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## A Torelli type theorem for exp-algebraic curves <sup>(\*)</sup>

INDRANIL BISWAS <sup>(1)</sup> AND KINGSHOOK BISWAS <sup>(2)</sup>

**ABSTRACT.** — An exp-algebraic curve consists of a compact Riemann surface  $S$  together with  $n$  equivalence classes of germs of meromorphic functions modulo germs of holomorphic functions,  $\mathcal{H} = \{[h_1], \dots, [h_n]\}$ , with poles of orders  $d_1, \dots, d_n \geq 1$  at points  $p_1, \dots, p_n$ . This data determines a space of functions  $\mathcal{O}_{\mathcal{H}}$  (respectively, a space of 1-forms  $\Omega_{\mathcal{H}}^0$ ) holomorphic on the punctured surface  $S' = S - \{p_1, \dots, p_n\}$  with exponential singularities at the points  $p_1, \dots, p_n$  of types  $[h_1], \dots, [h_n]$ , i.e., near  $p_i$  any  $f \in \mathcal{O}_{\mathcal{H}}$  is of the form  $f = ge^{h_i}$  for some germ of meromorphic function  $g$  (respectively, any  $\omega \in \Omega_{\mathcal{H}}^0$  is of the form  $\omega = \alpha e^{h_i}$  for some germ of meromorphic 1-form).

For any  $\omega \in \Omega_{\mathcal{H}}^0$  the completion of  $S'$  with respect to the flat metric  $|\omega|$  gives a space  $S^* = S' \cup \mathcal{R}$  obtained by adding a finite set  $\mathcal{R}$  of  $\sum_i d_i$  points, and it is known that integration along curves produces a nondegenerate pairing of the relative homology  $H_1(S^*, \mathcal{R}; \mathbb{C})$  with the de Rham cohomology group defined by  $H_{dR}^1(S, \mathcal{H}) := \Omega_{\mathcal{H}}^0/d\mathcal{O}_{\mathcal{H}}$ .

There is a degree zero line bundle  $L_{\mathcal{H}}$  associated to an exp-algebraic curve, with a natural isomorphism between  $\Omega_{\mathcal{H}}^0$  and the space  $W_{\mathcal{H}}$  of meromorphic  $L_{\mathcal{H}}$ -valued 1-forms which are holomorphic on  $S'$ , so that  $H_1(S^*, \mathcal{R}; \mathbb{C})$  maps to a subspace  $K_{\mathcal{H}} \subset W_{\mathcal{H}}^*$ . We show that the exp-algebraic curve  $(S, \mathcal{H})$  is determined uniquely by the pair  $(L_{\mathcal{H}}, K_{\mathcal{H}} \subset W_{\mathcal{H}}^*)$ .

**RÉSUMÉ.** — Une courbe exp-algébrique est une surface de Riemann  $S$  munie de  $n$  classes d'équivalence de germes de fonctions méromorphes modulo les germes de fonctions holomorphes  $\mathcal{H} = \{[h_1], \dots, [h_n]\}$ , avec des pôles d'ordre  $d_1, \dots, d_n \geq 1$  aux points  $p_1, \dots, p_n$ . Cette donnée détermine un espace de fonctions  $\mathcal{O}_{\mathcal{H}}$  (respectivement, un espace de 1-formes  $\Omega_{\mathcal{H}}^0$ ) holomorphes sur la surface épointée  $S' = S - \{p_1, \dots, p_n\}$  avec des singularités exponentielles aux points  $p_1, \dots, p_n$  de type  $[h_1], \dots, [h_n]$ , i.e., au voisinage du point  $p_i$  toute  $f \in \mathcal{O}_{\mathcal{H}}$  est de la forme  $f = ge^{h_i}$  pour un germe de fonction méromorphe  $g$  (respectivement toute forme  $\omega \in \Omega_{\mathcal{H}}^0$  est de la forme  $\omega = \alpha e^{h_i}$  pour un germe de 1-forme méromorphe  $\alpha$ ).

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Article proposé par Jean-Pierre Otal.

Pour toute  $\omega \in \Omega_{\mathcal{H}}^0$ , la complétion de  $S'$  par rapport à la métrique plate  $|\omega|$  donne un espace  $S^* = S' \cup \mathcal{R}$  obtenu en ajoutant un ensemble fini  $\mathcal{R}$  de  $\sum_i d_i$  points. Il est connu que l'intégration le long des courbes fournit un accouplement non dégénéré sur l'homologie relative  $H_1(S^*, \mathcal{R}; \mathbb{C})$  où le groupe de cohomologie de de Rham est défini par  $H_{dR}^1(S, \mathcal{H}) := \Omega_{\mathcal{H}}^0/d\mathcal{O}_{\mathcal{H}}$ .

Il existe un fibré en droites  $L_{\mathcal{H}}$  de degré zéro associé à toute courbe exp-algébrique, avec un isomorphisme naturel entre  $\Omega_{\mathcal{H}}^0$  et l'espace  $W_{\mathcal{H}}$  des 1-formes méromorphes à valeurs dans  $L_{\mathcal{H}}$ , holomorphes sur  $S'$  et tel que  $H_1(S^*, \mathcal{R}; \mathbb{C})$  s'envoie sur un sous-espace  $K_{\mathcal{H}} \subset W_{\mathcal{H}}^*$ . Nous montrons que la courbe exp-algébrique  $(S, \mathcal{H})$  est déterminée de façon univoque par la paire  $(L_{\mathcal{H}}, K_{\mathcal{H}} \subset W_{\mathcal{H}}^*)$ .

## 1. Introduction

A choice of nonconstant meromorphic function  $z$  on a compact Riemann surface  $S$  realizes  $S$  as a finite sheeted branched covering of the Riemann sphere  $\widehat{\mathbb{C}}$ . *Log-Riemann surfaces of finite type* are certain branched coverings, in a generalized sense, of  $\mathbb{C}$  by a punctured compact Riemann surface, namely, which are given by certain transcendental functions of infinite degree. Formally a log-Riemann surface consists of a Riemann surface together with a local holomorphic diffeomorphism  $\pi$  from the surface to  $\mathbb{C}$  such that the set of points  $\mathcal{R}$  added to the surface, in the completion  $S^* = S' \cup \mathcal{R}$  with respect to the path-metric induced by the flat metric  $|d\pi|$ , is discrete. Log-Riemann surfaces were defined and studied in [6] (see also [5]), where it was shown that the map  $\pi$  restricted to any small enough punctured metric neighbourhood of a point  $w^*$  in  $\mathcal{R}$  gives a covering of a punctured disc in  $\mathbb{C}$ , and is thus equivalent to either  $(z \mapsto z^n)$  restricted to a punctured disc  $\{0 < |z| < \epsilon\}$  (in which case we say  $w^*$  is a ramification point of order  $n$ ) or to  $(z \mapsto e^z)$  restricted to a half-plane  $\{\Re z < C\}$  (in which case we say  $w^*$  is a ramification point of infinite order).

A log-Riemann surface is said to be of finite type if it has finitely many ramification points and finitely generated fundamental group. We will only consider those for which the set of infinite order ramification points is nonempty (otherwise the map  $\pi$  has finite degree and is given by a meromorphic function on a compact Riemann surface). In [4, 7], uniformization theorems were proved for log-Riemann surfaces of finite type, which imply that a log-Riemann surface of finite type is given by a pair  $(S' = S - \{p_1, \dots, p_n\}, \pi)$ , where  $S$  is a compact Riemann surface, and  $\pi$  is a meromorphic function on the punctured surface  $S'$  such that the differential  $d\pi$  has essential singularities at the punctures of a specific type, namely *exponential singularities*.

Given a germ of meromorphic function  $h$  at a point  $p$  of a Riemann surface, a function  $f$  with an isolated singularity at  $p$  is said to have an exponential singularity of type  $h$  at  $p$  if locally  $f = ge^h$  for some germ of meromorphic function  $g$  at  $p$ , while a 1-form  $\omega$  is said to have an exponential singularity of type  $h$  at  $p$  if locally  $\omega = \alpha e^h$  for some germ of meromorphic 1-form  $\alpha$  at  $p$ . Note that the spaces of germs of functions and 1-forms with exponential singularity of type  $h$  at  $p$  only depend on the equivalence class  $[h]$  in the space  $\mathcal{M}_p/\mathcal{O}_p$  of germs of meromorphic functions at  $p$  modulo germs of holomorphic functions at  $p$ .

Thus the uniformization theorems of [4, 7] give us  $n$  germs of meromorphic functions  $h_1, \dots, h_n$  at the punctures  $p_1, \dots, p_n$ , with poles of orders  $d_1, \dots, d_n \geq 1$  say, such that near a puncture  $p_j$  the map  $\pi$  is of the form  $\int g_j e^{h_j} dz$ , where  $g_j$  is a germ of meromorphic function near  $p_j$  and  $z$  a local coordinate near  $p_j$ . The punctures correspond to ends of the log-Riemann surface, where at each puncture  $p_j$ ,  $d_j$  infinite order ramification points are added in the metric completion, so that the total number of infinite order ramification points is  $\sum_j d_j$ . The  $d_j$  infinite order ramification points added at a puncture  $p_j$  correspond to the  $d_j$  directions of approach to the puncture along which  $\Re h_j \rightarrow -\infty$  so that  $e^{h_j}$  decays exponentially and  $\int^z g_j e^{h_j} dz$  converges. In the case of genus zero with one puncture for example, which is considered in [7], the map  $\pi$  must have the form  $\int R(z) e^{P(z)} dz$  where  $R$  is a rational function and  $P$  is a polynomial of degree equal to the number of infinite order ramification points.

In [3], certain spaces of functions and 1-forms on a log-Riemann surface  $S^*$  of finite type were defined, giving rise to a de Rham cohomology group  $H_{dR}^1(S^*)$ . The integrals of the 1-forms considered along curves in  $S^*$  joining the infinite ramification points converge, giving rise to a pairing between  $H_{dR}^1(S^*)$  and  $H_1(S^*, \mathcal{R}; \mathbb{C})$ , which was shown to be nondegenerate ([3]).

The spaces of functions and 1-forms defined were observed to depend only on the types  $h_1, \dots, h_n$  of the exponential singularities, and so a notion less rigid than that of a log-Riemann surface was defined, namely the notion of an *exp-algebraic curve*, which consists of a compact Riemann surface  $S$  together with  $n$  equivalence classes of germs of meromorphic functions modulo germs of holomorphic functions,  $\mathcal{H} = \{[h_1], \dots, [h_n]\}$ , with poles of orders  $d_1, \dots, d_n \geq 1$  at points  $p_1, \dots, p_n$ . The relevant spaces of functions and 1-forms with exponential singularities at  $p_1, \dots, p_n$  of types  $[h_1], \dots, [h_n]$  can then be defined as follows:

$$\begin{aligned} \mathcal{M}_{\mathcal{H}} &:= \left\{ f \mid \begin{array}{l} f \text{ meromorphic function on } S' \\ \text{with exponential singularities of types } [h_1], \dots, [h_n] \end{array} \right\} \\ \mathcal{O}_{\mathcal{H}} &:= \{f \in \mathcal{M}_{\mathcal{H}} \mid f \text{ holomorphic on } S'\} \end{aligned}$$

$$\Omega_{\mathcal{H}} := \left\{ \omega \left| \begin{array}{l} \omega \text{ meromorphic 1-form on } S' \\ \text{with exponential singularities of types } [h_1], \dots, [h_n] \end{array} \right. \right\}$$

$$\Omega_{\mathcal{H}}^0 := \{ \omega \in \Omega_{\mathcal{H}} \mid \omega \text{ holomorphic on } S' \}.$$

For  $f \in \mathcal{M}_{\mathcal{H}}$  (respectively,  $\omega \in \Omega_{\mathcal{H}}$ ) we can define a divisor  $(f) = \sum_{p \in S} n_p \cdot p$  (respectively,  $(\omega) = \sum_{p \in S} m_p \cdot p$ ) by  $n_p = \text{ord}_p(f)$  if  $p \in S'$  and  $n_p = \text{ord}_{p_i}(g)$  if  $p = p_i$ , where  $g$  is a germ of meromorphic function at  $p_i$  such that  $f = ge^{h_i}$  (respectively,  $m_p = \text{ord}_p(\omega)$  if  $p \in S'$  and  $n_p = \text{ord}_{p_i}(\alpha)$  if  $p = p_i$ , where  $\alpha$  is a germ of meromorphic 1-form at  $p_i$  such that  $\omega = \alpha e^{h_i}$ ).

In [3] it is shown how to naturally associate to an exp-algebraic curve  $(S, \mathcal{H})$  a degree zero line bundle  $L_{\mathcal{H}}$  together with a meromorphic connection  $\nabla_{\mathcal{H}}$  with poles at  $p_1, \dots, p_n$ . The connection 1-form of  $\nabla_{\mathcal{H}}$  near  $p_i$  is given (with respect to an appropriate local trivialization) by  $dh_i$ , so that the pair  $(L_{\mathcal{H}}, \nabla_{\mathcal{H}})$  determines the exp-algebraic curve  $(S, \mathcal{H})$ . There are naturally defined isomorphisms between the space of meromorphic sections of  $L_{\mathcal{H}}$  (respectively, the space of meromorphic  $L_{\mathcal{H}}$ -valued 1-forms) and  $\mathcal{M}_{\mathcal{H}}$  (respectively,  $\Omega_{\mathcal{H}}$ ), such that a meromorphic section  $s$  of  $L_{\mathcal{H}}$  (respectively, a meromorphic  $L_{\mathcal{H}}$ -valued 1-form  $\alpha$ ) maps to an  $f \in \mathcal{M}_{\mathcal{H}}$  with the same divisor as  $s$  (respectively, an  $\omega \in \Omega_{\mathcal{H}}$  with the same divisor as  $\alpha$ ).

In particular the space  $W_{\mathcal{H}}$  of meromorphic  $L_{\mathcal{H}}$ -valued 1-forms which are holomorphic on  $S'$  is naturally isomorphic to the space  $\Omega_{\mathcal{H}}^0$ . Fixing an  $f \in \mathcal{O}_{\mathcal{H}}$  inducing a log-Riemann surface structure on  $S$ , with completion  $S^* = S' \cup \mathcal{R}$ , the 1-forms in  $\Omega_{\mathcal{H}}^0$  can be integrated along curves in  $H_1(S^*, \mathcal{R}; \mathbb{C})$ , giving a map

$$H_1(S^*, \mathcal{R}; \mathbb{C}) \longrightarrow (\Omega_{\mathcal{H}}^0)^* \simeq W_{\mathcal{H}}^*.$$

Let  $K_{\mathcal{H}} \subset W_{\mathcal{H}}^*$  denote the image of  $H_1(S^*, \mathcal{R}; \mathbb{C})$  in  $W_{\mathcal{H}}^*$ . Then our Torelli-type theorem for exp-algebraic curves states that the pair  $(L_{\mathcal{H}}, K_{\mathcal{H}})$  determines the exp-algebraic curve  $(S, \mathcal{H})$ :

**THEOREM 1.1.** — *Let  $(S, \mathcal{H}_1), (S, \mathcal{H}_2)$  be two exp-algebraic curves with the same underlying Riemann surface  $S$ , and the same set of punctures  $p_1, \dots, p_n$ . Suppose that  $H_1(S_1^*, \mathcal{R}; \mathbb{C})$  is nontrivial, that the line bundles  $L_{\mathcal{H}_1}, L_{\mathcal{H}_2}$  are isomorphic and that the induced isomorphism  $W_{\mathcal{H}_1}^* \longrightarrow W_{\mathcal{H}_2}^*$  maps  $K_{\mathcal{H}_1}$  to  $K_{\mathcal{H}_2}$ . Then  $\mathcal{H}_1 = \mathcal{H}_2$ .*

Finally, we mention briefly some appearances of functions with exponential singularities in the literature. Certain functions with exponential singularities, namely the  $n$ -point *Baker–Akhiezer functions* ([1, 2]), have been used in the algebro-geometric integration of integrable systems (see, for example, [14, 15] and the surveys [11, 12, 16, 17]). Given a divisor  $D$  on  $S'$ , an  $n$ -point Baker–Akhiezer function (with respect to the data  $(\{p_j\}, \{h_j\}, D)$ ) is a function  $f$  in the space  $\mathcal{M}(S^*)$  satisfying the additional properties that

the divisor  $(f)$  of zeroes and poles of  $f$  on  $S'$  satisfies  $(f) + D \geq 0$ , and that  $f \cdot e^{-h_j}$  is holomorphic at  $p_j$  for all  $j$ . For  $D$  a non-special divisor of degree at least  $g$ , the space of such Baker–Akhiezer functions is known to have dimension  $\deg D - g + 1$ .

Functions and differentials with exponential singularities on compact Riemann surfaces have also been studied by Cutillas Ripoll ([8, 9, 10]), where they arise naturally in the solution of the *Weierstrass problem* of realizing arbitrary divisors on compact Riemann surfaces, and by Taniguchi ([18, 19]), where entire functions satisfying certain topological conditions (called “structural finiteness”) are shown to be precisely those entire functions whose derivatives have an exponential singularity at  $\infty$ , namely functions of the form  $\int Q(z)e^{P(z)}dz$ , where  $P, Q$  are polynomials.

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## 2. Log-Riemann surfaces of finite type and exp-algebraic curves

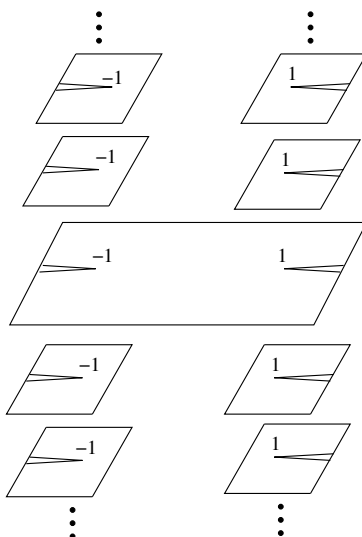
We recall some basic definitions and facts from [4, 6, 7].

DEFINITION 2.1. — *A log-Riemann surface is a pair  $(S, \pi)$ , where  $S$  is a Riemann surface and  $\pi : S \rightarrow \mathbb{C}$  is a local holomorphic diffeomorphism such that the set of points  $\mathcal{R}$  added to  $S$  in the completion  $S^* := S \sqcup \mathcal{R}$  with respect to the path metric induced by the flat metric  $|d\pi|$  is discrete.*

The map  $\pi$  extends to the metric completion  $S^*$  as a 1-Lipschitz map. In [6] it is shown that the map  $\pi$  restricted to a sufficiently small punctured metric neighbourhood  $B(w^*, r) - \{w^*\}$  of a ramification point is a covering of a punctured disc  $B(\pi(w^*), r) - \{\pi(w^*)\}$  in  $\mathbb{C}$ , and so has a well-defined degree  $1 \leq n \leq +\infty$ , called the order of the ramification point (we assume that the order is always at least 2, since order one points can always be added to  $S$  and  $\pi$  extended to these points in order to obtain a log-Riemann surface).

DEFINITION 2.2. — *A log-Riemann surface is of finite type if it has finitely many ramification points and finitely generated fundamental group.*

For example, the log-Riemann surface given by  $(\mathbb{C}, \pi = e^z)$  is of finite type (with the metric  $|d\pi|$  it is isometric to the Riemann surface of the logarithm, which is simply connected, with a single ramification point of infinite order), as is the log-Riemann surface given by the Gaussian integral  $(\mathbb{C}, \pi = \int e^{z^2} dz)$ , which has two ramification points, both of infinite order, as in the figure below:



Log-Riemann surface of the Gaussian integral

In [4], it is shown that a log-Riemann surface of finite type (which has at least one infinite order ramification point) is of the form  $(S', \pi)$ , where  $S'$  is a punctured compact Riemann surface  $S' = S - \{p_1, \dots, p_n\}$  and  $\pi$  is meromorphic on  $S'$  and  $d\pi$  has exponential singularities at the punctures  $p_1, \dots, p_n$ . Let  $h_1, \dots, h_n$  be the types of the exponential singularities of  $d\pi$  at the punctures  $p_1, \dots, p_n$ . As described in [4], each puncture  $p_j$  corresponds to an end of the log-Riemann surface where  $d_j$  infinite order ramification points are added,  $d_j$  being the order of the pole of  $h_j$  at  $p_j$ .

Let  $w^*$  be an infinite order ramification point associated to a puncture  $p_j$ . An  $\epsilon$ -ball  $B_\epsilon$  around  $w^*$  is isometric to the  $\epsilon$ -ball around the infinite order ramification point of the Riemann surface of the logarithm (given by cutting and pasting infinitely many discs together), and there is an argument function

$$\arg_{w^*} : B_\epsilon^* \longrightarrow \mathbb{R}$$

defined on the punctured ball  $B_\epsilon^*$ . While the function  $\pi$ , which is of the form  $\pi = \int e^{h_j \alpha_j}$  in a punctured neighbourhood of  $p_j$  for some meromorphic

1-form  $\alpha_j$ , extends continuously to  $w^*$  for the metric topology on  $S^*$ , in general functions of the form  $f = \int e^{h_j} \alpha$  (where  $\alpha$  is a 1-form meromorphic near  $p_j$ ) do *not* extend continuously to  $w^*$  for the metric topology ([5]). Limits of these functions in sectors  $\{p \in B_\epsilon^* \mid c_1 < \arg_{w^*}(p) < c_2\}$  do exist however and are independent of the sector; we say that the function is *Stolz continuous* at points of  $\mathcal{R}$ .

DEFINITION 2.3. — *Define spaces of functions and 1-forms on  $S^*$ :*

$$\begin{aligned} \mathcal{M}(S^*) &:= \left\{ f \text{ meromorphic function on } S' \mid \begin{array}{l} f \text{ has exponential singularities} \\ \text{at } p_1, \dots, p_n \text{ of types } h_1, \dots, h_n \end{array} \right\} \\ \mathcal{O}(S^*) &:= \{f \in \mathcal{M}(S^*) \mid f \text{ holomorphic on } S'\} \\ \Omega(S^*) &:= \left\{ \omega \text{ meromorphic 1-form on } S' \mid \begin{array}{l} \omega \text{ has exponential singularities} \\ \text{at } p_1, \dots, p_n \text{ of types } h_1, \dots, h_n \end{array} \right\} \\ \Omega^0(S^*) &:= \{\omega \in \Omega(S^*) \mid \omega \text{ holomorphic on } S'\} \end{aligned}$$

We remark that these are simply the spaces  $\mathcal{M}_{\mathcal{H}}, \mathcal{O}_{\mathcal{H}}, \Omega_{\mathcal{H}}, \Omega_{\mathcal{H}}^0$  defined in the introduction, where  $\mathcal{H} = \{[h_1], \dots, [h_n]\}$ . Functions in  $\mathcal{M}(S^*)$  are Stolz continuous at points of  $\mathcal{R}$  taking the value 0 there. The integrals of 1-forms  $\omega$  in  $\Omega_{II}(S^*)$  over curves  $\gamma : [a, b] \rightarrow S^*$  joining points  $w_1^*, w_2^*$  of  $\mathcal{R}$  converge if  $\gamma$  is disjoint from the poles of  $\omega$  and tends to these points through sectors

$$\{p \in B_\epsilon^* \mid c_1 < \arg_{w_1^*}(p) < c_2\}, \quad \{p \in B_\epsilon^* \mid c_1 < \arg_{w_2^*}(p) < c_2\}$$

(since any primitive of  $\omega$  on a sector is Stolz continuous).

The definitions of the above spaces only depend on the types  $\{[h_i] \in \mathcal{M}_{p_i}/\mathcal{O}_{p_i}\}$  of the exponential singularities of the 1-form  $d\pi$ , which do not change if  $d\pi$  is multiplied by a meromorphic function. It is natural to define then a structure less rigid than that of a log-Riemann surface of finite type.

DEFINITION 2.4 (Exp-algebraic curve). — *Given a punctured compact Riemann surface  $S' = S - \{p_1, \dots, p_n\}$ , two meromorphic functions  $\pi_1, \pi_2$  on  $S'$  inducing log-Riemann surface structures of finite type are considered equivalent if  $d\pi_1/d\pi_2$  is meromorphic on the compact surface  $S$ . An exp-algebraic curve is an equivalence class of such log-Riemann surface structures of finite type.*

It follows from the uniformization theorem of [4] that an exp-algebraic curve is given by the data of a punctured compact Riemann surface and  $n$  (equivalence classes of) germs of meromorphic functions  $\mathcal{H} = \{[h_i] \in \mathcal{M}_{p_i}/\mathcal{O}_{p_i}\}$  with poles at the punctures.

We can associate a topological space  $\widehat{S}$  to an exp-algebraic curve, given as a set by  $\widehat{S} = S' \cup \mathcal{R}$ , where  $\mathcal{R}$  is the set of infinite ramification points



added with respect to any map  $\pi$  in the equivalence class of log-Riemann surfaces of finite type, and the topology is the weakest topology such that all maps  $\tilde{\pi}$  in the equivalence class extend continuously to  $\widehat{S}$ .

Finally, for a meromorphic function  $f$  on  $S'$  (respectively, meromorphic 1-form  $\omega$  on  $S'$ ) with exponential singularities of types  $h_1, \dots, h_n$  at points  $p_1, \dots, p_n$  we can define a divisor  $(f) = \sum_{p \in S'} n_p \cdot p$  (respectively,  $(\omega) = \sum_{p \in S'} m_p \cdot p$ ) by  $n_p = \text{ord}_p(f)$  if  $p \in S'$  and  $n_p = \text{ord}_{p_i}(g)$  if  $p = p_i$ , where  $g$  is a germ of meromorphic function at  $p_i$  such that  $f = ge^{h_i}$  (respectively,  $m_p = \text{ord}_p(\omega)$  if  $p \in S'$  and  $m_p = \text{ord}_{p_i}(\alpha)$  if  $p = p_i$ , where  $\alpha$  is a germ of meromorphic 1-form at  $p_i$  such that  $\omega = \alpha e^{h_i}$ ).

Note that the divisor  $(f)$  can also be defined by  $n_p = \text{Res}(df/f, p)$ , so it follows from the Residue Theorem applied to the meromorphic 1-form  $df/f$  that the divisor  $(f)$  has degree zero.

### 3. Exp-algebraic curves and line bundles with meromorphic connections

Let  $(S, \mathcal{H} = \{h_1, \dots, h_n\})$  be an exp-algebraic curve, where  $S$  is a compact Riemann surface of genus  $g$  and  $h_1, \dots, h_n$  are germs of meromorphic functions at points  $p_1, \dots, p_n$ . Let  $\Omega(S)$  be the space of holomorphic 1-forms on  $S$ . The data  $\mathcal{H}$  defines a degree zero line bundle  $L_{\mathcal{H}}$  together with a transcendental section  $s_{\mathcal{H}}$  of this line bundle which is non-zero on the punctured surface  $S'$  as follows:

Solving the Mittag-Leffler problem locally for the distribution  $\{h_1, \dots, h_n\}$  gives meromorphic functions on an open cover such that the differences are holomorphic on intersections, and hence gives an element of  $H^1(S, \mathcal{O})$ . Under the exponential this gives a degree zero line bundle as an element of  $H^1(S, \mathcal{O}^*)$ . Explicitly this is constructed as follows:

Let

$$B_1, \dots, B_n$$

be pairwise disjoint coordinate disks around the punctures  $p_1, \dots, p_n$  and let  $V$  be an open subset of  $S'$  intersecting each disk  $B_i$  in an annulus  $U_i = V \cap B_i$  around  $p_i$  such that  $\{B_1, \dots, B_n, V\}$  is an open cover of  $S$ . Define a line bundle  $L_{\mathcal{H}}$  by taking the functions  $e^{-h_i}$  to be the transition functions for the line bundle on the intersections  $U_i$ . Define a holomorphic non-vanishing section of  $L_{\mathcal{H}}$  on  $S'$  by:

$$s_{\mathcal{H}} := \begin{cases} 1 & \text{on } V \\ e^{-h_i} & \text{on } B_i - \{p_i\} \end{cases}$$

Define a connection  $\nabla_{\mathcal{H}}$  on  $L_{\mathcal{H}}$  by declaring that  $\nabla_{\mathcal{H}}(s_{\mathcal{H}}) = 0$ . Then for any holomorphic section  $s$  on  $V$ , we have  $s = fs_{\mathcal{H}}$  for some holomorphic function  $f$ , and also  $\nabla_{\mathcal{H}}(s) = df s_{\mathcal{H}}$ , so  $\nabla_{\mathcal{H}}$  is holomorphic on  $V$ . On each disk  $B_i$ , letting  $s_i$  be the section which is a constant equal to 1 on  $B_i$  (with respect to the trivialization on  $B_i$ ), for any holomorphic section  $s$  on  $B_i$ , we have  $s = fs_i$  for some holomorphic function  $f$ , and also  $s_i = e^{h_i} s_{\mathcal{H}}$ , so

$$\begin{aligned} \nabla_{\mathcal{H}}(s) &= \nabla_{\mathcal{H}}(fs_i) \\ &= \nabla_{\mathcal{H}}(fe^{h_i} s_{\mathcal{H}}) \\ &= (df + fdh_i)e^{h_i} s_{\mathcal{H}} \\ &= (df + fdh_i)s_i \end{aligned}$$

thus the connection 1-form of  $\nabla_{\mathcal{H}}$  with respect to  $s_i$  is given by  $dh_i$ , so  $\nabla_{\mathcal{H}}$  is meromorphic on  $B_i$  with a single pole at  $p_i$  of order  $d_i + 1 \geq 2$ .

Let  $s_{\mathcal{H}}^*$  be the unique section of the dual bundle  $L_{\mathcal{H}}^*$  on  $S'$  such that  $s_{\mathcal{H}} \otimes s_{\mathcal{H}}^* = 1$  on  $S'$ . Then for any non-zero meromorphic section  $s$  of  $L_{\mathcal{H}}$ , the function

$$f := s \otimes s_{\mathcal{H}}^*$$

is meromorphic on  $S'$  with exponential singularities at  $p_1, \dots, p_n$  of types  $h_1, \dots, h_n$ , and the divisors of  $s$  and  $f$  coincide. Thus the line bundle  $L_{\mathcal{H}}$  has degree zero. In summary we have:

**THEOREM 3.1.** — *For any log-Riemann surface of finite type  $S^*$ , the line bundle  $L_{\mathcal{H}}$  has degree zero and the maps*

$$s \longmapsto s \otimes s_{\mathcal{H}}^*, \quad f \longmapsto f \cdot s_{\mathcal{H}}$$

(respectively,

$$\alpha \longmapsto \alpha \otimes s_{\mathcal{H}}^*, \quad \omega \longmapsto \omega \cdot s_{\mathcal{H}})$$

are mutually inverse isomorphisms between the spaces of meromorphic sections of  $L_{\mathcal{H}}$  and  $\mathcal{M}(S^*)$  (respectively, the spaces of meromorphic  $L_{\mathcal{H}}$ -valued 1-forms and  $\Omega(S^*)$ ) preserving divisors.

In particular the vector spaces  $\mathcal{M}(S^*), \mathcal{O}(S^*), \Omega(S^*), \Omega_{II}(S^*), \Omega^0(S^*)$  are all non-zero.

*Proof.* — Since the isomorphisms above preserve divisors, the spaces  $\mathcal{O}(S^*), \Omega^0(S^*)$  correspond to the spaces of meromorphic sections of  $L_{\mathcal{H}}$  and meromorphic  $L_{\mathcal{H}}$ -valued 1-forms which are holomorphic on  $S'$ , both of which are non-empty.  $\square$

PROPOSITION 3.2. — *The correspondence  $\mathcal{H} \mapsto (L_{\mathcal{H}}, \nabla_{\mathcal{H}})$  gives a one-to-one correspondence between exp-algebraic structures on  $S$  and degree zero line bundles on  $S$  with meromorphic connections with all poles of order at least two, zero residues, and trivial monodromy.*

*Proof.* — Since the connection 1-form of  $\nabla_{\mathcal{H}}$  is given by  $dh_i$  on  $B_i$ , all residues of  $\nabla_{\mathcal{H}}$  are equal to zero, while the monodromy of  $\nabla_{\mathcal{H}}$  is trivial since  $s_{\mathcal{H}}$  is a single-valued horizontal section.

Conversely, given such a meromorphic connection  $\nabla$  on a degree zero line bundle  $L$ , if  $p_1, \dots, p_n$  are the poles of  $\nabla$  and  $\omega_1, \dots, \omega_n$  are the connection 1-forms of  $\nabla$  with respect to trivializations near  $p_1, \dots, p_n$ , then each  $\omega_i$  has zero residue at  $p_i$  and pole order at least two, hence there exist meromorphic germs  $h_1, \dots, h_n$  near  $p_1, \dots, p_n$  such that  $\omega_i = dh_i$ . We obtain an exp-algebraic curve  $(S, \mathcal{H}(L, \nabla))$ .

It is clear for an exp-algebraic curve  $(S, \mathcal{H})$  that  $\mathcal{H}(L_{\mathcal{H}}, \nabla_{\mathcal{H}}) = \mathcal{H}$ , so the correspondences are inverses of each other.  $\square$

Finally we remark that by Serre Duality, the degree zero line bundle  $L_{\mathcal{H}}$ , given as an element of  $H^1(S, \mathcal{O})$ , can also be described as an element of  $H^0(S, \Omega)^* = \Omega(S)^*$  using residues, as the linear functional

$$\begin{aligned} \text{Res}_{\mathcal{H}} : \Omega(S) &\longrightarrow \mathbb{C} \\ \xi &\longmapsto \sum_i \text{Res}(\xi \cdot h_i, p_i) \end{aligned}$$

#### 4. Torelli-type theorem for exp-algebraic curves

We proceed to the proof of Theorem 1.1. We will need the following theorems from [3] and [13]:

THEOREM 4.1 ([3]). — *Let  $S^* = S' \cup \mathcal{R}$  be a log-Riemann surface of finite type, and let  $H^1_{dR,0}(S^*) = \Omega^0(S^*)/d\mathcal{O}(S^*)$ . Then the pairing  $H_1(S^*, \mathbb{R}; \mathbb{C}) \times H^1_{dR,0}(S^*) \longrightarrow \mathbb{C}$ , given by integration along curves, is nondegenerate.*

THEOREM 4.2 (Gusman, [13]). — *Let  $S$  be a compact Riemann surface and  $E \subset S$  a closed subset such that  $S - E$  has finitely many connected components  $V_1, \dots, V_m$ , and for each  $i$  let  $q_i$  be a point of  $V_i$ . Then any continuous function  $f$  on  $E$  which is holomorphic in the interior of  $E$  can be uniformly approximated on  $E$  by functions meromorphic on  $S$  with poles only in the set  $\{q_1, \dots, q_m\}$ .*

Let  $(S, \mathcal{H}_1), (S, \mathcal{H}_2)$  be two exp-algebraic curves with the same underlying Riemann surface  $S$  and the same set of punctures  $p_1, \dots, p_n$ , and suppose

the hypothesis of Theorem 1.1 holds, namely the line bundles  $L_{\mathcal{H}_1}, L_{\mathcal{H}_2}$  are isomorphic and the induced isomorphism

$$W_{\mathcal{H}_1}^* \longrightarrow W_{\mathcal{H}_2}^*$$

maps  $K_{\mathcal{H}_1}$  to  $K_{\mathcal{H}_2}$ . Since the spaces  $\mathcal{M}_{\mathcal{H}_1}, \mathcal{M}_{\mathcal{H}_2}$  are isomorphic to the spaces of meromorphic sections of  $L_{\mathcal{H}_1}$  and  $L_{\mathcal{H}_2}$  respectively, there is an induced isomorphism  $\mathcal{M}_{\mathcal{H}_1} \longrightarrow \mathcal{M}_{\mathcal{H}_2}$  which preserves divisors. We fix non-zero functions  $f_i \in \mathcal{M}_{\mathcal{H}_i}$ ,  $i = 1, 2$  which correspond to each other under this isomorphism, and let  $S_i^* = S' \cup \mathcal{R}_i$  denote the completions induced by the corresponding log-Riemann surface structures. We also fix a meromorphic 1-form  $\alpha_0$  on  $S$ . Then the divisor preserving isomorphisms  $\mathcal{M}_{\mathcal{H}_1} \longrightarrow \mathcal{M}_{\mathcal{H}_2}$  and  $\Omega_{\mathcal{H}_1} \longrightarrow \Omega_{\mathcal{H}_2}$  induced by the isomorphism  $L_{\mathcal{H}_1} \longrightarrow L_{\mathcal{H}_2}$  can be expressed as

$$g \cdot f_1 \longmapsto g \cdot f_2 \quad \text{and} \quad gf_1 \cdot \alpha_0 \longmapsto gf_2 \cdot \alpha_0$$

respectively, where  $g$  varies over all meromorphic functions on  $S$ .

LEMMA 4.3. — *For any meromorphic function  $g_2$  on  $S$  such that  $g_2 f_2 \in \mathcal{O}_{\mathcal{H}_2}$ , the 1-form  $g_2 f_1 \left( \frac{df_1}{f_1} - \frac{df_2}{f_2} \right)$  lies in the space  $d\mathcal{O}_{\mathcal{H}_1}$ .*

*Proof.* — The hypothesis of Theorem 1.1 implies that for any  $\gamma_1 \in H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$ , there is a

$$\gamma_2 \in H_1(S_2^*, \mathcal{R}_2; \mathbb{C})$$

such that  $\int_{\gamma_1} gf_1 \alpha_0 = \int_{\gamma_2} gf_2 \alpha_0$  for all meromorphic functions  $g$  on  $S$  such that  $gf_i \alpha_0$  is holomorphic on  $S'$  for  $i = 1, 2$ . If  $g_2$  is a meromorphic function on  $S$  such that  $g_2 f_2$  is holomorphic on  $S'$ , then

$$d(g_2 f_2) = g_2 f_2 \alpha_0$$

for some meromorphic function  $g$  on  $S$  such that  $gf_2 \alpha_0$  is holomorphic on  $S'$ . Since the isomorphism  $\Omega(\mathcal{H}_1) \longrightarrow \Omega(\mathcal{H}_2)$  is divisor preserving, we have that  $gf_1 \alpha_0$  is also holomorphic on  $S'$ , so for any  $\gamma_1 \in H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$  there is a  $\gamma_2 \in H_1(S_2^*, \mathcal{R}_2; \mathbb{C})$  such that

$$\int_{\gamma_1} gf_1 \alpha_0 = \int_{\gamma_2} gf_2 \alpha_0 = \int_{\gamma_2} d(g_2 f_2) = 0$$

Since this is true for all  $\gamma_1 \in H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$ , it follows from Theorem 4.1 that  $gf_1 \alpha_0 \in d\mathcal{O}_{\mathcal{H}_1}$ , so there exists a meromorphic function  $g_1$  on  $S$  such that  $g_1 f_1$  is holomorphic on  $S'$  and  $gf_1 \alpha_0 = d(g_1 f_1)$ .

It follows from the equalities  $gf_i \alpha_0 = d(g_i f_i)$ ,  $i = 1, 2$  that

$$dg_1 + g_1 \frac{df_1}{f_1} = g \alpha_0 = dg_2 + g_2 \frac{df_2}{f_2},$$

hence

$$dg_1 + g_1 \frac{df_1}{f_1} = \left( dg_2 + g_2 \frac{df_1}{f_1} \right) + g_2 \left( \frac{df_2}{f_2} - \frac{df_1}{f_1} \right),$$

so multiplying above by  $f_1$  gives

$$g_2 f_1 \left( \frac{df_2}{f_2} - \frac{df_1}{f_1} \right) = d(g_1 f_1) - d(g_2 f_1) \in d\mathcal{O}_{\mathcal{H}_1}$$

as required, since  $g_1 f_1, g_2 f_1 \in \mathcal{O}_{\mathcal{H}_1}$  (note that  $g_2 f_2 \in \mathcal{O}_{\mathcal{H}_2}$  implies  $g_2 f_1 \in \mathcal{O}_{\mathcal{H}_1}$ ).  $\square$

*Proof of Theorem 1.1.* — We consider different cases:

*Case 1. The genus of  $S$  is at least one.* — In this case there exists a closed curve  $\gamma$  disjoint from the punctures  $p_1, \dots, p_n$  and the poles and zeroes of  $f_1, f_2$  such that  $S - \gamma$  is connected. Fix a non-zero meromorphic function  $g_0$  on  $S$  such that  $g_0 f_1$  (and hence also  $g_0 f_2$ ) is holomorphic on  $S'$ .

If the meromorphic 1-form  $\omega = \frac{df_1}{f_1} - \frac{df_2}{f_2}$  (which is holomorphic outside the punctures and the zeroes and poles of  $f_1, f_2$ ) is not identically zero, then we can choose a continuous function  $u$  on  $\gamma$  such that  $\int_{\gamma} u g_0 f_1 \omega \neq 0$  (since the 1-form  $g_0 f_1 \omega$  is holomorphic and not identically zero on  $\gamma$ ). By Theorem 4.2, since  $S - \gamma$  is connected and contains  $p_1$ , we can choose a meromorphic function  $v$  on  $S$  which is holomorphic on  $S - \{p_1\}$  and uniformly close enough to  $u$  on  $\gamma$  such that  $\int_{\gamma} v g_0 f_1 \omega \neq 0$ . Letting  $g_2 = v g_0$ , we have that  $g_2 f_2$  is holomorphic on  $S'$  and  $\int_{\gamma} g_2 f_1 \omega \neq 0$ , contradicting Lemma 4.3. It follows that  $df_1/f_1 \equiv df_2/f_2$ , from which it follows easily that  $\mathcal{H}_1 = \mathcal{H}_2$ .

*Case 2. The genus of  $S$  is zero and the number  $n$  of punctures is at least two.* — In this case  $S = \widehat{\mathbb{C}}$  and we may assume  $p_1 = 0, p_2 = \infty$ . Fix a non-zero polynomial  $P$  such that  $P f_1, P f_2$  are holomorphic on  $S'$ . Then by Lemma 4.3, for all  $k \in \mathbb{Z}$ , taking  $g_2 = z^k P(z)$  we have

$$\text{Res}((z^k P) f_1 \omega, 0) = 0$$

from which it follows that the Laurent series of  $P f_1 \omega$  around  $z = 0$  vanishes identically, hence  $\omega \equiv 0$  and  $\mathcal{H}_1 = \mathcal{H}_2$ .

*Case 3. The genus of  $S$  is zero and there is only one puncture.* — In this case  $S = \widehat{\mathbb{C}}$  and we may assume the single puncture  $p_1 = \infty$ , and that the functions  $f_1, f_2$  are of the form  $f_i = e^{P_i}$  for some polynomials  $P_1, P_2$ . In this case it follows from the main theorem of [3] that the dimension of  $H_1(S_i^*, \mathcal{R}_i; \mathbb{C})$  equals  $\deg(P_i) - 1$ . Since  $K_{\mathcal{H}_1}$  and  $K_{\mathcal{H}_2}$  are isomorphic by hypothesis, it follows that  $\deg(P_1) = \deg(P_2) = d$  say, where  $d \geq 2$  since  $H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$  is non-trivial.

Let  $P_1(z) = a_d z^d + \dots + a_0, P_2(z) = b_d z^d + \dots + b_0$ . Let  $\gamma_1, \dots, \gamma_{d-1}$  be a basis for  $H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$  as described in Section 4 of [3], each  $\gamma_k$  being a curve joining a pair of ramification points  $w_0^*, w_k^*$ , where  $\mathcal{R}_1 = \{w_0^*, \dots, w_{d-1}^*\}$ . By hypothesis, for each curve  $\gamma_k \in H_1(S_1^*, \mathcal{R}_1; \mathbb{C})$  there is a  $\gamma_k' \in H_1(S_2^*, \mathcal{R}_2; \mathbb{C})$

such that

$$\int_{\gamma_k} Q(z)e^{P_1(z)} dz = \int_{\gamma'_k} Q(z)e^{P_2(z)} dz$$

for all polynomials  $Q$ . Consider the  $(d-1) \times d$  matrix

$$M = \begin{pmatrix} \int_{\gamma_1} e^{P_1(z)} dz & \dots & \int_{\gamma_1} z^{d-2} e^{P_1(z)} dz & \int_{\gamma_1} z^{d-1} e^{P_1(z)} dz \\ \vdots & \vdots & \ddots & \vdots \\ \int_{\gamma_{d-1}} e^{P_1(z)} dz & \dots & \int_{\gamma_{d-1}} z^{d-2} e^{P_1(z)} dz & \int_{\gamma_{d-1}} z^{d-1} e^{P_1(z)} dz \\ \int_{\gamma'_1} e^{P_2(z)} dz & \dots & \int_{\gamma'_1} z^{d-2} e^{P_2(z)} dz & \int_{\gamma'_1} z^{d-1} e^{P_2(z)} dz \\ \vdots & \vdots & \ddots & \vdots \\ \int_{\gamma'_{d-1}} e^{P_2(z)} dz & \dots & \int_{\gamma'_{d-1}} z^{d-2} e^{P_2(z)} dz & \int_{\gamma'_{d-1}} z^{d-1} e^{P_2(z)} dz \end{pmatrix}$$

It follows from Theorem III.1.5.1 of [5] that the  $(d-1)$  1-forms

$$z^k e^{P_1} dz, \quad k = 0, \dots, (d-2)$$

span  $H^1_{dR,0}(S^*_1)$ , and hence form a basis for  $H^1_{dR,0}(S^*_1)$ . Since by Theorem 4.1 the pairing with  $H_1(S^*_1, \mathcal{R}_1; \mathbb{C})$  is nondegenerate, it follows that the  $(d-1) \times (d-1)$  submatrix formed by the first  $(d-1)$  columns of  $M$  is nonsingular, thus  $M$  has rank  $(d-1)$ . On the other hand, since  $d(e^{P_i}) = P'_i e^{P_i} dz, i = 1, 2$ , it follows that

$$M \cdot \begin{pmatrix} a_1 \\ \vdots \\ (d-1)a_{d-1} \\ da_d \end{pmatrix} = M \cdot \begin{pmatrix} b_1 \\ \vdots \\ (d-1)b_{d-1} \\ db_d \end{pmatrix} = 0$$

hence there is a scalar  $\lambda$  such that  $kb_k = \lambda ka_k, k = 1, \dots, d-1$ , so  $P'_2 = \lambda P'_1$ . It follows from Lemma 4.3 that for any polynomial  $Q$  the 1-form

$$Qe^{P_1}(\lambda - 1)P'_1 dz = Qe^{P_1}(P'_2 - P'_1) dz$$

lies in  $d\mathcal{O}_{\mathcal{H}_1}$ . Thus if  $\lambda \neq 1$ , then  $QP'_1 e^{P_1} dz \in d\mathcal{O}_{\mathcal{H}_1}$ , hence

$$Q'e^{P_1} dz = d(Qe^{P_1}) - QP'_1 e^{P_1} dz \in d\mathcal{O}_{\mathcal{H}_1}$$

for all polynomials  $Q$ . Since all 1-forms in  $\Omega^0_{\mathcal{H}_1}$  are of the form  $Pe^{P_1} dz$  for some polynomial  $P$  and any  $P = Q'$  for some polynomial  $Q$ , it follows that  $H^1_{dR,0}(S^*_1)$  is trivial, a contradiction. Thus  $\lambda = 1$ , so  $P'_2 = P'_1$  and hence  $\mathcal{H}_1 = \mathcal{H}_2$ .  $\square$

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