

RECHERCHE COOPÉRATIVE SUR PROGRAMME N° 25

M. ADLER

P. VAN MOERBEKE

Matrix Integrals, Toda Symmetries, Virasoro Constraints and Orthogonal Polynomials

Les rencontres physiciens-mathématiciens de Strasbourg - RCP25, 1995, tome 47
« Conférences de M. Audin, D. Bernard, A. Bilal, B. Enriquez, E. Frenkel, F. Golse, M. Katz, R. Lawrence, O. Mathieu, P. Von Moerbeke, V. Ovsienko, N. Reshetikhin, S. Theisen », , exp. n° 9, p. 215-262

http://www.numdam.org/item?id=RCP25_1995__47__215_0

© Université Louis Pasteur (Strasbourg), 1995, tous droits réservés.

L'accès aux archives de la série « Recherche Coopérative sur Programme n° 25 » implique l'accord avec les conditions générales d'utilisation (<http://www.numdam.org/conditions>). Toute utilisation commerciale ou impression systématique est constitutive d'une infraction pénale. Toute copie ou impression de ce fichier doit contenir la présente mention de copyright.

NUMDAM

Article numérisé dans le cadre du programme
Numérisation de documents anciens mathématiques
<http://www.numdam.org/>

Matrix integrals, Toda symmetries, Virasoro constraints and orthogonal polynomials

M. Adler* P. van Moerbeke†

Symmetries of the infinite Toda lattice. The symmetries for the infinite Toda lattice,

$$(0.1) \quad \frac{\partial L}{\partial t_n} = \left[\frac{1}{2}(L^n)_s, L \right], \quad n = 1, 2, \dots,$$

viewed as isospectral deformations of bi-infinite tridiagonal matrices L , are time-dependent vector fields transversal to and commuting with the integrable Toda hierarchy. As is well known, this hierarchy is intimately related to the Lie algebra splitting of $gl(\infty)$,

$$(0.2) \quad gl(\infty) = \mathcal{D}_s \oplus \mathcal{D}_b \ni A = A_s + A_b,$$

into the algebras of skew-symmetric A_s and lower triangular (including the diagonal) matrices A_b (Borel matrices). We show that this splitting plays a prominent role also in the construction of the Toda symmetries and their action on τ -functions; it also plays a crucial role in obtaining the Virasoro constraints for matrix integrals and it ties up elegantly with the theory of orthogonal polynomials .

*Department of Mathematics, Brandeis University, Waltham, Mass 02254, USA. The support of a National Science Foundation grant # DMS 9203246 is gratefully acknowledged.

†Department of Mathematics, Université de Louvain, 1348 Louvain-la-Neuve, Belgium and Brandeis University, Waltham, Mass 02254, USA. The support of National Science Foundation # DMS 9203246, Nato, FNRS and Francqui Foundation grants is gratefully acknowledged.

Define matrices δ and ε , with $[\delta, \varepsilon] = 1$, acting on characters $\chi(z) = (\chi_n(z))_{n \in \mathbb{Z}} = (z^n)_{n \in \mathbb{Z}}$ as

$$(0.3) \quad \delta\chi = z\chi \text{ and } \varepsilon\chi = \frac{\partial}{\partial z}\chi.$$

This enables us to define a wave operator S , a wave vector Ψ ,

$$(0.4) \quad L = S\delta S^{-1} \text{ and } \Psi = S \exp^{\frac{1}{2} \sum_0^\infty t_i z^i} \chi(z),$$

and an operator M , reminiscent of Orlov and Schulman's M -operator for the KP-equation, such that

$$(0.5) \quad L\Psi = z\Psi \text{ and } M\Psi = \frac{\partial}{\partial z}\Psi,$$

thus leading to identities of the form:

$$(0.6) \quad M^\beta L^\alpha \Psi = z^\alpha \left(\frac{\partial}{\partial z}\right)^\beta \Psi.$$

The vector Ψ and the matrices S, L and M evolve in a way, which is compatible with the algebra splitting above,

$$(0.7) \quad \frac{\partial \Psi}{\partial t_n} = \frac{1}{2}(L^n)_s \Psi \text{ and } \frac{\partial S}{\partial t_n} = -\frac{1}{2}(L^n)_b S,$$

$$(0.8) \quad \frac{\partial L}{\partial t_n} = \left[\frac{1}{2}(L^n)_s, L\right] \text{ and } \frac{\partial M}{\partial t_n} = \left[\frac{1}{2}(L^n)_s, M\right],$$

and the wave vector Ψ has the following representation in terms of a vector¹ of τ -functions $\tau = (\tau_n)_{n \in \mathbb{Z}}$:

$$(0.9) \quad \Psi(t, z) = e^{\frac{1}{2} \sum t_i z^i} \left(z^n \frac{e^{-\eta \tau_n(t)}}{\sqrt{\tau_n(t) \tau_{n+1}(t)}} \right)_{n \in \mathbb{Z}} \equiv (z^n \Psi_n)_{n \in \mathbb{Z}}.$$

The wave vector defines a t -dependent flag

$$\dots \supset W_{k-1}^t \supset W_k^t \supset W_{k+1}^t \supset \dots$$

¹with $\eta = \sum_1^\infty \frac{z^{-i}}{i} \frac{\partial}{\partial t_i}$; note the 1/2 appearing in Ψ

of nested linear spaces, spanned by functions of z ,

$$(0.10) \quad W_k^t \equiv \text{span}\{z^k \Psi_k, z^{k+1} \Psi_{k+1}, \dots\}$$

Formula (0.6) motivates us to give the following definition of symmetry vector fields (symmetries), acting on the manifold of wave functions Ψ and inducing a Lax pair on the manifold of L -operators ²:

$$(0.11) \quad \mathbb{Y}_{z^\alpha (\frac{\partial}{\partial z})^\beta} \Psi = -(M^\beta L^\alpha)_b \Psi \quad \text{and} \quad \mathbb{Y}_{z^\alpha (\frac{\partial}{\partial z})^\beta} L = [-(M^\beta L^\alpha)_b, L].$$

It turns out that *only the vector fields*

$$(0.12) \quad \mathbb{Y}_{\ell, n} := \mathbb{Y}_{z^{n+\ell} (\frac{\partial}{\partial z})^n} = -(M^n L^{n+\ell})_b, \text{ for } n = 0, \ell \in \mathbb{Z} \text{ and } n = 1, \ell \geq -1,$$

conserve the tridiagonal nature of the matrices L . The expressions (0.12), for $n = 1$, $\ell < -1$ have no geometrical meaning, as the corresponding vector fields move you out of the space of tridiagonal matrices. This phenomenon is totally analogous to the KdV case (or pth Gel'fand-Dickey), where a certain algebra of symmetries, a representation of the sub-algebra ³ $\text{Diff}(S^1)^+ \subset \text{Diff}(S^1)$ of holomorphic vector fields on the circle, maintains the differential nature of the 2nd order operator $\frac{\partial^2}{\partial x^2} + q(x)$ (or pth order differential operator).

According to a non-commutative Lie algebra splitting theorem, due to ([A-S-V]), stated in section 2 and adapted to the Toda lattice, we have a Lie algebra anti-homomorphism:

$$(0.13) \quad w_2 \equiv \{z^{n+\ell} (\frac{\partial}{\partial z})^n, n = 0, \ell \in \mathbb{Z}, \text{ or } n = 1, \ell \geq -1\}$$

→ {tangent vector fields on the Ψ -manifold} :

$$z^{n+\ell} (\frac{\partial}{\partial z})^n \mapsto \mathbb{Y}_{z^{n+\ell} (\frac{\partial}{\partial z})^n}, \quad \text{acting on } \Psi \text{ as in (0.11),}$$

to wit,

$$(0.14) \quad [\mathbb{Y}_{\ell, 0}, \mathbb{Y}_{m, 1}] = \ell \mathbb{Y}_{m+\ell, 0} \quad \text{and} \quad [\mathbb{Y}_{\ell, 1}, \mathbb{Y}_{m, 1}] = (\ell - m) \mathbb{Y}_{m+\ell, 1}.$$

²sometimes $\mathbb{Y}_{M^\beta L^\alpha}$ will stand for $\mathbb{Y}_{z^\alpha (\frac{\partial}{\partial z})^\beta}$

³ $\text{Diff}(S^1)^+ := \text{span}\{z^{k+1} \frac{\partial}{\partial z}, k \geq -1\}$

Transferring symmetries from the wave vector to the τ -function . An important part of the paper (section 3) is devoted to understanding how, in the general Toda context, the symmetries $\mathbb{Y}_{\ell,n}$ acting on the manifold of wave vectors Ψ induce vector fields $\mathcal{L}_{\ell,n}$ on the manifold of τ -vectors $\tau = (\tau_j)_{j \in \mathbb{Z}}$, for $n = 0$ or 1 ; this new result is contained in Theorem 3.2:

$$(0.15) \quad \mathbb{Y}_{\ell,n} \log \Psi = (e^{-\eta} - 1) \mathcal{L}_{\ell,n} \log \tau + \frac{1}{2} \left(\mathcal{L}_{\ell,n} \log \left(\frac{\tau}{\tau_\delta} \right) \right). \quad (\text{Fundamental relation})$$

for $n = 0, \ell \in \mathbb{Z}$ and $n = 1, \ell \geq -1$

where “ $\mathbb{Y}_{\ell,n} \log$ ” and “ $\mathcal{L}_{\ell,n} \log$ ” act as logarithmic derivatives⁴, where $\mathcal{L}_{\ell,n} f = (\mathcal{L}_{\ell,n}^j f_j)_{j \in \mathbb{Z}}$, and⁵

$$(0.16) \quad \mathcal{L}_{\ell,1}^j = J_\ell^{(2)} + (2j - \ell - 1) J_\ell^{(1)} + (j^2 - j) J_\ell^{(0)}, \quad \mathcal{L}_{\ell,0}^j = 2J_\ell^{(1)} + 2j J_\ell^{(0)}.$$

Note the validity of the relation not only for infinite matrices, but also for semi-infinite matrices. Also note the robustness of formula (0.15): it has been shown to be valid in the KP-case (continuous) and the 2-dimensional Toda lattice (discrete) by [A-S-V]. We give here an independent proof of this relation, although it could probably have been derived from the [A-S-V]-vertex operator identity for the two-dimensional Toda lattice. The rest of the paper will be devoted to an application of the fundamental relation.

Orthogonal polynomials, skew-symmetric matrices and Virasoro constraints. Consider now in section 4 an orthonormal polynomial basis $(p_n(t, z))_{n \geq 0}$ of $\mathcal{H}^+ \equiv \{1, z, z^2, \dots\}$ with regard to the weight $\rho_0(z) e^{\sum_0^\infty t_i z^i} dz = e^{-V_0 + \sum_0^\infty t_i z^i}$ on the interval $[a, b]$, $-\infty \leq a < b \leq \infty$, satisfying:

$$(0.17) \quad -\frac{\rho'_0}{\rho_0} = V'_0 = \frac{\sum_0^\infty b_i z^i}{\sum_0^\infty a_i z^i} =: \frac{h_0}{f_0} \quad \text{and} \quad f_0(a) \rho(a) a^k = f_0(b) \rho(b) b^k = 0 \quad (k = 0, 1, \dots).$$

The polynomials $p_n(t, z)$ are t -deformations of $p_n(0, z)$, through the exponential in the weight. Then the semi-infinite vector Ψ and semi-infinite matrices L and M ,

⁴for instance $\mathbb{Y}_{\ell,n} \log \Psi_j := \frac{-((M^n L^{n+\ell})_b \Psi)_j}{\Psi_j}$ and $\left(\mathcal{L}_{\ell,n} \log \left(\frac{\tau}{\tau_\delta} \right) \right)_j \equiv \frac{\mathcal{L}_{\ell,n} \tau_j}{\tau_j} - \frac{\mathcal{L}_{\ell,n} \tau_{j+1}}{\tau_{j+1}}$

⁵set $J_n^{(0)} = \delta_{n,0}$, $J_n^{(1)} = \frac{\partial}{\partial t_n} + \frac{1}{2}(-n)t_{-n}$, and $J_n^{(2)} = \sum_{i+j=n} : J_i^{(1)} J_j^{(1)} :$

defined by

$$(0.18) \quad \Psi(t, z) \equiv \exp^{\frac{1}{2} \sum_0^\infty t_i z^i} (p_n(t, z))_{n \geq 0}, \quad z\Psi = L\Psi \quad \text{and} \quad \frac{\partial}{\partial z} \Psi = M\Psi$$

are solutions of the Toda differential equations (0.7) and (0.8). Moreover, $\Psi(t, z)$ can be represented by (0.9) with $\tau_0 = 1$ and

$$(0.19) \quad \tau_n = \frac{1}{\Omega_n n!} \int_{\mathcal{M}_n(a,b)} dZ e^{-\text{Tr} V_0(Z) + \sum_1^\infty t_i \text{Tr} Z^i}, \quad n \geq 1;$$

here the integration is taken over a subspace $\mathcal{M}_n(a, b)$ of the space of $n \times n$ Hermitean matrices Z , with eigenvalues $\in [a, b]$.

We prove in Theorem 4.2 that in terms of the matrices L and M , defined in (0.18) and in terms of the anti-commutator $\{A, B\} := \frac{1}{2}(AB + BA)$, the semi-infinite matrices⁶

$$(0.20) \quad V_m := \{Q, L^{m+1}\} = QL^{m+1} + \frac{m+1}{2} L^m f_0(L), \quad \text{with } V_{-1} = Q := Mf_0(L) + \frac{(f_0 \rho_0)'}{2\rho_0}(L).$$

are skew-symmetric for $m \geq -1$ and form a representation of the Lie algebra of holomorphic vector fields $\text{Diff}(S^1)^+$, i.e. they satisfy

$$(0.21) \quad [V_m, V_n] = (n - m) \sum_{i \geq 0} a_i V_{m+n+i}, \quad m, n \geq -1.$$

Thus, in terms of the splitting (0.2), we have for orthogonal polynomials the following identities:

$$(0.22) \quad (V_m)_b = 0, \quad \text{for all } m \geq -1,$$

leading to the *vanishing* of a whole algebra of symmetry vector fields \mathbb{Y}_{V_m} on the locus of wave functions Ψ , defined in (0.18); then using the fundamental relation (0.15) to transfer the vanishing statement to the τ -functions τ_n , we find the Virasoro-type constraints for the τ_n , $n \geq 0$ and for $m = -1, 0, 1, 2, \dots$:

$$(0.23) \quad \sum_{i \geq 0} \left(a_i (J_{i+m}^{(2)} + 2n J_{i+m}^{(1)} + n^2 J_{i+m}^{(0)}) - b_i (J_{i+m+1}^{(1)} + n J_{i+m+1}^{(0)}) \right) \tau_n = 0,$$

⁶the matrices V_m are not to be confused with the potential V_0 , appearing in the weight.

in terms of the coefficients a_i and b_i of f_0 and h_0 (see (0.18)). In his fundamental paper [W], Witten had observed, as an incidental fact, that in the case of Hermite polynomials $V_{-1} = M - L$ is a skew-symmetric matrix. In this paper we show that skew-symmetry plays a crucial role; in fact the *Virasoro constraints* (0.23) are tantamount to *the skew-symmetry of the semi-infinite matrices* (0.20).

They can also be obtained, with uninspired tears, upon substituting

$$(0.24) \quad Z \mapsto Z + \varepsilon f_0(Z) Z^{k+1}$$

in the integrand of (0.19); then the linear terms in ε in the integral (0.19) must vanish and yield the same Virasoro-type constraints (0.23) for each of the integrals τ_n as is carried out in the appendix.

At the same time, the methods above solve the “*string equation*”, which is : for given f_0 , find two semi-infinite matrices, a symmetric L and a skew-symmetric Q , satisfying

$$(0.25) \quad [L, Q] = f_0(L).$$

For the **classical orthogonal polynomials**, as explained in section 6, the matrices L and Q , matrix realizations of the operators z and $\sqrt{\frac{f_0}{\rho_0}} \frac{\partial}{\partial z} \sqrt{\rho_0 f_0}$ respectively, acting on the space of polynomials, are both tridiagonal, with L symmetric and Q skew-symmetric. In addition, the matrices L and Q stabilize the flag, defined in (0.10), in the following sense:

$$(0.28) \quad zW_k \subset W_{k-1} \quad \text{and} \quad T_{-1}W_k \subset W_{k-1}.$$

This result is related to a classical Theorem of Bochner; see [C].

The results in this paper have been lectured on at CIMPA (1991), Como, Utrecht (1992) and Cortona (1993); see the lecture notes [vM]. Grinevich, Orlov and Schulman made a laconic remark in a 1993 paper [GOS, p. 298] about defining symmetries for the Toda lattice. We thank A. Grünbaum, L. Haine, V. Kac, A. Magnus, A. Morozov, T. Shiota, Cr. Tracy and E. Witten for conversations, regarding various aspects of this work. We also thank S. D’Addato-Muës for unscrambling an often messy manuscript.

Table of contents:

1. The Toda lattice revisited
2. Symmetries of the Toda lattice and the w_2 -algebra
3. The action of the symmetries on the τ -function
4. Orthogonal polynomials, matrix integrals, skew-symmetric matrices and Virasoro constraints
5. Classical orthogonal polynomials
6. Appendix: Virasoro constraints via the integrals

1 The Toda lattice revisited

On \mathbb{Z} we define the function χ (character)

$$\chi : \mathbb{Z} \times \mathbb{C} \rightarrow \mathbb{C} : (n, z) \mapsto \chi_n(z) = z^n$$

and the matrix-operators δ and ε

$$(1.1) \quad \delta = \begin{pmatrix} \ddots & & & & & & & & & & \\ & 0 & 1 & & & & & & & & \\ & 0 & 1 & & & & & & & & \\ & & & 0 & 1 & & & & & & \\ & & & & & 0 & 1 & & & & \\ & & & & & & & 1 & & & \\ & & & & & & & & 0 & & \\ & & & & & & & & & \ddots & \end{pmatrix} \text{ and } \varepsilon = \begin{pmatrix} \ddots & & & & & & & & & & \\ & -2 & & & & & & & & & \\ & -1 & 0 & & & & & & & & \\ & & 0 & 0 & & & & & & & \\ & & & 0 & 0 & & & & & & \\ & & & & 1 & 0 & & & & & \\ & & & & & & 2 & 0 & & & \\ & & & & & & & & \ddots & & \end{pmatrix}$$

acting on χ as

$$(1.2) \quad \delta\chi = z\chi \text{ and } \varepsilon\chi = \frac{\partial}{\partial z}\chi;$$

they satisfy

$$[\delta, \varepsilon] = 1.$$

Proposition 1.1. *The infinite matrix⁷*

$$(1.3) \quad \tilde{L} = \sum_{j \leq 1} a_j \delta^j \in \mathcal{D}_{-\infty, 1}, \quad a_j(t) = \text{diag}(a_j(n, t))_{n \in \mathbb{Z}}, a_1 = 1,$$

⁷ $\mathcal{D}_{k, \ell}$ ($k < \ell \in \mathbb{Z}$) denotes the set of band matrices with zeros outside the strip (k, ℓ) . The symbols $(\cdot)_+$, $(\cdot)_-$, $(\cdot)_0$ denote the projection of a matrix onto $\mathcal{D}_{0, \infty}$, $\mathcal{D}_{-\infty, -1}$ and \mathcal{D}_{00} respectively.

subjected to the deformation equations

$$(1.4) \quad \frac{\partial \tilde{L}}{\partial t_n} = [(\tilde{L}^n)_+, \tilde{L}] = [-(\tilde{L}^n)_-, \tilde{L}], \quad n = 1, 2, \dots$$

has, for generic initial conditions, a representation in terms of τ -functions τ_n

$$(1.5) \quad \tilde{L} = \tilde{S} \delta \tilde{S}^{-1} = \left(\dots, \left(\frac{\gamma_n}{\gamma_{n-1}} \right)^2, \frac{\partial}{\partial t_1} \log \gamma_n^2, 1, 0, \dots \right)_{n \in \mathbb{Z}},$$

where⁸

$$(1.6) \quad \gamma_n = \sqrt{\frac{\tau_{n+1}}{\tau_n}}, \quad \tilde{S} = \frac{\tau(t - [\delta^{-1}])}{\tau(t)} = \frac{\sum_{n=0}^{\infty} p_n(-\tilde{\partial}) \tau(t) \delta^{-n}}{\tau(t)}$$

The wave operator \tilde{S} and the wave vector⁹

$$(1.7) \quad \tilde{\Psi} := e^{\sum_1^{\infty} t_i z^i} \tilde{S} \chi(z) = \left(z^n e^{\Sigma} \frac{e^{-\eta} \tau_n}{\tau_n} \right)_{n \in \mathbb{Z}} =: (z^n \tilde{\Psi}_n)_{n \in \mathbb{Z}}$$

satisfy

$$(1.8) \quad \tilde{L} \tilde{\Psi} = z \tilde{\Psi}, \quad \frac{\partial \tilde{\Psi}}{\partial t_n} = (\tilde{L}^n)_+ \tilde{\Psi}, \quad \frac{\partial \tilde{S}}{\partial t_n} = -(\tilde{L}^n)_- \tilde{S}.$$

Proof: The proof of this statement can be deduced from the work of Ueno-Takasaki [U-T]; we consider only a few points: from equation (1.6), it follows that:

$$(1.9) \quad \tilde{S} = I - A \delta^{-1} - B \delta^{-2} - \dots, \quad \text{and} \quad \tilde{S}^{-1} = I + A \delta^{-1} + B \delta^{-2} + A \delta^{-1} A \delta^{-1} + \dots$$

with

$$A = \frac{\partial}{\partial t_1} \log \tau, \quad \text{and} \quad B = -\frac{p_2(-\tilde{\partial}) \tau(t)}{\tau(t)}.$$

Then, calling $p_k \tau := p_k(-\tilde{\partial}) \tau$, we have

⁸The p_k 's are the elementary Schur polynomials $e^{\sum_1^{\infty} t_i z^i} = \sum_0^{\infty} p_k(t) z^k$ and $p_k(-\tilde{\partial}) := p_k\left(-\frac{\partial}{\partial t_1}, -\frac{1}{2} \frac{\partial}{\partial t_2}, -\frac{1}{3} \frac{\partial}{\partial t_3}, \dots\right)$. Also $[\alpha] := \left(\alpha, \frac{\alpha^2}{2}, \frac{\alpha^3}{3}, \dots\right)$.

⁹set $\eta = \sum_1^{\infty} \frac{z^{-i}}{i} \frac{\partial}{\partial t_i}$ and $\Sigma = \sum_1^{\infty} t_j z^j$

(1.10)

$$\begin{aligned}
\tilde{L} = \tilde{S}\delta\tilde{S}^{-1} &= \delta + (A_{n+1} - A_n)_{n \in \mathbb{Z}}\delta^0 + (B_{n+1} - B_n + A_n A_{n+1} - A_n^2)_{n \in \mathbb{Z}}\delta^{-1} + \dots \\
&= \delta + \left(\frac{\partial}{\partial t_1} \log \frac{\tau_{n+1}}{\tau_n} \right)_{n \in \mathbb{Z}} \delta^0 \\
&\quad + \left(-\frac{p_2 \tau_{n+1}}{\tau_{n+1}} + \frac{p_2 \tau_n}{\tau_n} + \frac{p_1 \tau_n}{\tau_n} \frac{p_1 \tau_{n+1}}{\tau_{n+1}} - \left(\frac{p_1 \tau_n}{\tau_n} \right)^2 \right)_{n \in \mathbb{Z}} \delta^{-1} + \dots,
\end{aligned}$$

yielding the representation (1.5), except for the δ^{-1} -term, which we discuss next.

To the Toda problem is associated a flag of nested planes $\tilde{W}_{n+1} \subset \tilde{W}_n \in Gr_n$,

$$\begin{aligned}
\tilde{W}_n &\equiv \text{span}\{z^n \tilde{\Psi}_n, z^{n+1} \tilde{\Psi}_{n+1}, \dots\} \\
&= \text{span}\left\{z^n \tilde{\Psi}_n, \frac{\partial}{\partial t_1} \tilde{\Psi}_n, \left(\frac{\partial}{\partial t_1}\right)^2 \tilde{\Psi}_n, \dots\right\}.
\end{aligned}$$

The inclusion $\tilde{W}_{n+1} \subset \tilde{W}_n$ implies, by noting $\tilde{\Psi}_k = 1 + O(z^{-1})$, that

$$(1.11) \quad z \tilde{\Psi}_{n+1} = \frac{\partial}{\partial t_1} \tilde{\Psi}_n - \alpha \tilde{\Psi}_n \quad \text{for some } \alpha = \alpha(t).$$

Then $\alpha(t) = \frac{\partial}{\partial t_1} \log \tau_{n+1}/\tau_n$ and putting this expression in (1.11) yields¹⁰

$$\{\tau_n(t - [z^{-1}]), \tau_{n+1}(t)\} + z(\tau_n(t - [z^{-1}])\tau_{n+1}(t) - \tau_{n+1}(t - [z^{-1}])\tau_n(t)) = 0.$$

Expanding this expression in powers of z^{-1} and dividing the coefficient of z^{-1} by $\tau_n \tau_{n+1}$ yield

$$-\frac{p_2 \tau_{n+1}}{\tau_{n+1}} + \frac{p_2 \tau_n}{\tau_n} + \frac{p_1 \tau_n}{\tau_n} \frac{p_1 \tau_{n+1}}{\tau_{n+1}} - \frac{\frac{\partial^2 \tau_n}{\partial t_1^2}}{\tau_n} = 0.$$

Combining this relation with the customary Hirota bilinear relations, the simplest one being:

$$-\frac{1}{2} \frac{\partial^2}{\partial t_1^2} \tau_n \circ \tau_n + \tau_{n-1} \tau_{n+1} = 0, \quad \text{i.e.} \quad \frac{\partial^2}{\partial t_1^2} \log \tau_n = \frac{\tau_{n-1} \tau_{n+1}}{\tau_n^2},$$

we find

$$-\frac{p_2 \tau_{n+1}}{\tau_{n+1}} + \frac{p_2 \tau_n}{\tau_n} + \frac{p_1 \tau_n}{\tau_n} \frac{p_1 \tau_{n+1}}{\tau_{n+1}} - \left(\frac{p_1 \tau_n}{\tau_n}\right)^2 = \frac{\partial^2}{\partial t_1^2} \log \tau_n = \frac{\tau_{n-1} \tau_{n+1}}{\tau_n^2},$$

¹⁰ $\{f, g\} = \frac{\partial f}{\partial t_1} g - f \frac{\partial g}{\partial t_1}$

and thus the representation (1.5) of \tilde{L} , ending the proof of Proposition 1.1.

Henceforth, we assume \tilde{L} as in proposition 1.1, but in addition *tridiagonal*: $\tilde{L} = \sum_{-1 \leq j \leq 1} a_j \delta^j$; this submanifold is invariant under the vector field (1.4); indeed, more generally if $\tilde{L} = \sum_{j \leq 1} a_j \delta^j$ is a $N+1$ band matrix, i.e. $a_j = 0$ for $j \leq -N \leq 0$, then \tilde{L} remains a $N+1$ band matrix under the Toda vector fields. Moreover consider the Lie algebra decomposition, alluded to in (0.2), of $gl(\infty) = \mathcal{D}_s \oplus \mathcal{D}_b \ni A = (A)_s + (A)_b$ in skew-symmetric plus lower Borel part (lower triangular, including the diagonal).

Theorem 1.2. *Considering the submanifold of tridiagonal matrices \tilde{L} of proposition 1.1 and remembering the form of the diagonal matrix $\gamma = (\gamma_n)_{n \in \mathbb{Z}}$, with $\gamma_n = \sqrt{\frac{\tau_{n+1}}{\tau_n}}$, we define a new wave operator S and wave vector Ψ :*

$$(1.12) \quad S := \gamma^{-1} \tilde{S} \quad \text{and} \quad \Psi := S \chi(z) e^{\Sigma/2};$$

also define

$$(1.13) \quad L := S \delta S^{-1} \quad \text{and} \quad M := S \left(\varepsilon + \frac{1}{2} \sum_1^\infty k t_k \delta^{k-1} \right) S^{-1}.$$

Then

$$(1.14) \quad L = \left(\dots, 0, \frac{\gamma_n}{\gamma_{n-1}}, \frac{\partial}{\partial t_1} \log \gamma_n^2, \frac{\gamma_{n+1}}{\gamma_n}, 0, \dots \right)_{n \in \mathbb{Z}}$$

is symmetric and

$$(1.15) \quad \Psi = \gamma^{-1} \tilde{\Psi} = e^{\Sigma/2} \gamma^{-1} \chi \frac{e^{-\eta \tau}}{\tau} =: (z^n \Psi_n)_{n \in \mathbb{Z}} \quad \text{with} \quad \Psi_n := e^{\Sigma/2} \frac{e^{-\eta \tau_n}}{\sqrt{\tau_n \tau_{n+1}}}.$$

The new quantities satisfy:

$$(1.16) \quad \frac{\partial \log \gamma}{\partial t_n} = \frac{1}{2} (L^n)_0, \quad \frac{\partial S}{\partial t_n} = -\frac{1}{2} (L^n)_b S \quad \text{and} \quad \frac{\partial \Psi}{\partial t_n} = \frac{1}{2} (L^n)_s \Psi,$$

$$(1.17) \quad L \Psi = z \Psi \quad \text{and} \quad M \Psi = \frac{\partial}{\partial z} \Psi, \quad \text{with} \quad [L, M] = 1,$$

and

$$(1.18) \quad \frac{\partial L}{\partial t_n} = \left[\frac{1}{2}(L^n)_s, L \right], \quad \frac{\partial M}{\partial t_n} = \left[\frac{1}{2}(L^n)_s, M \right].$$

Proof of Theorem 1.2: For a given initial condition $\gamma'(0)$, the system of partial differential equations in γ'

$$(1.19) \quad \frac{\partial}{\partial t_k} \log \gamma' = \frac{1}{2}(\tilde{L}^k)_0;$$

has, by Frobenius theorem, a unique solution, since

$$(1.20) \quad \begin{aligned} \left(\frac{\partial}{\partial t_k} \tilde{L}^n - \frac{\partial}{\partial t_n} \tilde{L}^k \right)_0 &= -[(\tilde{L}^k)_-, \tilde{L}^n]_0 + [\tilde{L}^k, (\tilde{L}^n)_+]_0 \\ &= -[(\tilde{L}^k)_-, (\tilde{L}^n)_+]_0 + [(\tilde{L}^k)_-, (\tilde{L}^n)_+]_0 = 0, \end{aligned}$$

using $[A_+, B_+]_0 = 0$ and $[A_-, B_-]_0 = 0$ for arbitrary matrices A and B . Given this solution $\gamma'(t)$, define $S' := \gamma'^{-1}\tilde{S}$ and $L' := S'\delta S'^{-1} = \gamma'^{-1}\tilde{L}\gamma'$, and using $\partial\tilde{S}/\partial t_n = -(\tilde{L}^n)_-\tilde{S}$, compute

$$\begin{aligned} \frac{\partial S'}{\partial t_k} &= \frac{\partial(\gamma'^{-1}\tilde{S})}{\partial t_k} = \frac{\partial\gamma'^{-1}}{\partial t_k}\tilde{S} + \gamma'^{-1}\frac{\partial\tilde{S}}{\partial t_k} \\ &= -\gamma'^{-1}\left(\frac{\partial\gamma'}{\partial t_k}\right)\gamma'^{-1}\tilde{S} + \gamma'^{-1}\frac{\partial\tilde{S}}{\partial t_k} \\ &= -\gamma'^{-1}\frac{1}{2}(\tilde{L}^k)_0\tilde{S} - \gamma'^{-1}(\tilde{L}^k)_-\tilde{S} \\ &= -\frac{1}{2}(L'^k)_0S' - (L'^k)_-S' \quad \text{since } L' = \gamma'^{-1}\tilde{L}\gamma' \text{ and } S' := \gamma'^{-1}\tilde{S} \\ &= -\left((L'^k)_- + \frac{1}{2}(L'^k)_0\right)S' = -\frac{1}{2}(L'^k)_{b'}S', \end{aligned}$$

where

$$A_{b'} := 2A_- + A_0 \quad \text{and} \quad A_{s'} := A - A_{b'}.$$

It follows at once that

$$(1.21) \quad \frac{\partial L'}{\partial t_n} = \left[-\frac{1}{2}(L'^n)_{b'}, L' \right] = \left[\frac{1}{2}(L'^n)_{s'}, L' \right]$$

Observe now that the manifold of symmetric tridiagonal matrices A is invariant under the vector fields

$$(1.22) \quad \frac{\partial A}{\partial t_n} = [-\frac{1}{2}(A^n)_{b'}, A] = [\frac{1}{2}(A^n)_{s'}, A],$$

since for A symmetric, the operations $()_{b'}$ and $()_{s'}$ coincide with the decomposition (0.2):

$$A_{b'} = A_b \quad \text{and} \quad A_{s'} = A_s.$$

Now according to formula (1.5), picking $\gamma'(0) := \gamma(0) = \sqrt{\frac{\tau_{n+1}(0)}{\tau_n(0)}}$ as initial condition for the system of pde's (1.19), makes $L'(0) = \gamma'(0)^{-1}\tilde{L}(0)\gamma(0)'$ symmetric. Since L' was shown to evolve according to (1.21) or (1.22), and since its initial condition is symmetric, the matrix L' remains symmetric in t . Since $L'(t) := \gamma'^{-1}(t)\tilde{L}(t)\gamma'(t)$ is symmetric and since, by definition, $L(t) := \gamma^{-1}(t)\tilde{L}(t)\gamma(t)$ is also symmetric, we have $L'(t) = L(t)$, and thus $\gamma'(t) = c\gamma(t)$ for some constant c ; but c must be 1, since $\gamma'(0) = \gamma(0)$. This proves (1.14), (1.16) and the first halves of (1.17) and (1.18).

Besides multiplication of Ψ by z , which is represented by the matrix L , we also consider differentiation $\partial/\partial z$ of Ψ , which we represent by a matrix M :

$$(1.23) \quad \begin{aligned} \frac{\partial \Psi}{\partial z} &= e^{\Sigma/2} S \frac{\partial}{\partial z} \chi + \frac{1}{2} \left(\sum_1^{\infty} kt_k z^{k-1} \right) e^{\Sigma/2} S \chi \\ &=: \left(P + \frac{1}{2} \sum_1^{\infty} kt_k L^{k-1} \right) \Psi =: M \Psi \end{aligned}$$

with

$$[L, M] = 1 \quad \text{and} \quad P := S \varepsilon S^{-1} \in \mathcal{D}_{-\infty, -1}.$$

Finally compute

$$\begin{aligned} \frac{\partial M}{\partial t_n} &= \frac{\partial S}{\partial t_n} (S^{-1} S) \left(\varepsilon + \frac{1}{2} \sum kt_k \delta^{k-1} \right) S^{-1} \\ &\quad + \frac{1}{2} n L^{n-1} - S \left(\varepsilon + \frac{1}{2} \sum kt_k \delta^{k-1} \right) S^{-1} \frac{\partial S}{\partial t_n} S^{-1} \\ &= -\frac{1}{2} (L^n)_b M + \left[\frac{1}{2} L^n, M \right] + \frac{1}{2} M (L^n)_b \\ &= \left[-\frac{1}{2} (L^n)_b + \frac{1}{2} L^n, M \right] \\ &= \left[\frac{1}{2} (L^n)_s, M \right], \end{aligned}$$

ending the proof of theorem 1.2.

Remark 1.2.1: Theorem 1.2 remains valid for semi-infinite matrices L ; the proof would only require minor modifications.

2 Symmetries of the Toda lattice and the w_2 -algebra

Symmetries are t -dependent vector fields on the manifold of wave functions Ψ , which commute with and are transversal to the Toda vector fields, without affecting the t -variables. We shall need the following Lie algebra splitting lemmas, dealing with operators and their eigenfunctions, due to [A-S-V].

Lemma 2.1. *Let \mathcal{D} be a Lie algebra with a vector space decomposition $\mathcal{D} = \mathcal{D}_+ \oplus \mathcal{D}_-$ into two Lie subalgebras \mathcal{D}_+ and \mathcal{D}_- ; let V be a representation space of \mathcal{D} , and let $\mathcal{M} \subset V$ be a submanifold preserved under the vector fields defined by the action of \mathcal{D}_- , i.e.,*

$$\mathcal{D}_- \cdot x \subset T_x \mathcal{M}, \quad \forall x \in \mathcal{M}.$$

For any function $p: \mathcal{M} \rightarrow \mathcal{D}$, let \mathbb{Y}_p be the vector field on \mathcal{M} defined by

$$\mathbb{Y}_p(x) := -p(x)_- \cdot x, \quad x \in \mathcal{M}.$$

(a) Consider a set \mathcal{A} of functions $p: \mathcal{M} \rightarrow \mathcal{D}$ such that

$$\mathbb{Y}_q p = [-q_-, p], \quad \forall p, q \in \mathcal{A},$$

holds. Then $\mathbb{Y}: p \mapsto \mathbb{Y}_p$ gives a Lie algebra homomorphism of the Lie algebra generated by \mathcal{A} to the Lie algebra $\mathcal{X}(\mathcal{M})$ of vector fields on \mathcal{M} :

$$[\mathbb{Y}_{p_1}, \mathbb{Y}_{p_2}] = \mathbb{Y}_{[p_1, p_2]}, \quad \forall p_1, p_2 \in \mathcal{A},$$

and hence we can assume without loss of generality that \mathcal{A} itself is a Lie algebra.

(b) Suppose for a subset $\mathcal{B} \subset \mathcal{A}$ of functions

$$\mathbb{Z}_q(x) := q(x)_+ \cdot x \in T_x \mathcal{M}, \quad \forall x \in \mathcal{M}, q \in \mathcal{B},$$

and hence defines another vector field $\mathbb{Z}_q \in \mathcal{X}(\mathcal{M})$ when $q \in \mathcal{B}$, and such that

$$\mathbb{Z}_q p = [q_+, p], \quad \forall p \in \mathcal{A}, q \in \mathcal{B},$$

holds. Then

$$[\mathbb{Y}_p, \mathbb{Z}_q] = 0, \quad \forall p \in \mathcal{A}, q \in \mathcal{B}.$$

Remark 2.1.1: A special case of this which applies to many integrable systems is: $V = \mathcal{D}'$, a Lie algebra containing \mathcal{D} , and \mathcal{D} acts on \mathcal{D}' by Lie bracket, i.e., $\mathbb{Y}_p(x) = [-p(x)_-, x]$, etc.

Proof: To sketch the proof, let $p_1, p_2, p \in \mathcal{A}$ and $q \in \mathcal{B}$; then the commutators have the following form:

$$[\mathbb{Y}_{p_1}, \mathbb{Y}_{p_2}](x) = Z_1(x) \quad \text{and} \quad [\mathbb{Z}_q, \mathbb{Y}_p](x) = Z_2x,$$

where, using \mathcal{D}_- and \mathcal{D}_+ are Lie subalgebras,

$$\begin{aligned} Z_1 &:= (\mathbb{Y}_{p_1}(p_2))_- - (\mathbb{Y}_{p_2}(p_1))_- + [p_{1-}, p_{2-}] \\ &= [-p_{1-}, p_{2-}]_- - [-p_{2-}, p_{1-}]_- + [p_{1-}, p_{2-}] \\ &= (-[p_{1-}, p_{2-}] - [p_{1-}, p_{2-}] + [p_{1-}, p_{2-}] - [p_{1+}, p_{2+}])_- = -[p_1, p_2]_-. \end{aligned}$$

and

$$\begin{aligned} Z_2 &:= (\mathbb{Z}_q(p))_- + (\mathbb{Y}_p(q))_+ - [q_+, p_-] \\ &= [q_+, p]_- + [-p_-, q]_+ - [q_+, p_-] \\ &= [q_+, p_-]_- + [-p_-, q_+]_+ - [q_+, p_-] = [q_+, p_-] - [q_+, p_-] = 0, \end{aligned}$$

ending the proof of the lemma.

In the setup of the lemma, if we are given a Lie algebra (anti)homomorphism $\phi : \mathfrak{g} \rightarrow \mathcal{A}$, we denote $\mathbb{Y}_{\phi(x)}$ by \mathbb{Y}_x and $\mathbb{Z}_{\phi(x)}$ by \mathbb{Z}_x if there is no fear of confusion.

Theorem 2.2. *Let L represent an infinite symmetric tridiagonal matrix, flowing according to the Toda vector fields. There is a Lie algebra anti-homomorphism*

$$w_2^+ = \left\{ z^{n+\ell} \left(\frac{\partial}{\partial z} \right)^n, n = 0, \ell \in \mathbb{Z} \text{ or } n = 1, \ell \geq -1 \right\} \rightarrow \left\{ \begin{array}{l} \text{vector fields on the} \\ \text{manifold of wave functions} \end{array} \right\}$$

$$z^{n+\ell} \left(\frac{\partial}{\partial z} \right)^n \longrightarrow \mathbb{Y}_{\ell, n} \Psi = -(M^n L^{n+\ell})_b \Psi$$

satisfying

$$[\mathbb{Y}_{\ell,0}, \mathbb{Y}_{m,0}] = \frac{\ell}{2}\delta_{\ell+m}, \quad [\mathbb{Y}_{\ell,0}, \mathbb{Y}_{m,1}] = \ell\mathbb{Y}_{m+\ell,0} \text{ and } [\mathbb{Y}_{\ell,1}, \mathbb{Y}_{m,1}] = (\ell - m)\mathbb{Y}_{m+\ell,1}.$$

They commute with the Toda vector fields:

$$[\mathbb{Y}_{\ell,n}, \frac{\partial}{\partial t_k}] = 0.$$

Note the vector fields $\mathbb{Y}_{\ell,n}$ induce vector fields on S and $L = S\delta S^{-1}$

$$\mathbb{Y}_{\ell,n}(S) = -(M^n L^{n+\ell})_b S \text{ and } \mathbb{Y}_{\ell,n}(L) = [-(M^n L^{n+\ell})_b, L].$$

Proof of Theorem 2.2: Taking into account the notation of 1.13 and in view of Lemma 2.1 and the remark 2.1.1, set

$$\mathcal{D} := gl(\infty), \quad \mathcal{D}_+ := \mathcal{D}_s, \quad \mathcal{D}_- := \mathcal{D}_b \quad \text{and} \quad \mathcal{D}' := \mathcal{D} \times \mathcal{D}$$

on which \mathcal{D} acts via diagonal embedding $\mathcal{D} \hookrightarrow \mathcal{D}' : p \mapsto (p, p)$.

$$V := \mathcal{D}$$

$\mathcal{M} :=$ respectively, the space of wave operators S , of wave functions Ψ or of pairs $(L, M) = (S\delta S^{-1}, S(\varepsilon + \frac{1}{2} \sum_1^\infty kt_k \delta^{k-1})S^{-1})$, with an infinite symmetric tridiagonal matrix L

$$\mathcal{A} := \text{span} \begin{cases} M^n L^{n+\ell}, & n = 0, \ell \in \mathbb{Z} \\ \text{or} & n = 1, \ell \geq -1 \end{cases}$$

$$\mathcal{B} := \text{span} \{L^\alpha, \alpha \in \mathbb{Z}\}$$

and

$$\mathfrak{g} := w_2^+$$

with the antihomomorphism $\phi : \mathfrak{g} \rightarrow \mathcal{A}$ given by

$$\phi(z^\alpha \partial_z^\beta) := M^\beta L^\alpha.$$

Then the vector fields take the form:

$$\mathbb{Y}_p \Psi = -p_b \Psi, \quad \mathbb{Y}_p S = -p_b S, \quad p \in \mathcal{A}$$

$$\begin{aligned} \mathbb{Y}_p(L, M) &= ([-p_b, L], [-p_b, M]), \quad p \in \mathcal{A} \\ \mathbb{Z}_{L^n/2}\Psi &= \frac{1}{2}(L^n)_s\Psi, \quad \mathbb{Z}_{L^n/2}S = -\frac{1}{2}(L^n)_bS \\ &= \frac{\partial}{\partial t_n}\Psi \quad \quad \quad = \frac{\partial}{\partial t_n}S \end{aligned}$$

by Theorem 1.2,

$$\mathbb{Z}_{L^n/2}(L, M) = \left(\left[\frac{1}{2}(L^n)_s, L\right], \left[\frac{1}{2}(L^n)_s, M\right]\right) = \frac{\partial}{\partial t_n}(L, M) \quad \text{by (1.18).}$$

Note that the vector fields

$$(2.1) \quad \mathbb{Y}_{m,0} \equiv \mathbb{Y}_{L^m} \text{ all } m \in \mathbb{Z} \text{ and } \mathbb{Y}_{\ell,1} = \mathbb{Y}_{ML^{\ell+1}}, \text{ all } \ell \in \mathbb{Z}, \geq -1$$

are tangent to \mathcal{M} . Indeed for $m < 0$, the vector field reads

$$(2.2) \quad \frac{\partial}{\partial s_m}\Psi = \mathbb{Y}_{m,0}\Psi = -(L^m)_b\Psi = -L^m\Psi = -z^m\Psi \quad \text{for } m < 0.$$

The solution to this equation with initial condition $\Psi^{(0)}$ is given by

$$\Psi = e^{-s_m z^m} \Psi^{(0)}(t, z)$$

i.e., every component of the vector $\Psi^{(0)}$ is multiplied by the same exponential factor, and so is each τ -function:

$$\tau_k(t) = \tau_k^0(t) e^{-m s_m t - m}.$$

Since the entries of the tridiagonal matrix only depend on ratios of τ -functions, this exponential factor is irrelevant for L .

In the same way $\mathbb{Y}_{m,0}$ ($m \geq 0$) is tangent to the space of symmetric tridiagonal matrices, because the solution to

$$(2.3) \quad \frac{\partial \Psi}{\partial s_m} = \mathbb{Y}_{m,0}\Psi = -(L^m)_b\Psi = (-L^m + (L^m)_s)\Psi = -z^m\Psi + 2\frac{\partial \Psi}{\partial t_m},$$

is given by

$$\Psi = e^{\frac{1}{2}\sum t_i z^i} \frac{\tau(t + 2s - [z])}{\tau(t)}.$$

Not only the vector fields $\mathbb{Y}_{\ell,0}$, but also the $\mathbb{Y}_{\ell,1}$'s ($\ell \geq -1$) are tangent to the space of symmetric tridiagonal matrices, because

$$(2.4) \quad \begin{aligned} \mathbb{Y}_{\ell,1}(L) &= [-(ML^{\ell+1})_b, L], \quad \text{having the form } a_1\delta + \sum_0^\infty a_{-i}\delta^{-i} \\ &= [-ML^{\ell+1}, L] + [(ML^{\ell+1})_s, L] \\ &= L^{\ell+1} + [(ML^{\ell+1})_s, L] = \text{symmetric matrix for } \ell \geq -1. \end{aligned}$$

With these data in mind, Lemma 2.1 implies Theorem 2.2.

3 The action of the symmetries on τ -functions

The main purpose of this section is to show that the symmetry vector fields \mathbb{Y} defined on the manifold of wave function Ψ induce certain precise vector fields on τ , given by the coefficients of the vertex operator expansion. The precise statement is contained in theorem 3.2. Before entering these details, we need a general statement:

Lemma 3.1. *Any vector field \mathbb{Y} defined on the manifold of wave functions Ψ and commuting with the Toda vector fields induce vector fields $\hat{\mathbb{Y}}$ on the manifold of τ -functions; they are related as follows, taking into account the fact that $\mathbb{Y} \log$ acts as a logarithmic derivative:*

$$(3.1) \quad \begin{aligned} \mathbb{Y} \log \Psi_n &= (e^{-\eta} - 1) \hat{\mathbb{Y}} \log \tau_n + \frac{1}{2} \hat{\mathbb{Y}} \log \frac{\tau_n}{\tau_{n+1}} \\ &\equiv \sum_1^{\infty} a_i^{(n)} z^{-i} + a_0^{(n)} \end{aligned}$$

where $\hat{\mathbb{Y}}$ is a vector field acting on τ -functions; the part of (3.1) containing $e^{-\eta} - 1$ is a power series in z^{-1} vanishing at $z = \infty$, whereas the other part is z -independent. For any two vector fields

$$(3.2) \quad [\mathbb{Y}, \mathbb{Y}'] \log \Psi_n = (e^{-\eta} - 1) [\hat{\mathbb{Y}}, \hat{\mathbb{Y}}'] \log \tau_n + \frac{1}{2} [\hat{\mathbb{Y}}, \hat{\mathbb{Y}}'] \log \frac{\tau_n}{\tau_{n+1}},$$

showing that the map above from the algebra of vector fields on wave functions to the algebra of vector fields on τ -functions is homomorphism.

Proof: In the computation below we use $\gamma_n = \sqrt{\frac{\tau_{n+1}}{\tau_n}}$ and the fact that $\mathbb{Y} := \cdot$ commutes with the Toda flows $\partial/\partial t_n$ and thus with η :

$$(3.3) \quad \begin{aligned} (\log \Psi_n) \cdot &= \left(\log \frac{e^{-\eta} \tau_n}{\tau_n} - \log \gamma_n \right) \cdot \quad \text{see (1.21)} \\ &= \frac{(e^{-\eta} \dot{\tau}_n)}{e^{-\eta} \tau_n} - \frac{\dot{\tau}_n}{\tau_n} + \frac{1}{2} \left(\log \frac{\tau_n}{\tau_{n+1}} \right) \cdot \\ &= (e^{-\eta} - 1) (\log \tau_n) \cdot + \frac{1}{2} \left(\log \frac{\tau_n}{\tau_{n+1}} \right) \cdot, \quad \text{using } [\eta, \mathbb{Y}] = 0. \end{aligned}$$

Applying the second vector field \mathbb{Y}' to relation (3.3) yields

$$\mathbb{Y}' \mathbb{Y} \log \Psi_n = (e^{-\eta} - 1) \mathbb{Y}' (\hat{\mathbb{Y}} \log \tau_n) + \frac{1}{2} \mathbb{Y}' \left(\hat{\mathbb{Y}} \log \frac{\tau_n}{\tau_{n+1}} \right)$$

with

$$\begin{aligned}
\mathbb{Y}'(\hat{\mathbb{Y}} \log f) &= \mathbb{Y}'\left(\frac{\hat{\mathbb{Y}}f}{f}\right) \\
&= \frac{\hat{\mathbb{Y}}'(\hat{\mathbb{Y}}f)}{f} - \frac{(\hat{\mathbb{Y}}'f)(\hat{\mathbb{Y}}f)}{f^2} \\
&= \frac{\hat{\mathbb{Y}}'(\hat{\mathbb{Y}}f)}{f} - \frac{(\hat{\mathbb{Y}}'f)(\hat{\mathbb{Y}}f)}{f^2}.
\end{aligned}$$

Using the relation above twice leads at once to (3.2), ending the proof of Lemma 3.1.

The vector fields $\mathbb{Y}_{\ell,n}$ on Ψ induce certain precise vector fields on τ , constructed from expressions $W_{\ell}^{(n+1)}$ appearing in the vertex operator expansion; notice the expressions $W_{\ell}^{(n+1)}$ differ slightly from the customary ones, because of the $1/2$ multiplying t but not $\partial/\partial t$:

$$\begin{aligned}
(3.4) \quad X(t, \lambda, \mu)\tau &= e^{\frac{1}{2}\sum_1^{\infty} t_i(\mu^i - \lambda^i)} e^{\sum_1^{\infty} (\lambda^{-i} - \mu^{-i})\frac{1}{i}\frac{\partial}{\partial t_i}} \tau \\
&= e^{\frac{1}{2}\sum t_i(\mu^i - \lambda^i)} \tau(t + [\lambda^{-1}] - [\mu^{-1}]) \\
&= \sum_{k=0}^{\infty} \frac{(\mu - \lambda)^k}{k!} \sum_{\ell=-\infty}^{\infty} \lambda^{-\ell-k} W_{\ell}^{(k)}(\tau).
\end{aligned}$$

For instance

$$(3.5) \quad W_n^{(0)} = J_n^{(0)} = \delta_{n,0}, \quad W_n^{(1)} = J_n^{(1)}, \quad W_n^{(2)} = J_n^{(2)} - (n+1)J_n^{(1)}$$

with

$$J_n^{(1)} = \begin{cases} \frac{\partial}{\partial t_n} & \text{for } n > 0 \\ 0 & \text{for } n = 0 \\ \frac{1}{2}(-n)t_{-n} & \text{for } n < 0 \end{cases} \quad J_n^{(2)} = \begin{cases} \sum_{\substack{i+j=n \\ i,j \geq 1}} \frac{\partial^2}{\partial t_i \partial t_j} + \sum_{\substack{-i+j=n \\ i,j \geq 1}} it_i \frac{\partial}{\partial t_j} & \text{for } n \geq 0 \\ \frac{1}{4} \sum_{\substack{i+j=-n \\ i,j \geq 1}} (it_i)(jt_j) + \sum_{i-j=-n} it_i \frac{\partial}{\partial t_j} & \text{for } n \leq 0. \end{cases}$$

We shall also need

$$\begin{aligned}
(3.6) \quad \mathcal{L}_{\ell,1}^j &:= W_{\ell}^{(2)} + 2jW_{\ell}^{(1)} + (j^2 - j)W_{\ell}^{(0)} = J_{\ell}^{(2)} + (2j - \ell - 1)J_{\ell}^{(1)} + (j^2 - j)J_{\ell}^{(0)} \\
\mathcal{L}_{\ell,0}^j &:= 2W_{\ell}^{(1)} + 2jW_{\ell}^{(0)} = 2J_{\ell}^{(1)} + 2jJ_{\ell}^{(0)}.
\end{aligned}$$

We also introduce $\tilde{W}_n^{(2)}$, which differs from $W_n^{(2)}$ above by a factor $1/2$,

$$(3.7) \quad \tilde{W}_n^{(2)} := J_n^{(2)} - \frac{n+1}{2} J_n^{(1)}, \text{ with } \tilde{W}_n^{(2)} = W_n^{(2)} = J_n^{(2)} \text{ for } n = -1, 0,$$

and an operator B_m in z and t

$$(3.8) \quad B_m := -z^{m+1} \frac{\partial}{\partial z} + \sum_{n > \max(-m, 0)} nt_n \frac{\partial}{\partial t_{n+m}}, \quad m \in \mathbb{Z},$$

which restricted to functions $f(t_1, t_2, \dots)$ of $t \in \mathbb{C}^\infty$ only yields

$$(3.9) \quad B_m f = J_m^{(2)} f \text{ for } m = -1, 0, 1.$$

The expressions $J_n^{(2)}$ form a Virasoro algebra with central extension

$$(3.10) \quad [J_\ell^{(1)}, J_m^{(1)}] = \frac{\ell}{2} \delta_{\ell+m} \quad [J_\ell^{(1)}, J_m^{(2)}] = \ell J_{m+\ell}^{(1)}$$

$$[J_\ell^{(2)}, J_m^{(2)}] = (\ell - m) J_{\ell+m}^{(2)} + \frac{\ell^3 - \ell}{12} \delta_{\ell+m}$$

and consequently the following Virasoro commutation relations hold, upon setting

$$(3.11) \quad V_\ell = J_\ell^{(2)} + (a\ell + b) J_\ell^{(1)} \quad , \quad c_\ell = \frac{\ell^3 - \ell}{12} + \frac{\ell(b^2 - a^2 \ell^2)}{2},$$

$$[V_\ell, V_m] = (\ell - m) V_{\ell+m} + c_\ell \delta_{\ell+m, 0}.$$

In particular, observe

$$[W_\ell^{(1)}, W_m^{(2)}] = \ell W_{\ell+m}^{(1)} + \frac{\ell^2 - \ell}{2} \delta_{\ell+m}, \quad [W_\ell^{(2)}, W_m^{(2)}] = (\ell - m) W_{\ell+m}^{(2)} - 5 \frac{(\ell^3 - \ell)}{12} \delta_{\ell+m}$$

and¹¹

$$(3.12) \quad [\mathcal{L}_{\ell,0}^{(j)}, \mathcal{L}_{m,1}^{(j)}] = \ell \mathcal{L}_{\ell+m,0}^{(j)} + c_{\ell,j} \delta_{\ell+m}, \quad [\mathcal{L}_{\ell,1}^{(j)}, \mathcal{L}_{m,1}^{(j)}] = (\ell - m) \mathcal{L}_{\ell+m,1}^{(j)} + c'_{\ell,j} \delta_{\ell+m}.$$

The purpose of this section is to prove the following relationship between the action of the symmetries on Ψ and τ .

¹¹with $c_{\ell,j} = \ell(\ell + 2j - 1)$ $c'_{\ell,j} = -\frac{\ell}{12}(5\ell^2 + 24j^2 + 7)$

Fundamental Theorem 3.2. *The following relationship holds*

$$(3.13) \quad \mathbb{Y}_{\ell,n} \log \Psi = (e^{-\eta} - 1) \mathcal{L}_{\ell,n} \log \tau + \frac{1}{2} \left(\mathcal{L}_{\ell,n} \log \tau - (\mathcal{L}_{\ell,n} \log \tau)_\delta \right)$$

for $n = 0, \text{ all } \ell \in \mathbb{Z}$
 $n = 1, \text{ all } \ell \geq -1$

where $\mathbb{Y}_{\ell,n} \log$ and $\mathcal{L}_{\ell,n} \log$ act as logarithmic derivatives and where

$$(\tau_\delta)_j = \tau_{j+1} \quad (\mathcal{L}_{\ell,n} \tau)_j = \mathcal{L}_{\ell,n}^j \tau_j \quad ((\mathcal{L}_{\ell,n})_\delta)_j = \mathcal{L}_{\ell,n}^{j+1}.$$

Corollary 3.2.1. *The following holds for $m \geq -1$:*

$$-\left(ML^{m+1} + \frac{m+1}{2} L^m \right)_b \Psi = \left(z^j \Psi_j \left((e^{-\eta} - 1) \frac{(J_m^{(2)} + 2jJ_m^{(1)} + j^2 J_m^{(0)}) \tau_j}{\tau_j} \right. \right.$$

$$\left. \left. + \frac{1}{2} \left(\frac{(J_m^{(2)} + 2jJ_m^{(1)} + j^2 J_m^{(0)}) \tau_j}{\tau_j} - \frac{(J_m^{(2)} + 2(j+1)J_m^{(1)} + (j+1)^2 J_m^{(0)}) \tau_{j+1}}{\tau_{j+1}} \right) \right) \right)_{j \in \mathbb{Z}},$$

where $J_\ell^{(i)}$ is defined in (3.5).

Remark that the statements of the theorem and the corollary are equally valid for semi-infinite matrices. Before giving the proof we need three lemmas.

Lemma 3.3. *The operator B_m defined in (3.8) interacts with $\eta = \sum_1^\infty \frac{z^{-i}}{i} \frac{\partial}{\partial t_i}$ and $\Sigma = \sum_1^\infty t_i z^i$ as follows¹²*

$$(3.14) \quad [B_m, \eta] = \sum_{k=1}^m z^{m-k} \frac{\partial}{\partial t_k} \quad \text{and} \quad B_m \Sigma = - \sum_{k=1}^{-m} z^{m+k} k t_k$$

$$[B_m, e^{-\eta}] = -e^{-\eta} [B_m, \eta];$$

thus

$$[B_m, \eta] = 0 \text{ when } m \leq 0 \text{ and } B_m \Sigma = 0 \text{ when } m \geq 0.$$

¹²with the understanding that

$$\sum_{j=1}^{\alpha} = 0 \quad \text{if } \alpha < 1.$$

Moreover given an arbitrary function $f(t_1, t_2, \dots)$ of $t \in \mathbb{C}^\infty$, define

$$(3.15) \quad \Phi = e^{\Sigma/2} \frac{e^{-\eta} f}{f}.$$

Then we have for $m \geq 0$

$$(3.16) \quad \begin{aligned} (i) \quad & -\frac{1}{2}z^{-m}\Phi = \Phi(e^{-\eta} - 1) \frac{W_{-m}^{(1)}(f)}{f}, \quad m > 0 \\ (ii) \quad & (B_{-m} + \frac{mt_m}{2})\Phi = \Phi(e^{-\eta} - 1) \frac{\bar{W}_{-m}^{(2)}(f)}{f}, \\ (iii) \quad & B_m\Phi = \Phi\left((e^{-\eta} - 1) \frac{(B_m - [B_m, \eta])f}{f} - \frac{[B_m, \eta]f}{f}\right). \end{aligned}$$

Proof: The first commutation relation (3.14) follows from a straightforward computation:

$$\begin{aligned} [B_m, \eta] &= \left[-z^{m+1} \frac{\partial}{\partial z}, \eta\right] + \left[\sum_{k > \max(-m, 0)} kt_k \frac{\partial}{\partial t_{k+m}}, \eta\right] \\ &= \sum_1^\infty z^{m-i} \frac{\partial}{\partial t_i} - \sum_1^\infty z^{-j} \frac{\partial}{\partial t_{j+m}} = \sum_1^m z^{m-i} \frac{\partial}{\partial t_i}. \end{aligned}$$

The third commutation relation (3.14) follows at once from the fact that the bracket $[B_m, \cdot]$ is a derivation and that $[[B_m, \eta], \eta]$. Also

$$B_m \Sigma = -\sum_1^\infty kt_k z^{k+m} + \sum_{k > \max(-m, 0)} kt_k z^{k+m} = -\sum_1^{\max(-m, 0)} kt_k z^{k+m}.$$

Next, given Φ defined as (3.15), we have that (using B_m is a derivation and (3.14)),

(3.17)

$$\begin{aligned} B_m \Phi &= B_m e^{\Sigma/2} \frac{e^{-\eta} f}{f} \\ &= \frac{e^{-\eta} f}{f} B_m e^{\Sigma/2} + e^{\Sigma/2} B_m \frac{e^{-\eta} f}{f} \\ &= \Phi\left((e^{-\eta} - 1) \frac{B_m f}{f} + \frac{1}{2} B_m \Sigma - e^{-\eta} \frac{[B_m, \eta]f}{f}\right) \\ &= \Phi\left((e^{-\eta} - 1) \frac{(B_m - [B_m, \eta])f}{f} + \frac{1}{2} B_m \Sigma - \frac{[B_m, \eta]f}{f}\right) \end{aligned}$$

which yields (3.16) (iii) for $m \geq 0$, taking into account the fact that $B_m \Sigma = 0$ for $m \geq 0$. Equation (3.16) (i) is straightforward, using $W_{-m}^{(1)} = \frac{1}{2} m t_m$.

Proving (3.16) (ii) is a bit more involved; indeed first observe that for $m \geq 0$

$$\begin{aligned} \tilde{W}_{-m}^{(2)} f &= \left(\sum_{n>m} n t_n \frac{\partial}{\partial t_{n-m}} + \frac{1}{4} \sum_{n=1}^{m-1} n t_n (m-n) t_{m-n} + \frac{1}{4} (m-1) m t_m \right) f \\ &= B_{-m} f + \frac{1}{4} \sum_{n=1}^{m-1} n t_n (m-n) t_{m-n} f + \frac{1}{4} (m-1) m t_m f; \end{aligned}$$

therefore

$$\begin{aligned} (3.19) \quad & (e^{-\eta} - 1) \frac{B_{-m}(f)}{f} \\ &= (e^{-\eta} - 1) \left(\frac{\tilde{W}_{-m}^{(2)} f}{f} - \frac{1}{4} \sum_{n=1}^{m-1} n t_n (m-n) t_{m-n} - \frac{1}{4} m(m-1) t_m \right) \\ &= (e^{-\eta} - 1) \frac{\tilde{W}_{-m}^{(2)}(f)}{f} \\ &\quad - \frac{1}{4} \sum_{n=1}^{m-1} n(m-n) \left(\left(t_n - \frac{1}{n} z^{-n} \right) \left(t_{m-n} - \frac{1}{m-n} z^{-m+n} \right) - t_n t_{m-n} \right) \\ &\quad - \frac{1}{4} m(m-1) \left(\left(t_m - \frac{1}{m} z^{-m} \right) - t_m \right) \\ &= (e^{-\eta} - 1) \frac{\tilde{W}_{-m}^{(2)}(f)}{f} + \frac{1}{2} \sum_{n=1}^{m-1} n t_n z^{n-m}. \end{aligned}$$

Using expression (3.17) for $B_m \Phi$, $-m \leq 0$, and $[B_m, \eta] = 0$ when $m \leq 0$, we find

$$\begin{aligned} \left(B_{-m} + \frac{m t_m}{2} \right) \Phi &= \Phi \left((e^{-\eta} - 1) \frac{B_{-m} f}{f} + \frac{1}{2} B_{-m} \Sigma + \frac{m t_m}{2} \right) \\ &= \Phi \left((e^{-\eta} - 1) \frac{B_{-m} f}{f} - \frac{1}{2} \sum_{k=1}^{m-1} z^{-m+k} k t_k \right), \text{ using (3.14)} \\ &= \Phi (e^{-\eta} - 1) \frac{\tilde{W}_{-m}^{(2)} f}{f}, \text{ using (3.19),} \end{aligned}$$

ending the proof of (3.14) (ii) and thus of Lemma 3.3.

Lemma 3.4. *The following holds ($\nu \equiv \varepsilon\partial = \text{diag}(\dots, \nu_i = i, \dots)$)*

$$(i) \quad (PL^2)_s = \nu L_s + L_-$$

$$(ii) \quad \frac{(PL^2)_s \Psi}{\Psi} = (e^{-\eta} - 1)(2\nu - I) \frac{\partial}{\partial t_1} \log \tau + \nu \left(z - \frac{\partial}{\partial t_1} \log \frac{\tau_s}{\tau} \right).$$

Proof: First consider

$$(3.20) \quad PL^{m+1} = S\varepsilon\partial^{m+1}S^{-1} = S\nu\partial^m S^{-1} = [S, \nu]\partial^m S^{-1} + \nu S\partial^m S^{-1} = [S, \nu]\partial^m S^{-1} + \nu L^m.$$

Since $\nu = \varepsilon\partial$ is diagonal, since $S \in \mathcal{D}_{-\infty, 0}$ and so $[S, \nu] \in \mathcal{D}_{-\infty, -1}$, we have

$$[S, \nu]\partial S^{-1} \in \mathcal{D}_{-\infty, 0} \quad \text{and thus} \quad ([S, \nu]\partial S^{-1})_s = 0.$$

This combined with the above observation leads to

$$(3.21) \quad \begin{aligned} (PL^2)_s &= (\nu L)_s = \nu L_{++} - (\nu L_{++})^\top \\ &= \nu L_{++} - L_- \nu \\ &= \nu(L_{++} - L_-) + \nu L_- - L_- \nu \\ &= \nu L_s + [\nu, L_-] \\ &= \nu L_s + L_-, \quad \text{since } [\nu, L_-] = L_-, \end{aligned}$$

since L_- just has a band one below the diagonal. In order to evaluate $(PL^2)_s \Psi$, we need to know $L_s \Psi$ and $L_- \Psi$. Anticipating (3.25), we have by (2.3) and (3.3)

$$\begin{aligned} \mathbb{Y}_{1,0} \Psi &= -L_b \Psi = 2\Psi(e^{-\eta} - 1) \frac{\partial}{\partial t_1} \log \tau - \Psi \frac{\partial}{\partial t_1} \log \frac{\tau_\delta}{\tau} \\ &= 2\Psi(e^{-\eta} - 1) \frac{\partial}{\partial t_1} \log \tau - L_0 \Psi, \quad \text{by (1.20),} \end{aligned}$$

and, since $L_b = 2L_- + L_0$,

$$(3.22) \quad L_- \Psi = \frac{1}{2}(L_b - L_0)\Psi = -\Psi(e^{-\eta} - 1) \frac{\partial}{\partial t_1} \log \tau,$$

whereas, using

$$\Psi = e^{\frac{1}{2}\Sigma t_i z^i} \left(z^j \gamma_j^{-1} \frac{\tau_j(t - [z^{-1}])}{\tau_j(t)} \right),$$

we have (using the logarithmic derivative)

$$(3.23) \quad L_s \Psi = 2 \frac{\partial \Psi}{\partial t_1} = 2\Psi(e^{-\eta} - 1) \frac{\partial}{\partial t_1} \log \tau + z\Psi - \Psi \frac{\partial}{\partial t_1} \log \frac{\tau_\delta}{\tau}.$$

Using these two formulas (3.22) and (3.23), in (3.21) we have

$$\begin{aligned} (PL^2)_s \Psi &= \nu L_s \Psi + L_- \Psi \\ &= \Psi(e^{-\eta} - 1)(2\nu - I) \frac{\partial}{\partial t_1} \log \tau + z\nu\Psi - \nu\Psi \frac{\partial}{\partial t_1} \log \frac{\tau_\delta}{\tau}. \end{aligned}$$

This lemma proves the main statement about symmetries for the $sl(2, \mathbb{C})$ part of the Virasoro symmetry algebra; this is the heart of the matter.

Lemma 3.5. *The vector fields $\{\mathbb{Y}_{-1,1}, \mathbb{Y}_{0,1}, \mathbb{Y}_{1,1}\}$ form a representation of $sl(2, \mathbb{C})$ and induce vector fields on τ as follows (in the notation (3.6)):*

$$(3.24) \quad \mathbb{Y}_{\ell,1} \log \Psi = \frac{-(ML^{\ell+1})_b \Psi}{\Psi} = (e^{-\eta} - 1) \frac{\mathcal{L}_{\ell,1}\tau}{\tau} + \frac{1}{2} \left(\frac{\mathcal{L}_{\ell,1}\tau}{\tau} - \left(\frac{\mathcal{L}_{\ell,1}\tau}{\tau} \right)_\delta \right)$$

for $\ell = -1, 0, 1$.

Also

$$(3.25) \quad \mathbb{Y}_{\ell,0} \log \Psi = \frac{-(L^\ell)_b \Psi}{\Psi} = (e^{-\eta} - 1) \frac{\mathcal{L}_{\ell,0}\tau}{\tau} + \frac{1}{2} \left(\frac{\mathcal{L}_{\ell,0}\tau}{\tau} - \left(\frac{\mathcal{L}_{\ell,0}\tau}{\tau} \right)_\delta \right)$$

for $\ell \in \mathbb{Z}$.

Proof of Lemma 3.5: Relation (3.25) will first be established for $\ell = -m < 0$:

$$\begin{aligned} \mathbb{Y}_{-m,0} \Psi &= -(L^{-m})_b \Psi = -L^{-m} \Psi, \quad \text{since } L^{-m} \in \mathcal{D}_b \text{ for } m \geq 0 \\ &= -z^{-m} \Psi \\ &= 2\gamma^{-1} \chi \left(-\frac{1}{2} z^{-m} \left(\frac{e^{\Sigma/2} e^{-\eta} \tau_n}{\tau_n} \right) \right)_{n \in \mathbb{Z}} \\ &= 2\Psi(e^{-\eta} - 1) \frac{W_{-m}^{(1)} \tau}{\tau}, \quad \text{applying (3.16)(i) componentwise to} \\ &\quad \Phi = e^{\Sigma/2} \frac{e^{-\eta} \tau_n}{\tau_n} \\ &= \Psi \left((e^{-\eta} - 1) \frac{2W_{-m}^{(1)} \tau}{\tau} + \frac{1}{2} \left(\frac{2W_{-m}^{(1)} \tau}{\tau} - \left(\frac{2W_{-m}^{(1)} \tau}{\tau} \right)_\delta \right) \right), \end{aligned}$$

the difference in brackets vanishing identically. The same will now be established for $\ell = m > 0$; indeed

$$\begin{aligned}
\mathbb{Y}_{m,0}\Psi &\equiv -(L^m)_b\Psi \\
&= (-L^m + (L^m)_s)\Psi \\
&= -z^m\Psi + 2\frac{\partial}{\partial t_m}\Psi, \quad \text{using (1.22)} \\
&= -z^m\Psi + z^m\Psi + 2e^{\Sigma/2}\chi\frac{\partial}{\partial t_m}\left(\frac{e^{-\eta}\tau}{\tau}\gamma^{-1}\right), \\
&\quad \text{using } \Psi = e^{\Sigma/2}\frac{e^{-\eta}\tau}{\tau}\gamma^{-1}\chi \\
&= 2e^{\Sigma/2}\chi\gamma^{-1}\frac{e^{-\eta}\tau}{\tau}\left((e^{-\eta}-1)\frac{\partial}{\partial t_m}\log\tau + \gamma\frac{\partial}{\partial t_m}\gamma^{-1}\right), \quad \text{using (3.3)} \\
&= \Psi\left((e^{-\eta}-1)\frac{2W_m^{(1)}\tau}{\tau} + \frac{1}{2}\left(\frac{2W_m^{(1)}\tau}{\tau} - \left(\frac{2W_m^{(1)}\tau}{\tau}\right)_\delta\right)\right) \\
&\quad \text{since } \gamma_j = \sqrt{\frac{\tau_{j+1}}{\tau_j}}, \text{ and } \gamma\frac{\partial}{\partial t_m}\gamma^{-1} = -\frac{\partial}{\partial t_m}\log\gamma.
\end{aligned}$$

Relation (3.25) for $\ell = 0$ is obvious, since

$$\frac{\mathbb{Y}_{0,0}\Psi}{\Psi} = \frac{-(L^0)_b\Psi}{\Psi} = -I = \frac{1}{2}(2\nu - 2(\nu)_\delta) = \frac{1}{2}\left(\frac{2\nu\tau}{\tau} - \left(\frac{2\nu\tau}{\tau}\right)_\delta\right) = \frac{1}{2}\left(\frac{\mathcal{L}_{0,0}\tau}{\tau} - \left(\frac{\mathcal{L}_{0,0}\tau}{\tau}\right)_\delta\right)$$

To prove (3.24), consider now

$$\begin{aligned}
(3.26) \quad &-(ML^{m+1})_b\Psi \\
&= (-ML^{m+1} + (ML^{m+1})_s)\Psi \\
&= \left(-z^{m+1}\frac{\partial}{\partial z} + \frac{1}{2}\sum_1^\infty kt_k(L^{k+m})_s + (PL^{m+1})_s\right)\Psi \\
&= \left(-z^{m+1}\frac{\partial}{\partial z} + \frac{1}{2}\sum_{k>\max(-m,0)} kt_k(L^{k+m})_s + (PL^{m+1})_s\right)\Psi, \quad \text{using (1.28)} \\
&\quad \text{since } (L^\alpha)_s = 0 \text{ for } \alpha \leq 0 \\
&= \left(-z^{m+1}\frac{\partial}{\partial z} + \sum_{k>\max(-m,0)} kt_k\frac{\partial}{\partial t_{k+m}}\right)\Psi + (PL^{m+1})_s\Psi \\
&= B_m\Psi + (PL^{m+1})_s\Psi \quad \text{using the definition (3.8) of } B_m, \\
&= (z^j\gamma_j^{-1}B_m(e^{\Sigma/2}\frac{e^{-\eta}\tau_j}{\tau_j}))_{j\in\mathbb{Z}} - z^m\nu\Psi - \Psi B_m\log\gamma + (PL^{m+1})_s\Psi,
\end{aligned}$$

remembering the definition (1.21) of Ψ , using the definition (3.8) of B_m , and using the fact that B_m is a derivation.

1. For $m = -1, 0$, we have

$$PL^{m+1} \in \mathcal{D}_{-\infty,0} \quad \text{and thus} \quad (PL^{m+1})_s = 0.$$

We set $m \mapsto -m$ with $m \geq 0$. Componentwise, the above expression reads, by adding and subtracting $mt_m/2$ ($m \geq 0$) and using definition (3.8) of B_{-m} and $\nu = \text{diag}(\dots, i, \dots)$:

$$\begin{aligned} & (- (ML^{-m+1})_b \Psi)_j \\ &= z^j \gamma_j^{-1} \left(B_{-m} + \frac{mt_m}{2} - jz^{-m} \right) e^{\Sigma/2} \frac{e^{-\eta} \tau_j}{\tau_j} - z^j \Psi_j \left(B_{-m} (\log \gamma_j) + \frac{mt_m}{2} \right) \\ &= z^j \gamma_j^{-1} \left(B_{-m} + \frac{mt_m}{2} + 2j(1 - \delta_{0,m}) \left(-\frac{z^{-m}}{2} \right) \right) \left(e^{\Sigma/2} \frac{e^{-\eta} \tau_j}{\tau_j} \right) \\ &\quad - z^j \Psi_j \left(B_{-m} \log \gamma_j + \frac{mt_m}{2} \right) - \frac{1}{2} z^j \Psi_j 2j \delta_{0,m} \\ &= z^j \Psi_j (e^{-\eta} - 1) \left(\frac{\tilde{W}_{-m}^{(2)}(\tau_j)}{\tau_j} + 2j \frac{W_{-m}^{(1)}(\tau_j)}{\tau_j} \right) \quad (\text{using (3.16)(i) and (ii)}) \\ &\quad + \frac{1}{2} z^j \Psi_j \left(-\frac{\tilde{W}_{-m}^{(2)}(\tau_{j+1})}{\tau_{j+1}} + \frac{\tilde{W}_{-m}^{(2)}(\tau_j)}{\tau_j} \right) \quad (\text{using } \gamma_j = \sqrt{\frac{\tau_{j+1}}{\tau_j}}, (3.9) \text{ and (3.7)}) \\ &\quad + \frac{1}{2} z^j \Psi_j \left(-2(j+1) \frac{W_{-m}^{(1)}(\tau_{j+1})}{\tau_{j+1}} + 2j \frac{W_{-m}^{(1)}(\tau_j)}{\tau_j} \right) \quad (\text{using } \frac{mt_m}{2} = W_{-m}^{(1)}) \\ &\quad + \frac{1}{2} z^j \Psi_j (-2j \delta_{0,m}) \\ &= z^j \Psi_j \left((e^{-\eta} - 1) \frac{(\tilde{W}_{-m}^{(2)} + 2jW_{-m}^{(1)} + (j^2 - j)W_{-m}^{(0)})\tau_j}{\tau_j} \right. \\ &\quad \left. + \frac{1}{2} \left(\frac{(\tilde{W}_{-m}^{(2)} + 2jW_{-m}^{(1)} + (j^2 - j)W_{-m}^{(0)})\tau_j}{\tau_j} \right. \right. \\ &\quad \left. \left. - \frac{(\tilde{W}_{-m}^{(2)} + 2(j+1)W_{-m}^{(1)} + ((j+1)^2 - (j+1))W_{-m}^{(0)})\tau_{j+1}}{\tau_{j+1}} \right) \right), \end{aligned}$$

since, in the last line, $-2j = (j^2 - j) - ((j+1)^2 - (j+1))$ and $\delta_{0,m} = W_{-m}^{(0)}$. Thus relation (3.24) for $m = -1$ and 0 follows from the simple observation (3.7) that $\tilde{W}_{-m}^{(2)} = W_{-m}^{(2)}$ for $m = 0, 1$.

2. For $m = 1$ in (3.24), we use the identities in Lemma 3.3(iii) and Lemma 3.4(ii) in (3.26):

$$\begin{aligned}
& -(ML^2)_\delta \Psi \\
&= \Psi(e^{-\eta} - 1) \frac{(B_1 - [B_1, \eta])\tau}{\tau} - \Psi \frac{[B_1, \eta]\tau}{\tau} - z\nu\Psi - \frac{1}{2}\Psi B_1 \log \frac{\tau_\delta}{\tau} + (PL^2)_s \Psi \\
&\quad \text{using (3.16)(iii)} \\
&= \Psi(e^{-\eta} - 1) \left(J_1^{(2)} - \frac{\partial}{\partial t_1} \right) \log \tau - \Psi \frac{\partial}{\partial t_1} \log \tau - z\nu\Psi - \frac{1}{2}\Psi J_1^{(2)} \log \frac{\tau_\delta}{\tau}, \\
&\quad + \Psi(e^{-\eta} - 1) (2\nu - I) \frac{\partial}{\partial t_1} \log \tau + z\nu\Psi - \nu\Psi \frac{\partial}{\partial t_1} \log \frac{\tau_\delta}{\tau} \\
&\quad \text{using (3.9), } [B_1, \eta] = \frac{\partial}{\partial t_1} \text{ (see (3.14)), and Lemma 3.4(ii),} \\
&= \Psi \left((e^{-\eta} - 1) \left(J_1^{(2)} + (2\nu - 2) \frac{\partial}{\partial t_1} \right) \log \tau + \frac{1}{2} \left(J_1^{(2)} + (2\nu - 2) \frac{\partial}{\partial t_1} \right) \log \tau \right. \\
&\quad \left. - \frac{1}{2} \left(J_1^{(2)} + 2\nu \frac{\partial}{\partial t_1} \right) \log \tau_\delta \right), \\
&= \Psi \left((e^{-\eta} - 1) \frac{\mathcal{L}_{1,1}\tau}{\tau} + \frac{1}{2} \left(\frac{\mathcal{L}_{1,1}\tau}{\tau} - \left(\frac{\mathcal{L}_{1,1}\tau}{\tau} \right)_\delta \right) \right),
\end{aligned}$$

using in the last line, the definition (3.6) of $\mathcal{L}_{1,1}$ and $\mathcal{L}_{1,1}^{j+1}\tau_{j+1} = ((\mathcal{L}_{1,1}\tau)_\delta)_j$, establishing (3.24) for $m = 1$, thus ending the proof of Lemma 3.5.

Proof of Theorem 3.2: The only remaining point is to establish (3.13) for $n = 1$ and all $\ell \leq 2$. To do this we use the underlying Lie algebra structure. First we have the following identity, using (3.2) and (3.1),

$$\begin{aligned}
& (e^{-\eta} - 1) \left[\hat{\mathbb{Y}}_{z^\alpha(\frac{\partial}{\partial z})^\beta}, \hat{\mathbb{Y}}_{z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}} \right] \log \tau_n + \frac{1}{2} \left[\hat{\mathbb{Y}}_{z^\alpha(\frac{\partial}{\partial z})^\beta}, \hat{\mathbb{Y}}_{z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}} \right] \log \frac{\tau_n}{\tau_{n+1}} \\
&= \left[\mathbb{Y}_{z^\alpha(\frac{\partial}{\partial z})^\beta}, \mathbb{Y}_{z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}} \right] \log \Psi_n \\
&= \mathbb{Y}_{\left[z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}, z^\alpha(\frac{\partial}{\partial z})^\beta \right]} \log \Psi_n \\
&= (e^{-\eta} - 1) \hat{\mathbb{Y}}_{\left[z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}, z^\alpha(\frac{\partial}{\partial z})^\beta \right]} \log \tau_n + \frac{1}{2} \hat{\mathbb{Y}}_{\left[z^{\alpha'}(\frac{\partial}{\partial z})^{\beta'}, z^\alpha(\frac{\partial}{\partial z})^\beta \right]} \log \frac{\tau_n}{\tau_{n+1}}.
\end{aligned}$$

The terms containing $(e^{-\eta} - 1)$ in the first and last expressions are power series in z^{-1} , with no constant term; the second terms are independent of z . Therefore, equating constant terms yield:

$$(i) \quad \left(\left[\hat{Y}_{z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta}, \hat{Y}_{z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}} \right] - \hat{Y}_{\left[z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}, z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta \right]} \right) \log \frac{\tau_n}{\tau_{n+1}} = 0$$

and thus also

$$(e^{-\eta} - 1) \left(\left[\hat{Y}_{z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta}, \hat{Y}_{z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}} \right] - \hat{Y}_{\left[z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}, z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta \right]} \right) \log \tau_n = 0.$$

Since $(e^{-\eta} - 1)f = 0$ implies $f = \text{constant}$, there exists a constant c depending on $\alpha, \beta, \alpha', \beta'$ and n such that

$$(ii) \quad \left(\left[\hat{Y}_{z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta}, \hat{Y}_{z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}} \right] - \hat{Y}_{\left[z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}, z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta \right]} \right) \log \tau_n = c_{\alpha\beta\alpha'\beta'}, n;$$

relation (i) says $c_{\alpha\beta\alpha'\beta'}$ is independent of n ; hence (ii) reads

The two relations (i) and (ii) combined imply

$$(3.27) \quad \left(\left[\hat{Y}_{z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta}, \hat{Y}_{z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}} \right] - \hat{Y}_{\left[z^{\alpha'} \left(\frac{\partial}{\partial z} \right)^{\beta'}, z^\alpha \left(\frac{\partial}{\partial z} \right)^\beta \right]} - c_{\alpha\beta\alpha'\beta'} \right) \tau_n = 0$$

with

$$c_{\alpha\beta\alpha'\beta'} \quad \text{independent of } n.$$

Applying (3.27) to

$$\left[z^{m+1} \frac{\partial}{\partial z}, z^\ell \right] = \ell z^{m+\ell} \quad \text{and} \quad \left[z^{\ell+1} \frac{\partial}{\partial z}, z^{m+1} \frac{\partial}{\partial z} \right] = (m - \ell) z^{m+\ell+1} \frac{\partial}{\partial z},$$

leads to

$$(3.28) \quad \left(\left[\hat{Y}_{\ell,0}, \hat{Y}_{m,1} \right] - \ell \hat{Y}_{\ell+m,0} - c_{\ell,m} \right) \tau_n = 0$$

and

$$\left(\left[\hat{Y}_{m,1}, \hat{Y}_{\ell,1} \right] - (m - \ell) \hat{Y}_{m+\ell,1} - c'_{m,\ell} \right) \tau_n = 0.$$

By virtue of (3.12), we have

$$(3.29) \quad \left[\mathcal{L}_{\ell,0}, \mathcal{L}_{m,1} \right] - \ell \mathcal{L}_{m+\ell,0} - \text{constant} = 0.$$

According to (3.25) we have

$$\hat{Y}_{\ell,0} = \mathcal{L}_{\ell,0}$$

implying by subtracting (3.29) from (3.28)

$$[\mathcal{L}_{\ell,0}, \hat{Y}_{m,1} - \mathcal{L}_{m,1}] = \text{constant, for } \ell, m \in \mathbb{Z}, m \geq -1.$$

The only operator commuting (modulo constant) with all $\mathcal{L}_{\ell,0} = 2\frac{\partial}{\partial t_1} + (-\ell)t_{-\ell}$ is given by linear combinations of a constant, t_α and $\partial/\partial t_\alpha$, i.e.:

$$(3.30) \quad \begin{aligned} \tilde{Y}_{m,1} - \mathcal{L}_{m,1} &= \sum_{j=-\infty}^{\infty} c_j^{(m)} J_{j+m}^{(1)}, \text{ for } m \geq 2, \quad (c_{-m}^{(m)} = 0) \\ &= 0 \text{ for } m = -1, 0, 1. \end{aligned}$$

Putting $\tilde{Y}_{m,1}$ from (3.30) into the second relation of (3.28) implies (modulo constants)

$$\left[\mathcal{L}_{m,1} + \sum_{j=-\infty}^{\infty} c_j^{(m)} J_{j+m}^{(1)}, \mathcal{L}_{\ell,1} + \sum_{j=-\infty}^{\infty} c_j^{(\ell)} J_{j+\ell}^{(1)} \right] = (m - \ell)(\mathcal{L}_{m+\ell,1} + \sum c_j^{(m+\ell)} J_{j+m+\ell}^{(1)})$$

which also equals by explicit computation, using (3.12):

$$= (m - \ell)\mathcal{L}_{m+\ell,1} - \sum c_j^{(\ell)} (j + \ell) J_{m+j+\ell}^{(1)} + \sum c_j^{(m)} (j + m) J_{m+j+\ell}^{(1)}.$$

Comparing the coefficients of the $J^{(1)}$'s in two expressions on the right hand side yields

$$(3.31) \quad (m - \ell)c_j^{(m+\ell)} = (m + j)c_j^{(m)} - (\ell + j)c_j^{(\ell)} \quad \text{provided } m + j + \ell \neq 0$$

with $c_j^{(m)} = 0$ for $m = -1, 0, 1$, all $j \in \mathbb{Z}$.

Setting $\ell = 0$ in (3.31), yields

$$j(c_j^{(m)} - c_j^{(0)}) = 0 \quad \text{and thus } c_j^{(m)} = c_j^{(0)} \quad \text{for } j \neq 0, -m,$$

implying

$$c_j^{(m)} = 0 \quad \text{all } m \geq -1 \quad \text{and } j \neq 0, -m.$$

Also, setting $j = 0$ and $\ell = -1$ in (3.31) yields

$$m c_0^{(m)} = (m + 1)c_0^{(m-1)} - c_0^{(-1)}, \quad \text{for } m \geq 2,$$

implying by induction, since $c_0^{(-1)} = c_0^{(1)} = 0$

$$c_0^{(m)} = 0 \quad \text{for all } m \geq -1,$$

concluding the proof.

Proof of Corollary 3.2.1: According to theorem 3.2, the vector field

$$\mathbb{Y}_{m,1} + \frac{m+1}{2}\mathbb{Y}_{m,0} = -(ML^{m+1} + \frac{m+1}{2}L^m)_b,$$

acting on Ψ , induces on τ_j the vector field

$$\begin{aligned} \mathcal{L}_{m,1}^j + \frac{m+1}{2}\mathcal{L}_{m,0}^j &= J_m^{(2)} + (2j - m - 1)J_m^{(1)} + (j^2 - j)\delta_{m,0} \\ &\quad + \frac{m+1}{2}(2J_m^{(1)} + 2j\delta_{m,0}) \\ &= J_m^{(2)} + 2jJ_m^{(1)} + j^2J_m^{(0)} \end{aligned}$$

establishing the corollary.

4 Orthogonal polynomials, matrix integrals, skew-symmetric matrices and Virasoro constraints

Remember from the introduction the orthogonal (orthonormal) polynomial basis of $\mathcal{H}^+ = \{1, z, z^2, \dots\}$ on the interval $[a, b]$, $-\infty \leq a < b \leq \infty$,

(4.1)

$$\tilde{p}_r(t, z) = z^r + \dots \text{ (monic) and } p_r(t, z) = \frac{1}{\sqrt{h_r(t)}}\tilde{p}_r(t, z) \text{ (orthonormal), } r \geq 0,$$

with regard to the t-dependent inner product (via the exponential $e^{\sum t_i z^i}$):

$$(4.2) \quad \langle u, v \rangle_t = \int_a^b uv \rho_t dz, \text{ with } \rho_t(z) = e^{-V_0(z) + \sum_1^\infty t_i z^i} = \rho_0(z) e^{\sum t_i z^i};$$

i.e.,

$$\langle \tilde{p}_i, \tilde{p}_j \rangle_t = h_i \delta_{ij} \text{ and } \langle p_i, p_j \rangle_t = \delta_{ij}.$$

Then the semi-infinite vector (of \langle, \rangle_0 -orthonormal functions)

$$(4.3) \quad \Psi(t, z) := e^{\frac{1}{2}\sum t_i z^i} p(t, z) := e^{\frac{1}{2}\sum t_i z^i} (p_0(t, z), p_1(t, z), \dots)^\top,$$

satisfies the orthogonality relations

$$(4.4) \quad \langle (\Psi(t, z))_i, (\Psi(t, z))_j \rangle_0 = \langle p_i(t, z), p_j(t, z) \rangle_t = \delta_{ij},$$

The weight is assumed to have the following property¹³:

$$(4.5) \quad -\frac{\rho'_0}{\rho_0} = V'_0 = \frac{\sum_0^\infty b_i z^i}{\sum_0^\infty a_i z^i} = \frac{h_0(z)}{f_0(z)} \quad \text{with} \quad \rho_0(a)f_0(a)a^k = \rho_0(b)f_0(b)b^k = 0, \quad k \geq 0.$$

Define semi-infinite matrices L and P such that

$$(4.6) \quad zp(t, z) = L(t)p(t, z), \quad \frac{\partial}{\partial z}p(t, z) = Pp(t, z)$$

The ideas of Theorem 4.1 are due to Bessis-Itzykson-Zuber [BIZ] and Witten [W].

Theorem 4.1. *The semi-infinite vector $\Psi(t, z)$ and the semi-infinite matrices $L(t)$ (symmetric), and $M(t) := P(t) + \frac{1}{2} \sum_1^\infty kt_k L^{k-1}$, satisfy*

$$(4.7) \quad z\Psi(t, z) = L(t)\Psi(t, z), \quad \text{and} \quad \frac{\partial}{\partial z}\Psi(t, z) = M\Psi(t, z)$$

and

$$(4.8) \quad \frac{\partial L}{\partial t_n} = \frac{1}{2}[(L^n)_s, L], \quad \frac{\partial M}{\partial t_n} = \frac{1}{2}[(L^n)_s, M], \quad \text{and} \quad \frac{\partial \Psi}{\partial t_n} = \frac{1}{2}(L^n)_s \Psi;$$

the wave vector $\Psi(t, z)$ and the L^2 -norms $h_n(t)$ admit the representation

$$(4.9) \quad \Psi(t, z) = e^{\frac{1}{2}\Sigma t_i z^i} \left(z^n \frac{\tau_n(t - [z^{-1}])}{\sqrt{\tau_n(t)\tau_{n+1}(t)}} \right)_{n \geq 0} \quad \text{and} \quad h_n(t) = \frac{\tau_{n+1}(t)}{\tau_n(t)}$$

with

$$(4.10) \quad \tau_n(t) = \frac{1}{\Omega_n n!} \int_{\mathcal{M}_n(a, b)} e^{-\text{Tr} V_0(Z) + \Sigma t_i \text{Tr} Z^i} dZ;$$

the integration is taken over the space $\mathcal{M}_n(a, b)$ of $n \times n$ Hermitean matrices with eigenvalues $\in [a, b]$.

¹³the choice of f_0 is not unique. When V'_0 is rational, then picking $f_0 =$ (polynomial in the denominator) is a canonical choice.

Proof: Step 1. Suppose $\dot{\Psi} = \mathcal{B}\Psi$ and $P(z, \frac{\partial}{\partial z})\Psi = \mathcal{P}\Psi$ where \mathcal{B} and \mathcal{P} are matrices and P is a polynomial with constant coefficients. Then

$$\dot{\mathcal{P}} = [\mathcal{B}, \mathcal{P}].$$

Indeed, this follows from differentiating $P(z, \frac{\partial}{\partial z})\Psi = \mathcal{P}\Psi$, and observing that

$$P\mathcal{B}\Psi = P\dot{\Psi} = \dot{\mathcal{P}}\Psi + \mathcal{P}\dot{\Psi} = \dot{\mathcal{P}}\Psi + \mathcal{P}\mathcal{B}\Psi.$$

Step 2. The matrix $L \in \mathcal{D}_{-\infty, 1}$ is symmetric because the operation of multiplication by z is symmetric with respect to \langle, \rangle on \mathcal{H}^+ and is represented by L in the basis p_i . Moreover, $P \in \mathcal{D}_{-\infty, -1}$ and $[L, P] = [L, M] = 1$. Also for $k \geq 0$,

$$(4.11) \quad \frac{\partial \Psi}{\partial z} = \frac{\partial p}{\partial z} e^{\frac{1}{2} \sum_1^\infty t_i z^i} + \frac{1}{2} \sum_1^\infty i t_i z^{i-1} p e^{\frac{1}{2} \sum_1^\infty t_i z^i} = \left(P + \frac{1}{2} \sum i t_i L^{i-1} \right) \Psi = M\Psi.$$

establishing (4.7).

Step 3. We now prove the first statement of (4.8). Since $\partial p_k / \partial t_i$ is again a polynomial of the same degree as p_k , we have:

$$(4.12) \quad \frac{\partial p_k}{\partial t_i} = \sum_{0 \leq \ell \leq k} A_{k\ell}^{(i)} p_\ell, \quad A^{(i)} \in \mathcal{D}_b.$$

The precise nature of $A^{(i)}$ is found as follows: for $\ell < k$,

$$\begin{aligned} 0 &= \frac{\partial}{\partial t_i} \int p_k(z) p_\ell(z) \rho_t(z) dz \\ &= \int \frac{\partial p_k}{\partial t_i} p_\ell \rho_t(z) dz + \int p_k \frac{\partial p_\ell}{\partial t_i} \rho_t(z) dz + \int dz \left(\frac{\partial}{\partial t_i} e^{-V_0 + \sum t_j z^j} \right) p_k p_\ell, \quad \text{using } \langle p_i, p_j \rangle = \delta_{ij} \\ &= \int \sum_{j \leq k} A_{kj}^{(i)} p_j p_\ell \rho_t(z) dz + \int \sum_j (L^i)_{kj} p_j p_\ell, \quad \text{using (4.12) and (4.6)} \\ &= A_{k\ell}^{(i)} + (L^i)_{k\ell} \end{aligned}$$

and for $\ell = k$,

$$\begin{aligned} 0 &= \frac{\partial}{\partial t_i} \int (p_k(z))^2 \rho_t(z) dz = 2 \int \sum_{m \leq k} A_{km}^{(i)} p_m p_k \rho_t(z) dz + \int \sum_j (L^i)_{kj} p_j p_k \rho_t(z) dz \\ &= 2A_{kk}^{(i)} + (L^i)_{kk}, \end{aligned}$$

implying

$$(4.13) \quad A^{(i)} = -(L^i)_- - \frac{1}{2}(L^i)_0 = -\frac{1}{2}(L^i)_b,$$

and thus

$$\frac{\partial \Psi}{\partial t_i} = \frac{\partial}{\partial t_i} e^{\Sigma/2} p = \frac{1}{2} e^{\Sigma/2} z^i p - \frac{1}{2} e^{\Sigma/2} (L^i)_b p = \frac{1}{2} (L^i - (L^i)_b) \Psi = \frac{1}{2} (L^i)_s \Psi.$$

Now using step 1, we have immediately (4.8). So Ψ satisfies the Toda equations (1.16) and behaves asymptotically as:

$$(4.14) \quad \Psi = e^{\frac{1}{2}\Sigma t_i z^i} \left(\frac{1}{\sqrt{h_n}} z^n (1 + O(z^{-1})) \right)_{n \in \mathbb{Z}}$$

Therefore in view of (1.15), we must have

$$\sqrt{h_n} = \gamma_n = \sqrt{\frac{\tau_{n+1}}{\tau_n}}.$$

Step 4. The integration (4.10) is taken with respect to the invariant measure

$$(4.15) \quad dZ = \prod_{1 \leq i \leq n} dZ_{ii} \prod_{1 \leq i < j \leq n} d(\operatorname{Re} Z_{ij}) d(\operatorname{Im} Z_{ij}).$$

Since the integrand only depends on the spectrum of Z and since the measure separates into an “angular” and a “radial” part, one first integrates out the former, accounting for the Ω_n and next the latter, in terms of the monic orthogonal polynomials \tilde{p}_i :

$$(4.16) \quad \begin{aligned} I_n &= \Omega_n \int_{[a,b]^n} dz_1 \dots dz_n \prod_{1 \leq i < j \leq n} (z_i - z_j)^2 \prod_{i=1}^n e^{-V(z_i)}, \\ &= \Omega_n \int_{[a,b]^n} dz_1 \dots dz_n (\det(\tilde{p}_{i-1}(z_j))_{1 \leq i \leq j \leq n})^2 \prod_{i=1}^n e^{-V(z_i)} \\ &= \Omega_n n! \int_a^b d\mu(z_1) \tilde{p}_0(z_1)^2 \int_a^b d\mu(z_2) \tilde{p}_1(z_2)^2 \dots \int_a^b d\mu(z_n) \tilde{p}_{n-1}(z_n)^2 \\ &= \Omega_n n! h_0 \dots h_{n-1} \\ &= \Omega_n n! \tau_0 \frac{\tau_1}{\tau_0} \frac{\tau_2}{\tau_1} \dots \frac{\tau_n}{\tau_{n-1}} = \Omega_n n! \tau_n, \text{ using } \tau_0 = 1 \end{aligned}$$

ending the proof of Theorem 4.1.

Next we show that the wave vector constructed from the orthogonal polynomial basis is a fixed point for an algebra of symmetries, which in turn implies Virasoro-like constraints on τ . The skew-symmetry of the matrix Q below had been pointed out by E. Witten [W] in the context of Hermite polynomials. The Virasoro constraints for the matrix integrals with the weight $\rho_0 = e^{-z^2}$ had been computed by E. Witten [W], Gerasimov, Marshakov, Mironov, Morozov and Orlov [GMMMO]; they relate to the deformations of Hermite polynomials. The case of deformations of Laguerre polynomials was worked out by Haine & Horozov [HH] and applied to questions of highest weight representation of the Virasoro algebra.

Theorem 4.2. *Consider the semi-infinite wave vector $\Psi(t, z)$, arising in the context of orthogonal polynomials with a weight $\rho_t(z)$ as in (4.2) and satisfying (4.5). Then $\Psi(t, z)$ is a fixed point for a Lie algebra of symmetry vector fields; that is*

$$(4.17) \quad \mathbb{V}_m \Psi := -(V_m)_b \Psi = 0, \quad \text{for } m \geq -1;$$

the symmetries \mathbb{V}_m form a (non-standard) representation of $\text{Diff}(S^1)^+$:

$$(4.18) \quad [\mathbb{V}_m, \mathbb{V}_n] = (m - n) \sum_{i \geq 0} a_i \mathbb{V}_{m+n+i}, \quad -1 \leq n, m < \infty,$$

and are defined by the semi-infinite matrices^{14 15}

$$(4.19) \quad V_m := \{Q, L^{m+1}\} = QL^{m+1} + \frac{m+1}{2} L^m f_0(L), \quad \text{with } Q := Mf_0(L) + g_0(L),$$

which are skew-symmetric on the locus of $\Psi(t, z)$ above. Moreover Q is a solution of the “string equation”

$$(4.20) \quad [L, Q] = f_0(L),$$

and the τ -vector satisfies the Virasoro constraints

$$(4.21) \quad \mathcal{V}_m^{(n)} \tau_k = \sum_{i \geq 0} \left(a_i (J_{i+m}^{(2)} + 2n J_{i+m}^{(1)} + n^2 J_{i+m}^{(0)}) - b_i (J_{i+m+1}^{(1)} + n J_{i+m+1}^{(0)}) \right) \tau_n = 0,$$

$$\text{for } m = -1, 0, 1, \dots, \quad n = 0, 1, 2, \dots,$$

with the $\mathcal{V}_m^{(n)}$, $m \geq -1$ (for fixed $n \geq 0$) satisfying the same Virasoro relations as (4.18), except for an additive constant.

¹⁴in terms of the anticommutator (0.20)

¹⁵set $g_0 := \frac{(f_0 \rho_0)'}{2\rho_0} = \frac{f_0 - h_0}{2}$, with $h_0 := -\frac{f_0 \rho_0'}{\rho_0}$

In preparation of the proof we give some elementary lemmas.

Lemma 4.3. Consider operators S_1 and S_f acting on a suitable space of functions of z , such that $[S_1, z] = 1$ and $S_f = \sqrt{f}S_1\sqrt{f}$; then the following holds¹⁶:

- (i) $S_f = \{S_1, f\}$ and $[S_f, z] = f$,
- (ii) $[\{S_1, h_1\}, \{S_1, h_2\}] = \{S_1, (h_1, h_2)\}$
- (iii) $\{S_1, h_1 h_2\} = \{\{S_1, h_1\}, h_2\} = \{\{S_1, h_2\}, h_1\}$
- (iv) $[\{S_1, fz^{m+1}\}, \{S_1, fz^{n+1}\}] = (n-m)\{S_1, f^2z^{m+n+1}\} = (n-m)\{\{S_1, fz^{m+n+1}\}, f\}$
- (v) the operators $\{S_1, z^{m+1}\}$, $m \in \mathbb{Z}$ form a representation of $\text{Diff}(S^1)$,

$$[\{S_1, z^{m+1}\}, \{S_1, z^{n+1}\}] = (n-m)\{S_1, z^{m+n+1}\}$$

(vi) given $f(z) = \sum_{i \geq 0} a_i z^i$, the $\{S_1, fz^{m+1}\}$, $m \in \mathbb{Z}$ also form a representation of $\text{Diff}(S')$:

$$[\{S_1, fz^{m+1}\}, \{S_1, fz^{n+1}\}] = (n-m) \sum_{i \geq 0} a_i \{S_1, fz^{m+n+i+1}\},$$

the map to the standard generators, $f^{-1}(z) = \sum_{i \geq -k} \bar{a}_i z^i$,

$$\{S_1, fz^{m+1}\} \mapsto \{S_1, z^{m+1}\} = \{S_1, f^{-1} \cdot fz^{m+1}\} = \sum_{i \geq -k} \bar{a}_i \{S_1, fz^{m+i+1}\}.$$

Proof: $[S_1, z] = 1$ implies $[S_1, z^n] = nz^{n-1}$, since $[S_1, \cdot]$ is a derivation, and thus $[S_1, h] = h'$, which leads to

$$S_f = \sqrt{f}S_1\sqrt{f} = \sqrt{f}[S_1, \sqrt{f}] + fS_1 = \frac{1}{2}(2fS_1 + f') = \frac{1}{2}(2fS_1 + [S_1, f]) = \{S_1, f\}.$$

The second part of (i), (ii) and (iii) follows by direct computation; (iv) is an immediate consequence of (ii), (iii) and the Wronskian identity

$$(fz^{m+1}, fz^{n+1}) = (n-m)f^2z^{m+n+1}.$$

The Virasoro relations (v) follow immediately from (iv), whereas (vi) follows from the argument:

$$[\{S_1, fz^{m+1}\}, \{S_1, fz^{n+1}\}] = (n-m)\{S_1, f^2z^{m+n+1}\}$$

¹⁶ $(h_1, h_2) = h_1h_2' - h_2h_1'$ denotes the Wronskian

$$\begin{aligned}
&= (n - m) \{ \{ S_1, f z^{m+n+1} \}, f \}, \quad \text{by (iv)} \\
&= (n - m) \sum_{i \geq 0} a_i \{ \{ S_1, f z^{m+n+1} \}, z^i \} \\
&= (n - m) \sum_{i \geq 0} a_i \{ S_1, f z^{m+n+i+1} \}, \quad \text{by (iii)}
\end{aligned}$$

ending the proof of lemma 4.3.

Lemma 4.4. Consider the function space $\mathcal{H} = \{\dots, z^{-1}, 1, z, \dots\}$ with a real inner product $\langle u, v \rangle_\rho = \int_a^b u v \rho dz$, $-\infty \leq a < b \leq \infty$ with regard to the weight ρ , with $\rho(a) = \rho(b) = 0$; also consider an arbitrary function $f = \sum_{i \geq 0} a_i z^i$ with $f(a)\rho(a)a^m = f(b)\rho(b)b^m = 0$, for $m \in \mathbb{Z}$. Then the first-order differential operator from \mathcal{H} to \mathcal{H}

$$S = f \frac{d}{dz} + g,$$

is skew-symmetric for $\langle \cdot, \cdot \rangle_\rho$ if and only if S takes on the form

$$(4.22) \quad S = \sqrt{\frac{f}{\rho}} \frac{d}{dz} \sqrt{f\rho} = \{S_1, f\}, \quad \text{where } S_1 = \frac{1}{\sqrt{\rho}} \frac{d}{dz} \sqrt{\rho} = \frac{d}{dz} + \frac{1}{2} \frac{\rho'}{\rho}$$

So, the operators $\{S_1, z^{m+1}\}$ and $\{S_1, f z^{m+1}\}$, for $m \in \mathbb{Z}$, form representations of $\text{Diff}(S^1)$ in the space of skew-symmetric operators $so(\mathcal{H}, \langle \cdot, \cdot \rangle_\rho)$.

Proof: First compute the expressions:

$$\begin{aligned}
\langle Su, v \rangle &= \int_a^b f \frac{du}{dz} v \rho dz + \int_a^b g u v \rho dz \\
&= u v f \rho \Big|_a^b - \int_a^b u \frac{d}{dz} (v f \rho) dz + \int_a^b g u v \rho dz \\
&= \int_a^b \rho u \left[\rho^{-1} \left(-\frac{d}{dz} f + g \right) (\rho v) \right] dz, \quad \text{using } f \rho(a) = f \rho(b) = 0
\end{aligned}$$

and

$$\langle u, Sv \rangle = \int_a^b \rho u \left(f \frac{d}{dz} + g \right) v dz.$$

Imposing S skew, i.e., $\langle Su, v \rangle = \langle u, S^T v \rangle = -\langle u, Sv \rangle$, leads to the operator identity

$$\rho^{-1} \left(-\frac{d}{dz} f + g \right) \rho = -\left(f \frac{d}{dz} + g \right),$$

in turn, leading to $g = \frac{1}{2} \rho^{-1} (f \rho)'$; thus S takes on the form (4.22). The last part of the proof of Lemma 4.4 follows at once from the above and Lemma 4.3 (iv) and (v).

Lemma 4.5. Consider the above inner-product $\langle u, v \rangle$ in the space $\mathcal{H}^+ = \{1, z, z^2, \dots\}$, for the weight ρ having a representation of the form

$$(4.23) \quad -\frac{\rho'}{\rho} = \frac{\sum_{i \geq 0} b_i z^i}{\sum_{i \geq 0} a_i z^i} \equiv \frac{h}{f}.$$

Let \mathcal{H}^+ have an orthonormal basis of functions $(\varphi_k)_{k \geq 0}$; then the operators $\{S_1, fz^{m+1}\}$ for $m \geq -1$ are maps from \mathcal{H}^+ to \mathcal{H}^+ and its representing matrices in that basis (i.e., $(\langle \{S_1, fz^{m+1}\} \varphi_k, \varphi_\ell \rangle)_{k, \ell \geq 0}$), for $m \geq -1$ form a closed Lie algebra $\subset so(0, \infty)$ ¹⁷.

Remark: The operators $\{S_1, z^{m+1}\}$ do not map \mathcal{H}^+ in \mathcal{H}^+ .

Proof: The operators,

$$\{S_1, fz^{m+1}\} = \{\{S_1, f\}, z^{m+1}\} : \mathcal{H} \rightarrow \mathcal{H}, \quad \text{for } m \geq -1,$$

which are skew-symmetric by Lemma 4.4, preserve the subspace \mathcal{H}^+ , since by virtue of (4.22),

$$(4.24) \quad \{S_1, f\} = f \frac{d}{dz} + \frac{(f \cdot \rho)'}{2\rho} = f \frac{d}{dz} + \frac{f' - h}{2}$$

contains holomorphic series f and $f' - h$, by (4.23). In a basis of functions $(\varphi_k)_{k \geq 0}$, orthonormal with respect to \langle, \rangle_ρ , the corresponding matrices will also be skew-symmetric.

Proof of Theorem 4.2: According to Lemma 4.5, the operators

$$(4.25) \quad T_m := T_m^{(\rho_0, f_0)} := \left\{ \frac{1}{\sqrt{\rho_0}} \frac{d}{dz} \sqrt{\rho_0}, f_0 z^{m+1} \right\} = \left\{ \left\{ \frac{1}{\sqrt{\rho_0}} \frac{d}{dz} \sqrt{\rho_0}, f_0 \right\}, z^{m+1} \right\}, \quad m \geq -1$$

map \mathcal{H}^+ into \mathcal{H}^+ and form an algebra with structure constants:

$$(4.26) \quad [T_m, T_n] = (n - m) \sum_{i \geq 0} a_i T_{m+n+i}, \quad m, n \geq -1.$$

Under the map ϕ (Theorem 2.2), the operators T_m get transformed into matrices $V_m = \phi(T_m)$, such that

$$(4.27) \quad T_m \Psi(t, z) = V_m \Psi(t, z);$$

¹⁷ $so(0, \infty)$ denotes the Lie algebra of semi-infinite skew-symmetric matrices.

namely (see footnote 15)

(4.28)

$$Q := V_{-1} = \phi(T_{-1}) = \phi\left(\left\{\frac{1}{\sqrt{\rho_0}}\frac{d}{dz}\sqrt{\rho_0}, f_0\right\}\right) = \phi\left(f_0\frac{d}{dz} + g_0\right) = Mf_0(L) + g_0(L)$$

and

$$\begin{aligned} (4.29) \quad V_m &:= \phi(T_m) \\ &= \phi(\{T_{-1}, z^{m+1}\}) \\ &= \phi\left(z^{m+1}T_{-1} + \frac{1}{2}[T_{-1}, z^{m+1}]\right) \\ &= \phi\left(z^{m+1}T_{-1} + \frac{1}{2}\left[f_0\frac{d}{dz}, z^{m+1}\right]\right) \\ &= \phi\left(z^{m+1}T_{-1} + \frac{m+1}{2}f_0z^{m+1}\right) \\ &= QL^{m+1} + \frac{m+1}{2}L^m f_0(L) \\ &= \sum_{i \geq 0} a_i ML^{i+m+1} + \sum_{i \geq 0} \frac{(i+1)a_{i+1} - b_i}{2} L^{i+m+1} + \frac{m+1}{2} \sum_{i \geq 0} a_i L^{i+m} \\ &= \sum_{i \geq 0} a_i \left(ML^{i+m+1} + \frac{i+m+1}{2}L^{i+m}\right) - \sum_{i \geq 0} \frac{b_i}{2} L^{i+m+1}, \end{aligned}$$

where we used

$$f_0 = \sum_{i \geq 0} a_i z^i \quad \text{and} \quad g_0 = \frac{(f_0 \rho_0)'}{2\rho_0} = \frac{1}{2} \sum_{i \geq 0} ((i+1)a_{i+1} - b_i) z^i.$$

In addition, according to Lemma 4.5, the z -operators T_m are skew-symmetric with regard to \langle, \rangle_0 and thus form a representation of $\text{Diff}(S^1)^+$

$$\text{Diff}(S^1)^+ \longrightarrow so(\mathcal{H}^+, \langle, \rangle_0) := \left\{ \begin{array}{l} \text{skew-symmetric operators} \\ \text{on } \mathcal{H}^+, \langle, \rangle_0 \end{array} \right\},$$

with structure constants given by (4.18). The components $e^{\sum t_i z^i} p_n(t, z)$, $n \geq 0$ of $\Psi(t, z)$ form an orthonormal basis of \mathcal{H}^+ , \langle, \rangle_0 , with regard to which the operators T_m are represented by semi-infinite skew-symmetric matrices; i.e., the anti-homomorphism ϕ restricts to the following map

$$\phi : so(\mathcal{H}^+, \langle, \rangle_0) \longrightarrow so(0, \infty) \quad (\text{anti-homomorphism}).$$

Hence the matrices V_m , $m \geq -1$ are skew-symmetric (i.e., $(V_m)_b = 0$) and thus, using (4.29), we have

$$(4.30) \quad \begin{aligned} \mathbb{0} = \mathbb{V}_m \Psi &= -(V_m)_b \Psi \\ &= \left(\sum_{i \geq 0} a_i (ML^{i+m+1} + \frac{i+m+1}{2} L^{i+m})_b - \sum_{i \geq 0} \frac{b_i}{2} (L^{i+m+1})_b \right) \Psi. \end{aligned}$$

In the final step, Theorem 3.2 and Corollary 3.2.1 lead to the promised τ -constraints (4.21), modulo a constant, i.e.,

$$(4.31) \quad \mathcal{V}_m^{(k)} \tau_k = c_m^{(k)} \tau_k \quad m \geq -1, k \geq 0.$$

By (3.27), this constant is independent of k , i.e.,

$$c_m^{(k)} = c_m^{(0)};$$

upon evaluating (4.31) at $k = 0$ and upon using $\tau_0 = 1$, we conclude $c_m^{(0)} = 0$, yielding (4.21), as claimed. Finally the map

$$T_m \mapsto \mathcal{V}_m, \quad m \geq -1$$

is an anti-homomorphism (modulo constants) by Lemma 3.1; we also have

$$(4.32) \quad \phi : [T_{-1}, z] = f_0(z) \mapsto [L, Q] = f_0(L),$$

which is the ‘‘string equation’’, concluding the proof of Theorem 4.2.

Remark 4. : Note that, if $f_0^{-1} = \sum_{i \geq -k} \bar{a}_i z^i$, the map

$$(4.33) \quad T_m \mapsto \bar{T}_m = \sum_{i \geq -k} \bar{a}_i T_{m+i}, \quad m \geq k-1$$

sends T_m into the standard representation of $\text{Diff}(S^1)$:

$$(4.34) \quad [\bar{T}_m, \bar{T}_n] = (n-m) \bar{T}_{m+n}, \quad m, n \geq k-1,$$

according to Lemma 4.3.

Example. In the next section we shall consider the classical orthogonal polynomials; we consider here, for a given polynomial $q(z)$, in the interval $[a, b]$ the weight

$$\rho_0 = (z - a)^\alpha e^{q(z)} (z - b)^\beta, \quad \text{with } f_0 = (z - a)(z - b) \quad \text{and } \alpha, \beta \in \mathbb{Z}, \geq 1.$$

It implies that (see footnote 15)

$$f_0(a)\rho_0(a) = f_0(b)\rho_0(b) = 0$$

and that both f_0 and

$$g_0 = \frac{(f_0\rho_0)'}{2\rho_0} = z - \frac{(z - a)(z - b)}{2} \left(\frac{\alpha}{z - a} + q' + \frac{\beta}{z - b} \right) - \frac{a + b}{2},$$

polynomial. Then $Q = Mf_0(L) + g_0(L)$ is skew-symmetric and $[L, Q] = f_0(L)$. The Virasoro constraints (4.21) are then given by a finite sum.

5 Classical orthogonal polynomials

It is interesting to revisit the classical orthogonal polynomials, from the point of view of this analysis. As a main feature, we note that, in this case, not only is L (multiplication by z) symmetric and tridiagonal, but there exists another operator, a first-order differential operator, which yields a *skew-symmetric and tridiagonal matrix*. It is precisely given by the matrix Q !

The classical orthogonal polynomials are characterized by Rodrigues' formula,

$$p_n = \frac{1}{K_n\rho_0} \left(\frac{d}{dz} \right)^n (\rho_0 X^n),$$

K_n constant, $X(z)$ polynomial in z of degree ≤ 2 , and $\rho_0 = e^{-V_0}$. Compare Rodrigues' formula for $n = 1$ with the one for g_0 , (see theorem 4.2, footnote 15)

$$\frac{K_1}{2} p_1 = \frac{1}{2\rho_0} \frac{d}{dz} (\rho_0 X) \quad \text{and} \quad g_0 = \frac{1}{2\rho_0} \frac{d}{dz} (\rho_0 f_0),$$

which leads to the natural identification

$$g_0 = \frac{K_1}{2} p_1 \quad \text{and} \quad f_0 = X$$

and thus

$$T_{-1} = f_0 \frac{d}{dz} + g_0 = X \frac{d}{dz} + \frac{K_1 p_1}{2} = X \frac{d}{dz} + \frac{X' - XV'_0}{2}.$$

Since both $(\text{degree } X) \leq 2$ and $(\text{degree } (X' - XV'_0)) \leq 1$, as will appear from the table below, we have that T_{-1} , acting on polynomials, raises the degree by at most 1:

$$T_{-1} p_k(0, z) = \sum_{i \leq k+1} Q_{ki} p_i(0, z),$$

while, since Q is skew-symmetric,

$$(6.1) \quad T_{-1} p_k(0, z) = (Qp(0, z))_k = -Q_{k,k-1} p_{k-1}(0, z) + Q_{k,k+1} p_{k+1}(0, z),$$

together with

$$(6.2) \quad z p_k(0, z) = L_{k-1,k} p_{k-1}(0, z) + L_{k,k} p_k(0, z) + L_{k,k+1} p_{k+1}(0, z).$$

This implies at the level of the flag

$$\dots \supset W_{k-1}^t \supset W_k^t \equiv \text{span}\{(\Psi)_k, (\Psi)_{k+1}, \dots\} \supset W_{k+1}^t \supset \dots$$

that

$$z W_k^t \subset W_{k-1}^t \quad \text{and} \quad T_{-1} W_k^t \subset W_{k-1}^t.$$

Thus the recursion operators z and T_{-1} serve to characterize the flag and so the wave vector Ψ . It is interesting to speculate on considering “ (p, q) -cases”, where, for instance,

$$z^p W_k^t \subset W_{k-p}^t \quad \text{and} \quad T_{-1} W_k^t \subset W_{k-p}^t.$$

The existence of two operators, a symmetric and a skew-symmetric one, both represented by tridiagonal matrices, probably characterize the orthogonal polynomials on the line. Related, it is interesting to point out a conjecture by Karlin and Szegö and a precise formulation by Al-Salam and Chihara, where classical orthogonal polynomials are characterized by orthogonality and the existence of a differentiation formula of the form

$$f_0(z) p'_n(z) = (\alpha_n z + \beta_n) p_n(z) + \gamma_n p_{n-1}(z).$$

We now have the following table:

$e^{-V_0(z)}dz$	Hermite $e^{-z^2}dz$	Laguerre $e^{-z}z^\alpha dz$	Jacobi $(1-z)^\alpha(1+z)^\beta dz$
(a, b)	$(-\infty, \infty)$	$(0, \infty)$	$(-1, 1)$
$T_{-1} = f_0 \frac{d}{dz} + g_0$	$\frac{d}{dz} - z$	$z \frac{d}{dz} - \frac{1}{2}(z - \alpha - 1)$	$(1-z^2) \frac{d}{dz} - \frac{1}{2}((\alpha + \beta + 2)z + (\alpha - \beta))$
string equation	$[L, Q] = 1$	$[L, Q] = L$	$[L, Q] = 1 - L^2$

We now give a detailed discussion for each case:

(a) weight $e^{-z^2}dz$.

The corresponding (monic) orthogonal Hermite polynomials satisfy the classic relations

$$z\tilde{p}_n = \frac{n}{2}\tilde{p}_{n-1} + \tilde{p}_{n+1}, \quad \text{and} \quad \frac{d}{dz}\tilde{p}_n = n\tilde{p}_{n-1}.$$

Therefore the matrices defined by

$$z\tilde{p}_n = \frac{n}{2}\tilde{p}_{n-1} + \tilde{p}_{n+1} \quad \left(\frac{d}{dz} - z\right)\tilde{p}_n = \frac{n}{2}\tilde{p}_{n-1} - \tilde{p}_{n+1}$$

can be turned simultaneously into symmetric and skew-symmetric matrices L and $Q = M - L$ respectively, by an appropriate diagonal conjugation. The string equation reads $[L, Q] = 1$ and the matrix integrals τ_n satisfy

$$\mathcal{V}_m^{(n)}\tau_n = (J_m^{(2)} + 2nJ_m^{(1)} - 2J_{m+2}^{(1)} + n^2\delta_{m,0})\tau_n = 0, m = -1, 0, 1, \dots$$

upon using formula (7.12) for $a_0 = 1$, $b_1 = 2$ and all other $a_i, b_i = 0$; this captures the original case of Bessis-Itzykson-Zuber and Witten []; Witten had pointed out in his Harvard lecture that $M - L$ is a skew-symmetric matrix.

(b) weight $e^{-z}z^\alpha dz$.

Again the classic relations for (monic) Laguerre polynomials,

$$\begin{aligned} z\tilde{p}_n &= n(n + \alpha)\tilde{p}_{n-1} + (2n + \alpha + 1)\tilde{p}_n + \tilde{p}_{n+1} \\ z\frac{d}{dz}\tilde{p}_n &= n(n + \alpha)\tilde{p}_{n-1} + n\tilde{p}_n \end{aligned}$$

yield symmetric and skew-symmetric matrices L and Q , after conjugation of

$$\begin{aligned} z\tilde{p}_n &= n(n+\alpha)\tilde{p}_{n-1} + (2n+\alpha+1)\tilde{p}_n + \tilde{p}_{n+1} \\ (2z\frac{\partial}{\partial z} - (z-\alpha-1))\tilde{p}_n &= n(n+\alpha)\tilde{p}_{n-1} + 0\cdot\tilde{p}_n - \tilde{p}_{n+1}. \end{aligned}$$

Setting $a_1 = 1$, $b_0 = -\alpha$, $b_1 = 1$ and all other $a_i = b_i = 0$, yields

$$\mathcal{V}_m^{(n)}\tau_n = (J_m^{(2)} + 2nJ_m^{(1)} + \alpha J_m^{(1)} - J_{m+1}^{(1)} + n(n+\alpha)\delta_{m,0})\tau_n = 0, m = 0, 1, 2, \dots,$$

and the string equation $[L, Q] = L$; this case was investigated by Haine and Horozov [HH].

(c) weight $(1-z)^\alpha(1+z)^\beta dz$.

The matrices L and Q will be defined by the operators acting on (monic) Jacobi polynomials

$$\begin{aligned} z\tilde{p}_n &= A_{n-1}\tilde{p}_{n-1} + B_n\tilde{p}_n + \tilde{p}_{n+1} \\ -\left(\frac{1}{n+1} + \frac{\alpha+\beta}{2}\right)^{-1}\left((1-z^2)\frac{d}{dz} + \frac{(f_0\rho_0)'}{2\rho_0}\right)\tilde{p}_n &= -A_{n-1}\tilde{p}_{n-1} + \tilde{p}_{n+1} \end{aligned}$$

with

$$\begin{aligned} A_{n-1} &= \frac{4n(n+\alpha+\beta)(n+\alpha)(n+\beta)}{(2n+\alpha+\beta)^2(2n+\alpha+\beta+1)(2n+\alpha+\beta-1)} \\ B_n &= -\frac{\alpha^2 - \beta^2}{(2n+\alpha+\beta)(2n+\alpha+\beta+2)}. \end{aligned}$$

Setting

$$a_0 = 1, a_1 = 0, a_2 = -1, b_0 = \alpha - \beta, b_1 = \alpha + \beta$$

and all other $a_i = b_j = 0$ leads to the constraints

$$(J_m^{(2)} - J_{m-2}^{(2)} - 2nJ_{m-2}^{(1)} + 2nJ_m^{(1)} - (\alpha-\beta)J_{m-1}^{(1)} - (\alpha+\beta)J_m^{(1)} - n^2\delta_{m,2} + n(\alpha-\beta)\delta_{m,1})\tau_n = 0, m = 1, 2, 3, \dots$$

and the string equation $[L, Q] = 1 - L^2$. Gegenbauer ($\alpha = \beta = \lambda - 1/2$) and Legendre ($\alpha = \beta = 0$) polynomials are limiting cases of Jacobi polynomials.

6 Appendix: Virasoro constraints via the integrals

The Virasoro constraints for the integrals can be shown in a direct way:

Lemma A.1. Given $f_0(z) = \sum_{j \geq 0} a_j z^j$, the following holds for $k \geq -1$:

$$(A.1) \quad e^{\sum_i t_i Z^i} \frac{\partial}{\partial \varepsilon} e^{\varepsilon f_0(Z)} Z^{k+1} \frac{\partial}{\partial Z} dZ \Big|_{\varepsilon=0} = dZ \sum_{r \geq 0} a_r \left(\sum_{i+j=r+k} \frac{\partial^2}{\partial t_i \partial t_j} + 2n \frac{\partial}{\partial t_{r+k}} + n^2 \delta_{r+k} \right) e^{\sum_1^\infty t_i Z^i},$$

where $\partial/\partial t_j = 0$ for $j \leq 0$.

Proof: We break up the proof of this Lemma in elementary steps, involving the diagonal part of dZ , i.e.,

$$dZ = dz_1 \dots dz_n \Delta(z)^2 \times \text{angular part.}$$

At first, we compute for $k \geq 0$:

$$(A.2) \quad \begin{aligned} & \frac{2}{\Delta(z)} \frac{\partial}{\partial \varepsilon} \left(e^{a\varepsilon \sum_{i=1}^n z_i^{k+1} \frac{\partial}{\partial z_i}} \right) \Delta(z) \\ &= 2a \frac{\partial}{\partial \varepsilon} \log \Delta(z_1 + a\varepsilon z_1^{k+1}, \dots, z_n + a\varepsilon z_n^{k+1}) \Big|_{\varepsilon=0} \\ &= 2a \left(\sum_{\substack{1 \leq \alpha < \beta \leq n \\ i+j=k \\ i,j>0}} z_\alpha^i z_\beta^j + (n-1) \sum_{1 \leq \alpha \leq n} z_\alpha^k \right) - an(n-1)\delta_{k,0} \end{aligned}$$

and for $k \geq -1$

$$(A.3) \quad \begin{aligned} & \frac{\frac{\partial}{\partial \varepsilon} e^{a\varepsilon \sum_{i=1}^n z_i^{k+1} \frac{\partial}{\partial z_i}} dz_1 \dots dz_n \Big|_{\varepsilon=0}}{dz_1 \dots dz_n} \\ &= a \frac{\partial}{\partial \varepsilon} \prod_{\alpha=1}^n (1 + \varepsilon(k+1)z_\alpha^k) \Big|_{\varepsilon=0} \\ &= a(k+1) \sum_{1 \leq \alpha \leq n} z_\alpha^k. \end{aligned}$$

Note that both expressions (A.2) and (A.3) vanish for $k=-1$. Also, we have for $k \geq 1$,

$$(A.4) \quad \frac{\sum_{\substack{i+j=k \\ i,j>0}} \frac{\partial^2}{\partial t_i \partial t_j} e^{\sum_{\substack{1 \leq i \leq \infty \\ 1 \leq \alpha \leq n}} t_i z_\alpha^i}}{e^{\sum_{\substack{1 \leq i \leq \infty \\ 1 \leq \alpha \leq n}} t_i z_\alpha^i}} = 2 \sum_{\substack{1 \leq \alpha < \beta \leq n \\ i+j=k \\ i,j>0}} z_\alpha^i z_\beta^j + (k-1) \sum_{1 \leq \alpha \leq n} z_\alpha^k$$

and

$$(A.5) \quad (2n \frac{\partial}{\partial t_k} \log) e^{\sum_{\substack{1 \leq i \leq \infty \\ 1 \leq \alpha \leq n}} t_i z_\alpha^i} = 2n \sum_{1 \leq \alpha \leq n} z_\alpha^k.$$

Summing up (A.2) and (A.3) yields for $k \geq 0$:

$$\frac{\frac{\partial}{\partial \varepsilon} e^{a\varepsilon \sum_{i=1}^n z_i^{k+1} \frac{\partial}{\partial z_i} \Delta^2(z) dz_1 \dots dz_n} \Big|_{\varepsilon=0}}{\Delta^2(z) dz_1 \dots dz_n} = a \left(2 \sum_{\substack{1 \leq \alpha < \beta \leq n \\ i+j=k \\ i,j>0}} z_\alpha^i z_\beta^j + (2n+k-1) \sum_{1 \leq \alpha \leq n} z_\alpha^k - n(n-1)\delta_k \right);$$

this expression vanishes for $k = -1$. This expression equals the sum of (A.4) and (A.5); thus

$$\frac{\frac{\partial}{\partial \varepsilon} e^{a\varepsilon \sum_{i=1}^n z_i^{k+1} \frac{\partial}{\partial z_i} \Delta^2(z) dz_1 \dots dz_n} \Big|_{\varepsilon=0}}{\Delta^2(z) dz_1 \dots dz_n} = \frac{a \left(\sum_{\substack{i+j=k \\ i,j>0}} \frac{\partial^2}{\partial t_i \partial t_j} + 2n \frac{\partial}{\partial t_k} + \delta_k n^2 \right) e^{\sum_{\substack{1 \leq i \leq \infty \\ 1 \leq \alpha \leq n}} t_i z_\alpha^i}}{e^{\sum_{\substack{1 \leq i \leq \infty \\ 1 \leq \alpha \leq n}} t_i z_\alpha^i}}$$

establishing Lemma A.1.

Theorem A.2. Let the weight $\rho_0 = e^{-V_0}$ have a representation (not necessarily unique) of the form

$$V'_0 = \frac{\sum_{i \geq 0} b_i z^i}{\sum_{i \geq 0} a_i z^i} \equiv \frac{h_0}{f_0}.$$

Then the matrix integral $\tau_n = \frac{I_n}{\Omega_n n!}$ satisfies the KP equation, and Virasoro-like constraints:

$$\sum_{i \geq 0} \left(a_i (J_{i+m}^{(2)} + 2n J_{i+m}^{(1)} + n^2 J_{i+m}^{(0)}) - b_i (J_{i+m+1}^{(1)} + n J_{i+m+1}^{(0)}) \right) \tau_n = 0 \quad \text{with } m \geq -1.$$

Proof: Shifting the integration variable Z by means of

$$Z \mapsto Z + \varepsilon f_0(Z) Z^{m+1}, \quad m \geq -1$$

and using the notation

$$\Phi(Z) = e^{-\text{Tr } V_0(Z) + \sum t_i \text{Tr } Z^i},$$

we compute, since the integral remains unchanged, that

$$\begin{aligned}
0 &= \frac{\partial}{\partial \varepsilon} \int_{\mathcal{M}_n} e^{\varepsilon f_0(Z)} Z^{m+1} \frac{\partial}{\partial Z} \Phi(Z) dZ \Big|_{\varepsilon=0} \\
&= \frac{\partial}{\partial \varepsilon} \int_{\mathcal{M}_n} e^{-\text{Tr} V_0(Z + \varepsilon f_0(Z) Z^{m+1})} e^{\sum_{\ell=1}^{\infty} t_{\ell} \text{Tr}(Z + \varepsilon f_0(Z) Z^{m+1})^{\ell}} e^{\varepsilon f_0(Z) Z^{m+1}} \frac{\partial}{\partial Z} (dZ) \Big|_{\varepsilon=0} \\
&= \frac{\partial}{\partial \varepsilon} \int_{\mathcal{M}_n} e^{\varepsilon(-\text{Tr} V_0'(Z) f_0(Z) Z^{m+1} + \sum_{\ell=1}^{\infty} t_{\ell} \text{Tr} f_0(Z) Z^{m+\ell}) + O(\varepsilon^2)} \Phi(Z) e^{\varepsilon f_0(Z) Z^{m+1}} \frac{\partial}{\partial Z} dZ \Big|_{\varepsilon=0} \\
&= \int_{\mathcal{M}_n} \left(-\text{Tr} h_0(Z) Z^{m+1} + \sum_{\ell=1}^{\infty} t_{\ell} \text{Tr} f_0(Z) Z^{m+\ell} \right. \\
&\quad \left. + \sum_{i \geq 0} a_i \left(\sum_{\alpha+\beta=i+m} \frac{\partial^2}{\partial t_{\alpha} \partial t_{\beta}} + 2n \frac{\partial}{\partial t_{i+m}} + n^2 \delta_{i+m} \right) \right) \Phi(Z) dZ \\
&\qquad\qquad\qquad \text{using Lemma A.1.} \\
&= \int_{\mathcal{M}_n} \left(-\sum_{i \geq 0} b_i \text{Tr} Z^{i+m+1} \right. \\
&\quad \left. + \sum_{i \geq 0} a_i \left(\sum_{\ell=1}^{\infty} t_{\ell} \text{Tr} Z^{i+m+\ell} + \sum_{\alpha+\beta=i+m} \frac{\partial^2}{\partial t_{\alpha} \partial t_{\beta}} + 2n \frac{\partial}{\partial t_{i+m}} + n^2 \delta_{i+m} \right) \right) \Phi(Z) dZ \\
&= \int_{\mathcal{M}_n} \left(-\sum_{i \geq 0, i > -m-1} b_i \frac{\partial}{\partial t_{i+m+1}} - n b_0 \delta_{m+1} \right. \\
&\quad \left. + \sum_{i \geq 0} a_i \left(\sum_{\ell=1}^{\infty} t_{\ell} \frac{\partial}{\partial t_{i+m+\ell}} + \sum_{\alpha+\beta=i+m} \frac{\partial^2}{\partial t_{\alpha} \partial t_{\beta}} + 2n \frac{\partial}{\partial t_{i+m}} + n^2 \delta_{i+m} \right) \right) \Phi(Z) dZ \\
&= \sum_{i \geq 0} \left(a_i (J_{i+m}^{(2)} + 2n J_{i+m}^{(1)} + n^2 J_{i+m}^{(0)}) - b_i (J_{i+m+1}^{(1)} + n J_{i+m+1}^{(0)}) \right) \tau_n,
\end{aligned}$$

ending the proof of Theorem A.2.

References

- [AGL] Alvarez-Gaumé, L., Gomez, C., Lacki, J. : Integrability in random matrix models, Phys. Letters B, vol 253,(1,2), 56-62.
- [A-S-V] Adler, M., Shiota, T., van Moerbeke, P. : From the w_{∞} -algebra to its central extension: a τ -function approach, Phys. Letters A, 1994 and A Lax pair representation for the Vertex operator and the central extension, Comm. Math. Phys. 1995.

- [A-vM2] Adler, M., van Moerbeke, P. : A matrix integral solution to two-dimensional W_p -Gravity, *Comm. Math. Phys.* 147, 25-56 (1992).
- [A-S] Al-Salam, W.A., Chihara, T.S.: Another characterization of the classical orthogonal polynomials, *SIAM J. Math. Anal.* 3, pp 65-70 (1972).
- [BIZ] Bessis, D., Itzykson, Cl., Zuber, J.-B. : Quantum field theory techniques in graphical enumeration, *Adv. Appl. Math.* 1, 109-157 (1980).
- [B-K] Brezin, E., Kazakov, V., *Phys. Lett.*,236 B 144 (1990).
- [C] Chihara, T.: An introduction to orthogonal polynomials, Gordon and Breach, NY, 1978.
- [DJKM] Date, E., Jimbo, M., Kashiwara, M., Miwa, T. : Transformation groups for soliton equations, *Proc. RIMS Symp. Nonlinear integrable systems, Classical and quantum theory (Kyoto 1981)*, pp. 39-119. Singapore : World Scientific 1983.
- [D1] Dickey, L. : Soliton equations and integrable systems, World Scientific (1991).
- [D2] Dickey, L. : Additional symmetries of KP, Grassmannian, and the string equation, preprint 1992.
- [D] Dijkgraaf, R. : Intersection Theory, Integrable Hierarchies and Topological Field Theory, Lecture notes at Cargese Summer school (1991).
- [Fa] Fastré, J. : Boson-correspondence for W-algebras, Bäcklund-Darboux transformations and the equation $[L, P] = L^n$, University of Louvain, doctoral dissertation (1993)
- [GMMMO] Gerasimov, A., Marshakov, A., Mironov, A., Morozov, A., Orlov, A. : Matrix models of Two-dimensional gravity and Toda theory, *Nuclear Physics B*357, 565-618 (1991).
- [G] Ginsparg, P. : Lectures given at Trieste Summer school (july 1991).
- [GOS] Grinevich, P.G., Orlov, A.Y., Schulman E.I. : On the symmetries of integrable systems, *Important developments in soliton theory*, Eds. A.S. Fokas, V.E.Zakharov, Springer-Verlag series in non-linear dynamics, p. 283-301 (1993).
- [G-M] Gross, D., Migdal, A. :*Phys. Rev. Lett.* 64, p.127 (1990).

- [G-N] Gross, D.J., Newman, M.J. : Unitary and hermitian matrices in an external field (II). The Kontsevich model and continuum Virasoro constraints, Nucl. Phys. B "80 (1992) 168-180.
- [H-H] Haine, L., Horozov, E. : Toda Orbits of Laguerre Polynomials and Representations of the Virasoro Algebra, Bulletin des Sciences Math. (1993).
- [K-R] Kac, V.G., Raina, A.K. : Bombay lectures on highest weight representations of infinite dimensional Lie Algebras, Adv. Series Math. Phys. vol. 2, 1987.
- [K-S] Karlin, S., Szegő, G.: On certain determinants whose elements are orthogonal polynomials, J. d'An. Math. 8, pp 1-157 (1961).
- [Kr] Krichever, I. : On Heisenberg Relations for the Ordinary Linear Differential Operators (1990).
- [Ma1] Martinec, E.J. : On the Origin of Integrability in Matrix Models, Comm. Math. Phys. 138, 437-449 (1991)
- [Ma2] Martinec, E.J. : An introduction to 2d Gravity and Solvable String Models (lecture notes at Trieste spring school 1991)
- [M-M] Mironov, A., Morozov, A. : On the origin of Virasoro constraints in matrix models : Lagrangian approach, Phys. Letters B vol 252, number 1, 47-52
- [O-Sc] Orlov, A.Y., Schulman, E.I. : Additional Symmetries for Integrable and Conformal Algebra Representation, Letters in Math. Phys., 12 171-179 (1986)
- [U-T] Ueno, K., Takasaki, K. : Toda Lattice Hierarchy, Adv. Studies in Pure Math. 4, (1984) 1-95.
- [vM2] van Moerbeke, P.: Integrable foundations of string theory, in Lectures on Integrable systems, Proceedings of the CIMPA-school, 1991, Ed.: O. Babelon, P. Cartier, Y. Kosmann-Schwarzbach, World scientific, pp 163-267 (1994).
- [VDL1] van de Leur, J.W. : The Adler-Shiota-van Moerbeke formula (preprint 1994)
- [VDL2] van de Leur, J.W. : (preprint 1994)
- [W1] Witten, Ed. : Two-dimensional gravity and intersection theory of moduli space, Harvard University lecture; May 1990, Journal of diff. geometry 1991.