



Examples of surfaces with canonical maps of degree 12, 13, 15, 16 and 18

Federico Fallucca¹

Received: 7 October 2022 / Accepted: 14 July 2023
© The Author(s) 2023

Abstract

In this note, we present examples of complex algebraic surfaces with canonical maps of degree 12, 13, 15, 16 and 18. They are constructed as quotients of a product of two curves of genus 10 and 19 using certain non-free actions of the group $S_3 \times \mathbb{Z}_3^2$. To our knowledge, there are no other examples in the literature of surfaces with canonical map of degree 13, 15 and 18.

Keywords Product–quotient surfaces · Surfaces of general type · Canonical map

Mathematics Subject Classification Primary: 14J29 · Secondary: 14J10

1 Introduction

Beauville has shown in [6] that if the image of the canonical map Φ_{K_S} of a surface has dimension 2, then its degree d is bounded as follows:

$$d := \deg(\Phi_{K_S}) \leq 9 + \frac{27 - 9q}{p_g - 2} \leq 36.$$

Note that the bound $d \leq 36$ was shown first by Persson in [21, Proposition 5.7]. Here, q is the irregularity and p_g the geometric genus of S . In particular, $28 \leq d$ is only possible if $q = 0$ and $p_g = 3$.

Motivated by this observation, the construction of surfaces with $p_g = 3$ and canonical map of degree d for every value $2 \leq d \leq 36$ is an interesting, but still widely open problem [16, Question 5.2]. For a long time, the only examples with $10 \leq d$ were the surfaces of Persson [21], with canonical map of degree 16, and Tan [27], with degree 12. In recent years, this problem attracted the attention of many authors, putting an increased effort in the construction of new examples. As a result, we have now examples in the literature for all degrees $2 \leq d \leq 12$ and $d = 14, 16, 20, 24, 27, 32$ and 36, see [11, 13, 14, 16–18, 22–25] and [19].

✉ Federico Fallucca
federico.fallucca@unitn.it

¹ Università di Trento, Via Sommarive 14, I-38123 Trento, TN, Italy

In this paper, we construct surfaces as quotients of a product of two curves $C_1 \times C_2$ modulo an action of the group $S_3 \times \mathbb{Z}_3^2$. Here C_1 is a fixed curve of genus 10 while C_2 is a curve of genus 19 varying in a one-dimensional family. Varying the action of $S_3 \times \mathbb{Z}_3^2$, we get four different one-dimensional families of canonical models of surfaces of general type with $K_S^2 = 24$, $p_g = 3$ and $q = 0$.

We write the canonical system of each of them in terms of invariant holomorphic two forms on the product $C_1 \times C_2$. It turns out that for none of them $|K_S|$ is base point-free, i.e., the canonical map $\Phi_{K_S} : S \dashrightarrow \mathbb{P}^2$ is just a rational map. To compute its degree, we resolve the indeterminacy by a sequence of blowups and compute the degree of the resulting morphism via elementary intersection theory. It turns out that the degree of the canonical map is not always constant in a family, and in fact, it assumes five different values: $d = 12, 13, 15, 16$ and 18 . To our knowledge, there are no other examples in the literature of surfaces with canonical map of degree 13, 15 and 18.¹

We point out that our surfaces are examples of product–quotient surfaces, i.e., quotients of product of two curves modulo an action of a finite group. In our cases, the action is diagonal and non-free, arising surfaces with 8 rational double points as singularities of type $\frac{1}{2}(1, 1)$. Product–quotient surfaces are studied for the first time by Catanese in [9]. They are revealed to being a very useful tool for building new examples of algebraic surfaces and studying their geometry in an accessible way. Apart from other works that mainly deal with irregular surfaces, we want to mention the complete classification of surfaces isogenous to a product with $p_g = q = 0$ [1] and the classification for $p_g = 1$ and $q = 0$ under the assumption that the action is diagonal [12], and the rigid but not infinitesimally rigid manifolds [5] of Bauer and Pignatelli that gave a negative answer to a question of Kodaira and Morrow [15, p.45].

Notation: An algebraic surface S is a *canonical model* if it has at most rational double points as singularities and ample canonical divisor. Recall that each surface of general type is birational to a unique canonical model. In particular, the minimal resolution of the singularities of S is its minimal model.

Let us denote by σ and τ a rotation (3-cycle) and a reflection (transposition) of S_3 , respectively. Consider also the three irreducible characters of S_3 , so the trivial character 1, the character sgn computing the sign of a permutation, and the only two-dimensional irreducible character $\mu := \frac{1}{2}(\chi_{reg} - sgn - 1)$, where χ_{reg} is the character of the regular representation of S_3 .

Let us fix a basis e_1, e_2 of \mathbb{Z}_3^2 and consider the dual characters ϵ_1, ϵ_2 of e_1 and e_2 , i.e., the characters defined by

$$\epsilon_i(ae_1 + be_2) := \zeta_3^{a\delta_{1i} + b\delta_{2i}}, \quad \zeta_3 := e^{\frac{2\pi i}{3}},$$

where δ_{ij} is the Kronecker delta.

Given a representation ρ on a vector space V and an isotypic component W of V of character χ , we can sometimes write W_χ instead of W for specifying its character.

When we write $\sqrt[n]{\lambda}$ we mean the first root of the complex number λ , i.e., if $\lambda = |\lambda| \cdot e^{i\theta}$, then $\sqrt[n]{\lambda} = \sqrt[n]{|\lambda|} \cdot e^{i\frac{\theta}{n}}$.

Finally, denote by $[j] \in \{0, 1\}$ the class of the integer number j modulo 2.

¹ During the preparation of this work, Bin Nguyen has communicated to us a different construction of a surface with canonical map of degree 13.

2 The surfaces

In this section, we construct a series of surfaces S , as quotients of a product of two curves C_1 and C_2 , modulo a suitable diagonal action of the group $S_3 \times \mathbb{Z}_3^2$. For any surface S , we determine the canonical map Φ_{K_S} and compute its degree.

We consider the projective space \mathbb{P}^3 with homogeneous coordinates x_0, \dots, x_3 and the weighted projective space $\mathbb{P}^3(1, 1, 1, 2)$ with homogeneous coordinates y_0, \dots, y_3 . Here y_3 is the variable of weight 2. We take the curves $C_1 \subseteq \mathbb{P}^3$ and $C_2 \subseteq \mathbb{P}^3(1, 1, 1, 2)$ as follows:

$$C_1: \begin{cases} x_2^3 = x_0^3 - x_1^3 \\ x_3^3 = x_0^3 + x_1^3 \end{cases}, \quad C_2: \begin{cases} y_2^3 = y_0^3 + y_1^3 \\ y_3^3 = y_0^6 + y_1^6 - 2\lambda y_0^3 y_1^3 \end{cases}, \lambda \neq -1, 1$$

Both curves are smooth; in fact, this is the reason why we assume $\lambda \neq -1, 1$ in the definition of C_2 .

On the first curve C_1 , we consider the action of $S_3 \times \mathbb{Z}_3^2$ given by

$$\begin{aligned} \phi_1: S_3 \times \mathbb{Z}_3^2 &\rightarrow \text{Aut}(C_1), \quad (\sigma^i \tau^j, (a, b)) \\ &\mapsto [(x_0 : x_1 : x_2 : x_3) \mapsto (\zeta_3^i x_{[j]} : x_{[j+1]} : (-1)^j \zeta_3^{2a+2i} x_2 : \zeta_3^{2b+2i} x_3)]. \end{aligned}$$

We leave to the reader to checking that this defines an action.

Note that the automorphisms $\phi_1(\sigma^i \tau^j, (a, b))$ are precisely the deck transformations of the cover

$$\pi_1: C_1 \xrightarrow{9:1} \mathbb{P}^1 \xrightarrow{6:1} \mathbb{P}^1, \quad (x_0 : x_1 : x_2 : x_3) \mapsto (x_0 : x_1) \mapsto (x_0^3 x_1^3 : (x_0^6 + x_1^6)/2).$$

In particular, $C_1 / (S_3 \times \mathbb{Z}_3^2) \simeq \mathbb{P}^1$ and π_1 is the quotient map. The cover is branched along $p_1 := (1 : 1)$, $p_2 := (0 : 1)$ and $p_3 := (-1 : 1)$, corresponding to the three orbits of the points with non-trivial stabilizer, of respective length 9, 18 and 9. A representative of each orbit and a generator of the stabilizer is given by:

	p_1	p_2	p_3
representative	$(1 : 1 : 0 : \sqrt[3]{2})$	$(1 : 0 : 1 : 1)$	$(1 : -\zeta_3 : \sqrt[3]{2} : 0)$
generator	$g_1 := (\tau, (1, 0))$	$g_2 := (\sigma^2, (2, 2))$	$g_3 := (\sigma\tau, (0, 1))$

On the second curve C_2 , the action ϕ_2 is defined as

$$\begin{aligned} \phi_2: S_3 \times \mathbb{Z}_3^2 &\rightarrow \text{Aut}(C_2), \quad (\sigma^i \tau^j, (a, b)) \\ &\mapsto [(y_0 : y_1 : y_2 : y_3) \mapsto (\zeta_3^i y_{[j]} : y_{[j+1]} : \zeta_3^{a+2b+2i} y_2 : \zeta_3^{2a+2b+i} y_3)]. \end{aligned}$$

As in the previous case, we leave to the reader to checking that this defines a group action and note that the automorphisms $\phi_2(\sigma^i \tau^j, (a, b))$ are precisely the deck transformations of the cover

$$\pi_2: C_2 \xrightarrow{9:1} \mathbb{P}^1 \xrightarrow{6:1} \mathbb{P}^1, \quad (y_0 : y_1 : y_2 : y_3) \mapsto (y_0 : y_1) \mapsto (y_0^3 y_1^3 : (y_0^6 + y_1^6)/2).$$

Hence, $C_2 / (S_3 \times \mathbb{Z}_3^2) \simeq \mathbb{P}^1$ and π_2 is the quotient map. The cover is branched along $q_1 := (1 : 1)$, $q_2 := (0 : 1)$, $q_3 := (1 : \lambda)$ and $q_4 := (-1 : 1)$, corresponding to the four orbits of the points with non-trivial stabilizer, of respective length 27, 18, 18 and 9. Note that the points q_j are pairwise distinct under the assumption $\lambda \neq -1, 1$.

A representative of each orbit and a generator of the stabilizer is given by:

	q_1	q_2	q_3	q_4
representative	$(1 : \zeta_3 : \sqrt[3]{2} : \sqrt[3]{2-2\lambda})$	$(0 : 1 : 1 : 1)$	$(1 : \sqrt[3]{\lambda - \sqrt{\lambda^2 - 1}} : \sqrt[3]{1 + \lambda - \sqrt{\lambda^2 - 1}} : 0)$	$(1 : -1 : 0 : \sqrt[3]{2+2\lambda})$
generator	$h_1 := (\sigma\tau, 0)$	$h_2 := (\sigma, (1, 0))$	$h_3 := (Id, (1, 1))$	$h_4 := (\tau, (1, 2))$

We compute the action of $S_3 \times \mathbb{Z}_3^2$ on $H^0(C_i, \Omega_{C_i}^1)$.

By standard adjunction theory, $H^0(C_1, \Omega_{C_1}^1)$ is isomorphic to $H^0(C_1, \mathcal{O}_{C_1}(2))$, isomorphism mapping a monomial $x_0^{2-\alpha-\beta-\gamma} x_1^\alpha x_2^\beta x_3^\gamma$ to the 1-form $\omega_{\alpha\beta\gamma}$ that in affine coordinates is

$$\omega_{\alpha\beta\gamma} := u^\alpha v^{\beta-2} t^{\gamma-2} du, \quad \text{where} \quad u := \frac{x_1}{x_0} \quad v := \frac{x_2}{x_0} \quad \text{and} \quad t := \frac{x_3}{x_0}.$$

The character of the *canonical* representation of C_1 , the action of $S_3 \times \mathbb{Z}_3^2$ on $H^0(C_1, \Omega_{C_1}^1)$, can be computed by the standard Chevalley–Weil formula and is amount to

$$\chi_{can}^1 = \epsilon_1^2 \cdot \epsilon_2^2 + sgn \cdot \epsilon_1 \cdot \epsilon_2 + sgn \cdot \epsilon_2 + sgn \cdot \epsilon_1 + \mu \cdot \epsilon_1 \cdot \epsilon_2 + \mu \cdot \epsilon_1^2 \cdot \epsilon_2 + \mu \cdot \epsilon_1 \cdot \epsilon_2^2.$$

We give an explicit decomposition into irreducible subspaces. Using the expression in affine coordinates we obtain

$$\begin{aligned} (\sigma^i \tau^j, (a, b)) \cdot \omega_{\alpha\beta\gamma} &= \phi_1 \left((\sigma^i \tau^j, (a, b))^{-1} \right)^* (\omega_{\alpha\beta\gamma}) \\ &= (-1)^{j(\beta-1)} \zeta_3^{a(\beta-2)+b(\gamma-2)+(\alpha-(2\alpha+\beta+\gamma-2)[j]+2\beta+2\gamma-7)i} \\ &\quad \omega_{(\alpha-(2\alpha+\beta+\gamma-2)[j])\beta\gamma}. \end{aligned}$$

A tedious but straightforward computation gives the following decomposition:

$$\begin{aligned} H^0(C_1, \Omega_{C_1}^1) &= \langle \omega_{011} \rangle_{\epsilon_1^2 \cdot \epsilon_2^2} \oplus \langle \omega_{100} \rangle_{sgn \cdot \epsilon_1 \cdot \epsilon_2} \oplus \langle \omega_{020} \rangle_{sgn \cdot \epsilon_2} \oplus \langle \omega_{002} \rangle_{sgn \cdot \epsilon_1} \oplus \\ &\quad \langle \omega_{000}, \omega_{200} \rangle_{\mu \cdot \epsilon_1 \cdot \epsilon_2} \oplus \langle \omega_{010}, \omega_{110} \rangle_{\mu \cdot \epsilon_1^2 \cdot \epsilon_2} \oplus \langle \omega_{001}, \omega_{101} \rangle_{\mu \cdot \epsilon_1 \cdot \epsilon_2^2}. \end{aligned}$$

Similarly, adjunction theory gives an isomorphism among $H^0(C_2, \Omega_{C_2}^1)$ and $H^0(C_2, \mathcal{O}_{C_2}(4))$ mapping a monomial $y_0^{4-\alpha-\beta-2\gamma} y_1^\alpha y_2^\beta y_3^\gamma$ to the 1-form $\omega'_{\alpha\beta\gamma}$ that in affine coordinates is

$$\omega'_{\alpha\beta\gamma} := (u')^\alpha (v')^{\beta-2} (t')^{\gamma-2} du', \quad \text{where} \quad u' := \frac{y_1}{y_0} \quad v' := \frac{y_2}{y_0} \quad \text{and} \quad t' := \frac{y_3}{y_0}.$$

We obtain a basis of the 19-dimensional space $H^0(C_2, \mathcal{O}_{C_2}(4))$ by taking the 22 monomials of degree 4 in the variables y_j and removing $y_0 y_2^3, y_1 y_2^3$ and y_2^4 that can be expressed in terms of the other monomials using the cubic equation defining C_2 . Accordingly we get a basis of $H^0(C_2, \Omega_{C_2}^1)$ by removing from that set $\omega'_{\alpha\beta\gamma}$ the 1-form $\omega'_{040}, \omega'_{030}$ and ω'_{130} . The *canonical* character of C_2 is given by Chevalley–Weil as

$$\begin{aligned} \chi_{can}^2 &= sgn \cdot \epsilon_1^2 \cdot \epsilon_2 + sgn \cdot \epsilon_1^2 \cdot \epsilon_2^2 + sgn \cdot \epsilon_1 \cdot \epsilon_2 + sgn \cdot \epsilon_1 + sgn \cdot \epsilon_2^2 + \mu \cdot \epsilon_1 + \mu \cdot \epsilon_2 \\ &\quad + 2\mu \cdot \epsilon_2^2 + sgn \cdot \epsilon_1^2 + \epsilon_1^2 + \mu \cdot \epsilon_1^2 + \mu \cdot \epsilon_1 \cdot \epsilon_2, \end{aligned}$$

and the action on $H^0(C_2, \Omega_{C_2}^1)$ computed in affine coordinates as above is

$$\begin{aligned} (\sigma^i \tau^j, (a, b)) \cdot \omega'_{\alpha\beta\gamma} &= \phi_2 \left((\sigma^i \tau^j, (a, b))^{-1} \right)^* (\omega'_{\alpha\beta\gamma}) \\ &= (-1)^j \zeta_3^{a(2\beta+\gamma)+b(\beta+\gamma-4)+(\alpha-(2\alpha+\beta+2\gamma-4)[j]+2\beta+\gamma+1)i} \\ &\quad \times \omega'_{(\alpha-(2\alpha+\beta+2\gamma-4)[j])\beta\gamma}. \end{aligned}$$

Another tedious computation gives the decomposition

$$\begin{aligned}
 H^0(C_2, \Omega_{C_2}^1) = & \langle \omega'_{002} \rangle_{sgn \cdot \epsilon_1^2 \cdot \epsilon_2} \oplus \langle \omega'_{021} \rangle_{sgn \cdot \epsilon_1^2 \cdot \epsilon_2^2} \oplus \langle \omega'_{120} \rangle_{sgn \cdot \epsilon_1 \cdot \epsilon_2} \\
 & \oplus \langle \omega'_{101} \rangle_{sgn \cdot \epsilon_1} \oplus \langle \omega'_{200} \rangle_{sgn \cdot \epsilon_2^2} \oplus \langle \omega'_{001}, \omega'_{201} \rangle_{\mu \cdot \epsilon_1} \oplus \langle \omega'_{011}, \omega'_{111} \rangle_{\mu \cdot \epsilon_2} \\
 & \oplus (\langle \omega'_{000}, \omega'_{400} \rangle \oplus \langle \omega'_{100}, \omega'_{300} \rangle)_{\mu \cdot \epsilon_2^2} \oplus \langle \omega'_{010} + \omega'_{310} \rangle_{sgn \cdot \epsilon_1^2} \oplus \langle \omega'_{010} - \omega'_{310} \rangle_{\epsilon_1^2} \\
 & \oplus \langle \omega'_{110}, \omega'_{210} \rangle_{\mu \cdot \epsilon_1^2} \oplus \langle \omega'_{220}, \omega'_{020} \rangle_{\mu \cdot \epsilon_1 \cdot \epsilon_2}.
 \end{aligned}$$

We consider unmixed quotients $S := (C_1 \times C_2) / (S_3 \times \mathbb{Z}_3^2)$ modulo a diagonal action $\phi_1 \times (\phi_2 \circ \Psi)$, where Ψ is one of the automorphisms of $S_3 \times \mathbb{Z}_3^2$.

Firstly we study the singularities of S . We observe that C_1 and C_2 have stabilizers of order 6, 3 and 6 and 2, 3, 3 and 6, respectively. Hence, 18 points of C_1 and 36 points of C_2 have stabilizer of even order. However, $S_3 \times \mathbb{Z}_3^2$ has only three elements of order 2 and they are in the same conjugacy class. This means that each of these three elements fix exactly $6 \cdot 12 = 72$ points of $C_1 \times C_2$. Thus, S can never be smooth, and if it admits only nodes, then they are in total $3 \cdot 72 / 27 = 8$.

Now let us consider the following automorphisms of $S_3 \times \mathbb{Z}_3^2$

$$\begin{aligned}
 \Psi_1 = Id, \quad \Psi_2 = & \left(\begin{array}{l} \sigma \mapsto \sigma \\ \tau \mapsto \tau\sigma \end{array}, \begin{pmatrix} 0 & 1 \\ 2 & 0 \end{pmatrix} \right), \\
 \Psi_3 = & \left(\begin{array}{l} \sigma \mapsto \sigma^2 \\ \tau \mapsto \tau \end{array}, \begin{pmatrix} 0 & 2 \\ 1 & 0 \end{pmatrix} \right), \quad \Psi_4 = \left(\begin{array}{l} \sigma \mapsto \sigma^2 \\ \tau \mapsto \tau \end{array}, \begin{pmatrix} 0 & 2 \\ 2 & 0 \end{pmatrix} \right).
 \end{aligned} \tag{1}$$

A direct computation shows us that for these four choices of Ψ the surface S has exactly 8 nodes and no other singularities.

Remark 2.1 The first example has been found by using the database [10]. Later on, we have run a systematic search over all automorphisms of $S_3 \times \mathbb{Z}_3^2$, proving that the obtained surfaces having only nodes are isomorphic to the four surfaces presented in this note.

The vector space $H^0(K_S)$ is isomorphic to the invariant subspace $(H^0(\Omega_{C_1}^1) \otimes H^0(\Omega_{C_2}^1))^{S_3 \times \mathbb{Z}_3^2}$, where the action on the tensor product is diagonal, i.e., $(\sigma^i \tau^j, (a, b)) \in S_3 \times \mathbb{Z}_3^2$ acts via

$$\phi_1((\sigma^i \tau^j, (a, b))^{-1})^* \otimes \phi_2(\Psi((\sigma^i \tau^j, (a, b))^{-1}))^*. \tag{2}$$

For each character, η of $S_3 \times \mathbb{Z}_3^2$ defines its twist by Ψ as

$$\eta_\Psi := \eta \circ \Psi^{-1}.$$

Pulling back $H^0(K_S)$ to $C_1 \times C_2$, we obtain

Lemma 2.2 *A basis of $H^0(K_S)$ is given by the $(S_3 \times \mathbb{Z}_3^2)$ -invariant 2 forms of $H^0(\Omega_{C_1}^1) \otimes H^0(\Omega_{C_2}^1)$ with respect to the action (2). Hence,*

$$(H^0(\Omega_{C_1}^1) \otimes H^0(\Omega_{C_2}^1))^{S_3 \times \mathbb{Z}_3^2} = \bigoplus_{\eta \neq 0} (H^0(\Omega_{C_1}^1)_{\eta} \otimes H^0(\Omega_{C_2}^1)_{\overline{\eta\Psi}})^{S_3 \times \mathbb{Z}_3^2},$$

where $H^0(\Omega_{C_i}^1)_\eta$ is the isotypic component of $H^0(\Omega_{C_i}^1)$ of character η . Moreover,

$$p_g = \langle \chi_{can}^1 \cdot \chi_{can}^2, 1 \rangle = \sum_{\eta \neq 0} \langle \chi_{can}^1, \eta \rangle \cdot \langle \chi_{can}^2, \overline{\eta\Psi} \rangle.$$

Denote by $\omega_{jklmrs} := \omega_{jkl} \otimes \omega'_{mrs}$. We can now state and prove our main result:

Theorem 2.3 *For all $\Psi \in \text{Aut}(S_3 \times \mathbb{Z}_3^2)$ in (1), the diagonal action $\phi_1 \times (\phi_2 \circ \Psi)$ of $S_3 \times \mathbb{Z}_3^2$ on the product of the two curves C_1 and C_2 is not free. The quotient is a canonical model of a regular surface S of general type with $K_S^2 = 24$, $p_g = 3$ and with 8 rational double points as singularities of type $\frac{1}{2}(1, 1)$. A basis of $H^0(K_S)$, the canonical map Φ_{K_S} in projective coordinates and its degree are stated in the table:*

No	Ψ	Basis of $H^0(K_S)$	$\Phi_{K_S}(x, y)$	$\text{deg}(\Phi_{K_S})$
1.	Id	$\{\omega_{100021}, \omega_{020200}, \omega_{002040}\}$	$(x_0x_1y_2^2y_3 : x_2^2y_0^2y_1^2 : x_3^2y_2^2)$	18
2.	Ψ_2	$\{\omega_{020101}, \omega_{002200}, \zeta_3\omega_{010020} - \omega_{110220}\}$	$(x_2^2y_0y_1y_3 : x_3^2y_0^2y_1^2 : x_2y_2^2(\zeta_3x_0y_0^2 - x_1y_1^2))$	$\begin{cases} 15 & \text{if } \lambda \neq 0 \\ 13 & \text{if } \lambda = 0 \end{cases}$
3.	Ψ_3	$\{\omega_{100002}, \omega_{020040}, \omega_{001220} + \omega_{101020}\}$	$(x_0x_1y_3^2 : x_2^2y_2^4 : x_3y_2^2(x_0y_1^2 + x_1y_0^2))$	$\begin{cases} 18 & \text{if } \lambda \neq 0 \\ 16 & \text{if } \lambda = 0 \end{cases}$
4.	Ψ_4	$\{\omega_{100120}, \omega_{020101}, \omega_{000020} + \omega_{200220}\}$	$(x_0x_1y_0y_1y_2^2 : x_2^2y_0y_1y_3 : y_2^2(x_0^2y_0^2 + x_1^2y_1^2))$	12

Proof We have already mentioned that for all Ψ in (1) the action is not free and the quotient S has 8 singularities of type $\frac{1}{2}(1, 1)$ and no other singularities. The genus of the two curves is $g(C_i) \geq 2$; hence, $C_1 \times C_2$ has ample canonical divisor, and so, S has ample canonical divisor too. It follows that S is a canonical model.

The self-intersection of the canonical divisor of each S is amount to

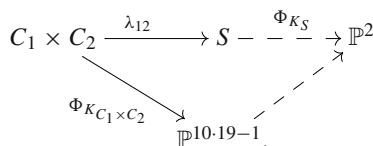
$$K_S^2 = \frac{8(g(C_1) - 1)(g(C_2) - 1)}{|S_3 \times \mathbb{Z}_3^2|} = 24.$$

They are regular surfaces, because they do not possess any nonzero holomorphic one forms, since $C_i / (S_3 \times \mathbb{Z}_3^2)$ is biholomorphic to \mathbb{P}^1 . The geometric genus of each S is therefore equal to (compare [4])

$$p_g = \chi(\mathcal{O}_S) - 1 = \frac{(g(C_1) - 1)(g(C_2) - 1)}{|S_3 \times \mathbb{Z}_3^2|} + \frac{1}{12} \left(8 \cdot \frac{3}{2} \right) - 1 = 3.$$

Using Lemma 2.2, we have computed a basis of $H^0(K_S)$. In fact, since we have proved that $p_g = 3$ it is enough to verify that the given elements of the table are invariant for the corresponding action. Applying the explicit isomorphisms from $H^0(C_1, \Omega_{C_1}^1)$ to $H^0(C_1, \mathcal{O}_{C_1}(2))$ and from $H^0(C_2, \Omega_{C_2}^1)$ to $H^0(C_2, \mathcal{O}_{C_2}(4))$, we obtain the product of quadrics and quartics defining the canonical map in the table.

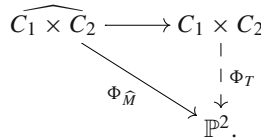
It remains to determine the degree of Φ_{K_S} for each surface S . Instead to work on S , it is convenient to work on $C_1 \times C_2$, which is smooth:



Note that the map $\Phi_{K_S} \circ \lambda_{12}$ is induced by the sublinear system $|T|$ of $|K_{C_1 \times C_2}|$ generated by the three invariant 2 forms defining Φ_{K_S} . In particular, the self-intersection of T is amount to

$$T^2 = (\lambda_{12}^* K_S)^2 = |S_3 \times \mathbb{Z}_3^2| \cdot K_S^2 = 54 \cdot 24.$$

We resolve the indeterminacy of $\Phi_T = \Phi_{K_S} \circ \lambda_{12}$ by a sequence of blowups, as explained in the textbook [7, Theorem II.7]:



Here the morphism $\Phi_{\widehat{M}}$ is induced by the base point-free linear system $|\widehat{M}|$ obtained as follows:

We blow up the base points of $|T|$, take the pullback of the mobile part $|M|$ of $|T|$ and remove the fixed part of this new linear system. We repeat the procedure, until we obtain a base point-free linear system $|\widehat{M}|$.

The self-intersection \widehat{M}^2 is positive if and only if $\Phi_{\widehat{M}}$ is not composed with a pencil. In this case, $\Phi_{\widehat{M}}$ is onto and it holds:

$$\deg(\Phi_{K_S}) = \frac{1}{|S_3 \times \mathbb{Z}_3^2|} \deg(\Phi_{\widehat{M}}) = \frac{1}{54} \widehat{M}^2.$$

For the computation of the resolution, it is convenient to write the divisors of the product of quadrics and quartics defining Φ_{K_S} (and hence Φ_T) as linear combinations of the curves $F_j := \{x_j = 0\}$ and $G_k := \{y_k = 0\}$ on $C_1 \times C_2$. We point out that these curves are reduced and intersect pairwise transversally thanks to the assumption $\lambda \neq -1, 1$. In particular, $(F_j, F_k) = (G_j, G_k) = 0$ and $(F_j, G_k) = 81$, for $k \neq 3$, while $(F_j, G_3) = 162$.

Consider the first surface in the table. Here, the divisors of the three products of quadrics and quartics spanning the subsystem $|T|$ are:

$$F_0 + F_1 + 2G_2 + G_3, \quad 2F_2 + 2G_0 + 2G_1 \quad \text{and} \quad 2F_3 + 4G_2.$$

Here $|T|$ has not fixed part and it has precisely 81 (non-reduced) base points $F_2 \cap G_2$. We can perform the computation of the difference $T^2 - \widehat{M}^2$ by applying Lemma 2.4 (for a proof see [11, Lemma 2.3]) recursively for each base point of $|T|$:

Lemma 2.4 *Let $|M|$ be a two-dimensional linear system on a surface S spanned by D_1, D_2 and D_3 . Assume that $|M|$ has only isolated base points, smooth for S , and that in a neighborhood of a base point p we can write the divisors D_i as*

$$D_1 = aH, \quad D_2 = bK \quad \text{and} \quad D_3 = cH + dK.$$

Here H and K are reduced, smooth and intersect transversally at p and a, b, c, d are nonnegative integers, $b \leq a$. Assume that

- $d \geq b$ or
- $b \neq 0$ and $c + md \geq a$, where $a = mb + q$ with $0 \leq q < b$.

Then after blowing up at most (ab) -times, we obtain a new linear system $|\widehat{M}|$ such that no infinitely near point of p is a base point of $|\widehat{M}|$. Moreover, $\widehat{M}^2 = M^2 - ab$.

In a neighborhood of each of these base points, the three divisors are, respectively,

$$2G_2, \quad 2F_2 \quad \text{and} \quad 4G_2.$$

Since F_2 and G_2 are transversal, we are in the situation of the Lemma 2.4 with $H = G_2$ and $K = F_2$, $a = b = 2$ and $c = 4$, $d = 0$. So $b \neq 0$ and $c + md \geq a$ and Lemma 2.4 applies. The correction term is $ab = 4$ for each of the 81 base points. Thus,

$$T^2 - \widehat{M}^2 = 4 \cdot 81.$$

The degree of the canonical map is therefore given by

$$\text{deg}(\Phi_{K_S}) = \frac{1}{54} \widehat{M}^2 = \frac{1}{54} (T^2 - (T^2 - \widehat{M}^2)) = \frac{1}{54} (54 \cdot 24 - 4 \cdot 81) = 18.$$

Now we take in exam the second surface in our table. Here the subsystem $|T|$ is spanned by:

$$D_1 := 2F_2 + G_0 + G_1 + G_3, \quad D_2 := 2F_3 + 2G_0 + 2G_1 \quad \text{and} \quad D_3 := F_2 + 2G_2 + \Delta,$$

where $\Delta = (\zeta_3 x_0 y_0^2 - x_1 y_1^2)$. The (set-theoretical) base locus is

$$F_2 \cap G_0, F_2 \cap G_1, \quad \Delta \cap G_0, \Delta \cap G_1, \quad \text{and} \quad \Delta \cap F_3 \cap G_3.$$

We remark that the other pieces of the base locus are empty. In fact, those points would belong to some $F_i \cap F_j$ or $G_i \cap G_j$ and we have already mentioned that they are pairwise disjoint.

We determine the correction term to the self-intersection number for each of these base points of $|T|$.

We consider first the 81 points $F_2 \cap G_i$, for $i = 0, 1$. Here F_2 and G_i intersect transversally at each of them. Around one of these points, the divisors D_k are given by $G_i + 2F_2, 2G_i$ and F_2 . We are in the situation of the Lemma 2.4 with $H = G_i$ and $K = F_2$, $a = d = 2$ and $b = c = 1$. Hence, $d \geq b$ and Lemma 2.4 applies, which yields $ab = 2$ as correction term.

We consider now the 81 base points $\Delta \cap G_i$. The local coordinates around one of these points are $X := x_j/x_i$ and $Y := y_i/y_j$, where $j = 0, 1, j \neq i$. So the divisors D_k are, respectively, given by

$$\{Y = 0\}, \quad 2\{Y = 0\} \quad \text{and} \quad \{\zeta_3^{1+i} Y^2 - X = 0\}.$$

Thus, D_1 and D_3 intersect transversally in $(0, 0)$ and we fall down once more in the situation of the Lemma 2.4. Here $H = D_3$ and $K = D_1$, $a = b = 1$, $c = 0$ and $d = 2$. Since $d \geq b$, then Lemma 2.4 is fulfilled and the correction term is amount to $ab = 1$.

We consider finally the points $\Delta \cap F_3 \cap G_3$. These points satisfy the equations

$$\begin{cases} y_3^3 = y_0^6 + y_1^6 - 2\lambda y_0^3 y_1^3 & = 0 \\ x_3^2 = x_0^3 + x_1^3 & = 0 \\ \zeta_3 x_0 y_0^2 - x_1 y_1^2 & = 0 \end{cases} \tag{3}$$

The last two equations imply that $x_1^3 = -x_0^3$ and

$$x_0^3 y_0^6 = (\zeta_3 x_0 y_0^2)^3 = (x_1 y_1^2)^3 = x_1^3 y_1^6 = -x_0^3 y_1^6.$$

Thus, $y_0^6 + y_1^6 = 0$, and comparing it with the first equation of 3, we get $\lambda y_0^3 y_1^3 = 0$. Therefore, $\Delta \cap F_3 \cap G_3$ is non-empty only if $\lambda = 0$.

Let us suppose $\lambda \neq 0$. Then

$$T^2 - \widehat{M}^2 = 2 \cdot 2 \cdot 81 + 2 \cdot 81 = 6 \cdot 81,$$

and the degree of the canonical map is amount to

$$\text{deg}(\Phi_{K_S}) = \frac{1}{54} (T^2 - (T^2 - \widehat{M}^2)) = \frac{1}{54} (54 \cdot 24 - 6 \cdot 81) = 15.$$

It remains to consider the case when $\lambda = 0$. The base points $\Delta \cap F_3 \cap G_3$ are the following 54 ones:

$$t_k := \left(\left(1 : -\zeta_3^{k_1} \sqrt[3]{2} \zeta_3^{k_2} : 0 \right), \left(1 : e^{\frac{\pi i}{6}} \zeta_6^{k_3} : \sqrt[6]{2} e^{\frac{\pi i}{12} (1-2[k_3])} \zeta_3^{k_4} : 0 \right) \right),$$

$$k_1 + k_3 \equiv 2 \pmod{3},$$

where $k_i = 0, 1, 2$, for $i \neq 3$, and $k_3 = 0, \dots, 5$. Fix coordinates $X := x_1/x_0 + \zeta_3^2$ and $Y := y_1/y_0 - e^{\frac{\pi i}{6}}$ around one of these points, for example that one for $k = (2, 0, 0, 0)$. The divisors D_k are locally given by

$$\{Y = 0\}, \quad 2\{X = 0\} \quad \text{and} \quad \{Y(2e^{\frac{\pi i 5}{6}} + Y - 2e^{\frac{\pi i 5}{6}} X - XY) = 0\} = \{Y = 0\}.$$

In this case, $H = \{X = 0\}$ and $K = \{Y = 0\}$ and $a = 2$ and $b = d = 1, c = 0$. The correction term is $ab = 2$.

Hence,

$$T^2 - \widehat{M}^2 = 2 \cdot 2 \cdot 81 + 2 \cdot 81 + 2 \cdot 54 = 6 \cdot 81 + 2 \cdot 54.$$

The degree of the canonical map is therefore given by

$$\text{deg}(\Phi_{K_S}) = \frac{1}{54} (T^2 - (T^2 - \widehat{M}^2)) = \frac{1}{54} (54 \cdot 24 - 6 \cdot 81 - 2 \cdot 54) = 13.$$

We leave to the reader to verifying with the same approach that the degree of the canonical map of the remaining two surfaces is amount to that ones stated in the table. \square

Acknowledgements The author would like to thank Fabrizio Catanese, Davide Frapporti, Bin Nguyen and Roberto Pignatelli for useful comments and discussions.

Funding Open access funding provided by Università degli Studi di Trento within the CRUI-CARE Agreement.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Bauer, I., Catanese, F., Grunewald, F.: The classification of surfaces with $p_g = q = 0$ isogenous to a product of curves. *Pure Appl. Math. Q.* **4**, 547–586 (2008)
2. Bauer, I., Catanese, F.: On rigid compact complex surfaces and manifolds. *Adv. Math.* **333**, 620–669 (2018)

3. I. Bauer, S. Garion, A.: Vdovina (Editors), Beauville surfaces and groups, Springer Proceedings in Mathematics & Statistics. In: Proceedings of the Conference Held at the University of Newcastle, Newcastle-upon-Tyne, June 7–9, 2012, **123** (2015)
4. Bauer, I., Pignatelli, R.: The classification of minimal product-quotient surfaces with $p_g = 0$. *Math. Comp.* **81**, 2389–2418 (2012)
5. Bauer, I., Pignatelli, R.: Rigid but not infinitesimally rigid compact complex manifolds. *Duke Math. J.* **170**, 1757–1780 (2021)
6. Beauville, A.: L'application canonique pour les surfaces de type général. *Invent. Math.* **55**, 121–140 (1979)
7. Beauville, A.: Arnaud, Complex algebraic surfaces, London Mathematical Society Student Texts, **34**, (1996)
8. Bosma, W., Cannon, J.: The Magma algebra system. I. The user language, computational algebra and number theory (London, 1993). *J. Symbolic Comput.* **24**, 235–265 (1997)
9. Catanese, F.: Fibred surfaces, varieties isogenous to a product and related moduli spaces. *Am. J. Math.* **122**, 1–44 (2000)
10. Conti, D., Ghigi, A., Pignatelli, R.: Topological types of actions on curves. *J. Symb. Comput.* **118C**, 17–31 (2023)
11. Fallucca, F., Gleissner, C.: Some surfaces with canonical maps of degree 10, 11 and 14. *Math. Nachr.* (2023). <https://doi.org/10.1002/mana.202200450>
12. Gleissner, C.: The classification of regular surfaces isogenous to a product of curves with $\chi(\mathcal{O}_S) = 2$, Beauville surfaces and groups, Springer Proc. Math. Stat., **123**, Springer, 79–95, (2015)
13. Gleissner, C., Pignatelli, R., Rito, C.: New surfaces with canonical map of high degree. *Commun. Anal. Geom.* **30**, 1809–1821 (2022). <https://doi.org/10.4310/CAG.2022.v30.n8.a5>
14. Lai, C.-J., Yeung, S.-K.: Examples of surfaces with canonical map of maximal degree. *Taiwanese J. Math.* **4**, 699–716 (2021)
15. Morrow, J., Kodaira, K.: Complex manifolds, Holt, Rinehart and Winston Inc. Que.-London, New York-Montreal (1971)
16. Lopes, M.M., Pardini, R.: On the degree of the canonical map of a surface of general type, The Art of Doing Algebraic Geometry, Trends in Mathematics, Birkhäuser. Cham., (2023). https://doi.org/10.1007/978-3-031-11938-5_13
17. Nguyen, B.: A new example of an algebraic surface with canonical map of degree 16. *Arch. Math. (Basel)* **113**, 385–390 (2019)
18. Nguyen, B.: Some examples of algebraic surfaces with canonical map of degree 20, *Comptes Rendus Mathématique. Académie des Sciences. Paris* **359**, 1145–1153 (2021)
19. Nguyen, B.: Some algebraic surfaces with canonical map of degree 10, 12 and 14. *Comm. Algebr.* (2023). <https://doi.org/10.1080/00927872.2023.2232869>
20. Pardini, R.: Abelian covers of algebraic varieties. *J. Reine Angew. Math.* **417**, 191–213 (1991)
21. Persson, U.: Double coverings and surfaces of general type, In Algebraic geometry vol. **687** of Lecture Notes in Math. Springer, 168–195 (1978)
22. Rito, C.: New canonical triple covers of surfaces. *Proc. Amer. Math. Soc.* **143**, 4647–653 (2015)
23. Rito, C.: A surface with canonical map of degree 24, *Internat. J. Math.*, **28**, (2017)
24. Rito, C.: A surface with $q = 2$ and canonical map of degree 16. *Michigan Math. J.* **66**, 99–105 (2017)
25. Rito, C.: Surfaces with canonical map of maximum degree. *J. Algebr. Geom.* **31**, 127–135 (2022)
26. Shafarevich, I.: Basic algebraic geometry 1. Varieties in projective space, Springer, Heidelberg (2013)
27. Tan, S.L.: Cusps on some algebraic surfaces and plane curves. *Complex Analysis, Complex Geometry and Related Topics - Namba* **60**, 106–121 (2003)