Curves of Given $p$-rank with Trivial Automorphism Group

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1. Introduction

Let $k$ be an algebraically closed field of characteristic $p > 0$. If $g \geq 3$, there exist a $k$-curve $C$ of genus $g$ with $\text{Aut}(C) = \{1\}$ and a hyperelliptic $k$-curve $D$ of genus $g$ with $\text{Aut}(D) \simeq \mathbb{Z}/2$ (see e.g. [16] and [8], respectively). In this paper, we extend these results to curves with given genus and $p$-rank.

If $C$ is a smooth projective $k$-curve of genus $g$ with Jacobian $\text{Jac}(C)$, then the $p$-rank of $C$ is the integer $f_C$ such that the cardinality of $\text{Jac}(C)[p](k)$ is $p^{f_C}$. It is known that $0 \leq f_C \leq g$. We prove the following result.

**Theorem 1.1.** Suppose $g \geq 3$ and $0 \leq f \leq g$.

(i) There exists a smooth projective $k$-curve $C$ of genus $g$ and $p$-rank $f$ with $\text{Aut}(C) = \{1\}$.

(ii) There exists a smooth projective hyperelliptic $k$-curve $D$ of genus $g$ and $p$-rank $f$ with $\text{Aut}(D) \simeq \mathbb{Z}/2$.

More generally, we consider the moduli space $\mathcal{M}_g$ of curves of genus $g$ over $k$. The $p$-rank induces a stratification $\mathcal{M}_{g,f}$ of $\mathcal{M}_g$ such that the geometric points of $\mathcal{M}_{g,f}$ parameterize $k$-curves of genus $g$ and $p$-rank at most $f$. Similarly, we consider the $p$-rank stratification $\mathcal{H}_{g,f}$ of the moduli space $\mathcal{H}_g$ of hyperelliptic $k$-curves of genus $g$. Our main results (Theorems 2.3 and 3.7) state that, for every geometric generic point $\eta$ of $\mathcal{M}_{g,f}$ (resp. $\mathcal{H}_{g,f}$), the corresponding curve $C_\eta$ satisfies $\text{Aut}(C_\eta) = \{1\}$ (resp. $\text{Aut}(D_\eta) \simeq \mathbb{Z}/2$).

For the proof of the first result, we consider the locus $\mathcal{M}_{g,f}^\ell$ of $\mathcal{M}_g$ parameterizing $k$-curves of genus $g$ that have an automorphism of order $\ell$. Results from [7] and [16] allow us to compare the dimensions of $\mathcal{M}_{g,f}$ and $\mathcal{M}_{g,f}^\ell$. The most difficult case, when $\ell = p$, involves wildly ramified covers and deformation results from [2]. For the proof of the second result, we compare the dimensions of $\mathcal{H}_{g,f}$ and $\mathcal{H}_{g,f}^\ell$ using [9] and [10]. When $p = 2$, this relies on [17]. The hardest case for hyperelliptic curves is when $p \geq 3$, $f = 0$, and $\ell = 4$; we use a degeneration argument to finish this case.
The statements and proofs of our main results would be simpler if more were
known about the geometry of \( M_{g,f} \) and \( H_{g,f} \). For example, one could reduce to
the case \( f = 0 \) if one knew that each irreducible component of \( M_{g,f} \) contained
a component of \( M_{g,0} \). But even the number of irreducible components of \( M_{g,f} \)
(or \( H_{g,f} \)) is known only in special cases.

We also sketch a second proof of the main results that uses degeneration to the
boundaries of \( M_{g,f} \) and \( H_{g,f} \) (see Remark 3.9).

**Remark 1.2.** There is no information in Theorem 1.1 about the field of definition
of the curves. In the literature, there are several results about curves with trivial
automorphism group that are defined over finite fields. In [14] and [15], the author
constructs an automorphism group for curves. In [14] and [15], the author
constructs an \( F_p \)-curve \( C_0 \) of genus \( g \) with \( \text{Aut}_{\overline{F}_p}(C_0) = \{1\} \) and a hyperelliptic
\( F_p \)-curve \( D_0 \) of genus \( g \) with \( \text{Aut}_{\overline{F}_p}(D_0) \simeq \mathbb{Z}/2 \). However, the \( p \)-ranks of \( C_0 \) and
\( D_0 \) are not considered.

For \( p = 2 \) and \( 0 \leq f \leq g \), the author of [19] constructs a hyperelliptic \( \mathbb{F}_p \)-curve
\( D_0 \) of genus \( g \) and \( p \)-rank \( f \) with \( \text{Aut}_{\mathbb{F}_p}(D_0) \simeq \mathbb{Z}/2 \). The analogous question for odd characteristic appears to be open. Furthermore, for all \( p \) it seems to be an open question whether there exists an \( \mathbb{F}_p \)-curve \( C_0 \) of genus \( g \) and \( p \)-rank \( f \) with
\( \text{Aut}_{\overline{F}_p}(C_0) = \{1\} \) [19, Ques. 1].

**Notation and Background.** All objects are defined over an algebraically
closed field \( k \) of characteristic \( p > 0 \). Let \( M_g \) be the moduli space of smooth
projective connected curves of genus \( g \), with tautological curve \( C_g \to M_g \). Let
\( H_g \) be the moduli space of smooth projective connected hyperelliptic curves of
 genus \( g \), with tautological curve \( D_g \to H_g \).

If \( C \) is a \( k \)-curve of genus \( g \), then the \( p \)-rank of \( C \) is the number \( f \in \{0, \ldots, g\} \)
such that \( \text{Jac}(C) \mid p \) \( (k) \cong (\mathbb{Z}/p)^f \). The \( p \)-rank is a discrete invariant that is lower
semicontinuous in families. It induces a stratification of \( M_g \) by closed reduced sub-
spaces \( M_{g,f} \) that parameterize curves of genus \( g \) with \( p \)-rank at most \( f \). Similarly,
let \( H_{g,f} \subset H_g \) be the locus of hyperelliptic curves of genus \( g \) with \( p \)-rank at most \( f \).

Recall that \( \dim(M_g) = 3g - 3 \) and \( \dim(H_g) = 2g - 1 \). Every irreducible
component of \( M_{g,f} \) has dimension \( 2g - 3 + f \) by [7, Thm. 2.3]. Every irreducible
component of \( H_{g,f} \) has dimension \( g - 1 + f \) by [9, Thm. 1] when \( p \geq 3 \) and by
[17, Cor. 1.3] when \( p = 2 \). In other words, the locus of curves of genus \( g \) and
\( p \)-rank \( f \) has pure codimension \( g - f \) in \( M_g \) and in \( H_g \).

Every irreducible component of \( M_{g,f} \) (resp. \( H_{g,f} \)) has a geometric generic
point \( \eta \). Let \( C_{g,\eta} \) (resp. \( D_{g,\eta} \)) denote the curve corresponding to the point \( \eta \).

Let \( \ell \) be prime. Let \( M_{g,\ell} \subset M_g \) denote the locus of curves that admit an auto-
morphism of order \( \ell \) (after pullback by a finite cover of the base). The locus \( M_{g,\ell} \)
is closed in \( M_g \). If \( D \) is a hyperelliptic curve, let \( \iota \) denote the unique hyperelliptic
involution of \( D \). Then \( \iota \) is in the center of \( \text{Aut}(D) \). Let \( H_{g,\ell} \subset H_g \) denote the locus of
hyperelliptic curves that admit a nonhyperelliptic automorphism of order \( \ell \). Let
\( H_{g,\ell}^{\text{4/}} \) denote the locus of hyperelliptic curves that admit an automorphism \( \sigma \) of
order 4 such that \( \sigma^2 = \iota \).
An Artin–Schreier curve is a curve that admits a structure as \((\mathbb{Z}/p)\)-cover of the projective line. Let \(\mathcal{AS}_g \subset \mathcal{M}_g\) denote the locus of Artin–Schreier curves of genus \(g\) and let \(\mathcal{AS}_{g,f} \subset \mathcal{M}_{g,f}\) denote its \(p\)-rank strata.

Unless stated otherwise, we assume \(g \geq 3\) and \(0 \leq f \leq g\).

## 2. The Case of \(\mathcal{M}_g\)

### 2.1. A Dimension Result

Suppose \(\Theta\) is an irreducible component of \(\mathcal{M}_g^\ell\) with generic point \(\xi\). Let \(Y\) be the quotient of \(\mathcal{C}_\xi\) by a group of order \(\ell\). Let \(g_Y\) and \(f_Y\) be respectively the genus and \(p\)-rank of \(Y\). Consider the \((\mathbb{Z}/\ell)\)-cover \(\phi: \mathcal{C}_\xi \to Y\). Let \(B \subset Y\) be the branch locus of \(\phi\). If \(\ell = p\), let \(j_b\) be the jump in the lower ramification filtration of \(\phi\) at a branch point \(b \in B\) [18, IV].

**Lemma 2.1.**

(i) If \(\ell \neq p\), then \(\dim(\Theta) \leq 2(g - g_Y)/(\ell - 1) + f_Y - 1\).

(ii) If \(\ell = p\), then \(\dim(\Theta) \leq 2(g - g_Y)/(\ell - 1) + f_Y - 1 - \sum_{b \in B} |j_b/p|\).

**Proof.** Let \(\phi: \mathcal{C}_\xi \to Y\) be as before, with branch locus \(B \subset Y\). Because \(g \geq 3\), if \(g_Y = 1\) then \(|B| > 0\). Let \(\mathcal{M}_{g_Y,f_Y,|B|}\) be the moduli space of curves of genus \(g_Y\) and \(p\)-rank at most \(f_Y\) with \(|B|\) marked points. Then \(\dim(\mathcal{M}_{g_Y,f_Y,|B|}) = 2g_Y - 3 + f_Y + |B|\) if \(g_Y \geq 1\). Also \(\dim(\mathcal{M}_{0,0,|B|}) = |B| - 3\) if \(|B| \geq 3\).

(i) Since \(\phi: \mathcal{C}_\xi \to Y\) is tamely ramified, the curve \(\mathcal{C}_\xi\) is determined by the quotient curve \(Y\), the branch locus \(B\), and ramification data that is discrete. Therefore, \(\dim(\Theta) \leq \dim(\mathcal{M}_{g_Y,f_Y,|B|})\) if \(g_Y \geq 1\) and \(\dim(\Theta) \leq |B| - 3\) if \(g_Y = 0\). By the Riemann–Hurwitz formula, \(2g - 2 = \ell(2g_Y - 2) + |B|\) if \(\ell \geq 1\). One can deduce that \(|B| = 2(g - g_Y)/(\ell - 1) + 2\) and the desired result follows.

(ii) By the Riemann–Hurwitz formula for wildly ramified covers [18, IV, Prop. 4],

\[
2g - 2 = p(2g_Y - 2) + \sum_{b \in B} (j_b + 1)(p - 1).
\]

For \(b \in B\), let \(\hat{\phi}_b: \mathcal{C}_z \to \hat{Y}_b\) be the germ of the cover \(\phi\) at the ramification point \(z\) above \(b\). By [2, p. 229], the dimension of the moduli space of covers \(\hat{\phi}_b\) with ramification break \(j_b\) is \(d_b = j_b - \lfloor j_b/p \rfloor\). The local/global principle of formal patching (found, for example, in [2, Prop. 5.1.3]) implies \(\dim(\Theta) \leq \dim(\mathcal{M}_{g_Y, f_Y, |B|}) + \sum_{b \in B} d_b\). Since \(|B| + \sum_{b \in B} j_b = 2(g - pg_Y)/(p - 1) + 2\), this simplifies to

\[
\dim(\Theta) \leq \frac{2(g - g_Y)}{p - 1} + f_Y - 1 - \sum_{b \in B} \left\lfloor \frac{j_b}{p} \right\rfloor.
\]

\[\square\]

### 2.2. No Automorphism of Order \(p\)

**Lemma 2.2.** Suppose \(\Gamma\) is a component of \(\mathcal{M}_{g,f}\) with geometric generic point \(\eta\). Then \(\mathcal{C}_\eta\) does not have an automorphism of order \(p\).
Proof. The strategy of the proof is to show that \( \dim(\Gamma \cap M_\ell^g) < \dim(\Gamma) \). Recall that \( \dim(\Gamma) = 2g - 3 + f \) by [7, Thm. 2.3].

Let \( \Theta \) be an irreducible component of \( \Gamma \cap M_\ell^g \), with geometric generic point \( \xi \). Consider the resulting cover \( \phi : C_\xi \to Y \), which is either étale or wildly ramified. Let \( g_Y \) and \( f_Y \) be respectively the genus and \( p \)-rank of \( Y \).

Suppose first that \( g_Y = 0 \). In other words, \( \xi \in \mathcal{AS}_{g,f} \) and \( C_\xi \) is an Artin–Schreier curve. By [17, Lemma 2.6], \( g = d(p - 1)/2 \) for some \( d \in \mathbb{N} \). If \( p = 2 \), then \( \dim(\mathcal{AS}_{g,f}) = g - 1 + f \) [17, Cor. 1.3]. If \( p \geq 3 \), then \( \dim(\mathcal{AS}_{g,f}) \leq d - 1 \) by [17, Thm. 1.1]. In either case, \( \dim(\Theta) \leq \dim(\mathcal{AS}_{g,f}) < \dim(\Gamma) \) since \( g \geq 3 \).

Now suppose that \( g_Y \geq 1 \). If \( p \geq 3 \), Lemma 2.1(ii) implies that \( \dim(\Theta) \leq g - g_Y - f_Y - 1 < 2g - 3 + f \).

If \( p = 2 \) and \( g_Y \geq 1 \), let \( |B| \) be the number of branch points of \( \phi \). By the Deuring–Shafarevich formula [5, Cor. 1.8], \( f - 1 = 2(f_Y - 1) + |B| \). Lemma 2.1(ii) implies that \( \dim(\Theta) \leq 2g - 2g_Y + (f - 1 - |B|)/2 - \sum_{b \in B} \lfloor j_b/2 \rfloor \). In particular, \( \dim(\Theta) < 2g - 2g_Y + f/2 \). So \( \dim(\Theta) < 2g - 3 + f \) if \( g_Y \geq 2 \).

Suppose \( p = 2 \) and \( g_Y = 1 \). The hypothesis \( g \geq 3 \) implies that \( \phi \) is ramified. So \( |B| \geq 1 \) and \( j_b \geq 1 \) for \( b \in B \). Then \( \dim(\Theta) < 2g - 3 + f/2 \).

Thus \( \dim(\Theta) < \dim(\Gamma) \) in all cases. This inequality implies that \( \eta \notin M_\ell^g \) and that \( \Aut(C_\eta) \) does not contain an automorphism of order \( p \).

2.3. The Main Result for \( M_{g,f} \)

**Theorem 2.3.** Suppose \( g \geq 3 \) and \( 0 \leq f \leq g \). Suppose \( \eta \) is the geometric generic point of an irreducible component \( \Gamma \) of \( M_{g,f} \). Then \( \Aut(C_\eta) = \{1\} \).

**Proof.** By Lemma 2.2, \( \Aut(C_\eta) \) contains no automorphism of order \( p \). Let \( \ell \neq p \) be prime. Consider an irreducible component \( \Theta \subset \Gamma \cap M_\ell^g \). The result follows in any case where \( \dim(\Theta) < \dim(\Gamma) = 2g - 3 + f \).

Let \( \xi \) be the geometric generic point of \( \Theta \). Let \( Y \) be the quotient of \( C_\xi \) by a group of order \( \ell \). Let \( g_Y \) and \( f_Y \) be the genus and \( p \)-rank of \( Y \).

If \( \ell \geq 3 \), then Lemma 2.1(i) implies \( \dim(\Theta) \leq g - g_Y + f_Y - 1 \). Thus \( \dim(\Theta) < 2g - 3 + f \) and \( C_\xi \) has no automorphism of order \( \ell \geq 3 \).

Suppose \( \ell = 2 \). If \( g_Y = 0 \), then \( C_\eta \) is hyperelliptic and in particular \( \dim(\Theta) \leq \dim(\mathcal{H}_{g,f}) = g - 1 + f < 2g - 3 + f \). If \( g_Y \geq 1 \), then \( \dim(\Theta) \leq 2g - 2g_Y + f_Y - 1 \), which is less than \( 2g - 3 + f \) except when \( g_Y = 1 \) and \( f_Y = f_Y \leq 1 \).

For the final case, when \( \ell = 2 \), \( g_Y = 1 \), and \( f = f_Y \), Lemma 2.1 alone does not suffice to prove the claim. Let \( M_{g,Y}^\ell \) be the moduli space of curves of genus \( g \) that are \((\mathbb{Z}/2)\)-covers of \( Y \). It is the geometric fiber over the moduli point of \( Y \) of a map from a proper, irreducible Hurwitz space to \( M_1 \) (see e.g. [3, Cor. 6.12]). Therefore, \( M_{g,Y}^\ell \) is irreducible. Now \( \xi \in M_{g,Y}^\ell \cap \Gamma \). The strategy is to show that there exists an \( s \in M_{g,Y}^\ell \) such that \( f_s > f_Y \). From this, it follows that \( M_{g,Y}^\ell \cap M_{g,f_Y} \) is a closed subset of \( M_{g,Y}^\ell \) of positive codimension. Then \( \Theta \) is a closed subset of \( \Gamma \) of positive codimension, and the proof is complete.

To construct \( s \), consider a \((\mathbb{Z}/2)\)-cover \( \psi_1 : Y \to \mathbb{P}^1 \). If \( g \) is odd (resp. even), let \( \psi_2 : X \to \mathbb{P}^1 \) be a \((\mathbb{Z}/2)\)-cover such that \( X \) has genus \((g - 1)/2 \) (resp. \( g/2 \))
and the branch locus of $\psi_2$ contains exactly two (resp. three) of the branch points of $\psi_1$. Since only two (resp. three) of the branch points of $\psi_2$ are specified, one can suppose $X$ is ordinary. Consider the fiber product $\psi : W \to P^1$ of $\psi_1$ and $\psi_2$. Following the construction of [9, Prop. 3], $W$ has genus $g$ and $p$-rank at least $g/2$. Since $W$ is a $(\mathbb{Z}/2\mathbb{Z})$-cover of $Y$, it corresponds to a point $s \in \mathcal{M}_g^{2,1}$ with $p$-rank at least $f_Y + 1$.

Here is the proof of part (i) of Theorem 1.1.

**Corollary 2.4.** Suppose $g \geq 3$ and $0 \leq f \leq g$. There exists a smooth projective $k$-curve $C$ of genus $g$ and $p$-rank $f$ with $\text{Aut}(C) = \{1\}$.

**Proof.** Let $\Gamma$ be an irreducible component of $\mathcal{M}_{g,f}$, with geometric generic point $\eta$. Let $\Gamma' \subset \Gamma$ be the open, dense subset parameterizing curves with $p$-rank exactly $f$ [7, Thm. 2.3]. By Theorem 2.3, $\text{Aut}(C_\eta) = 1$. The sheaf $\text{Aut}(C)$ is constructible on $\Gamma'$, but there are only finitely many possibilities for the automorphism group of a curve of genus $g$. Hence there is a nonempty open subspace $U \subset \Gamma'$ such that, for each $s \in U(k)$, $C_s$ has $p$-rank $f$ and $\text{Aut}(C_s) = 1$.

**Corollary 2.5.** Let $g \geq 3$ and $0 \leq f \leq g$. There exists a principally polarized abelian variety $(A, \lambda)$ over $k$ of dimension $g$ and $p$-rank $f$ with $\text{Aut}(A, \lambda) = \{\pm 1\}$.

**Proof.** Let $A$ be the Jacobian of the curve given in Corollary 2.4. The desired properties then follow from Torelli’s theorem [13, Thm. 12.1].

### 3. The Case of $\mathcal{H}_g$

Recall that $g \geq 3$ and $0 \leq f \leq g$.

#### 3.1. When $p = 2$

**Lemma 3.1.** Let $p = 2$ and suppose $\eta$ is the geometric generic point of a component $\Gamma$ of $\mathcal{H}_{g,f}$. Then $\text{Aut}(D_\eta) \cong \mathbb{Z}/2$.

**Proof.** The automorphism group of a hyperelliptic curve always contains a (central) copy of $\mathbb{Z}/2$. Let $U \subset \Gamma$ be the subset parameterizing curves with automorphism group $\mathbb{Z}/2$. As in the proof of Corollary 2.4, $U$ is open; it suffices to show that $U$ is nonempty.

By [17, Cor. 1.3], $\mathcal{H}_{g,0}$ is irreducible of dimension $g - 1$ when $p = 2$. For $g \geq 3$, there exists a hyperelliptic curve $D_0$ with $p$-rank 0 and $\text{Aut}(D_0) \cong \mathbb{Z}/2$ [19, Thm. 3]. The component $\Gamma$ contains $\mathcal{H}_{g,0}$ by [17, Cor. 4.6]. Then $U$ is nonempty because $U \cap \mathcal{H}_{g,0}$ is nonempty.

#### 3.2. No Automorphism of Order $p$

Suppose $p \geq 3$.

**Lemma 3.2.** If $p|(2g + 2)$ or $p|(2g + 1)$, then $\dim \mathcal{H}_g^p = \lfloor (2g + 2)/p \rfloor - 2$. Otherwise, $\mathcal{H}_g^p$ is empty.
Proof. Suppose \( s \in \mathcal{H}_g^s(k) \). There exists \( \sigma \in \text{Aut}(D_s) \) of order \( p \). Since \( \iota \) and \( \sigma \) commute, \( \sigma \) descends to an automorphism of \( D_s/(\iota) \cong \mathbb{P}^1 \). Let \( Z \) be the projective line \( D_s/(\sigma, \iota) \). Then \( D_s \to Z \) is the fiber product of the hyperelliptic cover \( \phi : D_s/(\sigma) \to Z \) and the \((\mathbb{Z}/p)\)-cover \( \psi : D_s/(\iota) \to Z \).

Since \( D_s/(\iota) \) has genus 0, it follows that the cover \( \psi \) is ramified only at one point \( b \) and that the jump \( j_b \) in the lower ramification filtration equals 1. After changing coordinates on \( D_s/(\iota) \) and \( Z \), the cover \( \psi \) is isomorphic to \( c^p - c = x \).

If \( \phi \) is not branched at \( \infty \), then each branch point of \( \phi \) lifts to \( p \) branch points of the cover \( D_s \to D_s/(\iota) \) and the branch locus of \( \phi \) consists of \((2g+2)/p\) points. On the other hand, if \( \phi \) is branched at \( \infty \) then the branch locus of \( \phi \) consists of \((2g+1)/p\) points. Therefore, if \( \mathcal{H}_g^s(k) \) is nonempty then either \( p|(2g+1) \) or \( p|(2g+2) \).

Moreover, any branch locus of size \((2g+2)/p\) uniquely determines such a cover \( \phi \). A point \( s \in \mathcal{H}_g^s \) is determined by the branch locus of \( \phi \) up to the action of affine linear transformations on \( Z \). Thus \( \dim(\mathcal{H}_g^s) = [(2g+2)/p] - 2 \).

**Lemma 3.3.** Let \( \eta \) be the geometric generic point of a component of \( \mathcal{H}_{g,f} \). Then \( \text{Aut}(D_\eta) \) contains no automorphism of order \( p \).

**Proof.** By Lemma 3.2, \( \mathcal{H}_g^s \) is either empty or of dimension \([(2g+2)/p] - 2 \). If \( g \geq 3 \), then \( \dim(\mathcal{H}_g^s) < g - 1 + f = \dim(\mathcal{H}_{g,f}) \). Thus \( D_\eta \) does not have an automorphism of order \( p \).

### 3.3. Extra Automorphisms of Order 2 and 4

Suppose \( p \geq 3 \). In this section, we show that the geometric generic point of any component of \( \mathcal{H}_{g,f} \) parameterizes a curve with no extra automorphism of order 2 or 4. The proof relies on degeneration and requires an analysis of curves of genus 2 and \( p \)-rank 0.

**Lemma 3.4.** Suppose \( p \geq 3 \) and \( g = 2 \). If \( \eta \) is a geometric generic point of \( \mathcal{H}_{2,0} \), then \( \text{Aut}(D_\eta) \cong \mathbb{Z}/2 \).

**Proof.** By [11, p. 130], \( \text{Aut}(D_\eta)/(\iota) \cong G \) where \( G \) is one of the following groups: \{1\}, \( \mathbb{Z}/5 \), \( \mathbb{Z}/2 \), \( S_3 \), \( \mathbb{Z}/2 \oplus \mathbb{Z}/2 \), \( D_{12} \), \( S_4 \), or \( \text{PGL}_2(\mathbb{Z}/5) \). Let \( T^G \subset \mathcal{H}_{2,0} \) be the sublocus parameterizing hyperelliptic curves \( D \) with \( \text{Aut}(D)/(\iota) \cong G \). Since every component of \( \mathcal{H}_{2,0} \) has dimension 1, it suffices to show that each \( T^G \) is 0-dimensional.

If \( G = \mathbb{Z}/5 \) and \( s \in T^G(k) \), then the Jacobian of \( D_s \) has an action by \( \mathbb{Z}/5 \) and thus must be one of the two abelian surfaces with complex multiplication by \( \mathbb{Z}[\zeta_5] \). Hence there exist at most two hyperelliptic curves \( D \) of genus 2 and \( p \)-rank 0 with \( \text{Aut}(D)/(\iota) \cong \mathbb{Z}/5 \).

Now let \( G \) be any nontrivial group from the list other than \( \mathbb{Z}/5 \). A curve of genus 2 and \( p \)-rank 0 is necessarily supersingular, and any supersingular hyperelliptic curve \( D \) of genus 2 with \( \text{Aut}(D)/(\iota) \cong G \) is superspecial by [11, Prop. 1.3]. Since there are only finitely many superspecial abelian surfaces, \( T^G \) is a proper closed subset of \( \mathcal{H}_{2,0} \) for each \( G \neq \{1\} \) on the list. Thus \( \text{Aut}(D_\eta) \cong \mathbb{Z}/2 \).
LEMMA 3.5. Suppose $p \geq 3$ and $g \geq 3$. Then:

(i) $\mathcal{H}_g^2$ is irreducible with dimension $g$;

(ii) there exists an $s \in \mathcal{H}_g^2(k)$ such that $D_s$ has $p$-rank at least 2; and

(iii) $\dim(\mathcal{H}_{g,0} \cap \mathcal{H}_g^2) < g - 1$.

Proof. Suppose $s \in \mathcal{H}_g^2(k)$. There is a Klein-4 cover $\phi: D_s \to \mathbb{P}_k^1$ such that $\phi$ is the fiber product of two hyperelliptic covers $\psi_i: C_i \to \mathbb{P}_k^1$ [9, Lemma 3].

If $g$ is even, then one can assume that $C_1$ and $C_2$ both have genus $g/2$ and that the branch loci of $\psi_1$ and $\psi_2$ differ in a single point. If $g$ is odd, then one can assume that $C_1$ has genus $(g+1)/2$, $C_2$ has genus $(g-1)/2$, and the branch locus of $\psi_2$ is contained in the branch locus of $\psi_1$ [9, Prop. 3]. In both cases, the third $(\mathbb{Z}/2)$-subquotient of $D_s$ has genus 0. In particular, if $f_s$ denotes the $p$-rank of $D_s$ then $f_s = f_{C_1} + f_{C_2}$ [9, Cor. 2].

(i) This is found in [9, Cor. 1].

(ii) One can choose $\psi_1$ so that $C_1$ is ordinary. Then $f_s \geq \lceil g/2 \rceil \geq 2$.

(iii) Suppose $s \in \mathcal{H}_{g,0}(k)$, so that $f_s = f_{C_1} = f_{C_2} = 0$. If $g$ is even, then the parameter space for choices of $\psi_1$ has dimension $\dim(\mathcal{H}_{g/2,0}) = g/2 - 1$. For fixed $\psi_1$, the parameter space for choices of $\psi_2$ has dimension 1. Similarly, if $g$ is odd, then the parameter space for choices of $\psi_1$ has dimension $\dim(\mathcal{H}_{(g+1)/2,0}) = (g-1)/2$. For fixed $\psi_1$, there are at most finitely many possibilities for $\psi_2$. In either case, $\dim(\mathcal{H}_{g,0} \cap \mathcal{H}_g^2) \leq \lfloor g/2 \rfloor < g - 1$. $\square$

LEMMA 3.6. Suppose $p \geq 3$ and $g \geq 3$. Then $\mathcal{H}_g^{4,i}$ is irreducible with dimension $g - 1$, and its geometric generic point parameterizes a curve with positive $p$-rank.

Proof. Suppose $s \in \mathcal{H}_g^{4,i}(k)$. Let $\sigma$ be an automorphism of $D_s$ of order 4 such that $\sigma^2 = \iota$. Consider the $(\mathbb{Z}/4)$-cover $D_s \to \mathbb{P}_k^1 \to \mathbb{P}_k^1$. Then $\beta$ is branched at two points and ramified at two points. Without loss of generality, one can suppose these are $0_s$ and $\infty_s$ on $\mathbb{P}_k^1$ and $0_s$ and $\infty_s$ on $\mathbb{P}_k^1$. This implies that the action of $\sigma$ on $\mathbb{P}_k^1$ is given by $\sigma(x) = -x$.

The inertia groups of $\beta \circ \alpha$ above 0 and $\infty$ are subgroups of $\langle \sigma \rangle \cong \mathbb{Z}/4$ that are not contained in $(\sigma^2)^2$. Thus they each have order 4, and $\alpha$ is branched over 0, and $\infty$. The other 2g branch points of $\alpha$ form orbits under the action of $\sigma$, and we can denote them by $\{\pm \lambda_1, \ldots, \pm \lambda_g\}$. Without loss of generality, one can suppose $\lambda_1 = 1$ and $\beta(\lambda_1) = 1$ and therefore $D_s$ has an affine equation of the form $y^2 = x(x^2 - 1) \prod_{i=1}^{g-1}(x^2 - \lambda_i^2)$.

Let $S = \mathbb{P}^1 - \{0, 1, \infty\}$. Let $\Delta \subset S^{g-1}$ be the weak diagonal consisting of all $(g-1)$-tuples $(x_1, \ldots, x_{g-1})$ such that $x_i = x_j$ for some $i \neq j$. Let $\Delta' \subset S^{g-1}$ consist of all $(g-1)$-tuples $(x_1, \ldots, x_{g-1})$ such that $x_i = -x_j$ for some $i \neq j$. There is a surjective morphism $\omega: (\mathbb{P}^1 - \{0, 1, \infty\})^{g-1} - (\Delta \cup \Delta') \to \mathcal{H}_g^{4,i}$, where $\omega$ sends $(\lambda_1, \ldots, \lambda_{g-1})$ to the isomorphism class of the curve with affine equation $y^2 = x(x^2 - 1) \prod_{i=1}^{g-1}(x^2 - \lambda_i^2)$. Thus $\mathcal{H}_g^{4,i}$ is irreducible.

There are only finitely many fractional linear transformations fixing the set $\{\pm \lambda_1, \ldots, \pm \lambda_{g-1}, \pm 1, 0, \infty\}$. Thus $\omega$ is finite-to-one and $\dim(\mathcal{H}_g^{4,i}) = g - 1$. 

Curves of Given $p$-rank with Trivial Automorphism Group
Suppose \( g \geq 3 \), and let \( \eta \) be the geometric generic point of \( \mathcal{H}^{4,\iota}_g \). To finish the proof, it suffices to show that the \( p \)-rank of \( \mathcal{D}_\eta \) is positive. Let \( T = \text{Spec}(k[[t]]) \) and \( T' = \text{Spec}(k((t))) \). Consider the image of the \( T' \)-point \((t\lambda_1, t\lambda_2, \lambda_3, \ldots, \lambda_{g-1})\) under \( \omega \). This gives a \( T' \)-point of \( \mathcal{H}^{4,\iota}_g \subset \mathcal{H}_g \). The moduli space \( \mathcal{H}_g \) of stable hyperelliptic curves is proper, so the \( T' \)-point of \( \mathcal{H}_g \) gives rise to a \( T \)-point of \( \mathcal{H}_g \). The special fiber of this \( T \)-point corresponds to a stable curve \( Y \). The stable curve \( Y \) has two components, \( Y_1 \) and \( Y_2 \), intersecting in an ordinary double point. Here \( Y_1 \) has genus 2 and affine equation \( y^2 = x_1(x_1^2 - \lambda_1^2)(x_1^2 - \lambda_2^2) \), while \( Y_2 \) has genus \( g - 2 \) and affine equation \( y^2 = \prod_{i=3}^{g-1}(x_i^2 - \lambda_i^2) \).

The moduli point \( s \in \mathcal{H}_g(k) \) of \( Y \) is in the closure of \( \mathcal{H}^{4,\iota}_g \). The automorphism \( \sigma \) extends to \( Y \) and stabilizes each of the two components \( Y_1 \) and \( Y_2 \). Therefore, the moduli point of \( Y_1 \) lies in \( \mathcal{H}^{4,\iota}_g \). There is a 1-parameter family of such curves \( Y_1 \) because one can vary the choice of \( \lambda_2 \). By Lemma 3.4, one can suppose that \( f_{Y_1} \neq 0 \). Now \( f_Y = f_{Y_1} + f_{Y_2} \) by [4, Ex. 9.2.8]. Thus \( f_Y \neq 0 \). Since the \( p \)-rank can only decrease under specialization and since \( s \) is in the closure of \( \eta \), the \( p \)-rank of \( \mathcal{D}_\eta \) is nonzero as well.

**3.4. Main Result for \( \mathcal{H}_g, f \)**

**Theorem 3.7.** Suppose \( g \geq 3 \) and \( 0 \leq f \leq g \). If \( \eta \) is the geometric generic point of an irreducible component of \( \mathcal{H}_g, f \), then \( \text{Aut}(\mathcal{D}_\eta) \simeq \mathbb{Z}/2 \).

**Proof.** Let \( \Gamma \) be the irreducible component of \( \mathcal{H}_g, f \) whose geometric generic point is \( \eta \). Suppose \( \sigma \in \text{Aut}(\mathcal{D}_\eta) \) has order \( \ell \) with \( \sigma \notin (i) \). Then \( p \geq 3 \) by Lemma 3.1. Without loss of generality, one can suppose that either \( \ell \) is prime or \( \ell = 4 \) with \( \sigma^2 = i \).

If \( \ell = 4 \) and \( \sigma^2 = i \), then \( \mathcal{H}^{4,\iota}_g \) is irreducible with dimension \( g - 1 \) by Lemma 3.6. This is strictly less than \( \dim(\Gamma) \) unless \( f = 0 \). If \( f = 0 \), the two dimensions are equal but the geometric generic point of \( \mathcal{H}^{4,\iota}_g \) corresponds to a curve of nonzero \( p \)-rank by Lemma 3.6. Thus \( \mathcal{D}_\eta \) has no automorphism \( \sigma \) of order \( 4 \) with \( \sigma^2 = i \).

If \( \ell \) is prime, one can suppose that \( \ell 
eq p \) by Lemma 3.3. In [10, p. 10], the authors use an argument similar to the proof of Lemma 3.2 to show that \( \mathcal{H}^{4,\iota}_g \) is empty unless \( \ell | (2g + 2 - i) \) for some \( i \in \{0, 1, 2\} \) and if \( \mathcal{H}^{4,\iota}_g \) is nonempty, then its dimension is \( d_{g,\ell} = -1 + (2g + 2 - i)/\ell \). If \( d_{g,\ell} < \dim(\Gamma) = g + f - 1 \) then \( \mathcal{D}_\eta \) cannot have an automorphism of order \( \ell \). This inequality is always satisfied when \( \ell \geq 3 \) since \( g \geq 3 \).

Suppose \( \ell = 2 \). Then \( d_{g,\ell} < \dim(\Gamma) \) unless \( f \leq 1 \). If \( f = 1 \) then the two dimensions are equal. By Lemma 3.5, \( \mathcal{H}^{2,\iota}_g \) is irreducible and contains the moduli point of a curve with \( p \)-rank at least 2. Therefore, the component \( \Gamma \) of \( \mathcal{H}^{2,\iota}_g \) is not the same as the unique irreducible component of \( \mathcal{H}^{2,\iota}_g \).

Finally, suppose \( \ell = 2 \) and \( f = 0 \). By Lemma 3.5(iii), \( \dim(\Gamma \cap \mathcal{H}_{g,0}) < g - 1 \). Thus \( \eta \notin \mathcal{H}^{2,\iota}_g \), and \( \text{Aut}(\mathcal{D}_\eta) \simeq \mathbb{Z}/2 \).

Part (ii) of Theorem 1.1 now follows from the next corollary.

**Corollary 3.8.** Suppose \( g \geq 3 \) and \( 0 \leq f \leq g \). There exists a smooth projective hyperelliptic \( k \)-curve \( D \) of genus \( g \) and \( p \)-rank \( f \) with \( \text{Aut}(D) \simeq \mathbb{Z}/2 \).
Proof. The result follows from Theorem 3.7 via the same argument used to deduce Corollary 2.4 from Theorem 2.3.

Remark 3.9. The proof of the last statement of Lemma 3.6 uses the intersection of $\overline{H}_{g,i}^{4}$ with the boundary component $\Delta_{i}$ of $\overline{H}_{g}$. More generally, one can give a different proof of the main results of this paper by using induction. Here are the main steps of the inductive proof. If $g \geq 3$ and $1 \leq i \leq g/2$, one can show that the closure of every component of $\mathcal{M}_{g,f}$ in $\overline{M}_{g}$ intersects the boundary component $\Delta_{i}$ by [6, p. 80] and [12]. Points of $\Delta_{i}$ correspond to singular curves $Y$ that have two components $Y_{1}$ and $Y_{2}$ of genera $i$ and $g - i$ (respectively) intersecting in an ordinary double point. Using a dimension argument, one can show that $Y_{1}$ and $Y_{2}$ are generically smooth and that their $p$-ranks $f_{1}$ and $f_{2}$ add up to $f$. If the generic point of a component of $\mathcal{M}_{g,f}$ parameterizes a curve with a nontrivial automorphism, then another dimension argument shows that this automorphism stabilizes each of $Y_{1}$ and $Y_{2}$. This would imply that the generic point of a component of $\mathcal{M}_{g-i,f}$ parameterizes a curve with nontrivial automorphism group, which would contradict the inductive hypothesis.

It can be shown using [7] that an analogous proof works for $H_{g,f}$ when $p \geq 3$. One can also use monodromy techniques to prove Corollary 2.5; see [1, Appl. 4.4].

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