

On the Pro- p Absolute Anabelian Geometry of Proper Hyperbolic Curves

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Abstract. In the present paper, we study the geometry of the stable models of proper hyperbolic curves over p -adic local fields via the study of the geometrically pro- p étale fundamental groups of the curves. In particular, we establish functorial “group-theoretic” algorithms for reconstructing various objects related to the geometry of stable models from the geometrically pro- p étale fundamental groups. As an application, we also give a pro- p “group-theoretic” criterion for good reduction of ordinary proper hyperbolic curves over p -adic local fields.

Introduction

Let p be a prime number, k a p -adic local field (i.e., a finite extension of \mathbb{Q}_p), \bar{k} an algebraic closure of k , and X a *proper hyperbolic curve* over k (i.e., a proper smooth geometrically connected curve over k of arithmetic genus ≥ 2). Write \underline{k} for the residue field of the ring of integers of k , $\bar{\underline{k}}$ for the algebraic closure of \underline{k} determined by \bar{k} (i.e., the residue field of the ring of integers of \bar{k}), $X_{\bar{\underline{k}}} \stackrel{\text{def}}{=} X \times_k \bar{k}$ for the proper hyperbolic curve over $\bar{\underline{k}}$ obtained by base changing X from k to \bar{k} , and

$$\Pi_X$$

for the geometrically pro- p étale fundamental group of X (cf. Definition 2.2). Then it is well-known (cf. Theorem 1.3) that the hyperbolic curve X has *stable reduction* over the ring of integers of \bar{k} . We shall write $X_{\bar{\underline{k}}}$ for the stable curve over $\bar{\underline{k}}$ obtained by forming the special fiber of the stable model of $X_{\bar{\underline{k}}}$.

In the present paper, we study the geometry of the stable curve $X_{\bar{\underline{k}}}$ via the study of the profinite group Π_X . In particular, we center around the

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task of establishing *functorial “group-theoretic” algorithms* whose input data consist of the abstract profinite group Π_X and whose output data consist of objects related to the geometry of the stable curve $X_{\bar{k}}$ (cf. the main result of the present paper, i.e., Theorem 3.7). By applying the *functorial “group-theoretic” algorithms* of the present paper, one may reconstruct, from Π_X , for instance, the following objects:

- The set of irreducible components of $X_{\bar{k}}$ whose normalizations are of *positive p -rank* (cf. Theorem 3.7, (viii)), as well as the (necessarily positive) p -ranks of the normalizations of elements of this set (cf. Theorem 3.7, (x)).
- The first Betti number of the (topological space determined by the) dual graph of $X_{\bar{k}}$ (cf. Theorem 3.7, (vii)).

We shall say that the proper hyperbolic curve X is *ordinary* if the arithmetic genus of X is equal to the p -rank of $X_{\bar{k}}$ (cf. Definition 2.6, (i)). Moreover, we shall say that a profinite group Π satisfies the condition (\dagger) if there exist a prime number l and an isomorphism of Π with the geometrically pro- l étale fundamental group of a proper hyperbolic curve over an l -adic local field (cf. Definition 3.6). (So the profinite group Π_X satisfies the condition (\dagger) .) Some of the consequences of the *functorial “group-theoretic” algorithms* of the present paper may be summarized as follows (cf. Theorem 3.7, (xi), (xiii)). In the following Theorem, the term “purely group-theoretic condition” is used to mean that “the condition in a discussion is phrased in language that only depends on the profinite group structure of the profinite group under consideration”:

THEOREM. *The following hold:*

- (i) *There exists a purely “group-theoretic” condition for profinite groups which satisfy (\dagger) such that the profinite group Π_X satisfies this condition if and only if the hyperbolic curve X is ordinary.*
- (ii) *There exists a purely “group-theoretic” condition for profinite groups which satisfy (\dagger) such that the profinite group Π_X satisfies this condition if and only if the hyperbolic curve X is ordinary and has good reduction over the ring of integers of k .*

In particular, we obtain the following result (cf. Corollary 3.8, (i), (iv), (vi)):

COROLLARY. For $\square \in \{\circ, \bullet\}$, let p_\square be a prime number, k_\square a p_\square -adic local field, and X_\square a proper hyperbolic curve over k_\square . Suppose that the geometrically pro- p_\circ étale fundamental group of X_\circ is isomorphic to the geometrically pro- p_\bullet étale fundamental group of X_\bullet . Then it holds that $p_\circ = p_\bullet$, and, moreover, the following hold:

(i) It holds that X_\circ is ordinary if and only if X_\bullet is ordinary.

(ii) Suppose, moreover, that either X_\circ or X_\bullet is ordinary. Then it holds that X_\circ has good reduction over the ring of integers of k_\circ if and only if X_\bullet has good reduction over the ring of integers of k_\bullet .

Note that the above Theorem (cf. also the above Corollary) may be regarded as a pro- p “group-theoretic” criterion for good reduction of ordinary proper hyperbolic curves over p -adic local fields. Here, let us recall (cf. Remark 3.8.1) that, for a nonempty set Σ of prime numbers such that $p \notin \Sigma$, we have already a pro- Σ “group-theoretic” criterion for good reduction of (not necessarily ordinary) hyperbolic curves over p -adic local fields proved by T. Oda (cf. [19], Theorem 3.2), A. Tamagawa (cf. [21], Theorem 5.3), and S. Mochizuki (cf. [13], Corollary 2.8).

Finally, let us discuss (cf. Remark 3.8.2) the p -adic criterion for good reduction of curves proved by F. Andreatta, A. Iovita, and M. Kim in [1] from the point of view of the present paper. The p -adic criterion of [1] asserts, roughly speaking, that X has good reduction over the ring of integers of k if and only if every member of a certain collection of finite-dimensional representations of $G_k \stackrel{\text{def}}{=} \text{Gal}(\bar{k}/k)$ over \mathbb{Q}_p determined by the profinite group Π_X and a splitting of the natural surjection $\Pi_X \rightarrow G_k$ arising from a k -rational point of X is crystalline (cf. [1], Theorem 1.9). Here, observe that this criterion (is interesting even in a certain point of view of anabelian geometry but) should be considered to be not “group-theoretic” (i.e., to be not useful in pro- p absolute anabelian geometry) by the following two reasons:

(1) The issue of whether or not a given finite-dimensional representation of G_k over \mathbb{Q}_p is crystalline is not “group-theoretic”. Indeed, it follows immediately from the discussion of [8], Remark 3.3.1, that there exist a prime number l , an l -adic local field L , an automorphism α of the absolute Galois group G_L of L , and a crystalline representation $\rho: G_L \rightarrow \text{GL}_n(\mathbb{Q}_l)$ such that the composite $G_L \xrightarrow{\alpha} G_L \xrightarrow{\rho} \text{GL}_n(\mathbb{Q}_l)$ is not crystalline.

(2) It is *not clear* that the issue of whether or not a given splitting of the natural surjection $\Pi_X \rightarrow G_k$ arises from a k -rational point of X is “*group-theoretic*”. Note that it follows from [6], Theorem A, that there exist a prime number l , an l -adic local field L , a proper hyperbolic curve C over L , and a splitting of the natural surjection from the geometrically pro- l étale fundamental group of C onto the absolute Galois group of L which does *not arise from an L -rational point of C* .

As a consequence of this discussion, one *cannot*, at least in the immediate literal sense, *drop* the ordinary hypothesis in the statement of the Corollary, (ii), even if one applies the p -adic criterion of [1].

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1. Stable Models

Throughout the present paper, let p be a prime number. In the present §1, we introduce some notations related to the geometry of the stable models of proper hyperbolic curves over p -adic local fields. We also recall a theorem of *P. Deligne* and *D. Mumford* (cf. Theorem 1.3 below) and a theorem of *M. Raynaud* (cf. Theorem 1.6 below).

DEFINITION 1.1. Let V be a proper variety over a field F . Then we shall write

$$g_V \stackrel{\text{def}}{=} (-1)^{\dim(V)} \cdot (\chi_{\text{Zar}}(\mathcal{O}_V) - 1)$$

for the *arithmetic genus* of V . If, moreover, F is algebraically closed and of characteristic p , then we shall write

$$\gamma_V \stackrel{\text{def}}{=} \dim_{\mathbb{F}_p} H_{\text{ét}}^1(V, \mathbb{F}_p)$$

for the p -rank of V .

In the remainder of the present §1, let k be a p -adic local field (i.e., a finite extension of \mathbb{Q}_p), \bar{k} an algebraic closure of k , and X a *proper hyperbolic curve* over k (i.e., a proper smooth geometrically connected curve over k such that $g_X \geq 2$) (cf. the discussion entitled “Curves” in [6], §0, for the

definition of the term “hyperbolic curve”). Write \underline{k} for the residue field of the ring of integers of k , \overline{k} for the algebraic closure of \underline{k} determined by \overline{k} (i.e., the residue field of the ring of integers of \overline{k}), and $X_{\overline{k}} \stackrel{\text{def}}{=} X \times_k \overline{k}$ for the proper hyperbolic curve over \overline{k} obtained by base changing X from k to \overline{k} .

DEFINITION 1.2. Let K be a(n) (possibly infinite) algebraic extension of k . Then we shall say that the hyperbolic curve X has *stable reduction* (respectively, *good reduction*) over the ring of integers of K if the structure morphism $X \times_k K \rightarrow \text{Spec}(K)$ extends to a stable curve (respectively, smooth stable curve) over the ring of integers of K (cf. [4], Definition 1.1).

DEFINITION 1.3 (Deligne-Mumford). In the notations introduced in the discussion preceding Definition 1.2, there exists a finite extension K of k such that the hyperbolic curve X has *stable reduction* over the ring of integers of K (cf. Definition 1.2). In particular, the hyperbolic curve X has *stable reduction* over the ring of integers of \overline{k} .

PROOF. This follows from [4], Corollary 2.7. \square

DEFINITION 1.4.

(i) We shall write

$$X_{\overline{k}}$$

for the stable curve over \overline{k} (of arithmetic genus g_X) obtained by forming the special fiber of the stable model of $X_{\overline{k}}$ over the ring of integers of \overline{k} (cf. Theorem 1.3).

(ii) We shall write

$$\mathbb{G}_X$$

for the *dual graph* of $X_{\overline{k}}$,

$$\text{Irr}(X)$$

for the set of irreducible components of $X_{\overline{k}}$ — i.e., the set of vertices of \mathbb{G}_X — and

$$b_1(X) \stackrel{\text{def}}{=} \dim_{\mathbb{Q}} H_1(\mathbb{G}_X, \mathbb{Q})$$

for the first Betti number of (the topological space determined by) \mathbb{G}_X .

(iii) Let $v \in \text{Irr}(X)$. Then we shall write

$$X_v$$

for the proper smooth (connected) curve over \bar{k} obtained by forming the normalization of the irreducible component of $X_{\bar{k}}$ corresponding to $v \in \text{Irr}(X)$,

$$g_v \stackrel{\text{def}}{=} g_{X_v}$$

for the *arithmetic genus* of X_v , and

$$\gamma_v \stackrel{\text{def}}{=} \gamma_{X_v}$$

for the *p-rank* of X_v .

(iv) We shall write

$$\text{Irr}(X)^{\gamma=0} \stackrel{\text{def}}{=} \{v \in \text{Irr}(X) \mid \gamma_v = 0\} \subseteq \text{Irr}(X)$$

for the set of irreducible components of $X_{\bar{k}}$ (whose normalizations are) of *p-rank zero* and

$$\text{Irr}(X)^{\gamma>0} \stackrel{\text{def}}{=} \text{Irr}(X) \setminus \text{Irr}(X)^{\gamma=0} = \{v \in \text{Irr}(X) \mid \gamma_v > 0\} \subseteq \text{Irr}(X)$$

for the set of irreducible components of $X_{\bar{k}}$ (whose normalizations are) of *positive p-rank*.

REMARK 1.4.1.

(i) It is well-known (cf., e.g., the discussion following [3], Definition 1.1) that, for each $v \in \text{Irr}(X)$, it holds that $g_v \geq \gamma_v \geq 0$.

(ii) It is also well-known (cf., e.g., [3], Lemma 1.3, as well as the proof of [3], Lemma 1.3) that

$$g_X = g_{X_{\bar{k}}} = b_1(X) + \sum_{v \in \text{Irr}(X)} g_v,$$

$$\gamma_{X_{\bar{k}}} = b_1(X) + \sum_{v \in \text{Irr}(X)} \gamma_v = b_1(X) + \sum_{v \in \text{Irr}(X)^{\gamma>0}} \gamma_v.$$

REMARK 1.4.2. Let $Y \rightarrow X$ be a connected finite étale covering of X (i.e., a finite étale morphism whose domain Y is connected).

(i) One verifies easily that Y is a *proper hyperbolic curve* over a finite extension k_Y of k (i.e., the algebraic closure of k in the function field of Y). Moreover, one also verifies easily that the covering $Y \rightarrow X$ determines a *connected finite étale covering* $Y_{\bar{k}} \stackrel{\text{def}}{=} Y \times_{k_Y} \bar{k} \rightarrow X_{\bar{k}}$ over \bar{k} .

(ii) It follows, in light of Theorem 1.3, from [11], Lemma 8.3, that the covering $Y_{\bar{k}} \rightarrow X_{\bar{k}}$ of (i) extends to a *uniquely determined proper (not necessarily finite) surjection* from the stable model of $Y_{\bar{k}}$ over the ring of integers of \bar{k} to the stable model of $X_{\bar{k}}$ over the ring of integers of \bar{k} . In particular, we obtain a *proper (not necessarily finite) surjection* $Y_{\underline{\bar{k}}} \rightarrow X_{\underline{\bar{k}}}$ over $\underline{\bar{k}}$.

(iii) One verifies immediately from the existence of the morphism $Y_{\underline{\bar{k}}} \rightarrow X_{\underline{\bar{k}}}$ of (ii) that the inequalities

$$b_1(Y) \geq b_1(X), \quad \#\text{Irr}(Y)^{\gamma > 0} \geq \#\text{Irr}(X)^{\gamma > 0}$$

hold.

DEFINITION 1.5. Let $Y \rightarrow X$ be a connected finite étale covering of X . Then we shall say that the covering $Y \rightarrow X$ is a *geometrically- p -covering* if the Galois closure of the connected finite étale covering $Y_{\bar{k}} \rightarrow X_{\bar{k}}$ over \bar{k} (cf. Remark 1.4.2, (i)) is of degree a power of p (cf. Remark 2.2.1 below).

REMARK 1.5.1. One verifies easily that the composite of finitely many *geometrically- p -coverings* is a *geometrically- p -covering*. Moreover, one also verifies easily that the connected finite étale covering obtained by the “composition” (i.e., obtained by considering the composite field of the function fields) of finitely many *geometrically- p -coverings* is a *geometrically- p -covering*.

THEOREM 1.6 (Raynaud). *In the notations introduced in the discussion preceding Definition 1.2, suppose that X has good reduction over the ring of integers of \bar{k} (cf. Definition 1.2). Then it holds that $b_1(Y) = 0$ (cf. Definition 1.4, (ii)) for every geometrically- p -covering $Y \rightarrow X$ (cf. Definition 1.5) of X .*

PROOF. Let $Y \rightarrow X$ be a geometrically- p -covering of X . Then it follows from Remark 1.4.2, (iii), that, to verify that $b_1(Y) = 0$, we may

assume without loss of generality, by replacing $Y \rightarrow X$ by the Galois closure, that the geometrically- p -covering $Y \rightarrow X$ is *Galois*. Then since the Galois group of the Galois covering $Y_{\bar{k}} \rightarrow X_{\bar{k}}$ (cf. Remark 1.4.2, (i)) is a p -group, the equality $b_1(Y) = 0$ follows from [16], Théorème 1, (ii). \square

2. Quotients of Pro- p Fundamental Groups

In the present §2, we discuss certain quotients (cf. Definition 2.3 and Definition 2.4 below) of the pro- p geometric étale fundamental groups (cf. Definition 2.2 below) of proper hyperbolic curves over p -adic local fields. In the present §2, we maintain the notations introduced in the discussion preceding Definition 1.2. Write $\pi_1(X)$ for the étale fundamental group of X relative to some choice of basepoint such that the algebraic closure of k determined by this basepoint coincides with \bar{k} , $G_k \stackrel{\text{def}}{=} \text{Gal}(\bar{k}/k)$ for the absolute Galois group of k determined by the algebraic closure \bar{k} , and $I_k \subseteq G_k$ for the inertia subgroup of G_k .

DEFINITION 2.1. Let $K \subseteq \bar{k}$ be a(n) (possibly infinite) algebraic extension of k . Then we shall say that X is *split* over K if the natural action of $G_K \stackrel{\text{def}}{=} \text{Gal}(\bar{k}/K) \subseteq G_k$ on the dual graph \mathbb{G}_X is trivial.

REMARK 2.1.1. Since the graph \mathbb{G}_X is *finite*, it is immediate that there exists a finite extension K of k over which the hyperbolic curve X is *split*.

DEFINITION 2.2. We shall write

$$\Delta_X$$

for the *pro- p geometric étale fundamental group* of X — i.e., the maximal pro- p quotient of the étale fundamental group $\pi_1(X_{\bar{k}})$ of $X_{\bar{k}}$ relative to the basepoint which defines $\pi_1(X)$ — and

$$\Pi_X$$

for the *geometrically pro- p étale fundamental group* of X — i.e., the quotient of $\pi_1(X)$ by the normal closed subgroup obtained by forming the kernel of the natural surjection from $\pi_1(X_{\bar{k}})$ ($\subseteq \pi_1(X)$) to Δ_X . Thus, we have an exact sequence of profinite groups

$$1 \longrightarrow \Delta_X \longrightarrow \Pi_X \longrightarrow G_k \longrightarrow 1,$$

which thus determines an outer action of G_k on Δ_X .

REMARK 2.2.1. Let $Y \rightarrow X$ be a connected finite étale covering of X . Then one verifies easily that the covering $Y \rightarrow X$ (is isomorphic to the covering which) corresponds to an *open subgroup of Π_X* if and only if the covering $Y \rightarrow X$ is a *geometrically- p -covering*.

DEFINITION 2.3.

(i) We shall write

$$\Delta_X^{\text{ét}}$$

for the *pro- p étale fundamental group of $X_{\bar{k}}$* — i.e., the maximal pro- p quotient of the étale fundamental group $\pi_1(X_{\bar{k}})$ of $X_{\bar{k}}$ relative to the basepoint determined by the basepoint which defines $\pi_1(X)$. Thus, the natural open immersion from $X_{\bar{k}}$ into the stable model of $X_{\bar{k}}$ over the ring of integers of \bar{k} determines a *surjection*

$$\Delta_X \twoheadrightarrow \Delta_X^{\text{ét}}.$$

(ii) Let $v \in \text{Irr}(X)$. Then we shall write

$$\mathfrak{D}_v \subseteq \Delta_X^{\text{ét}}$$

for the decomposition subgroup of $\Delta_X^{\text{ét}}$ (well-defined up to conjugation) associated to the irreducible component of $X_{\bar{k}}$ corresponding to $v \in \text{Irr}(X)$.

(iii) We shall write

$$\Delta_X^{\text{cmb}}$$

for the quotient of $\Delta_X^{\text{ét}}$ by the normal closed subgroup topologically normally generated by the \mathfrak{D}_v 's, where v ranges over the elements of $\text{Irr}(X)$. Thus, we have a natural surjection

$$\Delta_X^{\text{ét}} \twoheadrightarrow \Delta_X^{\text{cmb}}.$$

DEFINITION 2.4. We shall write

$$\Delta_X^{\text{ab}}, \quad \Delta_X^{\text{ét-ab}}, \quad \Delta_X^{\text{cmb-ab}}$$

for the respective abelianizations of Δ_X , $\Delta_X^{\text{ét}}$, Δ_X^{cmb} . Thus, Δ_X^{ab} , $\Delta_X^{\text{ét-ab}}$, $\Delta_X^{\text{cmb-ab}}$ have natural structures of \mathbb{Z}_p -modules, respectively.

REMARK 2.4.1.

(i) One verifies easily that if X has *stable reduction* over the ring of integers of k , then the quotients $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$ of Δ_X^{ab} are G_k -*stable*.

(ii) One also verifies easily from the various definitions involved that the following hold:

- If X has *stable reduction* over the ring of integers of k , then the action of I_k on the G_k -*stable* (cf. (i)) quotient $\Delta_X^{\text{ét-ab}}$ is *trivial*.

- If X is *split* over k , then the action of G_k on the G_k -*stable* (cf. (i)) quotient $\Delta_X^{\text{cmb-ab}}$ is *trivial*.

Here, let us recall the following well-known fact:

PROPOSITION 2.5. *The following hold:*

(i) *The profinite groups $\Delta_X^{\text{ét}}$, Δ_X^{cmb} are free pro- p of rank $\gamma_{X_{\overline{k}}}$, $b_1(X)$, respectively. In particular, the \mathbb{Z}_p -modules $\Delta_X^{\text{ét-ab}}$, $\Delta_X^{\text{cmb-ab}}$ are free of rank $\gamma_{X_{\overline{k}}}$, $b_1(X)$, respectively.*

(ii) *Let $v \in \text{Irr}(X)$. Then the profinite group \mathfrak{D}_v is free pro- p of rank γ_v . In particular, the abelianization $\mathfrak{D}_v^{\text{ab}}$ of \mathfrak{D}_v is a free \mathbb{Z}_p -module of rank γ_v .*

(iii) *The natural inclusions $\mathfrak{D}_v \hookrightarrow \Delta_X^{\text{ét}}$ — where v ranges over the elements of $\text{Irr}(X)$ — and the natural surjection $\Delta_X^{\text{ét}} \twoheadrightarrow \Delta_X^{\text{cmb}}$ determine an exact sequence of finitely generated free \mathbb{Z}_p -modules*

$$0 \longrightarrow \bigoplus_{v \in \text{Irr}(X)} \mathfrak{D}_v^{\text{ab}} \longrightarrow \Delta_X^{\text{ét-ab}} \longrightarrow \Delta_X^{\text{cmb-ab}} \longrightarrow 0.$$

(iv) *Let $v, w \in \text{Irr}(X)^{\gamma > 0}$. Then the following conditions are equivalent:*

- (1) It holds that $v = w$.
- (2) The conjugacy class of \mathfrak{D}_v coincides with the conjugacy class of \mathfrak{D}_w .
- (3) The intersection $\mathfrak{D}_v \cap \mathfrak{D}_w$ is nontrivial for some choices of \mathfrak{D}_v and \mathfrak{D}_w (i.e., among their conjugates).

(v) Let $v \in \text{Irr}(X)^{\gamma > 0}$. Then the closed subgroup $\mathfrak{D}_v \subseteq \Delta_X^{\text{ét}}$ is commensurably terminal, i.e., for $\delta \in \Delta_X^{\text{ét}}$, it holds that $\delta \in \mathfrak{D}_v$ if and only if the intersection $\mathfrak{D}_v \cap (\delta \mathfrak{D}_v \delta^{-1})$ is of finite index in both \mathfrak{D}_v and $\delta \mathfrak{D}_v \delta^{-1}$.

(vi) Suppose that X has stable reduction over the ring of integers of k (which thus implies that the quotients $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$ of Δ_X^{ab} are G_k -stable — cf. Remark 2.4.1, (i)). Then, for every open subgroup $J \subseteq G_k$ of G_k , there is no nontrivial torsion-free J -stable quotient of

$$\text{Ker}(\Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}})$$

on which J acts trivially.

PROOF. First, we verify assertion (i). Let us first observe that it follows immediately from the definition of Δ_X^{cmb} that Δ_X^{cmb} is naturally isomorphic to the pro- p completion of the topological fundamental group of the (topological space determined by the) graph \mathbb{G}_X . Next, let us recall the well-known fact that the topological fundamental group of the (topological space determined by the) graph \mathbb{G}_X is *free of rank* $b_1(X)$. Thus, the profinite group Δ_X^{cmb} is *free pro- p* of rank $b_1(X)$, as desired.

Next, to verify the assertion for $\Delta_X^{\text{ét}}$ in assertion (i), let us recall the well-known fact that $H_{\text{ét}}^2(X_{\bar{k}}, \mathbb{Z}/p\mathbb{Z}) = \{0\}$ (cf., e.g., [10], Chapter VI, Remark 1.5, (b)). Thus, it follows from [20], Corollary A.1.4, that $H^2(\Delta_X^{\text{ét}}, \mathbb{Z}/p\mathbb{Z}) = \{0\}$. In particular, it follows from [18], Theorem 7.7.4, that $\Delta_X^{\text{ét}}$ is *free pro- p* (of rank $\gamma_{\bar{k}}$ — cf. Definition 1.1). This completes the proof of assertion (i).

Next, we verify assertions (ii), (iii). For each $v \in \text{Irr}(X)$, write Δ_v for the maximal pro- p quotient of the étale fundamental group of the proper smooth curve X_v over \bar{k} . Then it follows from a similar argument to the argument applied in the proof of the assertion for $\Delta_X^{\text{ét}}$ in assertion (i) that

- (a) the profinite group Δ_v is *free pro- p of rank* γ_v (which thus implies that the abelianization Δ_v^{ab} of Δ_v is a *free \mathbb{Z}_p -module of rank* γ_v).

Next, let us observe that since \mathfrak{D}_v is a closed subgroup of a *free pro- p* (cf. assertion (i)) group $\Delta_X^{\text{ét}}$, it follows from [18], Corollary 7.7.5, that

(b) the profinite group \mathfrak{D}_v is *free pro- p* (which thus implies that the \mathbb{Z}_p -module $\mathfrak{D}_v^{\text{ab}}$ is *free*).

Moreover, it follows from the definition of \mathfrak{D}_v that

(c) the natural finite morphism $X_v \rightarrow X_{\bar{k}}$ over \bar{k} determines a *surjection* $\Delta_v \twoheadrightarrow \mathfrak{D}_v$ (well-defined up to $N_{\Delta_X^{\text{ét}}}(\mathfrak{D}_v)$ -conjugation — where we write $N_{\Delta_X^{\text{ét}}}(\mathfrak{D}_v)$ for the normalizer of \mathfrak{D}_v in $\Delta_X^{\text{ét}}$).

Thus, it follows from (a), (b), (c) that, to verify assertion (ii), it suffices to verify the following assertion:

(A) The surjection $\Delta_v^{\text{ab}} \twoheadrightarrow \mathfrak{D}_v^{\text{ab}}$ determined by the surjection of (c) is *injective*.

Next, let us observe that one verifies easily that the various homomorphisms appearing in the statement of assertion (iii) determine an *exact* sequence of \mathbb{Z}_p -modules

$$\bigoplus_{v \in \text{Irr}(X)} \mathfrak{D}_v^{\text{ab}} \longrightarrow \Delta_X^{\text{ét-ab}} \longrightarrow \Delta_X^{\text{cmb-ab}} \longrightarrow 0.$$

In particular, to verify assertion (iii), it suffices to verify the following assertion:

(B) The natural homomorphism $\bigoplus_{v \in \text{Irr}(X)} \mathfrak{D}_v^{\text{ab}} \rightarrow \Delta_X^{\text{ét-ab}}$ is *injective*.

Thus, we conclude (cf. (A), (B)) that, to complete the verification of assertions (ii), (iii), it suffices to verify the following assertion:

(C) The homomorphism $\bigoplus_{v \in \text{Irr}(X)} \Delta_v^{\text{ab}} \rightarrow \Delta_X^{\text{ét-ab}}$ determined by the natural finite morphisms $X_v \rightarrow X_{\bar{k}}$ — where v ranges over the elements of $\text{Irr}(X)$ — is *injective*.

On the other hand, (C) follows immediately from a similar argument to the argument applied in the proof of [7], Lemma 1.4 (cf. also Remark 2.5.1, (ii), below). This completes the proofs of assertions (ii), (iii).

Assertion (iv) follows immediately from assertions (ii), (iii), together with the fact that every nontrivial closed subgroup of a free pro- p group is *infinite* (cf. [18], Corollary 7.7.5). Assertion (v) is a formal consequence of assertion (iv). Assertion (vi) follows immediately from assertion (iii) (cf. also (A)) and [21], Proposition 3.3, (ii). This completes the proof of Proposition 2.5. \square

REMARK 2.5.1.

(i) One can also verify the equalities concerning $\gamma_{X_{\bar{k}}}$ of Remark 1.4.1, (ii), from Proposition 2.5, (i), (ii), (iii).

(ii) The assertion (C) in the proof of Proposition 2.5 also follows, in light of the exact sequence in the discussion preceding the assertion (B), from the equalities concerning $\gamma_{X_{\bar{k}}}$ of Remark 1.4.1, (ii), together with Proposition 2.5, (i), and the assertions (a), (c) in the proof of Proposition 2.5.

DEFINITION 2.6.

(i) We shall say that X is *ordinary* if g_X (i.e., $g_{X_{\bar{k}}}$ — cf. Remark 1.4.1, (ii)) is equal to $\gamma_{\bar{k}}$.

(ii) We shall say that X is *rationally degenerate* if $g_v = 0$ for every $v \in \text{Irr}(X)$.

Here, let us recall the following well-known fact:

LEMMA 2.7. *The following hold:*

(i) *It holds that X is ordinary if and only if $g_v = \gamma_v$ for every $v \in \text{Irr}(X)$.*

(ii) *It holds that X is rationally degenerate if and only if the following condition is satisfied: The hyperbolic curve X is ordinary, and $\text{Irr}(X)^{\gamma > 0} = \emptyset$.*

(iii) *If X is ordinary, then it holds that either $b_1(X) \neq 0$, $\text{Irr}(X)^{\gamma=0} = \emptyset$, or $\#\text{Irr}(X)^{\gamma > 0} \geq 3$.*

PROOF. Assertion (i) follows from Remark 1.4.1, (i), (ii). Assertion (ii) follows from assertion (i), together with Remark 1.4.1, (i). Assertion (iii) follows immediately from assertion (i), together with the definition of a stable curve. \square

DEFINITION 2.8. Let C be a hyperbolic curve over \bar{k} . Then we shall say that $X_{\bar{k}}$ is *p -isogenous* to C if there exist a hyperbolic curve Z over \bar{k} and finite étale coverings $Z \rightarrow X_{\bar{k}}$, $Z \rightarrow C$ over \bar{k} such that the respective Galois closures of $Z \rightarrow X_{\bar{k}}$, $Z \rightarrow C$ are of degree a power of p .

THEOREM 2.9. *In the notations introduced at the beginning of §2, consider the following conditions:*

(1) *The hyperbolic curve X has good reduction over the ring of integers of \bar{k} (cf. Definition 1.2).*

(2) *The hyperbolic curve $X_{\bar{k}}$ is p -isogenous (cf. Definition 2.8) to a hyperbolic curve over \bar{k} which has good reduction over the ring of integers of \bar{k} .*

(3) *It holds that $b_1(Y) = 0$ (cf. Definition 1.4, (ii)) for every geometrically- p -covering $Y \rightarrow X$ (cf. Definition 1.5) of X .*

(4) *It holds that $\#\text{Irr}(Y)^{\gamma>0} \leq 1$ (cf. Definition 1.4, (iv)) for every geometrically- p -covering $Y \rightarrow X$ of X .*

Then the following hold:

(i) *The implications*

$$(1) \implies (2) \implies (3) \implies (4)$$

hold.

(ii) *Suppose that there exists a geometrically- p -covering $Y \rightarrow X$ of X such that $\text{Irr}(Y)^{\gamma>0} \neq \emptyset$. Then the equivalence*

$$(3) \iff (4)$$

holds.

(iii) *Suppose that X is ordinary (cf. Definition 2.6, (i)). Then the equivalence*

$$(1) \iff (3)$$

holds.

PROOF. First, we verify assertion (i). The implication $(1) \implies (2)$ is immediate. The implication $(2) \implies (3)$ follows, in light of Remark 1.4.2, (iii), and Remark 1.5.1, from Theorem 1.6. Finally, we verify the implication $(3) \implies (4)$. Suppose that condition (4) is not satisfied, i.e., that there exist a geometrically- p -covering $Y \rightarrow X$ and distinct elements $v_1, v_2 \in \text{Irr}(Y)^{\gamma>0}$. Then it follows from Proposition 2.5, (ii), (iii), that there exists a Galois geometrically- p -covering $Z \rightarrow Y$ of Y such that

- the surjection $\Delta_Y \twoheadrightarrow \Delta_Y/\Delta_Z$ (cf. Remark 2.2.1) *factors through* $\Delta_Y \twoheadrightarrow \Delta_Y^{\text{ét}}$,

- $\Delta_Y/\Delta_Z \cong \mathbb{Z}/p\mathbb{Z}$, and, moreover,
- for each $w \in \text{Irr}(Y)$, it holds that the image of the composite $\mathfrak{D}_w \hookrightarrow \Delta_Y^{\text{ét}} \twoheadrightarrow \Delta_Y/\Delta_Z$ is *nontrivial* if and only if $w \in \{v_1, v_2\}$.

Then, by considering *liftings* in \mathbb{G}_Z — relative to the finite étale covering $Z_{\bar{k}} \rightarrow Y_{\bar{k}}$ (cf. Remark 1.4.2, (ii)) — of a “simple path” in \mathbb{G}_Y from v_1 to v_2 (i.e., a connected subgraph γ of \mathbb{G}_Y which is a *tree* such that, for each vertex w of γ , there exist *at most two* branches of edges of γ that abut to w , and, moreover, the set of vertices w of γ such that there exists *precisely one* branch of an edge of γ that abuts to w *coincides* with the set $\{v_1, v_2\}$), one verifies easily that $b_1(Z) \neq 0$, which thus implies (cf. Remark 1.5.1) that condition (3) is not satisfied. This completes the proof of the implication (3) \Rightarrow (4), hence also of assertion (i).

Next, we verify assertion (ii). Suppose that there exists a geometrically- p -covering $Y \rightarrow X$ of X such that $\text{Irr}(Y)^{\gamma > 0} \neq \emptyset$, and that condition (3) is not satisfied. Thus, it follows from Remark 1.4.2, (iii), and Remark 1.5.1 that there exists a geometrically- p -covering $Z \rightarrow Y$ of Y such that $b_1(Z) \neq 0$, which thus implies that $\Delta_Z^{\text{cmb-ab}} \otimes_{\mathbb{Z}_p} \mathbb{Z}/p\mathbb{Z} \neq \{0\}$ (cf. Proposition 2.5, (i)). Let $W \rightarrow Z$ be a geometrically- p -covering of Z such that the open subgroup $\Delta_W \subseteq \Delta_Z$ (cf. Remark 2.2.1) *coincides* with the kernel of the natural surjection $\Delta_Z \twoheadrightarrow \Delta_Z^{\text{cmb-ab}} \otimes_{\mathbb{Z}_p} \mathbb{Z}/p\mathbb{Z}$. Then it is immediate that

$$\begin{aligned} 0 < \#\text{Irr}(Y)^{\gamma > 0} &\leq \#\text{Irr}(Z)^{\gamma > 0} < \#(\Delta_Z^{\text{cmb-ab}} \otimes_{\mathbb{Z}_p} \mathbb{Z}/p\mathbb{Z}) \cdot \#\text{Irr}(Z)^{\gamma > 0} \\ &= \#\text{Irr}(W)^{\gamma > 0} \end{aligned}$$

(cf. Remark 1.4.2, (iii)). Thus, condition (4) is not satisfied (cf. Remark 1.5.1). This completes the proof of assertion (ii).

Finally, we verify assertion (iii). Suppose that X is *ordinary*, and that condition (3) is satisfied (which thus implies that condition (4) is satisfied — cf. assertion (i)). Then it follows from Lemma 2.7, (iii), together with the fact that $b_1(X) = 0$ (cf. condition (3)), that it holds that either $\text{Irr}(X)^{\gamma=0} = \emptyset$ or $\#\text{Irr}(X)^{\gamma > 0} \geq 3$. In particular, it follows from the fact that $\#\text{Irr}(X)^{\gamma > 0} \leq 1$ (cf. condition (4)) that $\text{Irr}(X)^{\gamma=0} = \emptyset$. Thus, again by the fact that $\#\text{Irr}(X)^{\gamma > 0} \leq 1$ (cf. condition (4)), it follows that

$$1 \geq \#\text{Irr}(X)^{\gamma > 0} = \#\text{Irr}(X) - \#\text{Irr}(X)^{\gamma=0} = \#\text{Irr}(X).$$

In particular, again by the fact that $b_1(X) = 0$ (cf. condition (3)), it follows

that $X_{\bar{k}}$ is *smooth* over \bar{k} , as desired. This completes the proof of assertion (iii). \square

REMARK 2.9.1. Suppose that we are in the situation of Theorem 2.9:

(i) In general, the implication (2) \Rightarrow (1) does *not hold* as follows: Let us recall the well-known fact that the \mathbb{Z}_p -module Δ_X^{ab} is *free of rank* $2g_X$ ($= 2g_{X_{\bar{k}}} > \gamma_{X_{\bar{k}}}$). Thus, it follows from Proposition 2.5, (i), that the natural surjection $\Delta_X \rightarrow \Delta_X^{\text{ét}}$ is *not an isomorphism*. Now suppose that X has *good reduction* over the ring of integers of \bar{k} . Thus, it follows from [21], Lemma 5.5, that there exists a geometrically- p -covering $Y \rightarrow X$ of X such that Y does *not have good reduction* over the ring of integers of \bar{k} . Then the hyperbolic curve Y *violates* the implication (2) \Rightarrow (1).

(ii) It follows from (i) that, in general, the implication (3) \Rightarrow (1), hence also the implication (4) \Rightarrow (1), does *not hold*.

COROLLARY 2.10. *In the notations introduced at the beginning of §2, let Y be an ordinary (cf. Definition 2.6, (i)) proper hyperbolic curve over k that has good reduction over the ring of integers of \bar{k} (cf. Definition 1.2). Consider the following conditions:*

(1) *The hyperbolic curve X is ordinary.*

(2) *The hyperbolic curve X has good reduction over the ring of integers of \bar{k} .*

Then the following hold:

(i) *If $X_{\bar{k}}$ is p -isogenous (cf. Definition 2.8) to $Y_{\bar{k}}$, then the implication*

$$(1) \implies (2)$$

holds.

(ii) *If there exists a geometrically- p -covering $X \rightarrow Y$ (cf. Definition 1.5) over k such that the connected finite étale covering $X_{\bar{k}} \rightarrow Y_{\bar{k}}$ over \bar{k} (cf. Remark 1.4.2, (i)) is Galois, then the equivalence*

$$(1) \iff (2)$$

holds.

PROOF. First, we verify assertion (i). Suppose that X is *ordinary*, and that $X_{\bar{k}}$ is p -isogenous to $Y_{\bar{k}}$. Since X satisfies condition (2) of Theorem 2.9,

it follows from Theorem 2.9, (i), that X satisfies condition (3) of Theorem 2.9. Thus, since (we have assumed that) X is *ordinary*, it follows from Theorem 2.9, (iii), that the hyperbolic curve X has *good reduction* over the ring of integers of \bar{k} , as desired. This completes the proof of assertion (i).

The implication (2) \Rightarrow (1) in the case where there exists a geometrically- p -covering $X \rightarrow Y$ over k such that the connected finite étale covering $X_{\bar{k}} \rightarrow Y_{\bar{k}}$ over \bar{k} is *Galois* follows immediately from [21], Lemma 5.5, together with the *Riemann-Roch formula* (for genus) and the *Deuring-Shafarevich formula* (for p -rank — cf., e.g., [3], Theorem 3.1). This completes the proof of Corollary 2.10. \square

REMARK 2.10.2. Note that Corollary 2.10, (ii), may be regarded as a *special case* of [17], Proposition 3.

3. Pro- p Group-theoretic Algorithms

In the present §3, we establish functorial “group-theoretic” algorithms for reconstructing various objects related to the geometry of the stable models of proper hyperbolic curves over p -adic local fields from the geometrically pro- p étale fundamental groups of the curves (cf. Theorem 3.7 below). In the present §3, we maintain the notations introduced at the beginning of §2.

DEFINITION 3.1. We shall write

$$\Lambda_X \stackrel{\text{def}}{=} \text{Hom}_{\mathbb{Z}_p}(H^2(\Delta_X, \mathbb{Z}_p), \mathbb{Z}_p)$$

for the *pro- p cyclotome* associated to X . By the action of G_k on Λ_X determined by the natural outer action of G_k on Δ_X (cf. Definition 2.2), let us regard Λ_X as a G_k -module (cf. Remark 3.1.1 below).

REMARK 3.1.1 One verifies easily (cf., e.g., [10], Chapter V, Theorem 2.1, (a)) that the G_k -module Λ_X is isomorphic to the G_k -module “ $\mathbb{Z}_p(1)$ ” obtained by forming the projective limit $\varprojlim_n \mu_{p^n}(\bar{k})$ — where the projective limit is taken over the positive integers n — of the groups $\mu_{p^n}(\bar{k}) \subseteq \bar{k}^\times$ of p^n -th roots of unity in \bar{k} .

Let us first recall the following well-known fact:

LEMMA 3.2. *Suppose that X has stable reduction over the ring of integers of k . Then there exists a sequence of G_k -stable \mathbb{Z}_p -submodules of Δ_X^{ab}*

$$F_0 = \{0\} \subseteq F_1 \subseteq F_2 \subseteq F_3 \subseteq F_4 \subseteq F_5 = \Delta_X^{\text{ab}}$$

which satisfies the following conditions:

- (1) For each $0 \leq i \leq 4$, the quotient F_{i+1}/F_i is a free \mathbb{Z}_p -module.
- (2) The submodule F_3 (respectively, F_4) coincides with the kernel of the natural surjection $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}}$ (respectively, $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$). In particular, we obtain G_k -equivariant isomorphisms

$$F_5/F_3 \xrightarrow{\sim} \Delta_X^{\text{ét-ab}}, \quad F_5/F_4 \xrightarrow{\sim} \Delta_X^{\text{cmb-ab}}.$$

- (3) There exist G_k -equivariant isomorphisms

$$F_1 \cong \text{Hom}_{\mathbb{Z}_p}(\Delta_X^{\text{cmb-ab}}, \Lambda_X), \quad F_2 \cong \text{Hom}_{\mathbb{Z}_p}(\Delta_X^{\text{ét-ab}}, \Lambda_X).$$

- (4) For every open subgroup $J \subseteq I_k$ of I_k , there is no nontrivial torsion-free J -stable quotient of F_3/F_2 on which J acts trivially.

PROOF. This follows immediately, in light of Remark 3.1.1, from, for instance, the discussion preceding [11], Lemma 8.1, together with [11], Lemma 8.1. \square

LEMMA 3.3. *The following hold:*

(i) *Let V be a finite-dimensional representation of G_k over \mathbb{Q}_p . Suppose that the restriction of V to I_k is isomorphic to an extension of the direct product of finitely many copies of the trivial representation \mathbb{Q}_p by the direct product of finitely many copies of the representation $\Lambda_X \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$. Then the representation V of G_k is semistable.*

(ii) *Suppose that X is ordinary. Then it holds that X has stable reduction over the ring of integers of k if and only if the finite-dimensional representation $\Delta_X^{\text{ab}} \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ of I_k over \mathbb{Q}_p (i.e., obtained by considering the restriction to I_k of the natural action of G_k on $\Delta_X^{\text{ab}} \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$) is isomorphic to an extension of the direct product of g_X copies of the trivial representation \mathbb{Q}_p by the direct product of g_X copies of the representation $\Lambda_X \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$.*

PROOF. First, we verify assertion (i). Let us first observe that it follows from [5], Proposition of §5.1.5, that the representation V of G_k is *semistable* if and only if the restriction of V to I_k is *semistable*. Thus, to verify assertion (i), we may assume without loss of generality that the *representation* V of G_k is isomorphic to an extension of the direct product of finitely many copies of the trivial representation \mathbb{Q}_p by the direct product of finitely many copies of the representation $\Lambda_X \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$. Then the assertion that the representation V of G_k is *semistable* follows immediately from the second comment following the table in the final discussion of [2], §16. This completes the proof of assertion (i).

Next, we verify assertion (ii). First, we verify the *necessity*. Suppose that X has *stable reduction* over the ring of integers of k . Then since (we have assumed that) X is *ordinary*, it follows from Proposition 2.5, (i), that the \mathbb{Z}_p -module $\Delta_X^{\text{ét-ab}}$ is *free of rank* g_X . Thus, since (it is well-known that) the \mathbb{Z}_p -module Δ_X^{ab} is *free of rank* $2g_X$, the *necessity* follows immediately, in light of Remark 2.4.1, (ii), from Lemma 3.2. This completes the proof of the *necessity*.

Finally, we verify the *sufficiency*. Suppose that the representation $\Delta_X^{\text{ab}} \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ of I_k is isomorphic to an extension of the direct product of g_X copies of the trivial representation \mathbb{Q}_p by the direct product of g_X copies of the representation $\Lambda_X \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$. Then it follows from assertion (i) that the representation $\Delta_X^{\text{ab}} \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ of G_k is *semistable*. In particular, it follows from [2], Theorem 14.1, that the Jacobian variety of X has *semistable reduction* (i.e., over the ring of integers of k). Thus, it follows from [4], Theorem 2.4, that X has *stable reduction* over the ring of integers of k . This completes the proof of assertion (ii), hence also of Lemma 3.3. \square

LEMMA 3.4. *The following hold:*

(i) *The closed subgroup $\Delta_X \subseteq \Pi_X$ of Π_X may be characterized as the uniquely determined maximal nontrivial pro- l — for some prime number l — topologically finitely generated normal closed subgroup of Π_X .*

(ii) *The quotient $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}}$ (respectively, $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$) of Δ_X^{ab} may be characterized as the uniquely determined maximal torsion-free quotient of Δ_X^{ab} which satisfies the following condition: There exists an open subgroup $J \subseteq G_k$ of G_k such that this quotient is J -stable, and, moreover, the resulting action of $J \cap I_k$ (respectively, J) on this quotient is trivial.*

PROOF. First, we verify assertion (i) (cf. Remark 3.4.1 below). Let l be a prime number and $N \subseteq \Pi_X$ a maximal *nontrivial pro- l topologically finitely generated normal* closed subgroup of Π_X . Then it is immediate that the image $\overline{N} \subseteq G_k$ of N in G_k is a *pro- l topologically finitely generated normal* closed subgroup of G_k . Now let us recall from [14], Theorem 1.7, (ii), that G_k is *elastic*. (Here, let us recall that a profinite group is *elastic* if a topologically finitely generated closed subgroup of this profinite group is normal in an open subgroup of this profinite group, then this closed subgroup is either trivial or of finite index — cf. [14], Definition 1.1, (ii).) In particular, the closed subgroup \overline{N} is either *trivial* or *open* in G_k (cf. also [9], Proposition 1.2). Thus, since (one verifies easily — by considering, for instance, the quotient determined by the maximal unramified extension — that) every open subgroup of G_k is *not pro- l* , we conclude that $\overline{N} = \{1\}$, i.e., that $N \subseteq \Delta_X$. Thus, since Δ_X is *pro- p* , and (we have assumed that) N is *nontrivial* and *pro- l* , it holds that $l = p$. Moreover, since (it is immediate from the well-known structure of the étale fundamental groups of hyperbolic curves over algebraically closed fields of characteristic zero that) Δ_X is a *nontrivial pro- p topologically finitely generated normal* closed subgroup of Π_X , it follows from the *maximality* of N that $N = \Delta_X$, as desired. This completes the proof of assertion (i).

Next, we verify assertion (ii). Let us first observe that, to verify assertion (ii), we may assume without loss of generality, by replacing k by a suitable finite extension of k contained in \overline{k} , that X has *stable reduction* over the ring of integers of k (cf. Theorem 1.3) and is *split* over k (cf. Remark 2.1.1), which thus implies that (the quotients $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$ are G_k -*stable* — cf. Remark 2.4.1, (i) — and, moreover)

(a) the action of I_k (respectively, G_k) on $\Delta_X^{\text{ét-ab}}$ (respectively, $\Delta_X^{\text{cmb-ab}}$) is *trivial* (cf. Remark 2.4.1, (ii)).

Thus, in light of Proposition 2.5, (i), to complete the verification of assertion (ii), it suffices to verify the following assertion:

If $\Delta_X^{\text{ab}} \twoheadrightarrow Q$ is a *torsion-free G_k -stable* quotient of Δ_X^{ab} on which I_k (respectively, G_k) acts *trivially*, then the surjection $\Delta_X^{\text{ab}} \twoheadrightarrow Q$ *factors* through the surjection $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ét-ab}}$ (respectively, $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}$).

To this end, let $\Delta_X^{\text{ab}} \twoheadrightarrow Q$ be a *torsion-free G_k -stable* quotient of Δ_X^{ab} . Now

let us recall the sequence of G_k -stable \mathbb{Z}_p -submodules of Δ_X^{ab}

$$F_0 = \{0\} \subseteq F_1 \subseteq F_2 \subseteq F_3 \subseteq F_4 \subseteq F_5 = \Delta_X^{\text{ab}}$$

as in Lemma 3.2.

To verify the non-resp'd portion of assertion (ii), suppose that the action of I_k on Q is *trivial*. Then it follows from (a), together with condition (3) of Lemma 3.2, that we have an I_k -equivariant isomorphism of F_2 with the direct product of finitely many copies of Λ_X . Now let us recall that the character $I_k \rightarrow \mathbb{Z}_p^\times$ determined by the action of I_k on Λ_X *coincides* with the p -adic cyclotomic character (cf. Remark 3.1.1), which thus implies that the image of this character $I_k \rightarrow \mathbb{Z}_p^\times$ is *open* in \mathbb{Z}_p^\times . Thus, the image of the composite $F_2 \hookrightarrow \Delta_X^{\text{ab}} \twoheadrightarrow Q$ is *zero*. Moreover, it follows from condition (4) of Lemma 3.2 that the image of $F_3/F_2 \subseteq \Delta_X^{\text{ab}}/F_2$ via the resulting surjection $\Delta_X^{\text{ab}}/F_2 \twoheadrightarrow Q$ is *zero*. Thus, the surjection $\Delta_X^{\text{ab}} \twoheadrightarrow Q$ *factors* through the surjection $\Delta_X^{\text{ab}} \twoheadrightarrow \Delta_X^{\text{ab}}/F_3 = \Delta_X^{\text{ét-ab}}$ (cf. condition (2) of Lemma 3.2). This completes the proof of the non-resp'd portion of assertion (ii).

Next, to verify the resp'd portion of assertion (ii), suppose that the action of (not only I_k but also) G_k on the quotient Q is *trivial*. Thus, it follows from the above proof of the non-resp'd portion of assertion (ii) that, to verify the resp'd portion of assertion (ii), it suffices to verify that the image of F_4/F_3 via the resulting surjection $\Delta_X^{\text{ab}}/F_3 \twoheadrightarrow Q$ is *zero* (cf. condition (2) of Lemma 3.2). On the other hand, this follows from Proposition 2.5, (vi), together with condition (2) of Lemma 3.2. This completes the proof of the resp'd portion of assertion (ii), hence also of assertion (ii). \square

REMARK 3.4.1. Note that Lemma 3.4, (i), is a *special case* of [14], Theorem 2.6, (iv). Note, moreover, that the assertion for $\Delta_X^{\text{ét-ab}}$ in Lemma 3.4, (ii), may be considered to be *essentially the same* as [11], Lemma 8.2.

LEMMA 3.5. *The following hold:*

(i) *Let $N \subseteq \Delta_X^{\text{ét}}$ be a normal open subgroup of $\Delta_X^{\text{ét}}$. Write $Z \rightarrow X_{\bar{k}}$ for the finite étale Galois covering corresponding to $N \subseteq \Delta_X^{\text{ét}}$ and $b_1(Z)$ for the first Betti number of the (topological space determined by the) dual graph of Z . Then the following conditions are equivalent:*

(1) *There exists an element $v \in \text{Irr}(X)$ such that $Z \times_{X_{\bar{k}}} X_v$ is connected, and, moreover, for each $w \in \text{Irr}(X) \setminus \{v\}$, the restriction of the*

covering $Z \rightarrow X_{\bar{k}}$ to the generic point of the irreducible component corresponding to w is trivial.

(2) It holds that

$$b_1(Z) = [\Delta_X^{\text{ét}} : N] \cdot b_1(X).$$

(ii) Consider the following set \mathcal{I}_X and the following equivalence relation $\sim_{\mathcal{I}_X}$:

- Write \mathcal{I}_X for the set of minimal normal open subgroups $N \subseteq \Delta_X^{\text{ét}}$ of $\Delta_X^{\text{ét}}$ such that $\Delta_X^{\text{ét}}/N$ is abelian and annihilated by p , and, moreover, the subgroup N satisfies conditions (1), (2) of (i).

- For two elements N_1, N_2 of \mathcal{I}_X , write $N_1 \sim_{\mathcal{I}_X} N_2$ if $\text{Im}(N_1 \hookrightarrow \Delta_X^{\text{ét}} \twoheadrightarrow \Delta_X^{\text{ét-ab}}) \cap \text{Ker}(\Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}}) = \text{Im}(N_2 \hookrightarrow \Delta_X^{\text{ét}} \twoheadrightarrow \Delta_X^{\text{ét-ab}}) \cap \text{Ker}(\Delta_X^{\text{ét-ab}} \twoheadrightarrow \Delta_X^{\text{cmb-ab}})$.

Then there exists a bijection

$$\text{Irr}(X)^{\gamma > 0} \xrightarrow{\sim} \mathcal{I}_X / \sim_{\mathcal{I}_X}$$

which satisfies the following condition: Let N be an element of \mathcal{I}_X . Write $v \in \text{Irr}(X)$ for the element corresponding, via the bijection, to (the class determined by) N . Then it holds that $\text{Ker}(\Delta_X^{\text{ét}} \twoheadrightarrow \Delta_X^{\text{cmb}}) \subseteq N \cdot \mathfrak{D}_v$. (Note that since $\Delta_X^{\text{ét}}/N$ is abelian, the subgroup $N \cdot \mathfrak{D}_v \subseteq \Delta_X^{\text{ét}}$ does not depend on the choice of \mathfrak{D}_v among the conjugates.)

PROOF. First, we verify assertion (i). Write $\text{Irr}(Z)$ for the set of irreducible components of Z . Write, moreover, $\text{Nd}(X), \text{Nd}(Z)$ for the sets of nodes of the stable curves $X_{\bar{k}}, Z$, respectively. Then let us first observe that since the covering $Z \rightarrow X_{\bar{k}}$ is Galois and of degree a power of p , one verifies easily that condition (1) is equivalent to the following condition (1') (cf. also the discussion of [15], Remark 1.2.3, (iii), related to the term ‘‘vertically purely totally ramified’’):

(1') The equality

$$\#\text{Irr}(Z) = [\Delta_X^{\text{ét}} : N] \cdot (\#\text{Irr}(X) - 1) + 1$$

holds.

Next, let us observe that it follows from a well-known fact concerning the first Betti numbers of (the topological spaces determined by) connected graphs that condition (2) is *equivalent* to the following condition (2'):

(2') The equality

$$1 - \#\text{Irr}(Z) + \#\text{Nd}(Z) = [\Delta_X^{\text{ét}} : N] \cdot (1 - \#\text{Irr}(X) + \#\text{Nd}(X))$$

holds.

On the other hand, since the covering $Z \rightarrow X_{\bar{k}}$ is *finite étale*, it holds that

$$\#\text{Nd}(Z) = [\Delta_X^{\text{ét}} : N] \cdot \#\text{Nd}(X).$$

Thus, assertion (i) holds. This completes the proof of assertion (i).

Assertion (ii) follows immediately from assertion (i), together with Proposition 2.5, (i), (ii), (iii). This completes the proof of Lemma 3.5. \square

REMARK 3.5.1. Note that Lemma 3.5, (i), may be regarded as a “*pro- p variant*” of the discussion of [15], Remark 1.2.3, (iii), related to the term “*vertically purely totally ramified*”. Note, moreover, that Lemma 3.5, (ii), may be regarded as a “*pro- p variant*” of the discussion of [15], Remark 1.2.3, (iv), related to the “*functorial characterization of the set of vertices of \mathcal{G}* ”.

DEFINITION 3.6. We shall say that a profinite group Π *satisfies the condition* (\dagger) if there exist a prime number l and an isomorphism of Π with the geometrically pro- l étale fundamental group of a proper hyperbolic curve over an l -adic local field.

REMARK 3.6.1. One verifies easily (cf. Remark 1.4.2, (i)) that if a profinite group satisfies the condition (\dagger) , then every open subgroup of this profinite group satisfies the condition (\dagger) .

THEOREM 3.7. *In the notations introduced at the beginning of §3, let*

$$\Pi$$

be a profinite group which satisfies the condition (\dagger) (cf. Definition 3.6). Suppose that Π is isomorphic to the geometrically pro- p étale fundamental group Π_X of X (cf. Definition 2.2). Let

$$\alpha: \Pi \xrightarrow{\sim} \Pi_X$$

be an isomorphism of profinite groups. Then the following hold:

(i) We shall write

$$\Delta_{\Pi} \subseteq \Pi$$

for the (uniquely determined) maximal nontrivial pro- l — for some prime number l — topologically finitely generated normal closed subgroup of Π . Then α restricts to an isomorphism of profinite groups

$$\alpha_{\Delta}: \Delta_{\Pi} \xrightarrow{\sim} \Delta_X$$

(cf. Definition 2.2).

(ii) We shall write

$$G_{\Pi} \stackrel{\text{def}}{=} \Pi/\Delta_{\Pi}$$

for the quotient of Π by Δ_{Π} . Then α determines an isomorphism of profinite groups

$$\alpha_G: G_{\Pi} \xrightarrow{\sim} G_k.$$

(iii) The profinite group G_{Π} is of MLF-type (i.e., a profinite group isomorphic to the absolute Galois group of a finite extension of \mathbb{Q}_l for some prime number l — cf. [9], Definition 1.1; also [9], Proposition 1.2, (i)). Thus, by applying the functorial “group-theoretic” algorithm of [9], Theorem 1.4, (3), to G_{Π} , we obtain a normal closed subgroup

$$I_{\Pi} \stackrel{\text{def}}{=} I(G_{\Pi}) \subseteq G_{\Pi}.$$

Then the isomorphism α_G of (ii) restricts to an isomorphism of profinite groups

$$\alpha_I: I_{\Pi} \xrightarrow{\sim} I_k.$$

(iv) We shall write

$$p_{\Pi}$$

for the (uniquely determined) prime number such that Δ_{Π} is pro- p_{Π} . Then it holds that

$$p_{\Pi} = p.$$

(v) We shall write

$$\Delta_{\Pi}^{\acute{e}t} \stackrel{\text{def}}{=} \Delta_{\Pi}/J_{\Pi}^{\acute{e}t} \quad (\text{respectively, } \Delta_{\Pi}^{\text{cmb}} \stackrel{\text{def}}{=} \Delta_{\Pi}/J_{\Pi}^{\text{cmb}})$$

for the quotient of Δ_{Π} by the normal closed subgroup

$$J_{\Pi}^{\acute{e}t} \subseteq \Delta_{\Pi} \quad (\text{respectively, } J_{\Pi}^{\text{cmb}} \subseteq \Delta_{\Pi})$$

obtained by forming the intersection of the normal open subgroups $N \subseteq \Delta_{\Pi}$ of Δ_{Π} which satisfy the following condition: Let

$$N_0 = N \subseteq N_1 \subseteq \cdots \subseteq N_{r-1} \subseteq N_r = \Delta_{\Pi}$$

be a finite sequence of normal open subgroups of Δ_{Π} such that N_{i+1}/N_i is abelian for each $0 \leq i \leq r-1$ (note that since Δ_{Π} is pro- p_{Π} , one verifies easily that such a sequence always exists) and

$$P_0 \subseteq P_1 \subseteq \cdots \subseteq P_{r-1} \subseteq P_r = \Pi$$

a finite sequence of open subgroups of Π such that $P_i \cap \Delta_{\Pi} = N_i$ (which thus implies that P_i/N_i may be regarded as an open subgroup of G_{Π}) for each $0 \leq i \leq r$. Then, for each $0 \leq i \leq r-1$, the surjection $N_{i+1} \rightarrow N_{i+1}/N_i$ factors through the surjection onto the (uniquely determined) maximal abelian torsion-free quotient of N_{i+1} which satisfies the following condition: There exists an open subgroup $J_{i+1} \subseteq P_{i+1}/N_{i+1}$ of P_{i+1}/N_{i+1} such that this quotient is J_{i+1} -stable, and, moreover, the resulting action of $J_{i+1} \cap I_{\Pi}$ (respectively, J_{i+1}) on this quotient is trivial. Then the isomorphism α_{Δ} of (i) determines a commutative diagram of profinite groups

$$\begin{array}{ccccc} \Delta_{\Pi} & \longrightarrow & \Delta_{\Pi}^{\acute{e}t} & \longrightarrow & \Delta_{\Pi}^{\text{cmb}} \\ \alpha_{\Delta} \downarrow \wr & & \alpha_{\Delta}^{\acute{e}t} \downarrow \wr & & \alpha_{\Delta}^{\text{cmb}} \downarrow \wr \\ \Delta_X & \longrightarrow & \Delta_X^{\acute{e}t} & \longrightarrow & \Delta_X^{\text{cmb}} \end{array}$$

(cf. Definition 2.3, (i), (iii)) — where the horizontal arrows are the natural surjections, and the vertical arrows are isomorphisms of profinite groups.

(vi) We shall write

$$\Delta_{\Pi}^{\text{ab}} \twoheadrightarrow \Delta_{\Pi}^{\acute{e}t\text{-ab}} \twoheadrightarrow \Delta_{\Pi}^{\text{cmb-ab}}$$

for the respective abelianizations of Δ_Π , $\Delta_\Pi^{\acute{e}t}$, Δ_Π^{cmb} . Then the diagram of (v) determines a commutative diagram of profinite groups

$$\begin{array}{ccccc} \Delta_\Pi^{\text{ab}} & \longrightarrow & \Delta_\Pi^{\acute{e}t\text{-ab}} & \longrightarrow & \Delta_\Pi^{\text{cmb-ab}} \\ \alpha_\Delta^{\text{ab}} \downarrow \wr & & \alpha_\Delta^{\acute{e}t\text{-ab}} \downarrow \wr & & \alpha_\Delta^{\text{cmb-ab}} \downarrow \wr \\ \Delta_X^{\text{ab}} & \longrightarrow & \Delta_X^{\acute{e}t\text{-ab}} & \longrightarrow & \Delta_X^{\text{cmb-ab}} \end{array}$$

(cf. Definition 2.4) — where the horizontal arrows are the natural surjections, and the vertical arrows are isomorphisms of profinite groups.

(vii) We shall write

$$\begin{aligned} g_\Pi &\stackrel{\text{def}}{=} \frac{1}{2} \cdot \text{rank}_{\mathbb{Z}_{p\Pi}}(\Delta_\Pi^{\text{ab}}), & \gamma_\Pi &\stackrel{\text{def}}{=} \text{rank}_{\mathbb{Z}_{p\Pi}}(\Delta_\Pi^{\acute{e}t\text{-ab}}), \\ b_1(\Pi) &\stackrel{\text{def}}{=} \text{rank}_{\mathbb{Z}_{p\Pi}}(\Delta_\Pi^{\text{cmb-ab}}). \end{aligned}$$

Then it holds that

$$g_\Pi = g_X, \quad \gamma_\Pi = \gamma_{X_{\bar{\mathbb{K}}}}, \quad b_1(\Pi) = b_1(X)$$

(cf. Definition 1.1; Definition 1.4, (ii)).

(viii) We shall write

$$\mathcal{I}_\Pi$$

for the set of minimal normal open subgroups $N \subseteq \Delta_\Pi$ of Δ_Π such that N contains $J_\Pi^{\acute{e}t}$, Δ_X/N is abelian and annihilated by p_Π , and, moreover, there exists an open subgroup $P \subseteq \Pi$ of Π such that $P \cap \Delta_\Pi = N$ and $b_1(P) = [\Delta_\Pi : N] \cdot b_1(\Pi)$, where we write $b_1(P)$ for the integer obtained by applying the “group-theoretic” algorithm “ $b_1(-)$ ” of (vii) to the profinite group P (which satisfies the condition (\dagger) — cf. Remark 3.6.1);

$$\sim_{\mathcal{I}_\Pi}$$

for the equivalence relation on the set \mathcal{I}_Π defined as follows: For two elements N_1, N_2 of \mathcal{I}_Π , we write $N_1 \sim_{\mathcal{I}_\Pi} N_2$ if $\text{Im}(N_1 \hookrightarrow \Delta_\Pi \twoheadrightarrow \Delta_\Pi^{\acute{e}t\text{-ab}}) \cap \text{Ker}(\Delta_\Pi^{\acute{e}t\text{-ab}} \twoheadrightarrow \Delta_\Pi^{\text{cmb-ab}}) = \text{Im}(N_2 \hookrightarrow \Delta_\Pi \twoheadrightarrow \Delta_\Pi^{\acute{e}t\text{-ab}}) \cap \text{Ker}(\Delta_\Pi^{\acute{e}t\text{-ab}} \twoheadrightarrow \Delta_\Pi^{\text{cmb-ab}})$;

$$\text{Irr}(\Pi)^{\gamma > 0} \stackrel{\text{def}}{=} \mathcal{I}_\Pi / \sim_{\mathcal{I}_\Pi}.$$

Then the isomorphism $\alpha_{\Delta}^{\text{ét}}$ of (v) determines — relative to the bijection of Lemma 3.5, (ii) — a bijection

$$\alpha^{\text{Irr}}: \text{Irr}(\Pi)^{\gamma>0} \xrightarrow{\sim} \text{Irr}(X)^{\gamma>0}$$

(cf. Definition 1.4, (iv)).

(ix) Let $v_{\Pi} \in \text{Irr}(\Pi)^{\gamma>0}$. Then we shall write

$$\mathfrak{D}_{v_{\Pi}} \subseteq \Delta_{\Pi}^{\text{ét}}$$

for the (uniquely determined, up to conjugation) maximal closed subgroup of $\Delta_{\Pi}^{\text{ét}}$ such that

- for each normal open subgroup $P \subseteq \Pi$ of Π such that $J_{\Pi}^{\text{ét}} \subseteq P$, the closed subgroup $\mathfrak{D}_{v_{\Pi}} \subseteq \Delta_{\Pi}^{\text{ét}}$ is contained in the stabilizer (with respect to the action induced by the action by conjugation) of an element of the set $\text{Irr}(P)^{\gamma>0}$ obtained by applying the “group-theoretic” algorithm “ $\text{Irr}(-)^{\gamma>0}$ ” of (viii) to the profinite group P (which satisfies the condition (\dagger) — cf. Remark 3.6.1), and, moreover,

- if $N \subseteq \Delta_{\Pi}$ is an element of \mathcal{I}_{Π} which determines the class $v_{\Pi} \in \text{Irr}(\Pi)^{\gamma>0}$, then it holds that $\text{Ker}(\Delta_{\Pi}^{\text{ét}} \twoheadrightarrow \Delta_{\Pi}^{\text{cmb}}) \subseteq \text{Im}(N \hookrightarrow \Delta_{\Pi} \twoheadrightarrow \Delta_{\Pi}^{\text{ét}}) \cdot \mathfrak{D}_{v_{\Pi}}$. (Note that since Δ_{Π}/N is abelian, the subgroup $\text{Im}(N \hookrightarrow \Delta_{\Pi} \twoheadrightarrow \Delta_{\Pi}^{\text{ét}}) \cdot \mathfrak{D}_{v_{\Pi}}$ does not depend on the choice of $\mathfrak{D}_{v_{\Pi}}$ among the conjugates.)

Then the isomorphism $\alpha_{\Delta}^{\text{ét}}$ of (v) determines a bijection between the set of conjugates of $\mathfrak{D}_{v_{\Pi}} \subseteq \Delta_{\Pi}^{\text{ét}}$ and the set of conjugates of $\mathfrak{D}_{\alpha^{\text{Irr}}(v_{\Pi})} \subseteq \Delta_X^{\text{ét}}$ (cf. Definition 2.3, (ii)).

(x) Let $v_{\Pi} \in \text{Irr}(\Pi)^{\gamma>0}$. Then we shall write

$$\gamma_{v_{\Pi}} \stackrel{\text{def}}{=} \text{rank}_{\mathbb{Z}_{p\Pi}}(\mathfrak{D}_{v_{\Pi}}^{\text{ab}})$$

— where we write $\mathfrak{D}_{v_{\Pi}}^{\text{ab}}$ for the abelianization of $\mathfrak{D}_{v_{\Pi}}$. Then it holds that

$$\gamma_{v_{\Pi}} = \gamma_{\alpha^{\text{Irr}}(v_{\Pi})}$$

(cf. Definition 1.4, (iii)).

(xi) We shall say that the profinite group Π is ordinary if the equality $g_{\Pi} = \gamma_{\Pi}$ holds. We shall say that the profinite group Π is rationally degenerate if Π is ordinary, and, moreover, $\text{Irr}(\Pi)^{\gamma>0} = \emptyset$. Then it holds that Π

is ordinary (respectively, rationally degenerate) if and only if X is ordinary (cf. Definition 2.6, (i)) (respectively, rationally degenerate (cf. Definition 2.6, (ii))).

(xii) Suppose that Π is ordinary (which thus implies that X is ordinary — cf. (xi)). Then we shall say that the profinite group Π has stable reduction if the representation $\Delta_{\Pi}^{\text{ab}} \otimes_{\mathbb{Z}_{p\Pi}} \mathbb{Q}_{p\Pi}$ of I_{Π} is isomorphic to an extension of the direct product of g_{Π} copies of the trivial representation $\mathbb{Q}_{p\Pi}$ by the direct product of g_{Π} copies of the representation

$$\text{Hom}_{\mathbb{Z}_{p\Pi}}(H^2(\Delta_{\Pi}, \mathbb{Z}_{p\Pi}), \mathbb{Q}_{p\Pi}).$$

Then it holds that Π has stable reduction if and only if X has stable reduction over the ring of integers of k (cf. Definition 1.2).

(xiii) Suppose that Π is ordinary (which thus implies that X is ordinary — cf. (xi)). Then we shall say that the profinite group Π has good reduction if Π has stable reduction, and, moreover, $b_1(P) = 0$ for every open subgroup $P \subseteq \Pi$ of Π , where we write $b_1(P)$ for the integer obtained by applying the “group-theoretic” algorithm “ $b_1(-)$ ” of (vii) to the profinite group P (which satisfies the condition (\dagger) — cf. Remark 3.6.1). Then it holds that Π has good reduction if and only if X has good reduction over the ring of integers of k (cf. Definition 1.2).

PROOF. Assertions (i), (ii) follow from Lemma 3.4, (i). Assertion (iii) follows from [9], Theorem 1.4, (ii), together with assertion (ii). Assertion (iv) follows from assertion (i). Assertions (v), (vi) follow from Lemma 3.4, (ii), together with assertions (i), (ii), (iii). The assertion for g_{Π} in assertion (vii) follows from assertions (iv), (vi), together with the well-known fact that the \mathbb{Z}_p -module Δ_X^{ab} is free of rank $2g_X$. The assertion for γ_{Π} and $b_1(\Pi)$ in assertion (vii) follows from Proposition 2.5, (i), together with assertion (iv), (vi). Assertions (viii), (ix) follow, in light of the finiteness of $\text{Irr}(-)^{\gamma > 0}$, from Lemma 3.5, (ii), together with assertions (i), (iv), (v), (vii). Assertion (x) follows from Proposition 2.5, (ii), together with assertions (iv), (ix). Assertion (xi) follows from Lemma 2.7, (ii), together with assertions (vii), (viii). Assertion (xii) follows, in light of Definition 3.1, from Lemma 3.3, (ii), together with assertions (i), (iii), (iv), (vi), (vii), (xi). Assertion (xiii) follows from Theorem 2.9, (iii), together with assertions (vii), (xi), (xii). This completes the proof of Theorem 3.7. \square

COROLLARY 3.8. For $\square \in \{\circ, \bullet\}$, let p_\square be a prime number, k_\square a p_\square -adic local field, and X_\square a proper hyperbolic curve over k_\square ; write Π_{X_\square} for the geometrically pro- p_\square étale fundamental group of X_\square (cf. Definition 2.2). Let

$$\alpha: \Pi_{X_\circ} \xrightarrow{\sim} \Pi_{X_\bullet}$$

be an isomorphism of profinite groups. Then the following hold:

(i) It holds that $p_\circ = p_\bullet$, $g_{X_\circ} = g_{X_\bullet}$ (cf. Definition 1.1), and $b_1(X_\circ) = b_1(X_\bullet)$ (cf. Definition 1.4, (ii)).

(ii) The isomorphism α determines a commutative diagram of profinite groups

$$\begin{array}{ccccc} \Delta_{X_\circ} & \longrightarrow & \Delta_{X_\circ}^{\text{ét}} & \longrightarrow & \Delta_{X_\circ}^{\text{cmb}} \\ \alpha_\Delta \downarrow \wr & & \alpha_\Delta^{\text{ét}} \downarrow \wr & & \alpha_\Delta^{\text{cmb}} \downarrow \wr \\ \Delta_{X_\bullet} & \longrightarrow & \Delta_{X_\bullet}^{\text{ét}} & \longrightarrow & \Delta_{X_\bullet}^{\text{cmb}} \end{array}$$

(cf. Definition 2.3, (i), (iii)) — where the horizontal arrows are the natural surjections, and the vertical arrows are isomorphisms of profinite groups.

(iii) There exists a bijection

$$\alpha^{\text{Irr}}: \text{Irr}(X_\circ)^{\gamma > 0} \xrightarrow{\sim} \text{Irr}(X_\bullet)^{\gamma > 0}$$

(cf. Definition 1.4, (iv)) such that, for each $v \in \text{Irr}(X_\circ)^{\gamma > 0}$,

(1) the isomorphism $\alpha_\Delta^{\text{ét}}$ (cf. (ii)) determines a bijection between the set of conjugates of $\mathfrak{D}_v \subseteq \Delta_{X_\circ}^{\text{ét}}$ (cf. Definition 2.3, (ii)) and the set of conjugates of $\mathfrak{D}_{\alpha^{\text{Irr}}(v)} \subseteq \Delta_{X_\bullet}^{\text{ét}}$, and

(2) it holds that $\gamma_v = \gamma_{\alpha^{\text{Irr}}(v)}$ (cf. Definition 1.4, (iii)).

(iv) It holds that X_\circ is ordinary (cf. Definition 2.6, (i)) (respectively, rationally degenerate (cf. Definition 2.6, (ii))) if and only if X_\bullet is ordinary (respectively, rationally degenerate).

(v) Suppose, moreover, that either X_\circ or X_\bullet is ordinary. Then it holds that X_\circ has stable reduction over the ring of integers of k_\circ (cf. Definition 1.2) if and only if X_\bullet has stable reduction over the ring of integers of k_\bullet .

(vi) Suppose, moreover, that either X_\circ or X_\bullet is ordinary. Then it holds that X_\circ has good reduction over the ring of integers of k_\circ (cf. Definition 1.2) if and only if X_\bullet has good reduction over the ring of integers of k_\bullet .

PROOF. Assertion (i) follows from Theorem 3.7, (iv), (vii). Assertion (ii) follows from Theorem 3.7, (v). Assertion (iii) follows from Theorem 3.7, (viii), (ix), (x). Assertion (iv) follows from Theorem 3.7, (xi). Assertion (v) follows, in light of assertion (iv), from Theorem 3.7, (xii). Assertion (vi) follows, in light of assertion (iv), from Theorem 3.7, (xiii). This completes the proof of Corollary 3.8. \square

REMARK 3.8.1.

(i) Note that Theorem 3.7, (xiii), may be regarded as a *pro- p “group-theoretic” criterion for good reduction* of *ordinary* proper hyperbolic curves over p -adic local fields. As a consequence of the “*group-theoreticity*”, Theorem 3.7, (xiii), implies in fact Corollary 3.8, (vi).

(ii) Let Σ be a nonempty set of prime numbers such that $p \notin \Sigma$. Then we have a *pro- Σ “group-theoretic” criterion for good reduction* of (not necessarily ordinary) hyperbolic curves over p -adic local fields in the following sense: Let C be a (not necessarily proper) hyperbolic curve over the p -adic local field k (cf. the discussion entitled “Curves” in [6], §0, for the definition of the term “hyperbolic curve”) and Π a profinite group which is isomorphic to the geometrically pro- Σ étale fundamental group of C (i.e., the quotient of the étale fundamental group of C obtained by replacing “pro- p ” in the definition of the “geometrically pro- p étale fundamental group Π_X ” in Definition 2.2 by pro- Σ). Then it follows from [14], Theorem 2.6, (iv), that one may define a normal closed subgroup $\Delta_\Pi \subseteq \Pi$ of Π which corresponds to the pro- Σ geometric étale fundamental group of C (i.e., the quotient of the étale fundamental group of $C \times_k \bar{k}$ obtained by replacing “pro- p ” in the definition of the “pro- p geometric étale fundamental group Δ_X ” in Definition 2.2 by pro- Σ). Thus, one may also define a normal closed subgroup $I_\Pi \subseteq \Pi/\Delta_\Pi$ of Π/Δ_Π which corresponds to the inertia subgroup I_k of G_k (cf., e.g., Theorem 3.7, (iii)). Then [19], Theorem 3.2, and [21], Theorem 5.3, assert that

it holds that C has *good reduction* over the ring of integers of k (cf. [21], Definition 5.1) if and only if the image of the restriction of the action $\Pi \rightarrow \text{Aut}(\Delta_\Pi)$ by conjugation to the closed subgroup $\Pi \times_{\Pi/\Delta_\Pi} I_\Pi \subseteq \Pi$ is contained in the *subgroup of inner automorphisms* of Δ_Π .

(iii) Note that, by (the proof of) [13], Corollary 2.8, in the situation of (ii), one may establish a functorial “group-theoretic” algorithm for reconstructing, from Π , the dual semi-graph of the special fiber of the stable model of $C \times_k \bar{k}$ over the ring of integers of \bar{k} .

REMARK 3.8.2. Let us discuss the p -adic criterion for good reduction of curves proved by *F. Andreatta*, *A. Iovita*, and *M. Kim* in [1] from the point of view of the present paper:

(i) In [1], *F. Andreatta*, *A. Iovita*, and *M. Kim* proved a p -adic criterion for good reduction of curves. Here, let us recall [1], Theorem 1.9, briefly from the point of view of the present paper:

In the notations introduced at the beginning of §3 of the present paper, by considering (neutral tannakian) categories of certain finite-dimensional unipotent representations of the profinite group Δ_X over \mathbb{Q}_p , one may define, for each positive integer n , a finite-dimensional representation $\mathcal{E}_n^{\text{ét}}$ of Π_X over \mathbb{Q}_p . Let $b \in X(k)$ be a k -rational point of X . Then, by restricting the representation $\mathcal{E}_n^{\text{ét}}$ to the splitting (well-defined up to Δ_X -conjugation) of the natural surjection $\Pi_X \twoheadrightarrow G_k$ induced by b , one obtains, for each positive integer n , a finite-dimensional representation $\mathcal{E}_{n,b}^{\text{ét}}$ of G_k over \mathbb{Q}_p . Then [1], Theorem 1.9, asserts that X has *good reduction* over the ring of integers of k if and only if the representation $\mathcal{E}_{n,b}^{\text{ét}}$ of G_k is *crystalline* for every positive integer n .

(ii) The p -adic criterion of (i) (is interesting even in a certain point of view of anabelian geometry but) should be considered to be *not “group-theoretic”* (i.e., to be *not useful* in *pro- p absolute anabelian geometry*) by the following two reasons:

(1) The issue of whether or not a given finite-dimensional representation of G_k over \mathbb{Q}_p is *crystalline* is *not “group-theoretic”*. Indeed, it follows immediately from the discussion of [8], Remark 3.3.1, that there exist a prime number l , an l -adic local field L , an automorphism α of the absolute Galois group G_L of L , and a *crystalline* representation $\rho: G_L \rightarrow \text{GL}_n(\mathbb{Q}_l)$ such that the composite $G_L \xrightarrow{\alpha} G_L \xrightarrow{\rho} \text{GL}_n(\mathbb{Q}_l)$ is *not crystalline*.

(2) It is *not clear* that the issue of whether or not a given splitting of the natural surjection $\Pi_X \twoheadrightarrow G_k$ arises from a k -rational point of X is “*group-theoretic*”. Note that it follows from [6], Theorem A, that there exist a prime number l , an l -adic local field L , a proper hyperbolic curve C over L , and a splitting of the natural surjection from the geometrically pro- l étale fundamental group of C onto the absolute Galois group of L which does *not arise from an L -rational point of C* .

(iii) As a consequence of the discussion of (ii), the p -adic criterion of (i) does *not*, at least in the immediate literal sense, *imply* the following assertion:

(3) In the situation of Corollary 3.8, it holds that X_\circ has *good reduction* over the ring of integers of k_\circ if and only if X_\bullet has *good reduction* over the ring of integers of k_\bullet .

Note that it is not clear to the author at the time of writing whether or not the above assertion (3) is valid (without ordinary assumption).

(iv) In an attempt to apply the p -adic criterion of (i) to the study of assertion (3), in order to avoid the problem arising from the fact that the issue of whether or not a given finite-dimensional representation of G_k over \mathbb{Q}_p is *crystalline* is *not “group-theoretic”* (i.e., (1) of the discussion of (ii)), one may consider the following assumption:

(4) In the situation of Corollary 3.8, if we write $p \stackrel{\text{def}}{=} p_\circ = p_\bullet$ (cf. Corollary 3.8, (i)) and $\alpha_G: \text{Gal}(\bar{k}_\circ/k_\circ) \xrightarrow{\sim} \text{Gal}(\bar{k}_\bullet/k_\bullet)$ — where $\bar{k}_\circ, \bar{k}_\bullet$ are respective appropriate algebraic closures of k_\circ, k_\bullet — for the isomorphism induced by α (cf. Theorem 3.7, (ii)), then, for every finite extension k'_\bullet of k_\bullet in \bar{k}_\bullet and every *crystalline* representation $\rho: \text{Gal}(\bar{k}_\bullet/k'_\bullet) \rightarrow \text{GL}_n(\mathbb{Q}_p)$ of $\text{Gal}(\bar{k}_\bullet/k'_\bullet)$, the composite $\text{Gal}(\bar{k}_\circ/k'_\circ) \xrightarrow{\alpha_G} \text{Gal}(\bar{k}_\bullet/k'_\bullet) \xrightarrow{\rho} \text{GL}_n(\mathbb{Q}_p)$ — where we write k'_\circ for the finite extension of k_\circ in \bar{k}_\circ corresponding, via α_G , to k'_\bullet — is a *crystalline* representation of $\text{Gal}(\bar{k}_\circ/k'_\circ)$.

On the other hand, it follows immediately from a similar argument to the argument applied in the proof of [8], Theorem, that assumption (4) implies that the isomorphism α_G arises from an isomorphism of fields $\bar{k}_\bullet \xrightarrow{\sim} \bar{k}_\circ$ which restricts to an isomorphism of fields $k_\bullet \xrightarrow{\sim} k_\circ$. In particular, it follows immediately from [12], Theorem A, that α arises from an isomorphism of schemes $X_\circ \xrightarrow{\sim} X_\bullet$, which thus implies the equivalence discussed in assertion

(3). That is to say, assertion (3) under assumption (4) may be verified without the p -adic criterion of (i).

References

- [1] Andreatta, F., Iovita, A. and M. Kim, A p -adic nonabelian criterion for good reduction of curves, *Duke Math. J.* *164* (2015), no. *13*, 2597–2642.
- [2] Berger, L., On p -adic Galois representations, *Elliptic curves, Hilbert modular forms and Galois deformations*, 3–19, Adv. Courses Math. CRM Barcelona, Birkhäuser/Springer, Basel, 2013.
- [3] Bouw, I. I., The p -rank of curves and covers of curves, *Courbes semi-stables et groupe fondamental en géométrie algébrique* (Luminy, 1998), 267–277, Progr. Math., *187*, Birkhäuser, Basel, 2000.
- [4] Deligne, P. and D. Mumford, The irreducibility of the space of curves of given genus, *Inst. Hautes Études Sci. Publ. Math.* No. *36* (1969), 75–109.
- [5] Fontaine, J.-M., Représentations p -adiques semi-stables. With an appendix by Pierre Colmez, *Périodes p -adiques* (Bures-sur-Yvette, 1988), Astérisque No. *223* (1994), 113–184.
- [6] Hoshi, Y., Existence of nongeometric pro- p Galois sections of hyperbolic curves, *Publ. Res. Inst. Math. Sci.* *46* (2010), no. *4*, 829–848.
- [7] Hoshi, Y. and S. Mochizuki, On the combinatorial anabelian geometry of nodally nondegenerate outer representations, *Hiroshima Math. J.* *41* (2011), no. *3*, 275–342.
- [8] Hoshi, Y., A note on the geometricity of open homomorphisms between the absolute Galois groups of p -adic local fields, *Kodai Math. J.* *36* (2013), no. *2*, 284–298.
- [9] Hoshi, Y., *Mono-anabelian reconstruction of number fields*, RIMS Preprint *1819* (March 2015).
- [10] Milne, J. S., *Etale cohomology*, Princeton Mathematical Series, *33*. Princeton University Press, Princeton, N.J., 1980.
- [11] Mochizuki, S., The profinite Grothendieck conjecture for closed hyperbolic curves over number fields, *J. Math. Sci. Univ. Tokyo* *3* (1996), no. *3*, 571–627.
- [12] Mochizuki, S., The local pro- p anabelian geometry of curves, *Invent. Math.* *138* (1999), no. *2*, 319–423.
- [13] Mochizuki, S., A combinatorial version of the Grothendieck conjecture, *Tohoku Math. J. (2)* *59* (2007), no. *3*, 455–479.
- [14] Mochizuki, S., Topics in absolute anabelian geometry I: generalities, *J. Math. Sci. Univ. Tokyo* *19* (2012), no. *2*, 139–242.
- [15] Mochizuki, S., *Inter-universal Teichmüller theory I: Construction of Hodge theaters*, RIMS Preprint *1756* (August 2012).

- [16] Raynaud, M., p -groupes et réduction semi-stable des courbes, *The Grothendieck Festschrift, Vol. III*, 179–197, Progr. Math., 88, Birkhäuser Boston, Boston, MA, 1990.
- [17] Raynaud, M., Mauvaise réduction des courbes et p -rang, C. R. Acad. Sci. Paris Sér. I Math. 319 (1994), no. 12, 1279–1282.
- [18] Ribes, L. and P. Zalesskii, *Profinite groups*, Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge. A Series of Modern Surveys in Mathematics, 40. Springer-Verlag, Berlin, 2000.
- [19] Oda, T., A note on ramification of the Galois representation on the fundamental group of an algebraic curve. II, J. Number Theory 53 (1995), no. 2, 342–355.
- [20] Stix, J., Projective anabelian curves in positive characteristic and descent theory for log-étale covers, *Dissertation*, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, 2002. Bonner Mathematische Schriften, 354. Universität Bonn, Mathematisches Institut, Bonn, 2002.
- [21] Tamagawa, A., The Grothendieck conjecture for affine curves, *Compositio Math.* 109 (1997), no. 2, 135–194.

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