\tau_k(l)}} \\ &= \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k-1}(l)} e^{-\sum_{j=1}^{\infty} \frac{1}{j(-\lambda)^j} \frac{\partial}{\partial x_j} \frac{\tau_{k-1}(l)}{\tau_k(l)}} = \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k-1}(l)} \sum_{n=0}^{\infty} p_n(-\tilde{\partial}) \frac{\tau_{k-1}(l)}{\tau_k(l)} (-\lambda)^{-n}. \end{aligned}$$

Therefore Equation (2.15) in Theorem 2.2 implies

$$b_n^{(k)} = (-1)^n p_n(-\tilde{\partial}) \frac{\tau_k(l)}{\tau_{k-1}(l)}. \quad (2.39)$$

Similarly we have from (2.34), (2.33) and (2.24)

$$\begin{aligned} \frac{\Psi_{k+1}^*(t, \lambda)}{\Psi_k^*(t, \lambda)} &= \frac{1}{\lambda} \frac{\tau_{k+1}(l+1) \tau_k(l)}{\tau_k(l+1) \tau_{k+1}(l)} = \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k+1}(l)} e^{\frac{\partial}{\partial t} \frac{\tau_{k+1}(l)}{\tau_k(l)}} \\ &= \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k+1}(l)} e^{\sum_{j=1}^{\infty} \frac{1}{j(-\lambda)^j} \frac{\partial}{\partial x_j} \frac{\tau_{k+1}(l)}{\tau_k(l)}} = \frac{1}{\lambda} \frac{\tau_k(l)}{\tau_{k+1}(l)} \sum_{n=0}^{\infty} p_n(\tilde{\partial}) \frac{\tau_{k+1}(l)}{\tau_k(l)} (-\lambda)^{-n}. \end{aligned}$$

Therefore comparing with (2.17) we obtain

$$a_n^{(k)} = p_n(\tilde{\partial}) \frac{\tau_{k+1}(l)}{\tau_k(l)}, \quad (2.40)$$

which proves Proposition 2.3. \square

3. Painlevé equations

3.1. Local Lax pair

Originally the relations between determinant formula of the solutions and auxiliary linear problem have been derived for the Painlevé II and IV equations [10, 11]. In the particular case of the rational solutions of the Painlevé II and IV equations these results give the relation between determinant formula and the Airy function found in [7, 3]. It may be natural to regard those relationships as originating from the Toda equation, since the sequence of τ functions generated by the Bäcklund transformations of Painlevé equations are described by the Toda equation [20, 21, 22, 23, 8, 12]. In this section, we show that the results for the Painlevé II equation can be recovered from the results in the section 2. The key ingredient of the correspondence is the local Lax pair, which is the auxiliary linear problem for Toda equation formulated by a pair of 2×2 matrices[1]:

$$\tilde{L}_n \phi_n = \phi_{n+1}, \quad \tilde{L}_n(t, \lambda) = \begin{pmatrix} -I_n + \lambda & -e^{-y_n} \\ e^{y_n} & 0 \end{pmatrix}, \quad (3.1)$$

$$\frac{d\phi_n}{dt} = \tilde{B}_n \phi_n, \quad \tilde{B}_n(t, \lambda) = \begin{pmatrix} -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \lambda + \begin{pmatrix} 0 & e^{-y_n} \\ -e^{y_{n-1}} & 0 \end{pmatrix}, \quad (3.2)$$

$$\phi_n = \begin{pmatrix} \phi_n^{(1)} \\ \phi_n^{(2)} \end{pmatrix}, \quad y_n = \log \frac{\tau_{n-1}}{\tau_n}. \quad (3.3)$$

Similarly, the adjoint linear problem is given by

$$\tilde{L}_n^* \phi_n^* = \phi_{n-1}^*, \quad \tilde{L}_n^*(t, \lambda) = \begin{pmatrix} -I_n + \lambda & e^{y_n} \\ -e^{-y_n} & 0 \end{pmatrix}, \quad (3.4)$$

$$\frac{d\phi_n^*}{dt} = \tilde{B}_n^* \phi_n^*, \quad \tilde{B}_n^*(t, \lambda) = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & -\frac{1}{2} \end{pmatrix} \lambda + \begin{pmatrix} 0 & e^{y_n} \\ -e^{-y_{n+1}} & 0 \end{pmatrix}, \quad (3.5)$$

$$\phi_n^* = \begin{pmatrix} \phi_n^{*(1)} \\ \phi_n^{*(2)} \end{pmatrix}. \quad (3.6)$$

Compatibility condition for each problem

$$\frac{d\tilde{L}_n}{dt} = \tilde{B}_{n+1} \tilde{L}_n - \tilde{L}_n \tilde{B}_n, \quad \frac{d\tilde{L}_n^*}{dt} = -\tilde{B}_{n-1}^* \tilde{L}_n^* + \tilde{L}_n^* \tilde{B}_n^*, \quad (3.7)$$

gives Toda equation (1.2), respectively. By comparing (3.1) and (3.2) with (2.3), similarly by comparing (3.4) and (3.5) with (2.6), one sees that there is a relationship between the solutions of the linear problems:

$$\phi_n^{(1)} = e^{-\frac{1}{2}\lambda t} \Psi_n, \quad \phi_n^{(2)} = e^{-\frac{1}{2}\lambda t} \frac{\tau_{n-2}}{\tau_{n-1}} \Psi_{n-1}, \quad (3.8)$$

$$\phi_n^{*(1)} = e^{\frac{1}{2}\lambda t} \Psi_n^*, \quad \phi_n^{*(2)} = -e^{\frac{1}{2}\lambda t} \frac{\tau_{n+1}}{\tau_n} \Psi_{n+1}^*. \quad (3.9)$$

3.2. Painlevé II equation

In this section we consider the Painlevé II equation (P_{II})

$$\frac{d^2u}{dt^2} = 2u^3 - 4tu + 4\left(\alpha + \frac{1}{2}\right). \quad (3.10)$$

We denote (3.10) as P_{II}[α] when it is necessary to specify the parameter α explicitly. Suppose that τ_0 and τ_1 satisfy the bilinear equations

$$(D_t^2 - 2t) \tau_1 \cdot \tau_0 = 0, \quad (3.11)$$

$$(D_t^3 - 2tD_t - 4(\alpha + \frac{1}{2})) \tau_1 \cdot \tau_0 = 0, \quad (3.12)$$

then it is easily verified that

$$u = \frac{d}{dt} \log \frac{\tau_1}{\tau_0} \quad (3.13)$$

satisfies P_{II}[α] (3.10). If we generate the sequence τ_n ($n \in \mathbb{Z}$) by the Toda equation

$$\frac{1}{2}D_t^2 \tau_n \cdot \tau_n = \tau_{n+1}\tau_{n-1}, \quad (3.14)$$

then it is shown that τ_n satisfy

$$(D_t^2 - 2t) \tau_{n+1} \cdot \tau_n = 0, \quad (3.15)$$

$$(D_t^3 - 2tD_t - 4(\alpha + \frac{1}{2} + n)) \tau_{n+1} \cdot \tau_n = 0, \quad (3.16)$$

and that

$$u = \frac{d}{dt} \log \frac{\tau_{n+1}}{\tau_n} \quad (3.17)$$

satisfies P_{II}[$\alpha + n$]. In this sense, the Toda equation (3.14) describes the Bäcklund transformation of P_{II} (see, for example, [18]). Therefore one can apply Proposition 2.1 to obtain the determinant formula: for fixed $k \in \mathbb{Z}$ we have

$$\frac{\tau_{k+n}}{\tau_k} = \begin{cases} \det(a_{i+j-2}^{(k)})_{i,j=1,\dots,n} & n > 0, \\ 1 & n = 0, \\ \det(b_{i+j-2}^{(k)})_{i,j=1,\dots,|n|} & n < 0, \end{cases} \quad (3.18)$$

where

$$\begin{cases} a_i^{(k)} = a_{i-1}^{(k)'} + \frac{\tau_{k-1}}{\tau_k} \sum_{l=0}^{i-2} a_l^{(k)} a_{i-2-l}^{(k)}, & a_0^{(k)} = \frac{\tau_{k+1}}{\tau_k}, \\ b_i^{(k)} = b_{i-1}^{(k)'} + \frac{\tau_{k+1}}{\tau_k} \sum_{l=0}^{i-2} b_l^{(k)} b_{i-2-l}^{(k)}, & b_0^{(k)} = \frac{\tau_{k-1}}{\tau_k}. \end{cases} \quad (3.19)$$

Now consider the auxiliary linear problem for P_{II}[α] (3.10)[8]:

$$\begin{aligned} \frac{\partial Y}{\partial \lambda} = AY, \quad A = & \begin{pmatrix} \frac{1}{4} & 0 \\ 0 & -\frac{1}{4} \end{pmatrix} \lambda^2 + \begin{pmatrix} 0 & -\frac{1}{2} \frac{\tau_1}{\tau_0} \\ \frac{1}{2} \frac{\tau_{-1}}{\tau_0} & 0 \end{pmatrix} \lambda \\ & + \begin{pmatrix} -\frac{z+t}{2} & \frac{1}{2} \left(\frac{\tau_1}{\tau_0}\right)' \\ \frac{1}{2} \left(\frac{\tau_{-1}}{\tau_0}\right)' & \frac{z+t}{2} \end{pmatrix}, \end{aligned} \quad (3.20)$$

$$\frac{\partial Y}{\partial t} = BY, \quad B = \begin{pmatrix} -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \lambda + \begin{pmatrix} 0 & \frac{\tau_1}{\tau_0} \\ -\frac{\tau_{-1}}{\tau_0} & 0 \end{pmatrix}, \quad (3.21)$$

$$Y = \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix}, \quad z = -\frac{\tau_1 \tau_{-1}}{\tau_0^2}. \quad (3.22)$$

Comparing (3.21) with (3.2), we immediately find that

$$B = \widetilde{B}_1, \quad Y = \phi_1. \quad (3.23)$$

We note that it is possible to regard (3.20) as the equation defining λ -flow which is consistent with evolution in t . Also, the linear equation (3.1) describes the Bäcklund transformation. Similarly, we have the adjoint problem

$$\begin{aligned} \frac{\partial Y^*}{\partial \lambda} = A^* Y^*, \quad A^* = & \begin{pmatrix} \frac{1}{4} & 0 \\ 0 & -\frac{1}{4} \end{pmatrix} \lambda^2 + \begin{pmatrix} 0 & \frac{1}{2} \frac{\tau_{-1}}{\tau_0} \\ -\frac{1}{2} \frac{\tau_1}{\tau_0} & 0 \end{pmatrix} \lambda \\ & + \begin{pmatrix} -\frac{z+t}{2} & \frac{1}{2} \left(\frac{\tau_{-1}}{\tau_0} \right)' \\ \frac{1}{2} \left(\frac{\tau_1}{\tau_0} \right)' & \frac{z+t}{2} \end{pmatrix}, \end{aligned} \quad (3.24)$$

$$\frac{\partial Y^*}{\partial t} = B^* Y^*, \quad B^* = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & -\frac{1}{2} \end{pmatrix} \lambda + \begin{pmatrix} 0 & \frac{\tau_{-1}}{\tau_0} \\ -\frac{\tau_1}{\tau_0} & 0 \end{pmatrix}, \quad (3.25)$$

$$Y^* = \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix}, \quad z = -\frac{\tau_1 \tau_{-1}}{\tau_0^2}, \quad (3.26)$$

where we have a correspondence

$$B^* = \widetilde{B}_0^*, \quad Y^* = \phi_1^*. \quad (3.27)$$

Therefore, if we apply Theorem 2.2 noticing (3.8) and (3.9), we have the following:

Proposition 3.1 *We put*

$$\Lambda(t, \lambda) = \frac{Y_2}{Y_1}, \quad \Pi(t, \lambda) = \frac{Y_2^*}{Y_1^*}. \quad (3.28)$$

- (i) *The ratios Λ and Π admit two kinds of asymptotic expansions as functions of λ as $\lambda \rightarrow \infty$*

$$\Lambda^{(-1)}(t, \lambda) = u_{-1} \lambda^{-1} + u_{-2} \lambda^{-2} + \dots, \quad (3.29)$$

$$\Lambda^{(1)}(t, \lambda) = v_1 \lambda + v_0 + v_{-1} \lambda^{-1} + \dots, \quad (3.30)$$

and

$$\Pi^{(-1)}(t, \lambda) = u_{-1} \lambda^{-1} + u_{-2} \lambda^{-2} + \dots, \quad (3.31)$$

$$\Pi^{(1)}(t, \lambda) = v_1 \lambda + v_0 + v_{-1} \lambda^{-1} + \dots, \quad (3.32)$$

respectively.

- (ii) *The above asymptotic expansions are related to the Hankel determinants entries $a_i^{(k)}$ and $b_i^{(k)}$ as follows:*

$$\Lambda^{(-1)}(t, \lambda) = \frac{1}{\lambda} \sum_{i=0}^{\infty} b_i^{(0)} \lambda^{-i}, \quad (3.33)$$

$$\Lambda^{(1)}(t, \lambda) = \frac{\tau_0}{\tau_1} \left[\lambda - \frac{\left(\frac{\tau_0}{\tau_1} \right)'}{\frac{\tau_0}{\tau_1}} - \frac{1}{\lambda} \frac{\tau_0}{\tau_1} \sum_{i=0}^{\infty} a_i^{(1)} (-\lambda)^{-i} \right], \quad (3.34)$$

and

$$\Pi^{(-1)}(t, \lambda) = \frac{1}{(-\lambda)} \sum_{i=0}^{\infty} a_i^{(0)} (-\lambda)^{-i}, \quad (3.35)$$

$$\Pi^{(1)}(t, \lambda) = -\frac{\tau_0}{\tau_{-1}} \left[\lambda - \frac{\left(\frac{\tau_{-1}}{\tau_0}\right)'}{\frac{\tau_{-1}}{\tau_0}} - \frac{1}{\lambda} \frac{\tau_0}{\tau_{-1}} \sum_{i=0}^{\infty} b_i^{(-1)} \lambda^{-i} \right]. \quad (3.36)$$

(iii) $\Lambda^{(\pm 1)}$ and $\Pi^{(\pm 1)}$ are related as follows:

$$\Pi^{(1)}(t, \lambda) \Lambda^{(-1)}(t, \lambda) = 1, \quad \Pi^{(-1)}(t, \lambda) \Lambda^{(1)}(t, \lambda) = 1. \quad (3.37)$$

Proposition 3.1 is equivalent to the results presented in [7, 10]. In other words, the relations between determinant formula for the solution of P_{II} and auxiliary linear problems originate from the structure of the Toda equation. We also note that one can recover the results for the Painlevé IV equation[3, 11] in similar manner.

4. Toda equation on finite lattice

4.1. Determinant formula

Let us consider the Toda equation on the finite lattice. Namely, we impose the boundary condition

$$\begin{aligned} V_0 &= 0, & V_N &= 0, \\ y_0 &= -\infty, & y_{N+1} &= \infty, \\ \alpha_0 &= 0, & \alpha_N &= 0, \end{aligned} \quad (4.1)$$

on the Toda equation (1.1), (1.2) and (1.3), respectively. In order to realize this condition on the level of the τ function, we proceed as follows: in the bilinear equation (1.5), imposing the boundary condition on the left edge of lattice

$$\tau_{-1} = 0, \quad \tau_0 \neq 0, \quad (4.2)$$

it immediately follows $\tau_{-2} = 0$ and one can restrict the Toda equation on the semi-infinite lattice $n \geq 0$. In this case, the determinant formula reduces to

$$\frac{\tau_k}{\tau_0} = \det(a_{i+j-2}^{(0)})_{i,j=1,\dots,k} \quad (n \geq 1), \quad a_{i+1}^{(0)} = a_i^{(0)'}, \quad a_0^{(0)} = \frac{\tau_1}{\tau_0}, \quad (4.3)$$

which is equivalent to (1.9). Moreover, imposing the boundary condition on the right edge of lattice

$$\tau_N \neq 0, \quad \tau_{N+1} = 0, \quad (4.4)$$

then we have the finite Toda equation

$$\tau_n'' \tau_n - (\tau_n')^2 = \tau_{n+1} \tau_{n-1}, \quad n = 0, \dots, N, \quad \tau_{-1} = \tau_{N+1} = 0. \quad (4.5)$$

It is easily verified that the boundary condition (4.4) is satisfied by putting

$$a_0^{(0)} = \sum_{i=1}^N c_i e^{\mu_i t}, \quad (4.6)$$

where c_i and μ_i ($i = 1, \dots, N$) are arbitrary constants.

It is sometimes convenient to consider the finite Toda equation in the form of (1.3). One reason for this is that the auxiliary linear problem associated with (1.3)

$$\alpha_{n-1} \Phi_{n-1} + \beta_n \Phi_n + \alpha_n \Phi_{n+1} = \mu \Phi_n, \quad \frac{d\Phi_n}{dt} = -\alpha_{n-1} \Phi_{n-1} + \alpha_n \Phi_{n+1}, \quad (4.7)$$

or

$$L\Phi = \mu\Phi, \quad \frac{d\Phi}{dt} = B\Phi, \quad \Phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \vdots \\ \Phi_N \end{pmatrix}, \quad (4.8)$$

$$L = \begin{pmatrix} \beta_1 & \alpha_1 & & & & \\ \alpha_1 & \beta_2 & \alpha_2 & & & \\ & \ddots & \ddots & \ddots & & \\ & & \alpha_{N-2} & \beta_{N-1} & \alpha_N & \\ & & 0 & \alpha_{N-1} & \beta_N & \end{pmatrix}, \quad B = \begin{pmatrix} 0 & \alpha_1 & & & & \\ -\alpha_1 & 0 & \alpha_2 & & & \\ & \ddots & \ddots & \ddots & & \\ & & -\alpha_{n-2} & 0 & \alpha_N & \\ & & 0 & -\alpha_{N-1} & 0 & \end{pmatrix}, \quad (4.9)$$

is self-adjoint[2]. The solutions of the linear problem (2.3) and adjoint linear problem (2.6) are related to Φ_n as

$$\Psi_n = e^{-\mu t} (-1)^n e^{-\frac{y_n}{2}} \Phi_n, \quad \Psi_n^* = e^{\mu t} (-1)^n e^{\frac{y_n}{2}} \Phi_n, \quad \mu = -\frac{1}{2}\lambda, \quad (4.10)$$

respectively.

Remark 4.1 *The relationship between entries of determinants and the solutions of linear problems are given by applying Theorem 2.2 as*

$$\Omega_0^{(-1)}(t, \lambda) = \left[\frac{\Psi_1^*(t, \lambda)}{\Psi_0^*(t, \lambda)} \right]^{(-1)} = \frac{1}{\lambda} \frac{1}{a_0^{(0)}} \sum_{i=0}^{\infty} a_i^{(0)} (-\lambda)^{-i}. \quad (4.11)$$

However it is not possible to express (4.11) in terms of the solutions of the linear problem (4.7) Φ_n by using the correspondence (4.10), since Φ_0 is not defined for the finite lattice.

4.2. Results of Moser and Nakamura

Moser [16] considered (N, N) entry of the resolvent of matrix L :

$$f(\mu) = (\mu I - L)_{NN}^{-1} = \frac{\Delta_{N-1}}{\Delta_N}, \quad (4.12)$$

where Δ_n is given by

$$\Delta_n = \begin{vmatrix} \mu - \beta_1 & -\alpha_1 & & & & \\ -\alpha_1 & \mu - \beta_2 & -\alpha_2 & & & \\ & \ddots & \ddots & \ddots & & \\ & & -\alpha_{n-2} & \mu - \beta_{n-1} & -\alpha_{n-1} & \\ & & 0 & -\alpha_{n-1} & \mu - \beta_n & \end{vmatrix}. \quad (4.13)$$

We note that $f(\mu)$ is a rational function in μ , since Δ_n is the n -th degree polynomial in μ . By investigating analytic properties of $f(\mu)$, Moser derived the action-angle variables of the finite Toda equation to establish the complete integrability. Nakamura [17] further investigated the expansion of $f(\mu)$ around $\mu = \infty$ to obtain

$$f(\mu) = \frac{\Delta_{N-1}}{\Delta_N} = \frac{1}{\mu} \frac{1}{g_0} \sum_{i=0}^{\infty} g_i (-2\mu)^{-i}, \quad g'_i = g_{i+1}, \quad (4.14)$$

and claimed that g_i are the entries of the determinant formula (4.3), which is quite similar to our result. Let us discuss this result from our point of view.

By expanding the determinant in (4.13) with respect to n -th row, we have the recurrence relation of Δ_n

$$\Delta_n = (\mu - \beta_n)\Delta_{n-1} - \alpha_{n-1}^2\Delta_{n-2}. \quad (4.15)$$

Also, one can show by induction

$$\Delta'_n = -2\alpha_n^2\Delta_{n-1}. \quad (4.16)$$

Comparing (4.15) and (4.16) with the linear problems (2.3) and (4.7), we have from (1.4) and (4.10)

$$\Delta_n = (-2)^{-n} \Psi_{n+1} = 2^{-n} e^{-\frac{y_n}{2}} \Phi_{n+1}. \quad (4.17)$$

Now Proposition 2.1 and Theorem 2.2 with $k = N$ yield

$$\begin{aligned} \frac{\tau_{N-n}}{\tau_N} &= \det(b_{i+j-2}^{(N)})_{i,j=1,\dots,n}, \\ b_i^{(N)} &= b_{i-1}^{(N)'} + \frac{\tau_{N+1}}{\tau_N} \sum_{j=0}^{i-2} b_j^{(N)} b_{i-2-j}^{(N)}, \quad b_0^{(N)} = \frac{\tau_{N-1}}{\tau_N}, \end{aligned} \quad (4.18)$$

$$\left[\frac{\Psi_N(t, \lambda)}{\Psi_{N+1}(t, \lambda)} \right]^{(-1)} = \frac{1}{\lambda} \frac{\tau_N}{\tau_{N-1}} \sum_{i=0}^{\infty} b_i^{(N)} \lambda^{-i}.$$

Then taking the boundary condition (4.4) into account, noticing that Δ_n is polynomial of degree n in $\mu = -\frac{\lambda}{2}$, Equation (4.18) can be rewritten by using (4.17) as

$$\begin{aligned} \frac{\Delta_{N-1}}{\Delta_N} &= \frac{1}{\mu} \frac{\tau_N}{\tau_{N-1}} \sum_{i=0}^{\infty} b_i^{(N)} (-2\mu)^{-i}, \quad b_i^{(N)} = b_{i-1}^{(N)'}, \\ \frac{\tau_{N-n}}{\tau_N} &= \det(b_{i+j-2}^{(N)})_{i,j=1,\dots,n}, \quad b_0^{(N)} = \frac{\tau_{N-1}}{\tau_N}, \end{aligned} \quad (4.19)$$

which is nothing but (4.14). In order to satisfy the boundary condition (4.2) at the left edge of lattice, we choose $b_0^{(N)}$ to be sum of N terms of exponential function.

In summary, Nakamura's result may be interpreted as the determinant formula viewed from opposite direction of the lattice. Namely, starting from $n = N$ under normalization $\tau_N = 1$, it describes such formula that expresses τ_{N-n} in terms of $n \times n$ determinant. Since τ function of the finite Toda equation is invariant with respect to inversion of the lattice ($n \rightarrow N - n$), it is also possible to regard this formula as expressing τ_n as $n \times n$ determinant under the normalization $\tau_0 = 1$. Also, it should be remarked that the resolvent of L appeared because Δ_n , principal minor determinant of $\mu I - L$, satisfies the auxiliary linear problem of the finite Toda equation.

Remark 4.2 In order to obtain "normal" determinant formula, we may consider (1, 1) entry of the resolvent of L

$$g(\mu) = (\mu I - L)_{11}^{-1} = \frac{\bar{\Delta}_1}{\bar{\Delta}_0}, \quad (4.20)$$

$$\bar{\Delta}_n = \begin{vmatrix} \mu - \beta_{n+1} & -\alpha_{n+1} & & & & & \\ -\alpha_{n+1} & \mu - \beta_{n+2} & -\alpha_{n+2} & & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -\alpha_{N-2} & \mu - \beta_{N-1} & -\alpha_{N-1} & \\ & & & 0 & -\alpha_{N-1} & \mu - \beta_N & \end{vmatrix}. \quad (4.21)$$

The recurrence relations for $\bar{\Delta}_n$ are given by

$$\bar{\Delta}_n = (\mu - \beta_{n+1})\bar{\Delta}_{n+1} - \alpha_{n+2}^2\bar{\Delta}_{n+2}, \quad \bar{\Delta}'_n = 2\alpha_n^2\bar{\Delta}_{n+1}, \quad (4.22)$$

which implies

$$\bar{\Delta}_n = (-2)^n \Psi_n^* = 2^n e^{\frac{y_n}{2}} \Phi_n. \quad (4.23)$$

Therefore Proposition 2.1 and Theorem 2.2 yield

$$\begin{aligned} \frac{\bar{\Delta}_1}{\bar{\Delta}_0} &= \frac{1}{\mu} \frac{\tau_0}{\tau_1} \sum_{i=0}^{\infty} a_i^{(0)} (2\mu)^{-i}, \quad a_i^{(0)} = a_{i-1}^{(0)'}, \quad a_0^{(0)} = \frac{\tau_1}{\tau_0}, \\ \frac{\tau_n}{\tau_0} &= \det(a_{i+j-2}^{(0)})_{i,j=1,\dots,n}. \end{aligned} \quad (4.24)$$

5. Concluding remarks

In this article we have established the relationship between the Hankel determinant formula and the auxiliary linear problem. We have also presented a compact formula of the τ function in the framework of the KP theory. The similar phenomena that have been observed in the Painlevé II and IV equation can be recovered from this result. We have also pointed out that Moser and Nakamura's result on the finite Toda equation can be understood naturally in our framework.

Since the Toda equation can be seen in various context, we expect that the structure presented in this article can be observed in wide area of physical and mathematical sciences. Moreover, it might be an intriguing problem to study whether similar phenomenon can be observed or not for the periodic lattice, where the theta functions play the role of the τ functions.

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