String equations in Whitham hierarchies: \(\tau\)-functions and Virasoro constraints

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Abstract

A scheme for solving Whitham hierarchies satisfying a special class of string equations is presented. The \(\tau\)-function of the corresponding solutions is obtained and the differential expressions of the underlying Virasoro constraints are characterized. Illustrative examples of exact solutions of Whitham hierarchies are derived and applications to conformal maps dynamics are indicated.

Key words: Whitham hierarchies, string equations, tau functions.

1 Introduction

Nonlinear integrable models of dispersionless type [1]-[4] arise in several branches of physics and applied mathematics. They have gained prominence after the discovery of their relevance in the formalism of quantum topological fields [5]-[6], and of their role in the theory of deformations of conformal and quasiconformal maps on the complex plane [7]-[9]. Recently, new applications have been found [10]-[16] which include dynamics of conformal maps, growth processes of Laplacian type and large $N$ limits of random matrix partition functions.

From the point of view of the theory of integrable systems, these models turn to be furnished by members of the so called universal Whitham hierarchies introduced by Krichever in [4]-[5]. A particularly important example of these hierarchies is the dispersionless Toda (dToda) hierarchy [10]-[13], [17]-[18]. The solutions of dispersionless integrable models underlying many of their applications satisfy special systems of constraints called string equations, which possess attractive mathematical properties and interesting physical meaning. Takasaki and Takebe [19]-[22] showed the relevance of string equations for studying the dispersionless KP and Toda hierarchies and, in particular, for characterizing their associated symmetry groups. Nevertheless, although some schemes for solving string equations in the dispersionless KP and Toda hierarchies were provided in [23]-[25], general efficient methods of solution for string equations are still lacking.

In a recent work [26] a general formalism of Whitham hierarchies based on a factorization problem on a Lie group of canonical transformations has been proposed. It leads to a natural formulation of string equations in terms of dressing transformations. The present paper is concerned with the analysis of these string equations and, in particular, their applications for characterizing exact solutions of Whitham hierarchies. Thus we provide a solution scheme for an special class of string equations which determines not only the solutions of the algebraic orbits of the Whitham hierarchy [5], but also the solutions arising in the above mentioned applications of dispersionless integrable models [24]-[25]. We characterize the $\tau$-function corresponding to these solutions and, by taking advantage of the string equations, we also derive the differential expressions of the underlying Virasoro constraints.

The elements of the phase space for a zero genus Whitham hierarchy are characterized by a finite set $(q_\alpha, z_\alpha^{-1}(p))$, $\alpha = 0, \ldots, M$, of punctures $q_\alpha$, where $q_0 := \infty$, of the complex $p$-plane and an associated set of local coordinates of the form

$$z_\alpha = \begin{cases} 
p + \sum_{n=1}^{\infty} \frac{d_{\alpha n}}{p^n}, & \alpha = 0, 
n \frac{d_i}{p - q_i} + \sum_{n=0}^{\infty} d_{\alpha n}(p - q_i)^n, & \alpha = i = 1, \ldots, M.
\end{cases}
\tag{1}
$$

The set of flows of the Whitham hierarchy can be formulated as the following infinite system of quasiclassical Lax equations

$$\frac{\partial z_\alpha}{\partial t_{\mu \nu}} = \{\Omega_{\mu \nu}, z_\alpha\},
\tag{2}
$$

where the Poisson bracket is defined as

$$\{F, G\} := \frac{\partial F}{\partial p} \frac{\partial G}{\partial x} - \frac{\partial F}{\partial x} \frac{\partial G}{\partial p}.$$
and the Hamiltonian functions are

\[ \Omega_{\mu n} := \begin{cases} (z_\mu^n)(\mu,+) & n \geq 1, \\ -\log(p - q_i) & n = 0, \quad \mu = i = 1, \ldots, M. \end{cases} \]

(3)

Here \((\cdot)(\cdot,+)\) and \((\cdot)(0,+)\) stand for the projectors on the subspaces generated by \(\{(p - q_i)^{-n}\}_{n=1}^\infty\) and \(\{p^n\}_{n=0}^\infty\) in the corresponding spaces of Laurent series. For \(M = 0\) and \(M = 1\) these systems represent the dispersionless versions of the KP and Toda hierarchies, respectively.

In what follows Greek and Latin suffixes will be used to label indices of the sets \(\{0, \ldots, M\}\) and \(\{1, \ldots, M\}\), respectively. In our analysis we use an extended Lax formalism with Orlov functions

\[ m_\alpha(z, t) = \sum_{n=1}^\infty n t_{n\alpha} z^{-1} z^n + \sum_{n=2}^\infty \frac{v_{n\alpha}}{z^n}, \quad t_{00} := -\sum_{i=1}^M t_{i0}, \]

(4)

such that

\[ \{z_\alpha, m_\alpha\} = 1, \quad \forall \alpha, \]

and verifying the same Lax equations (2) as the variables \(z_\alpha\).

The basic notions about the Whitham hierarchy which are necessary for the subsequent discussion are introduced in Sec. 2. String equations and symmetries are discussed in Sec. 3, where the main results concerning the construction of solutions from meromorphic string equations and their Virasoro invariance are proved. Section 4 presents a scheme for solving an special class of string equations, which is illustrated with several explicit examples. A formula for the corresponding \(\tau\)-function is given which generalizes the expression of the \(\tau\)-function of analytic curves found in [10]. Finally, we analyze the Virasoro symmetries associated to the string equations and obtain the corresponding Virasoro constraints in differential form.

2 The Whitham hierarchy

In order to display the main features of the Whitham hierarchy it is convenient to use the following concise formulation in terms of equations

\[ dz_\alpha \wedge dm_\alpha = d\omega, \quad \forall \alpha, \]

(5)

where \(\omega\) is the one-form defined by

\[ \omega := \sum_{\mu, n} \Omega_{\mu n} dt_{\mu n}. \]

(6)

To see how to get from the system (5) to the Whitham hierarchy, note that by identifying the coefficients of \(dp \wedge dt_{\mu n}\) and \(dx \wedge dt_{\mu n}\) in (5) we obtain

\[ \begin{cases} \frac{\partial z_\alpha}{\partial p} \frac{\partial m_\alpha}{\partial t_{\mu n}} - \frac{\partial m_\alpha}{\partial p} \frac{\partial z_\alpha}{\partial t_{\mu n}} = \frac{\partial \Omega_{\mu n}}{\partial p}, \\ \frac{\partial z_\alpha}{\partial x} \frac{\partial m_\alpha}{\partial t_{\mu n}} - \frac{\partial m_\alpha}{\partial x} \frac{\partial z_\alpha}{\partial t_{\mu n}} = \frac{\partial \Omega_{\mu n}}{\partial x}. \end{cases} \]

(7)
and, in particular, since $\Omega_{01} = p$, for $(\mu, n) = (0, 1)$, the system (7) implies
\[ \{ z_\alpha, m_\alpha \} = 1. \]

Thus, using this fact and solving (7) for $\frac{\partial z_\alpha}{\partial t_{\mu n}}$ and $\frac{\partial m_\alpha}{\partial t_{\mu n}}$, we deduce
\[ \frac{\partial z_\alpha}{\partial t_{\mu n}} = \{ \Omega_{\mu n}, z_\alpha \}, \quad \frac{\partial m_\alpha}{\partial t_{\mu n}} = \{ \Omega_{\mu n}, m_\alpha \}. \]

It is now natural to introduce the $S$-functions of the Whitham hierarchy. Indeed as a consequence of (5) we find
\[ d \left( m_\alpha \, dz_\alpha + \sum_{\mu, n} \Omega_{\mu n} dt_{\mu n} \right) = 0, \quad \forall \alpha, \]
so that there exist functions $S_\alpha(z_\alpha, t)$ such that
\[ dS_\alpha = m_\alpha \, dz_\alpha + \sum_{\mu, n} \Omega_{\mu n} dt_{\mu n}, \quad \forall \alpha, \tag{8} \]
and from (4) we see that they admit expansions of the form
\[ S_\alpha = \sum_{n \geq 1} z_\alpha^n \log z_\alpha - v_{a1}(t) - \sum_{n \geq 1} \frac{v_{a0} + 1}{n} \, v_n, \quad z_\alpha \to \infty. \tag{9} \]

It is important to notice that from (1)-(4) and (8) it follows that
\[ dS_0 = \sum_{n \geq 1} \left( n \, z_0^{n-1} t_{0n} \, dz_0 + (z_0^n)_{(0,+)} dt_{0n} \right) + \frac{t_{00}}{z_0} \, dz_0 + O \left( \frac{1}{z_0^n} \right) \, dz_0, \quad z_0 \to \infty, \]

and consequently we may take
\[ v_{01}(t) = 0. \]

To proceed further some analytic properties of the dynamical variables of the Whitham hierarchy are required. Thus we will henceforth suppose that there exist positively oriented closed curves $\Gamma_\mu$ in the complex planes of the variables $z_\mu$ such that each function $z_\mu(p)$ determines a conformal map of the right-exterior of a circle $\gamma_\mu := z_\mu^{-1}(\Gamma_\mu)$ on the exterior of $\Gamma_\mu$ (we will assume that the circle $\gamma_0$ encircles all the $\gamma_i, (i = 1, \ldots M)$) (see figure 1). Moreover, for each $\alpha$ the functions $S_\alpha$ and $m_\alpha$ will be assumed to be analytic in the exterior of $\Gamma_\alpha$. Under these conditions one can prove that
\[ \partial_{\beta, n} v_{\alpha, n+1} = \partial_{\alpha, n} v_{\beta, m+1}, \quad \forall \alpha, \beta, n, m. \tag{10} \]

In other words, it is ensured the existence of a free-energy function $F = F(t)$, the logarithm $F = \log \tau$ of the dispersionless $\tau$-function, verifying
\[ dF = \sum_{(\alpha, n) \neq (0, 0)} v_{\alpha, n+1} dt_{\alpha n}. \tag{11} \]

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We indicate the strategy for proving (10) by considering the case $\alpha = i$, $\beta = j \geq 1$, $n, m \geq 1$ of (10). From (4) and (8) it follows that

$$v_{i,n+1} = \frac{1}{2\pi i} \oint_{\Gamma_i} z_i^n m_i d z_i, \quad \partial_{j,m} S_i = (z_j^m)_{(i,+)};$$

so that

$$\partial_{j,m} v_{i,n+1} = \frac{1}{2\pi i} \oint_{\Gamma_j} z_j^n d (z_j^m)_{(j,+)} = \frac{1}{2\pi i} \oint_{\Gamma_j} (z_j^n)_{(i,+)} d (z_j^m)_{(j,+)}$$

$$= \frac{1}{2\pi i} \oint_{\Gamma_j} (z_j^m)_{(j,+)} d (z_i^n)_{(i,+)} = \partial_{i,n} v_{j,m+1},$$

where we have taken into account that $(z_j^n)_{(i,+)} \partial_p (z_j^m)_{(j,+)}$ is a rational function of $p$ which has finite poles at $q_i$ and $q_j$ only and a zero residue at $\infty$.

### 3 String equations and symmetries

As it was shown in [26], the analysis of the factorization problem for the Whitham hierarchy shows that this hierarchy admits a natural formulation in terms of systems of string equations of the form

$$\left\{ \begin{array}{l} P_i(z_i, m_i) = P_0(z_0, m_0), \\
Q_i(z_i, m_i) = Q_0(z_0, m_0), \\
i = 1, 2, \ldots, M, \end{array} \right.$$  \hspace{1cm} (13)

where $\{P_\alpha, Q_\alpha\}_{\alpha=0}^M$ are pairs of canonically conjugate variables

$$\{P_\alpha(p, x), Q_\alpha(p, x)\} = 1, \quad \forall \alpha.$$  \hspace{1cm} (14)

In what follows we consider the problem of finding systems of the form (13) which are appropriate to generate exact solutions of the Whitham hierarchy.

Figure 1: Right-exterior of $\gamma_\mu$ and $\Gamma_\mu$
Given a solution \((z_\alpha(p,t), m_\alpha(p,t))\) of a system (13), if we denote
\[
P_\alpha(p,t) := P_\alpha(z_\alpha(p,t), m_\alpha(p,t)), \quad Q_\alpha(p,t) := Q_\alpha(z_\alpha(p,t), m_\alpha(p,t)),
\]
then (13) and (14) imply
\[
dP_\alpha \wedge dQ_\alpha = dP_\beta \wedge dQ_\beta, \quad \forall \alpha, \beta
\]
(15) and
\[
dP_\alpha \wedge dQ_\alpha = dz_\alpha \wedge dm_\alpha, \quad \forall \alpha,
\]
(16) respectively. Hence solutions of the system of string equations verify
\[
dP_\alpha \wedge dQ_\alpha = dz_\beta \wedge dm_\beta, \quad \forall \alpha, \beta.
\]
(17)

The next result provides a convenient framework for our subsequent discussion of solutions of (13).

**Theorem 1.** Let \((z_\alpha(p,t), m_\alpha(p,t))\) be a solution of (13) which admits expansions of the form (1)-(4) and such that the coefficients of the the two-forms (17) are meromorphic functions of the complex variable \(p\) with finite poles at \(\{q_1, \ldots, q_M\}\) only. Then \((z_\alpha(p,t), m_\alpha(p,t))\) is a solution of the Whitham hierarchy.

**Proof.** In view of the hypothesis of the theorem the coefficients of the two-forms (17) with respect to the basis
\[
\{dp \wedge dt_{\alpha n}, \ dt_{\alpha n} \wedge dt_{\beta m}\}
\]
are determined by their principal parts at \(q_\mu, (\mu = 0, \ldots, M)\), so that by taking (17) into account we may write
\[
dz_\alpha \wedge dm_\alpha = \sum_{\mu=0}^{M} (dz_\mu \wedge dm_\mu)_{(\mu, +)}, \quad \forall \alpha.
\]
Moreover the terms in these decompositions can be found by using the expansions (4) of the functions \(m_\mu\) as follows
\[
dz_\mu \wedge dm_\mu = dz_\mu \wedge \left( \sum_{n=1}^{\infty} nz_\mu^{n-1}dt_{\mu n} + \frac{dt_{\mu 0}}{z_\mu} + \sum_{n \geq 2} \frac{dv_{\mu n}}{z_\mu^n} \right)
\]
\[
= d \left( \sum_{n=1}^{\infty} z_\mu^n dt_{\mu n} + \log z_\mu dt_{\mu 0} - \sum_{n \geq 2} \frac{1}{n-1} z_\mu^{n-1} dv_{\mu n} \right),
\]
so that
\[
(dz_\mu \wedge dm_\mu)_{(\mu, +)} = d \left( \sum_{n=1}^{\infty} (z_\mu^n)_{(\mu, +)} dt_{\mu n} - (1 - \delta_{\mu 0}) \log(p - q_\mu) dt_{\mu 0} \right)
\]
\[
= d \left( \sum_{n} \Omega_{\mu n} dt_{\mu n} \right).
\]
Thus we find
\[
dz_\alpha \wedge dm_\alpha = d\omega = d \left( \sum_{\mu, n} \Omega_{\mu n} dt_{\mu n} \right), \quad \forall \alpha,
\]
and, consequently, this proves that the functions \((z_\alpha(p,t), m_\alpha(p,t))\) determine a solution of the Whitham hierarchy. \(\square\)
Following the dressing scheme of [19]-[22] it can be shown [26] that each solution of the Whitham hierarchy is determined by an associated system of string equations.

As it was shown in [26] a complete formulation of the symmetry group of the Whitham hierarchy is obtained by considering deformations of the associated factorization problem. On the other hand, a natural representation of this group is provided by the following symmetries of string equations implemented by Hamiltonian vector fields:

**Theorem 2.** Given a vector function

\[ F := (F_0(z_0, m_0), \ldots, F_M(z_M, m_M)), \]  

(18)

the infinitesimal deformation

\[ \delta_F P_\alpha := \{F_\alpha, P_\alpha\}, \quad \delta_F Q_\alpha := \{F_\alpha, Q_\alpha\}, \]

\[ \delta_F z_\alpha := \{z_\alpha, (F_\alpha)_-\}, \quad \delta_F m_\alpha := \{m_\alpha, (F_\alpha)_-\}, \]  

(19)

where

\[ (F_\alpha)_- := F_\alpha - \sum_\beta (F_\beta)_\beta+, \]  

determines a symmetry of the system of string equations (13).

**Proof.** We have to prove that given a solution \((z_\alpha, m_\alpha)\) of (13), then at first order in \(\varepsilon\)

\[ \begin{cases} (P_i + \varepsilon \delta_F P_i)(z_i + \varepsilon \delta_F z_i, m_i + \varepsilon \delta_F m_i) = (P_0 + \varepsilon \delta_F P_0)(z_0 + \varepsilon \delta_F z_0, m_0 + \varepsilon \delta_F m_0), \\ (Q_i + \varepsilon \delta_F Q_i)(z_i + \varepsilon \delta_F z_i, m_i + \varepsilon \delta_F m_i) = (Q_0 + \varepsilon \delta_F Q_0)(z_0 + \varepsilon \delta_F z_0, m_0 + \varepsilon \delta_F m_0), \end{cases} \]  

(20)

for all \(i = 1, \ldots, M\). Let us consider the first group of equations of (20), they can be rewritten as

\[ \frac{\partial P_i}{\partial z_i} \delta_F z_i + \frac{\partial P_i}{\partial m_i} \delta_F m_i + \{F_i, P_i\} = \frac{\partial P_0}{\partial z_0} \delta_F z_0 + \frac{\partial P_0}{\partial m_0} \delta_F m_0 + \{F_0, P_0\}, \]

or, equivalently, by taking (19) into account, as

\[ \{F_i - (F_i)_-, P_i\} = \{F_0 - (F_0)_-, P_0\}, \quad \forall i. \]  

(21)

By hypothesis \(P_i(z_i, m_i) = P_0(z_0, m_0)\). On the other hand

\[ F_i - (F_i)_- = F_0 - (F_0)_- = \sum_\beta (F_\beta)_\beta+, \]

so that (21) is satisfied. The proof for the second group of equations of (20) is identical. \(\square\)

We note that the condition for a solution \((z_\alpha, m_\alpha)\) of the string equations (13) to be invariant under a symmetry (19) is

\[ (F_\alpha(z_\alpha, m_\alpha))_+ = 0, \quad \forall \alpha, \]  

(22)
or equivalently

\[ F_\alpha = \sum_\mu (F_\mu)_{(\mu,+)} , \quad \forall \alpha. \]  

In other words, the functions \( F_\alpha(z_\alpha, m_\alpha) \) must reduce to a unique meromorphic function of \( p \) with finite poles at the punctures \( q_i \) only. As a consequence it follows that, under the hypothesis of Theorem 1, solutions of the Whitham hierarchy satisfying a system of string equations (13) are invariant under the symmetries generated by

\[ \mathbb{P} = (P_0(z_0, m_0), \ldots, P_M(z_M, m_M)), \quad \mathbb{Q} = (Q_0(z_0, m_0), \ldots, Q_M(z_M, m_M)), \]

and, more generally, they are invariant under the symmetries generated by

\[ \mathcal{V}_{rs} = (P_0^{r+1} Q_0^{s+1}, \ldots, P_M^{r+1} Q_M^{s+1}), \quad r \geq -1, \ s \geq 0, \]

which determine a Poisson Lie algebra \( \mathcal{W} \) of symmetries

\[ \{ \mathcal{V}_{rs}, \mathcal{V}_{r's'} \} = ((r + 1)(s' + 1) - (r' + 1)(s + 1))\mathcal{V}_{r+r's+s'}. \]

In particular the functions \( \mathcal{V}_r := \mathcal{V}_{r0} \) and \( \mathcal{V}_s := -\mathcal{V}_{0s} \) generate two Virasoro algebras.

\[ \{ \mathcal{V}_r, \mathcal{V}_r' \} = (r - r')\mathcal{V}_{r+r'}, \quad \{ \mathcal{V}_s, \mathcal{V}_s' \} = (s - s')\mathcal{V}_{s+s'}. \]

### 4 A solvable class of string equations

In [26] a class of string equations was introduced which manifests special properties with respect to the group of dressing transformations. We next provide a scheme of solution for this class.

Let us consider systems of string equations associated to splittings

\[ \{1, \ldots, M\} = I \cup J, \ I \cap J = \emptyset \]

of the form

\[ i \in I \left\{ \begin{array}{l} \frac{z^n_i}{z^n_i - 1} = \frac{z^{n_0}}{z^{n_0} - 1} \\ \frac{1}{n_i z^{n_i - 1}_i} = \frac{1}{n_0 z^{n_0 - 1}_0} \end{array} \right. \quad , \quad j \in J \left\{ \begin{array}{l} \frac{-n_0 m_j}{n_j z^{n_j - 1}_j} = \frac{z^{n_0}}{z^{n_0} - 1} \\ \frac{1}{n_j z^j} = \frac{1}{n_0 z^{n_0 - 1}_0} \end{array} \right. \]

where \( n_\alpha \) are arbitrary positive integers. For \( J = \emptyset \) these systems furnish the solutions describing the algebraic orbits of the Whitham hierarchy [5], while the case \( I = \emptyset \) includes the systems of string equations considered by Takasaki [18] and Wiegmann-Zabrodin [10]-[14] in their applications of the dToda hierarchy. The discussion of our scheme for solving (25) requires the consideration of the two cases \( J = \emptyset \) and \( J \neq \emptyset \) separately. In what follows we consider solutions with only a finite number of times \( t_{\mu n} \) different from zero.
4.1 The case $J = \emptyset$

The corresponding system is given by

$$\begin{cases}
z_i^{n_i} = z_0^{n_0}, \\
1/n_i z_i^{n_i-1} = 1/n_0 z_0^{n_0-1},
\end{cases} \quad i = 1, \ldots, M. \tag{26}$$

The first group of equations (26) is satisfied by setting

$$z_i^{n_i} = z_0^{n_0} = E(p) := p^{n_0} + u_{n_0-2}p^{n_0-2} + \cdots + u_0 + \sum_{i=1}^M \sum_{s=1}^{n_i} \frac{v_i}{(p - q_i)^s}, \tag{27}$$

and, obviously, appropriate branches of $z_\mu$ can be defined which are compatible with the required asymptotic expansions (1). On the other hand, notice that the remaining string equations in (26) can be rewritten as

$$m_i = m_0 \frac{dz_0}{dz_i}, \tag{28}$$

so that they are verified by taking

$$m_\alpha = \frac{\partial S}{\partial z_\alpha}, \quad \forall \alpha, \tag{29}$$

for a given function $S(p, t)$, which means that all the $S_\alpha$ are equal to $S$. Moreover, it is straightforward to prove that the expansions (4) are satisfied if we set

$$S = \sum_{n=1}^{N_0} t_{0n}(z_0^n)(0,+) + \sum_{j=1}^M \left( \sum_{n=1}^{N_j} t_{jn}(z_j^n)(j,+) - t_{j0} \ln(p - q_j) \right). \tag{30}$$

In order to satisfy the hypothesis of Theorem 1, the functions $z_0^{n_0}$ and $m_0/z_0^{n_0-1}$ must be rational functions of $p$ with possible finite poles at the points $q_i$ only. In view of (27) this condition is verified by $z_0^n$. On the other hand, (26) and (29) imply that

$$\frac{1}{n_0} m_0 z_0^{n_0-1} = \frac{\partial_p S}{\partial_p E}. \tag{31}$$

Therefore, the requirements of Theorem 1 are satisfied provided that

$$\partial_p S(p_r) = 0, \tag{31}$$

where $p_r$ are the zeros of

$$\partial_p E(p_r) = 0.$$

We observe that the number of zeros $p_r$ is

$$M + n_0 - 1 + \sum_{i=1}^{M} n_i.$$
which equals the number of unknowns \( \{ q_i, u_0, \ldots, u_{n_0-2}, v_is \} \). Equations (31) coincide with those formulated by Krichever in [5] for determining the algebraic orbits of the Whitham hierarchy.

Example: \( M = 2, n_0 = n_1 = n_2 = 1, N_0 = 2, N_1 = N_2 = 1 \)

In this case (27) reads

\[
z_\alpha = E(p) = p + \frac{v_1}{p - q_1} + \frac{v_2}{p - q_2}, \quad 0 \leq \alpha \leq 2,
\]

and (31) leads to

\[
-t_{10} - t_{20} + 2t_{02}v_1 + 2t_{02}v_2 = 0,
\]

\[
q_1t_{10} + 2q_2t_{10} + 2q_1t_{20} + q_2t_{20} + t_{01}v_1 - 4q_2t_{02}v_1 - t_{11}v_1
\]

\[
+ t_{01}v_2 - 4q_1t_{02}v_2 - t_{21}v_2 = 0,
\]

\[
-2q_1q_2t_{10} - q_2^2t_{10} - q_1^2t_{20} - 2q_1q_2t_{20} - 2q_2t_{01}v_1 + 2q_2^2t_{02}v_1
\]

\[
+ 2q_2t_{11}v_1 - 2q_1t_{01}v_2 + 2q_1^2t_{02}v_2 + 2q_1t_{21}v_2 = 0,
\]

\[
q_1q_2t_{10} + q_1^2q_2t_{20} + q_2^2t_{01}v_1 - q_2^2t_{11}v_1 + q_1^2t_{01}v_2 - q_1^2t_{21}v_2 = 0.
\]

By solving this system we obtain

\[
z_\alpha = E(p) = p + \frac{2t_{10} + t_{20}}{4t_{02}(p - 2t_{01}t_{10} - 2t_{10}t_{11} + 2t_{01}t_{20} - t_{11}t_{20} - t_{20}t_{21})} \left( p + \frac{2t_{01}t_{10} - 2t_{10}t_{11} + 2t_{01}t_{20} - t_{11}t_{20} - t_{20}t_{21}}{4t_{02}(t_{10} + t_{20})} \right),
\]

\[
0 \leq \alpha \leq 2.
\]

4.2 The case \( J \neq \emptyset \)

Now we consider the system (25) for the generic case \( J \neq \emptyset \). We look for functions \( m_\alpha \) of the form

\[
m_\alpha(z, t) = \sum_{n=1}^{N_\alpha} n^\alpha t^{n-1} + \sum_{n \geq 2} \frac{2n^\alpha t^{n-1}}{z_\alpha^{n-1}}, \quad t_{00} = -\sum_{i=1}^{M} t_{i0},
\]

for arbitrary positive integers \( N_\alpha \). In order to verify the hypothesis of Theorem 1 and the expansions (1), we set

\[
z_{0i}^{n_0} = z_{i1}^{n_1} = E_1(p) := p^{n_0} + u_{n_0-2}p^{n_0-2} + \cdots + u_0 + \sum_{l \in I} \sum_{n=1}^{n_l} \frac{a_{ln}}{(p - q_l)^n} + \sum_{k \in J} \sum_{n=1}^{n_k} \frac{b_{kn}}{(p - q_k)^n}, \quad \forall i \in I,
\]

\[
z_{ij}^{n_j} = E_2(p) := \sum_{n=0}^{n_0} c_n p^n + \sum_{l \in I} \sum_{n=1}^{n_l} \frac{\tilde{a}_{ln}}{(p - q_l)^n} + \sum_{k \in J} \sum_{n=1}^{n_k} \frac{\tilde{b}_{kn}}{(p - q_k)^n}, \quad \forall j \in J,
\]

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where \( n_{00}, n_{0i}, n_{0k} \) (\( l \in I, k \in J \)), the poles \( q_i \) and the coefficients of \( E_1 \) and \( E_2 \) are to be determined.

By introducing the functions

\[
\mathcal{M}_\alpha := m_\alpha z_\alpha,
\]

and taking (33)-(34) into account it follows that the system of string equations (25) reduces to

\[
\mathcal{M}_0 = \frac{n_0}{n_i} \mathcal{M}_i = \frac{n_0}{n_j} \mathcal{M}_j = E_1(p) E_2(p) \quad \forall i \in I, j \in J
\]

On the other hand, due to their rational character, the functions \( \mathcal{M}_\alpha \) can be written in terms of their principal parts at the poles \( q_\beta \)

\[
\mathcal{M}_\alpha = \sum_{\beta=0}^{M} (\mathcal{M}_\alpha)_{(\beta,+)},
\]

and by taking (4) into account we get

\[
(\mathcal{M}_0)_{(0,+)} = \sum_{n=1}^{N_0} n t_{0n} (z_0^n)_{(0,+)} + t_{00}, \quad t_{00} = -\sum_{i=1}^{M} t_{i0},
\]

\[
(\mathcal{M}_i)_{(i,+)} = \sum_{n=1}^{N_i} n t_{in} (z_i^n)_{(i,+)}.
\]

Therefore (36) is satisfied by

\[
\mathcal{M}_0 = \sum_{n=1}^{N_0} n t_{0n} (z_0^n)_{(0,+)} + t_{00} + \sum_{i \in I} \sum_{n=1}^{N_i} n t_{in} (z_i^n)_{(i,+)} - \sum_{j \in J} \sum_{n=1}^{N_j} n t_{jn} (z_j^n)_{(j,+)}, \quad t_{00} = -\sum_{j=1}^{M} t_{j0}
\]

\[
\mathcal{M}_i = \frac{n_i}{n} \mathcal{M}_0, \quad \mathcal{M}_j = -\frac{n_j}{n} \mathcal{M}_0, \quad \forall i \in I, j \in J,
\]

provided \( \mathcal{M}_0 \) verifies the equation

\[
\mathcal{M}_0 = E_1(p) E_2(p).
\]

At this point notice that from (33),(34) and (36) it follows that (38) is the only equation to be satisfied in order to solve the system of string equations (25). Both sides of (38) are rational functions of \( p \) with finite poles at \( \{q_1, \ldots, q_M\} \) only, so that (38) holds if and only if the principal parts of both members at \( \{q_0, q_1, \ldots, q_M\} \) coincide. Now we have that:

- At \( q_0 = \infty \), the function \( \mathcal{M}_0 \) has a pole of order \( N_0 \), while \( E_1(p) E_2(p) \) has a pole of order \( n_{00} + n_0 \), consequently (38) requires that \( n_{00} = N_0 - n_0 \), so that identifying the principal parts at \( q_0 \) represents \( N_0 + 1 \) equations.

- At \( q_i \) (\( i \in I \)), the function \( \mathcal{M}_0 \) has a pole of order \( N_i \) and \( E_1(p) E_2(p) \) has a pole of order \( n_i + n_{0i} \). Hence \( n_{0i} = N_i - n_i \) and identifying the corresponding principal parts leads to \( N_i \) equations.
At $q_j$, $(j \in J)$, the function $M_0$ has a pole of order $N_j$ and $E_1(p)E_2(p)$ has a pole of order $n_{0j} + n_j$. Hence $n_{0j} = N_j - n_j$ and identifying the corresponding principal parts leads to $N_j$ equations.

Thus, Eq. (38) leads to $N_0 + \sum_{i=1}^M N_i + 1$ equations. On the other hand we have $N_0 + \sum_{i=1}^M N_i + M$ unknown coefficients given by

$$
\begin{align*}
q_i, & \quad i = 1, 2, \ldots, M, \\
a_{i1}, \ldots, a_{in_i}, & \quad \bar{a}_{i1}, \ldots, \bar{a}_{iN_i-n_i}, \quad i \in I, \\
b_{j1}, \ldots, b_{jN_j-n_j}, & \quad \bar{b}_{j1}, \ldots, \bar{b}_{jn_j}, \quad j \in J, \\
u_0, \ldots, u_{n_0-2}, & \\
c_0, \ldots, c_{N_0-n_0}
\end{align*}
$$

(39)

The additional $M-1$ equations required for determining these coefficients arise by imposing the asymptotic behaviour (1)-(4) to $(z_\alpha, m_\alpha)$. Note that (33) and (34) imply that the functions $z_\alpha$ have the asymptotic form (1). In what concerns the functions $m_\alpha$, from the expression (37) for $M_0$ it follows that

$$
M_0 = \sum_{n=1}^{N_0} nt_0 z_0^n + t_{00} + O\left(\frac{1}{z_0}\right), \quad z_0 \to \infty,
$$

so that $m_0$ satisfies an expansion of the form (4). But in order for $m_i$ ($i = 1, 2, \ldots, M$) to satisfy (4) we must impose that

$$
\text{Res}(m_i, z_i = \infty) = t_{i0}, \quad i = 1, 2, \ldots, M.
$$

(40)

However, let us see that as a consequence of the string equations (25) it follows that

$$
\sum_{\alpha=0}^M \text{Res}(m_\alpha, z_\alpha = \infty) = 0,
$$

(41)

and, consequently, only $M-1$ of the equations (40) need to be imposed. Indeed, we have

$$
2\pi i \sum_{\alpha=0}^M \text{Res}(m_\alpha, z_\alpha = \infty) = \sum_{\alpha=0}^M \oint_{\Gamma_\alpha} m_\alpha dz_\alpha = \sum_{\alpha=0}^M \oint_{\gamma_\alpha} m_\alpha \partial_p z_\alpha dp.
$$

On the other hand (33),(34) and (36) imply

$$
m_i \partial_p z_i = m_0 \partial_p z_0, \quad i \in I,
$$

$$
m_j \partial_p z_j = m_0 \partial_p z_0 - \frac{1}{n_0} \partial_p (E_1(p)E_2(p)), \quad j \in J,
$$

so that

$$
2\pi i \sum_{\alpha=0}^M \text{Res}(m_\alpha, z_\alpha = \infty) = \oint_{\gamma} m_0 \partial_p z_0 dp = 0, \quad \gamma := \sum_{\alpha=0}^M \gamma_\alpha,
$$

(39)
where we have taken into account that
\[ m_0 \partial_p z_0 = \frac{1}{n_0} E_2(p) \partial_p E_1(p), \]
is a rational function of \( p \) with finite poles at \( q_i \) only, and the fact that
\[ \gamma \sim 0 \quad \text{in} \quad \mathbb{C} \setminus \{q_1, \ldots, q_M\}. \]

In this way we have a system of
\[ N_0 + \sum_{i=1}^{M} N_i + M, \]
equations to determine the same number of unknown coefficients. Therefore, according to Theorem 1, this method furnishes solutions of the Whitham hierarchy.

4.3 Examples
1) \( M = 1, \ I = \emptyset, \ n_0 = 2, \ n_1 = 1, \ N_0 = N_1 = 3 \)

Note that in this case all the equations come from (38). We set
\[ z_0^2 = p^2 + u_0 + \frac{a_1}{p-q} + \frac{a_2}{(p-q)^2}, \quad z_1 = \frac{b_1}{p-q} + c_0 + c_1 p. \]

From (38) one obtains the system
\[ p^3: \quad 3 t_{03} = c_1, \]
\[ p^2: \quad 2 t_{02} = c_0, \]
\[ p^1: \quad t_{01} + \frac{9 t_{03} u_0}{2} = b_1 + c_1 u_0, \]
\[ p^0: \quad \frac{9 a_1 t_{03}}{2} - t_{10} + 2 t_{02} u_0 = a_1 c_1 + b_1 q + c_0 u_0, \]
\[ (p-q)^{-3}: \quad -6 b_1^2 t_{13} = a_2, \]
\[ (p-q)^{-2}: \quad -2 b_1^2 (2 t_{12} + 9 (c_0 + c_1 q) t_{13}) = a_1 b_1 + a_2 (c_0 + c_1 q), \]
\[ (p-q)^{-1}: \quad -2 b_1 \left(t_{11} + 4 (c_0 + c_1 q) t_{12} + 9 \left(c_0^2 + 2 c_0 c_1 q + c_1 b_1 + c_1^2 q^2\right) t_{13}\right) = a_2 c_1 + a_1 (c_0 + c_1 q) + b_1 \left(q^2 + u_0\right), \]
and by solving these equations we find

\[ z_0^2 = p^2 - \frac{2 \left( qt_{01} + t_{10} + 6t_{01}t_{03}t_{12} + 36t_{01}t_{02}t_{03}t_{13} + 54qt_{01}t_{03}^2t_{13} \right)}{3t_{03} (q + 6t_{03}t_{12} + 36t_{02}t_{03}t_{13} + 54qt_{03}^2t_{13})} + \frac{4t_{10} (t_{12} + 6t_{02}t_{13} + 9qt_{03}t_{13})}{(p - q) (q + 54qt_{03}^2t_{13} + 6t_{03} (t_{12} + 6t_{02}t_{13}))} - \frac{6t_{10}^2t_{13}}{(p - q)^2(q + 54qt_{03}^2t_{13} + 6t_{03} (t_{12} + 6t_{02}t_{13}))^2}. \]

\[ z_1 = \frac{t_{10}}{(p - q) (q + 6t_{03}t_{12} + 36t_{02}t_{03}t_{13} + 54qt_{03}^2t_{13})} + 2t_{02} + 3pt_{03}, \]

where \( q \) is determined by the implicit equation

\[-2qt_{01} + 3q^3t_{03} - 2t_{10} + 6qt_{03}t_{11} - 12t_{01}t_{03}t_{12} + 24qt_{02}t_{03}t_{12} + 54q^2t_{03}^2t_{12} + 36t_{03}^2t_{11}t_{12} + 144t_{02}t_{03}^2t_{12}^2 + 216t_{03}^3t_{12}^2 - 72t_{01}t_{02}t_{03}t_{13} + 72qt_{02}^2t_{03}t_{13} - 108qt_{01}t_{03}^2t_{13} + 324q^2t_{02}t_{03}^2t_{13} + 324q^3t_{03}^3t_{13} - 108t_{03}^2t_{10}t_{13} + 216t_{02}t_{03}^2t_{11}t_{13} + 324qt_{03}^3t_{11}t_{13} + 1296t_{02}^2t_{03}^2t_{12}t_{13} + 3888qt_{02}t_{03}^3t_{12}t_{13} + 2916q^2t_{03}^4t_{12}t_{13} + 2592t_{02}^3t_{03}^2t_{13}^2 + 11664qt_{02}^2t_{03}^3t_{13}^2 - 17496q^2t_{02}t_{03}^4t_{13}^2 + 8748q^3t_{03}^5t_{13}^2 = 0. \]

2) \( M = 2, I = 0, n_0 = n_1 = n_2 = 1, N_0 = N_1 = 2, N_2 = 1 \)

In this case there are three punctures \( \{q_0 = \infty, q_1, q_2\} \) and we have to impose equation (40) for \( i = 1 \). We take

\[ z_0 = p + \frac{a_1}{p - q_1}, \quad z_1 = z_2 = \frac{b_1}{p - q_1} + \frac{b_2}{p - q_2} + c_0 + c_1p. \]
Then, by identifying powers of \( p \), \((p - q_1)^{-1}\) and \((p - q_2)^{-1}\) in (38) the following system of equations arises

\[
\begin{align*}
    p^2 & : \quad 2t_{02} = c_1, \\
    p^1 & : \quad t_{01} = c_0, \\
    p^0 & : \quad 4a_1t_{02} - t_{10} - t_{20} = b_1 + b_2 + a_1c_1, \\
    (p - q_1)^{-2} & : \quad -2b_1t_{12} = a_1, \\
    (p - q_1)^{-1} & : \quad -b_1t_{11} - 4b_1 \left( c_0 + c_1q_1 + \frac{b_2}{q_1 - q_2} \right) t_{12} = b_1q_1 + a_1 \left( c_0 + c_1q_1 + \frac{b_2}{q_1 - q_2} \right), \\
    (p - q_2)^{-1} & : \quad -t_{21} = q_2 - \frac{a_1}{q_1 - q_2}.
\end{align*}
\]

Moreover, by taking (37) into account, from (40) we get

\[
\begin{align*}
    -q_1t_{01} - 2 \left( 2a_1 + q_1^2 \right) t_{02} - \left( c_0 + c_1q_1 + \frac{b_2}{q_1 - q_2} \right) t_{11} - 2 \left( 2b_1 \left( c_1 - \frac{b_2}{(q_1 - q_2)^2} \right) + \left( c_0 + c_1q_1 + \frac{b_2}{q_1 - q_2} \right)^2 \right) t_{12} + t_{20} + \frac{b_2t_{21}}{q_1 - q_2} = 0.
\end{align*}
\]

These equations lead to

\[
\begin{align*}
    z_0 &= p - \frac{1}{2(1 + 4t_{02}t_{12})(p - q_1)} \left( r^2 (1 + 4t_{02}t_{12}) - 2t_{12}(t_{10} + t_{20}) \right. \\
    & \quad \left. + r \left( t_{11} + 2t_{01}t_{12} - t_{21} - 4t_{02}t_{12}t_{21} \right) \right), \\
    z_1 &= \frac{1}{4t_{12}(1 + 4t_{02}t_{12})(p - q_1)} \left( r^2 (1 + 4t_{02}t_{12}) - 2t_{12}(t_{10} + t_{20}) \right. \\
    & \quad \left. + r \left( t_{11} + 2t_{01}t_{12} - t_{21} - 4t_{02}t_{12}t_{21} \right) \right) \\
    & \quad + \frac{1}{4t_{12}(p - q_2)} \left( -r^2 (1 + 4t_{02}t_{12}) - 2t_{12}(t_{10} + t_{20}) \right. \\
    & \quad \left. + r \left( -t_{11} - 2t_{01}t_{12} + t_{21} + 4t_{02}t_{12}t_{21} \right) \right) + t_{01} + 2pt_{02},
\end{align*}
\]

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where

\[ q_1 = \frac{1}{2r(1 + 4t_{02}t_{12})}\left(r^2(1 + 4t_{02}t_{12}) + 2t_{12}(t_{10} + t_{20}) - r(t_{11} + 2t_{01}t_{12} + t_{21} + 4t_{02}t_{12}t_{21})\right), \]

\[ q_2 = -\frac{1}{2r(1 + 4t_{02}t_{12})}\left(r^2(1 + 4t_{02}t_{12}) - 2t_{12}(t_{10} + t_{20}) + r(t_{11} + 2t_{01}t_{12} + t_{21} + 4t_{02}t_{12}t_{21})\right), \]

and \( r \) is determined by the equation:

\[ 3r^4(1 + 4t_{02}t_{12})^2 - 4t_{12}^2(t_{10} + t_{20})^2 + 4r^3(1 + 4t_{02}t_{12})(t_{11} + 2t_{01}t_{12} - (1 + 4t_{02}t_{12})t_{21}) + r^2\left(t_{11} + 2t_{01}t_{12}^2 - 4t_{02}t_{12}(t_{10} + t_{20}) - 16t_{02}t_{12}^2t_{20} - 4t_{01}t_{12}t_{21} + 16t_{02}t_{12}^2t_{21} + 8t_{02}t_{12}t_{21}^2 + 16t_{02}^2t_{12}^2t_{21}^2 + 2t_{11} + 2t_{01}t_{12}^2 - (1 + 4t_{02}t_{12})t_{21}^2\right) = 0. \]

3) \( M = 2 \), \( I = \{1\} \), \( J = \{2\} \), \( n_0 = n_1 = n_2 = N_0 = 1 \), \( N_1 = N_2 = 2 \).

In this case we take

\[ z_0 = z_1 = E_1(p) = p + \frac{v_{11}}{p - q_1} + \frac{v_{21}}{p - q_2}, \quad z_2 = E_2(p) = \frac{w_{21}}{p - q_2} + \frac{w_{11}}{p - q_1} + c_0. \]
By equating the coefficients of $p^1, p^0, (p - q_i)^{-j}, i, j = 1, 2$ in (38) one finds

\[ p^1: \quad t_{01} = c_0, \]
\[ p^0: \quad -t_{10} - t_{20} = w_{11} + w_{21}, \]
\[ (p - q_1)^{-2}: \quad 2t_{12}v_{11}^2 = v_{11}w_{11}, \]
\[ (p - q_1)^{-1}: \quad v_{11}\left(t_{11} + 4t_{12}\left(q_1 + \frac{v_{21}}{q_1 - q_2}\right)\right) \]
\[ = \left(q_1 + \frac{v_{21}}{q_1 - q_2}\right)w_{11} + v_{11}\left(c_0 + \frac{w_{21}}{q_1 - q_2}\right), \]
\[ (p - q_2)^{-2}: \quad -2t_{22}w_{21}^2 = v_{21}w_{21}, \]
\[ (p - q_2)^{-1}: \quad -(t_{21}w_{21}) - 4t_{22}\left(c_0 + \frac{w_{11}}{-q_1 + q_2}\right)w_{21} \]
\[ = c_0v_{21} + \frac{v_{21}w_{11} + (- (q_1q_2) + q_2^2 + v_{11})w_{21}}{-q_1 + q_2}, \]

and (40) leads to the equation

\[ -q_2t_{01} + t_{10} - \frac{t_{11}v_{11}}{-q_1 + q_2} - 2t_{12}\left(\frac{v_{11}^2}{(-q_1 + q_2)^2} + \frac{2v_{11}\left(q_1 + \frac{v_{21}}{q_1 - q_2}\right)}{-q_1 + q_2}\right) \]
\[ -t_{21}\left(c_0 + \frac{w_{11}}{-q_1 + q_2}\right) - 2t_{22}\left(c_0 + \frac{w_{11}}{-q_1 + q_2}\right)^2 - \frac{2w_{11}w_{21}}{(q_1 - q_2)^2} = 0. \]

By solving these equations one obtains

\[ E_1(p) = p \]
\[ -2r_1^2t_{12} + (t_{10} + t_{20})\left(1 + 4t_{12}t_{22}\right) - r_1\left(t_{01} - t_{11} + 2t_{12}t_{21} + 4t_{01}t_{12}t_{22}\right) \]
\[ -\frac{t_{22}\left(2r_1^2t_{12} - (t_{10} + t_{20})\left(1 + 4t_{12}t_{22}\right) - r_1\left(t_{01} - t_{11} + 2t_{12}t_{21} + 4t_{01}t_{12}t_{22}\right)\right)}{(p - q_2)\left(1 + 4t_{12}t_{22}\right)}, \]

\[ E_2(p) = t_{01} \]
\[ -2r_1^2t_{12} + (t_{10} + t_{20})\left(1 + 4t_{12}t_{22}\right) - r_1\left(t_{01} - t_{11} + 2t_{12}t_{21} + 4t_{01}t_{12}t_{22}\right) \]
\[ + \frac{2r_1^2t_{12} - (t_{10} + t_{20})\left(1 + 4t_{12}t_{22}\right) - r_1\left(t_{01} - t_{11} + 2t_{12}t_{21} + 4t_{01}t_{12}t_{22}\right)}{2(p - q_2)\left(1 + 4t_{12}t_{22}\right)}, \]

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where
\[ q_1 = \frac{r_1}{2} - \frac{(t_{10} + t_{20})(1 + 4t_{12}t_{22}) + r_1(t_{11} + 2t_{12}t_{21} + t_{01}(-1 + 4t_{12}t_{22}))}{4r_1t_{12}}, \]
\[ q_2 = -\frac{r_1}{2} - \frac{(t_{10} + t_{20})(1 + 4t_{12}t_{22}) + r_1(t_{11} + 2t_{12}t_{21} + t_{01}(-1 + 4t_{12}t_{22}))}{4r_1t_{12}}, \]
and \( r_1 \) satisfies the equation:
\[ -12r_1^4t_{12}^2 + (t_{10} + t_{20})^2(1 + 4t_{12}t_{22})^2 + 8r_1^3t_{12}(t_{01} + 2t_{12}t_{21} + 4t_{01}t_{12}t_{22}) - r_1^2\left((t_{11}^2 - 4t_{11}t_{12}t_{21} - 2t_{01}(t_{11} - 2t_{12}t_{21})(1 + 4t_{12}t_{22}) + (t_{01} + 4t_{01}t_{12}t_{22})^2 + 4t_{12}(-t_{10} + t_{20} + t_{12}t_{21}^2 - 4t_{01}t_{12}t_{22} + 4t_{12}t_{20}t_{22})\right) = 0. \]

### 4.4 S-functions

According to the identities
\[ \partial_p S_\alpha = \mathcal{M}_\alpha \partial_p \log z_\alpha, \quad \mathcal{M}_\alpha = m_\alpha z_\alpha, \]
it follows at once from (33),(34) and (36) that the functions \( \partial_p S_\alpha \) are rational functions of \( p \) with finite poles at the points \( q_i \ (i = 1, \ldots , M) \) only. Thus we may decompose the functions \( \partial_p S_\alpha \) into their principal parts
\[ \partial_p S_\alpha = \sum_{\beta} \left( \partial_p S_\alpha \right)_{(\beta,+)}, \quad (\text{42}) \]
and, in view of the asymptotic behaviour (9), we may write
\[ \left( \partial_p S_\alpha \right)_{(\alpha,+)} = \partial_p R_\alpha. \quad (\text{43}) \]

where
\[ R_\alpha := \sum_{n \geq 1} (z_\alpha^n)_{(\alpha,+)} t_{\alpha n} - (1 - \delta_{\alpha0}) t_{\alpha0} \log(p - q_\alpha). \quad (\text{44}) \]

Furthermore, from (33), (34) and (36) we obtain
\[ \begin{cases} 
\partial_p S_i = \partial_p S_0, \quad \forall i \in I, \\
\partial_p S_j = \partial_p S_0 - \frac{1}{n_0} \partial_p (E_1 E_2), \quad \forall j \in J,
\end{cases} \quad (\text{45}) \]
which leads to
\[ S_\alpha = \begin{cases} 
\sum_{\beta} R_{\beta} + \frac{1}{n_0} \sum_{j \in J} (E_1 E_2)_{(j,+)} , \quad \alpha \in \{0\} \cup I, \\
\sum_{\beta} R_{\beta} - \frac{1}{n_0} (E_1 E_2)_{(0,+)} - \frac{1}{n_0} \sum_{i \in I} (E_1 E_2)_{(i,+)} , \quad \alpha \in J.
\end{cases} \quad (\text{46}) \]

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In principle (45) implies the expressions (46) plus additional \( p \)-independent terms \( w_p(t) \). However these terms can be removed by using (8) and (9). Indeed, the asymptotic behavior (9) for \( S_0 \) requires \( w_0 = 0 \).

On the other hand (8) says that
\[
dS_i - dS_0 = m_i dz_i - m_0 dz_0,
\]
so that by using the string equations (25) we deduce
\[
dw_i = \begin{cases} 
   dS_i - dS_0 = 0, & i \in I, \\
   dS_i - dS_0 + \frac{1}{m_0} d(E_1 E_2) = 0, & i \in J.
\end{cases}
\]

### 4.5 \( \tau \)-functions

**Theorem 3.** The \( \tau \)-function for the solutions of the Whitham hierarchy associated with the class of string equations (25) is given by

\[
2 \log \tau = \sum_{\alpha} \frac{1}{2 \pi i} \oint_{\Gamma_{\alpha}} \left( \sum_{n \geq 1} z_{\alpha}^n t_{\alpha} \right) m_{\alpha} dz_{\alpha} - \sum_{j \in J} \frac{1}{4 \pi i} \oint_{\Gamma_j} z_j m_j^2 dz_j + \sum_i t_{i0} v_{i1} - \frac{\log(-1)}{2} \sum_{i \neq j} t_{i0} t_{j0} \tag{47}
\]

\[
= \sum_{\alpha} \sum_{n \geq 0} t_{\alpha n} v_{\alpha n+1} - \sum_{j \in J} \frac{1}{n_j} \sum_{n \geq 1} n_j t_{jn} v_{jn+1} - \sum_{j \in J} \frac{t_{j0}^2}{2 n_j} - \frac{\log(-1)}{2} \sum_{i \neq j} t_{i0} t_{j0}
\]

**Proof.** Our strategy to prove (47) is to start from the free-energy function for the algebraic orbits of the Whitham hierarchy [5]

\[
F_0 := \sum_{\alpha} \frac{1}{4 \pi i} \oint_{\Gamma_{\alpha}} \left( \sum_{n \geq 1} z_{\alpha}^n t_{\alpha} \right) m_{\alpha} dz_{\alpha} + \frac{1}{2} \sum_i t_{i0} v_{i1}, \tag{48}
\]

and determine the appropriate modifications to get the free-energy function for the solutions of the class of string equations (25).

By differentiating \( F_0 \) with respect to \( t_{ln}, n \geq 1 \) we get

\[
\partial_{t_{ln}} F_0 = \frac{1}{4 \pi i} \oint_{\Gamma_l} z_l^n m_l dz_l + \sum_{\alpha} \frac{1}{4 \pi i} \oint_{\gamma_{\alpha}} \left( \sum_{m \geq 1} z_{\alpha}^m t_{\alpha m} \right) \partial_p \left( (z_l^n)_{(l,+)} \right) dp + \frac{1}{2} \sum_i t_{i0} \partial_{t_{ln}} v_{i1}, \tag{49}
\]

and arguing as in the derivation of (12), we find that

\[
\oint_{\gamma_{\alpha}} \left( \sum_{m \geq 1} z_{\alpha}^m t_{\alpha m} \right) \partial_p \left( (z_l^n)_{(l,+)} \right) dp = \oint_{\gamma_l} z_l^n \partial_p \left( \sum_{m \geq 1} (z_{\alpha}^m)_{(\alpha,+)} t_{\alpha m} \right) dp.
\]

On the other hand, for \( i \neq l \) we have

\[
\partial_{t_{ln}} S_l = (z_l^n)_{(l,+)} = -\partial_{t_{ln}} v_{i1} + \mathcal{O} \left( \frac{1}{z_l} \right), \quad p \to q_i,
\]

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so that
\[
\partial_{i,n}v_{i1} = -(z^n_i)(l,+)\xi_i = \frac{1}{2\pi i} \oint_{\gamma_i} \frac{(z^n_i)(l,+)dp}{p - q_i}
\]
\[
= -\frac{1}{2\pi i} \oint_{\gamma_i} (z^n_i)(l,+)\partial_p \log(p - q_i)dp = -\frac{1}{2\pi i} \oint_{\gamma_i} z^n_i \partial_p \log(p - q_i)dp, \quad i \neq l,
\]
and the same expression turns out to hold for \(i = l\). Hence (49) can be rewritten as
\[
\partial_{i,n}F_0 = \frac{1}{2} v_{ln+1} + \frac{1}{4\pi i} \oint_{\gamma_i} z^n_i \sum_{\alpha} \partial_p \left( \sum_{m=1} (z^{m}_{\alpha}(l,+)t_{\alpha m} - (1 - \delta_{\alpha 0})t_{\alpha 0}\log(p - q_\alpha)) \right) dp
\]
\[
= v_{ln+1} + \frac{1}{4\pi i} \oint_{\gamma_i} z^n_i \left( \sum_{\alpha} \partial_p R_\alpha - \partial_p S_l \right) dp
\]
\[
= v_{ln+1} + \sum_{\alpha} \frac{1}{4\pi i} \oint_{\gamma_{\alpha}} (z^n_i)(l,+) \left( \partial_p R_\alpha - (\partial_p S_l)(l,+) \right) dp
\]
(50)
Furthermore, we have that
\[
\frac{1}{4\pi i} \oint_{\gamma_0} (z^n_i)(l,+) \left( \partial_p R_\alpha - (\partial_p S_l)(l,+) \right) dp = -\frac{1}{4\pi i} \oint_{\gamma_0} (z^n_i)(l,+) \left( \partial_p R_\alpha - (\partial_p S_l)(l,+) \right) dp
\]
\[
= -\frac{1}{4\pi i} \oint_{\gamma_0} (z^n_i)(l,+) \left( \partial_p S_\alpha - \partial_p S_l \right) dp,
\]
so that from (45) and by taking into account that
\[
\oint_{\gamma_0} (z^n_i)(l,+) \partial_p (E_1 E_2) dp = -\sum_{i=1}^{M} \oint_{\gamma_i} (z^n_i)(l,+) \partial_p (E_1 E_2) dp,
\]
we get
\[
\partial_{i,n}F_0 = v_{ln+1} + \frac{1}{n_0} \sum_{j \in J} \frac{1}{4\pi i} \oint_{\gamma_j} (z^n_i)(l,+) \partial_p (E_1 E_2) dp
\]
\[
= v_{ln+1} + \sum_{j \in J} \frac{1}{4\pi i n_j} \oint_{\Gamma_j} z_j m_j \partial_{l,n} m_j dz_j = v_{ln+1} + \partial_{l,n} \left( \sum_{j \in J} \frac{1}{8\pi i n_j} \oint_{\Gamma_j} z_j m_j^2 dz_j \right),
\]
(51)
which shows that
\[
\partial_{l,n} \log \tau = v_{ln+1},
\]
By a similar procedure one finds
\[
\partial_{l,n} \log \tau = v_{ln+1}, \quad n \geq 1.
\]
Nevertheless, proving that
\[ \partial_{l,0} \log \tau = v_{1l}, \quad l = 1, \ldots, M. \] (52)
requires a more involved analysis. Firstly we differentiate \( F_0 \) with respect to \( t_{l0} \)
\[
\partial_{l,0} F_0 = \sum_{\alpha} \frac{1}{4\pi i} \oint_{\gamma_\alpha} \left( \sum_{m \geq 1} z_{\alpha}^m t_{am} \right) \partial_p \left( -\log(p - q_l) \right) dp + \frac{1}{2} \sum_{i} t_{i0} \partial_{l,0} v_{i1} + \frac{1}{2} v_{1l}, \tag{53}
\]
and use the following relations
\[
\oint_{\gamma_\alpha} \left( \sum_{m \geq 1} z_{\alpha}^m t_{am} \right) \frac{1}{p - q_l} dp = -\oint_{\gamma_\alpha} \left( \sum_{m \geq 1} (z_{\alpha}^m)_{(a,+)} t_{am} \right) \frac{1}{p - q_l} dp, \quad \alpha \neq l,
\]
\[
\oint_{\gamma_l} \left( \sum_{m \geq 1} z_l^m t_{lm} \right) \frac{1}{p - q_l} dp = -2\pi i \lim_{p \to q_l} \left( \sum_{m \geq 1} (z_l^m - (z_l^m)_{(l,+)} ) t_{lm} \right),
\]
\[
\partial_{l,0} v_{i1} = \log(q_i - q_l), \quad i \neq l, \quad \partial_{l,0} v_{i1} = \lim_{p \to q_l} \log(z_l(p - q_l)).
\]
Then (53) becomes
\[
\partial_{l,0} F_0 = \frac{1}{2} v_{1l} + \frac{1}{4\pi i} \oint_{\gamma_l} \frac{dp}{p - q_l} \left( \sum_{\alpha \neq l} \sum_{m \geq 1} (z_{\alpha}^m)_{(a,+)} t_{am} - (1 - \delta_{a0}) t_{a0} \log(p - q_a) \right)
\]
\[+ \frac{1}{2} \lim_{p \to q_l} \left( \sum_{m \geq 1} (z_l^m - (z_l^m)_{(l,+)} ) t_{lm} + t_{l0} \log(z_l(p - q_l)) \right) + \frac{\log(-1)}{2} \sum_{i \neq l} t_{i0}. \tag{54}
\]
Furthermore, from the asymptotic expansion (9) of \( S_l \) we have that
\[
v_{1l} = \lim_{p \to q_l} \left( \sum_{m \geq 1} z_l^m t_{lm} + t_{l0} \log z_l - S_l \right),
\]
which allows us to rewrite (54) in the form
\[
\partial_{l,0} F_0 = v_{1l} + \frac{1}{4\pi i} \oint_{\gamma_l} \frac{dp}{p - q_l} \sum_{\alpha \neq l} R_{\alpha} + \frac{1}{2} \lim_{p \to q_l} \left( S_l - R_l \right) + \frac{\log(-1)}{2} \sum_{i \neq l} t_{i0}
\]
\[= v_{1l} + \frac{1}{4\pi i} \oint_{\gamma_l} \frac{dp}{p - q_l} \left( \sum_{\alpha} R_{\alpha} - S_l \right) + \frac{\log(-1)}{2} \sum_{i \neq l} t_{i0}. \tag{55}
\]
Now by using (46) it is straightforward to see that
\[
\frac{1}{4\pi i} \oint_{\gamma_l} \frac{dp}{p - q_l} \left( \sum_{\alpha} R_{\alpha} - S_l \right) = \frac{1}{n_0} \sum_{j \in J} \frac{1}{4\pi i} \oint_{\gamma_l} \frac{dp}{p - q_l} \int_{\Gamma_j} \frac{1}{4\pi i} \oint_{\gamma_j} z_j m_j \partial_{l,0} m_j dz_j, \tag{56}
\]
which shows that (55) is equivalent to (52). \( \square \)
Figure 2: Conformal map \( z = z(p) \)

### 4.6 Conformal maps dynamics

We will outline how our scheme applies for characterizing dToda dynamics of conformal maps, and, in particular, how (47) gives rise to the expression of the \( \tau \)-function of analytic curves found in [10].

Given a simply-connected domain \( D \) bounded by a closed path \( \Gamma \) in the \( z \)-plane, there exist [27] a unique circle \( \gamma \) in the \( p \)-plane and a unique conformal map \( z = z(p) \) satisfying

\[
\sum_{n=1}^{\infty} \frac{d_n}{p^n}, \quad z \to \infty,
\]

such that \( z = z(p) \) transforms the exterior of \( \gamma \) into the exterior of \( \Gamma \) (see figure 2). Note that the conformal map used by Wiegmann-Zabrodin [10] is given by \( z(r p + q) \), where \( q \) and \( r \) are the center and the radius of \( \gamma \), respectively.

Let us define the function

\[
\tilde{z}(p) = \overline{z(I_\gamma(p))},
\]

where \( I_\gamma \) denotes the inversion with respect to the circle \( \gamma \)

\[
I_\gamma(p) := q + \frac{r^2}{p - q}.
\]

It is clear that

\[
\tilde{z}(p) = \overline{z(p)}, \quad \forall p \in \gamma.
\]

If \( \Gamma \) is assumed to be an analytic curve, then it can be described by an equation of the form

\[
\tilde{z} = S(z),
\]

where \( S(z) := \tilde{z}(p(z)) \) (the Schwarz function) is analytic in a neighborhood of \( \gamma \). Thus, if \( \Gamma \) encircles the origin, \( S(z) \) can be expanded as

\[
S(z) = \sum_{n \geq 1} n t_n z^{n-1} + \frac{t_0}{z} + \sum_{n \geq 1} \frac{v_n(t)}{z^{n+1}},
\]

22
where the coefficients $t_n (n \geq 0)$, the exterior harmonic moments of $\Gamma$, determine the curve $\Gamma$ and the conformal map (57). Note, in particular, that the coefficient $t_0$

$$t_0 = \frac{1}{2\pi i} \oint_{\Gamma} \bar{z} \mathrm{d}z = \frac{1}{\pi} \int_D \mathrm{d}x \mathrm{d}y,$$

represents the area of $D$.

In this way, by considering the harmonic moments as independent complex parameters, if we define

$$q_1 = q, \quad z_0(p) = z(p), \quad z_1(p) = \bar{z}(p),$$

$$t_{0n} := t_n, \quad t_{1n} = -\bar{t}_n, \quad n \geq 0,$$

$$m_0 = S(z_0), \quad m_1 = -z(p(z_1)),$$

we obtain a solution of the system of string equations

$$-m_1 = z_0, \quad z_1 = m_0. \quad (61)$$

Furthermore, by taking into account that

$$v_{1n+1} = -\bar{v}_{0n+1} = -\bar{v}_n, \quad n \geq 1,$$

and the identity

$$t_0^2 + 2 \sum_{n \geq 1} n t_n v_n = \frac{1}{2\pi i} \oint_{\Gamma} z S(z)^2 \mathrm{d}z = \frac{1}{2\pi i} \oint_{\Gamma} z \bar{z}^2 \mathrm{d}z$$

$$= \frac{1}{\pi} \int_D |z|^2 \mathrm{d}x \mathrm{d}y = t_0^2 + 2 \sum_{n \geq 1} n t_n \bar{v}_n,$$

we see that (47) reduces to

$$2 \log \tau = \frac{1}{2} \sum_{n \geq 1} (2 - n)(t_n v_n + \bar{t}_n \bar{v}_n) + t_0 v_0 - \frac{t_0^2}{2}, \quad (62)$$

where $v_0 := -v_{11}$, which is the expression for the $\tau$-function associated to analytic curves obtained in [10]. Notice that (61) is the simplest nontrivial case ($I = \emptyset$, $J = \{1\}$, $n_0 = n_1 = 1$) of the class of string equations (25).

### 4.7 Symmetry constraints

As we proved above, solutions $(z_\alpha, m_\alpha)$ of systems of string equations (13) are invariant under the symmetries

$$V_{rs} = (P_{0+1}^r Q_{0+1}^s, \ldots, P_{M+1}^r Q_{M+1}^s), \quad r \geq -1, \ s \geq 0.$$

Moreover, as a consequence of (13) we have that the following identities hold

$$P_{0+1}^r Q_{0+1}^s = P_{i+1}^r Q_{i+1}^s = P_{j+1}^r Q_{j+1}^s = P_{0+1}^r Q_{j+1}^s, \quad \forall i \in I, \ j \in J, \quad (63)$$

for the values of the functions $P_\mu$ and $Q_\mu$ at a solution $(z_\alpha, m_\alpha)$. In particular these identities lead to the following expressions for the constraints arising from the invariance of (25) under the action of $V_{rs}$.
Theorem 4. If \((z_{\alpha}, m_{\alpha})\) is a solution of the string equations (25) then it satisfies the identities
\[
\sum_{\alpha \in \{0\} \cup J} \oint_{\Gamma_{\alpha}} \left( \frac{z_{\alpha}}{n_{\alpha}} \right)^{s} z_{\alpha}^{(r-s)_{\alpha}} m_{\alpha} s_{+1} \ dz_{\alpha} + \left( -1 \right)^{s+1} \frac{1}{r+1} \int_{0}^{r} z_{\alpha}^{(s-r)_{\alpha}} m_{\alpha} s_{+1} \ dz_{\alpha} = 0,
\]
for all \(r, s \geq 0\).

Proof. From (33)-(36) we find that (63) takes the form
\[
z_{0}^{n_{0}(r+1)} \left( \frac{m_{0}}{n_{0} z_{0}^{n_{0}+1}} \right)^{s+1} = n_{i}^{s} \left( \frac{m_{i}}{n_{i} z_{i}^{n_{i}+1}} \right)^{s+1} = \left( \frac{z_{j}}{n_{j}} \right)^{s+1} \left( - \frac{n_{0} m_{j}}{n_{j} z_{j}^{n_{j}+1}} \right)^{r+1}
\]
and we have that
\[
z_{0}^{n_{0}(r+1)} \left( \frac{m_{0}}{n_{0} z_{0}^{n_{0}+1}} \right)^{s+1} \partial_{p} \log E_{1} = n_{i}^{s} \left( \frac{m_{i}}{n_{i} z_{i}^{n_{i}+1}} \right)^{s+1} \partial_{p} \log E_{1} = \left( \frac{E_{1}^{r+1} E_{2}^{s+1}}{(r+1)n_{0}^{s+1}} \right)
\]
\[
\left( \frac{z_{j}}{n_{j}} \right)^{s+1} \left( - \frac{n_{0} m_{j}}{n_{j} z_{j}^{n_{j}+1}} \right)^{r+1} \partial_{p} \log E_{2} = \frac{r+1}{s+1} z_{0}^{n_{0}(r+1)} \left( \frac{m_{0}}{n_{0} z_{0}^{n_{0}+1}} \right)^{s+1} \partial_{p} \log E_{1} + \partial_{p} \left( \frac{E_{1}^{r+1} E_{2}^{s+1}}{(s+1)n_{0}^{s+1}} \right)
\]
for all \(r, s \geq 0\) and \(i \in I, j \in J\). Hence if we proceed as in the proof of (41) and take into account that
\[
\partial_{p} \log E_{1} = n_{0} \partial_{p} \log z_{0} = n_{i} \partial_{p} \log z_{i}, \quad \forall i \in I,
\]
\[
\partial_{p} \log E_{2} = n_{j} \partial_{p} \log z_{j}, \quad \forall j \in J,
\]
it is straightforward to prove that
\[
\sum_{\alpha \in \{0\} \cup J} \oint_{\Gamma_{\alpha}} z_{\alpha}^{n_{\alpha}(r+1)} \left( \frac{m_{\alpha}}{n_{\alpha} z_{\alpha}^{n_{\alpha}+1}} \right)^{s+1} n_{\alpha} \ dz_{\alpha} = \sum_{j \in J} \frac{s+1}{r+1} \oint_{\gamma} \left( \frac{z_{j}}{n_{j}} \right)^{s+1} \left( - \frac{n_{0} m_{j}}{n_{j} z_{j}^{n_{j}+1}} \right)^{r+1} n_{j} \ dz_{j}
\]
\[
\oint_{\gamma} z_{0}^{n_{0}(r+1)} \left( \frac{m_{0}}{n_{0} z_{0}^{n_{0}+1}} \right)^{s+1} \partial_{p} \log E_{1} dp = \oint_{\gamma} \left( \frac{E_{1}^{r+1} E_{2}^{s+1}}{(r+1)n_{0}^{s+1}} \right) dp = 0,
\]
where \(\gamma := \sum_{\alpha=0}^{M} \gamma_{\alpha}\). This proves that the identities (64) hold.

By evaluating the integrals of the left-hand side we obtain the symmetry constraints in terms of differential equations for the free-energy function \(F = \log \tau\).

Examples

For \(r = s = 0\) the equation (67) reduces to (41), so that it implies
\[
\sum_{\alpha} l_{\alpha} = 0.
\]
The cases \((r,s) = (1,0)\) and \((r,s) = (2,0)\) correspond to the Virasoro constraints induced by \(V_1\) and \(V_2\), respectively, and lead to the identities

\[
\sum_{\alpha \in \{0\} \cup J} \partial_{\alpha,n_0} F - \sum_{j \in J} \frac{n_0}{n_j} \left( \sum_{n-n' = n_j - 1} nt_{jn} \partial_{j,n'-1} F + \frac{1}{2} \sum_{n+n' = n_j} nn' t_{jn} t_{jn'} \right) = 0,
\]

\[
\sum_{\alpha \in \{0\} \cup J} \partial_{\alpha,2n_0} F + \sum_{j \in J} \left( \frac{n_0}{n_j} \right)^2 \left( \sum_{n-n' - n'' = 2n_j - 2} nt_{jn} (\partial_{j,n'-1} F) (\partial_{j,n''-1} F) + 2 \sum_{n - n' = 2n_j - 1} nt_{jn} t_{jn'} \partial_{j,n'-1} F \right)
\]

\[
+ \sum_{n+n'-n'' = 2n_j - 1} nn' t_{jn} t_{jn'} \partial_{j,n'-1} F + 2n_j t_{jn} 2n_j \partial_{j,0}^2 + \sum_{n+n' = 2n_j} nn' t_{jn} t_{jn'} t_{j0}
\]

\[
+ \frac{1}{3} \sum_{n+n'+n'' = 2n_j} nn'' t_{jn} t_{jn'} t_{jn''} = 0.
\]

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References


