# GENUS 3 HYPERELLIPTIC CURVES WITH (2,4,4)- SPLIT JACOBIANS 

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#### Abstract

We study degree 2 and 4 elliptic subcovers of hyperelliptic curves of genus 3 defined over $\mathbb{C}$. The family of genus 3 hyperelliptic curves which have a degree 2 cover to an elliptic curve $E$ and degree 4 covers to elliptic curves $E_{1}$ and $E_{2}$ is a 2-dimensional subvariety of the hyperelliptic moduli $\mathcal{H}_{3}$. We determine this subvariety explicitly. For any given moduli point $\mathfrak{p} \in \mathcal{H}_{3}$ we determine explicitly if the corresponding genus 3 curve $\mathcal{X}$ belongs or not to such family. When it does, we can determine elliptic subcovers $E$, $E_{1}$, and $E_{2}$ in terms of the absolute invariants $t_{1}, \ldots, t_{6}$ as in [20]. This variety provides a new family of hyperelliptic curves of genus 3 for which the Jacobians completely split. The sublocus of such family when $E_{1} \cong E_{2}$ is a 1-dimensional variety which we determine explicitly. We can also determine $\mathcal{X}$ and $E$ starting form the $j$-invariant of $E_{1}$.


## 1. Introduction

Let $\mathcal{M}_{g}$ denote the moduli space of genus $g \geq 2$ algebraic curves defined over an algebraically closed field $k$ and $\mathcal{H}_{g}$ the hyperelliptic submoduli in $\mathcal{M}_{g}$. The sublocus of genus $g$ hyperelliptic curves with an elliptic involution is a $g$-dimensional subvariety of $\mathcal{H}_{g}$. For $g=2$ this space is denoted by $\mathcal{L}_{2}$ and studied in Shaska/Völklein [33] and for $g=3$ is denoted by $\mathcal{S}_{2}$ and is computed and discussed in detail in [21]. In both cases, a birational parametrization of these spaces is found via dihedral invariants which are introduced by this author in [9,24,25] and generalized for any genus $g \geq 2$ in [10]. We denote the parameters for $\mathcal{L}_{2}$ by $u, v$ and for $\mathcal{S}_{2}$ by $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ as in respective papers. Hence, for the case $g=3$ there is a birational map

$$
\begin{align*}
\mathcal{S}_{2} & \longrightarrow \mathcal{H}_{3} \\
\phi:\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) & \longrightarrow\left(t_{1}, \ldots, t_{6}\right), \tag{1.1}
\end{align*}
$$

where $t_{1}, \ldots, t_{6}$ are the absolute invariants as defined in [20] satisfying the equation of the genus 3 hyperelliptic moduli; see [20] for details.

The dihedral invariants $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ provide a birational parametrization of the locus $\mathcal{S}_{2}$. Hence, a generic curve in $\mathcal{S}_{2}$ is uniquely determined by the corresponding triple $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$.

Let $\mathcal{X}$ be a curve in the locus $\mathcal{S}_{2}$. Then there is a degree 2 map $f_{1}: \mathcal{X} \rightarrow E$ for some elliptic curve $E$. Thus, the Jacobian of $\mathcal{X}$ splits as $\operatorname{Jac}(\mathcal{X}) \cong E \times A$, where $A$ is a genus 2 Jacobian. Hence, there is a map $f_{2}: \mathcal{X} \rightarrow C$ for some genus 2 curve $C$. The equations of $\mathcal{X}, E$, and $C$ are given in Thm. 1. For any fixed curve $\mathcal{X} \in \mathcal{S}_{2}$, the subcovers $E$ and $C$ are uniquely determined in terms of the invariants $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$.

[^0]In section three we give the splitting of the Jacobians for all genus 3 algebraic curves, when this splitting is induced by automorphisms. The case for hyperelliptic curves was done in [16], we complete the non-hyperelliptic cases. The proof requires the Poincare duality and some basic group theory.

In this paper, we are mostly interested in the case when the Jacobian of the genus two curve $C$ also splits. The Jacobian of $C$ can split as an $(n, n)$-structure; see [27]. The loci of such genus 2 curves with $(3,3)$-split or $(5,5)$-split have been studied respectively in in [27] and [14]. We focus on the case when the Jacobian of $C$ is $(2,2)$-split, which corresponds to the case when the Klein 4-group $V_{4} \hookrightarrow$ Aut $(C)$. Hence, Jac $\mathcal{X}$ splits completely as a product of three elliptic curves. We say that Jac $\mathcal{X}$ is (2, 4, 4)-split.

Let the locus of genus 3 hyperelliptic curves whose Jacobian is (2,4,4)-split be denoted by $\mathcal{T}$. Then, there is a rational map $\psi: \mathcal{T} \rightarrow \mathcal{L}_{2}$ such that

$$
\begin{equation*}
\psi:\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) \longrightarrow(u, v) \tag{1.2}
\end{equation*}
$$

which has degree 70 and can be explicitly computed, even though the rational expressions of $u$ and $v$ in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ are quite large.

There are three components of $\mathcal{T}$ which we denote them by $\mathcal{T}_{i}, i=1,2,3$. Two of these components are well known and the correspond to the cases when $V_{4}$ is embedded in the reduced automorphism group of $\mathcal{X}$. These cases correspond to the singular locus of $\mathcal{S}_{2}$ and are precisely the locus $\operatorname{det}(\operatorname{Jac}(\phi))=0$, see [24]. This happens for all genus $g \geq 2$ as noted by Geyer [8], Shaska/Völklein [33], and shown in [24]. The third component $\mathcal{T}_{3}$ is more interesting to us. It doesn't seem to have any group theoretic reason for this component to be there in the first place. We find the equation of this component it terms of the $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ invariants. It is an equation

$$
\begin{equation*}
F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0 \tag{1.3}
\end{equation*}
$$

as in Eq. (4.2). In this locus, the elliptic subfields of the genus two field $k(C)$ can be determined explicitly.

The main goal of this paper is to determine explicitly the family $\mathcal{T}_{3}$ of genus 3 curves and relations among its elliptic subcovers. We have the maps

$$
\begin{align*}
\mathcal{T}_{3} & \xrightarrow{\psi} \mathcal{L}_{2} \xrightarrow{\psi_{0}} k^{2}  \tag{1.4}\\
\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) & \rightarrow(u, v) \rightarrow\left(j_{1}, j_{2}\right)
\end{align*}
$$

where $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ satisfy Eq. (4.2) and $u, v$ are given explicitly by Eq. (4.1) and Thm. (3) in [33]. The degree deg $\psi_{0}=2$ and $\operatorname{deg} \psi=70$.

Since $\mathcal{T}_{3}$ is a subvariety of $\mathcal{H}_{3}$ it would be desirable to express its equation in terms of a coordinate in $\mathcal{H}_{3}$. One can use the absolute invariants of the genus 3 hyperelliptic curves $t_{1}, \ldots, t_{6}$ as defined in [20] and the expressions of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ in terms of these invariants as computed in [21].

Further, we focus our attention to the sublocus $\mathcal{V}$ of $\mathcal{L}_{2}$ such that the genus 2 field $k(C)$ has isomorphic elliptic subfields. Such locus was discovered by Shaska/Völklein in [33] and it is somewhat surprising. It does not rise from a family of genus two curves with a fixed automorphism group as other families, see [33] for details. Using this sublocus of $\mathcal{M}_{2}$ we discover a rather unusual embedding $\mathcal{M}_{1} \hookrightarrow \mathcal{M}_{2}$ as noted in [33]. Let $\mathfrak{T} \subset \mathcal{T}_{3} \subset \mathcal{H}_{3}$ be the subvariety of $\mathcal{T}_{3}$ obtained by adding the condition
$j_{1}=j_{2}$. Then, $\mathfrak{T}$ is a 1 -dimensional variety defined by equation

$$
\left\{\begin{array}{l}
F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0  \tag{1.5}\\
F_{2}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0
\end{array}\right.
$$

where $F_{2}$ is the discriminant of the quadratic polynomial roots of which are $j$ invariants $j_{1}$ and $j_{2}$; cf. Lemma 3. Hence, we have the maps

$$
\begin{array}{r}
k \rightarrow \mathfrak{T} \hookrightarrow \mathcal{V} \hookrightarrow k \\
t \rightarrow\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) \rightarrow(u, v) \rightarrow j_{1} \tag{1.6}
\end{array}
$$

Next we study whether the above maps are invertible. That would provide birational parametrizations for varieties $\mathcal{V}$ and $\mathfrak{T}$. The variety $\mathcal{V}$ is known to have a birational parametrization from Thm. (3) in [33]. The map can be inverted as

$$
\begin{equation*}
j \rightarrow \quad(u, v)=\left(9-\frac{j}{256}, 9\left(6-\frac{j}{256}\right)\right) \tag{1.7}
\end{equation*}
$$

see [33] for details. The main computational task of this paper is to find a birational parametrization of $\mathfrak{T}$.

Given $(u, v) \in \mathcal{V}$ there is a unique (up to isomorphism) genus 2 curve $C$ corresponding to this point in $\mathcal{V}$. From Lemma 3, every genus 2 curve can be written as in Eq. (4.6). Hence, there exists a triple $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ corresponding to $(u, v)$.

If $j \in \mathbb{Q}$, then it is a well-known fact that the corresponding elliptic curve $E_{j}$ can be chosen defined over $\mathbb{Q}$. From the above expressions we see that $u, v \in \mathbb{Q}$. Then, from [26] the corresponding genus two curve $C$ has also minimal field of definition $\mathbb{Q}$. The same holds for $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ and the genus 3 corresponding curve $\mathcal{X}$.

## 2. Hyperelliptic curves with extra involutions

In this section, we will go over some basic properties of genus three hyperelliptic fields which have an elliptic involution. For details on genus 3 curves the reader can check further $[3-7,13,15,19,22-26,28-31]$.

Let $K$ be a genus 3 hyperelliptic field over the ground field $k$. Then $K$ has exactly one genus 0 subfield of degree 2 , call it $k(X)$. It is the fixed field of the hyperelliptic involution $\omega_{0}$ in Aut $(K)$. Thus, $\omega_{0}$ is central in Aut $(K)$, where Aut $(K)$ denotes the group Aut $(K / k)$. It induces a subgroup of Aut $(k(X))$ which is naturally isomorphic to $\overline{\operatorname{Aut}}(K):=\operatorname{Aut}(K) /\left\langle\omega_{0}\right\rangle$. The latter is called the reduced automorphism group of $K$.

An elliptic involution of $G=$ Aut $(K)$ is an involution which fixes an elliptic subfield. An involution of $\bar{G}=\overline{\operatorname{Aut}}(K)$ is called elliptic if it is the image of an elliptic involution of $G$.

If $\omega_{1}$ is an elliptic involution in $G$ then $\omega_{2}:=\omega_{0} \omega_{1}$ is another involution (not necessarily elliptic). So the non-hyperelliptic involutions come naturally in (unordered) pairs $\omega_{1}, \omega_{2}$. These pairs correspond bijectively to the Klein 4-groups in $G$.

Definition 1. We will consider pairs $(K, \varepsilon)$ with $K$ a genus 3 hyperelliptic field and $\varepsilon$ an elliptic involution in $\bar{G}$. Two such pairs $(K, \varepsilon)$ and $\left(K^{\prime}, \varepsilon^{\prime}\right)$ are called isomorphic if there is a $k$-isomorphism $\alpha: K \rightarrow K^{\prime}$ with $\varepsilon^{\prime}=\alpha \varepsilon \alpha^{-1}$.

Let $\varepsilon$ be an elliptic involution in $\bar{G}$. We can choose the generator $X$ of $\operatorname{Fix}\left(\omega_{0}\right)$ such that $\varepsilon(X)=-X$. Then $K=k(X, Y)$ where $X, Y$ satisfy equation

$$
Y^{2}=\left(X^{2}-\alpha_{1}^{2}\right)\left(X^{2}-\alpha_{2}^{2}\right)\left(X^{2}-\alpha_{3}^{2}\right)\left(X^{2}-\alpha_{4}^{2}\right)
$$

for some $\alpha_{i} \in k, i=1, \ldots, 4$. Denote by

$$
\begin{align*}
& s_{1}=-\left(\alpha_{1}^{2}+\alpha_{2}^{2}+\alpha_{3}^{2}+\alpha_{4}^{2}\right) \\
& s_{2}=\left(\alpha_{1} \alpha_{2}\right)^{2}+\left(\alpha_{1} \alpha_{3}\right)^{2}+\left(\alpha_{1} \alpha_{4}\right)^{2}+\left(\alpha_{2} \alpha_{3}\right)^{2}+\left(\alpha_{2} \alpha_{4}\right)^{2}+\left(\alpha_{3} \alpha_{4}\right)^{2} \\
& s_{3}=-\left(\alpha_{1} \alpha_{2} \alpha_{3}\right)^{2}-\left(\alpha_{4} \alpha_{1} \alpha_{2}\right)^{2}-\left(\alpha_{4} \alpha_{3} \alpha_{1}\right)^{2}-\left(\alpha_{4} \alpha_{3} \alpha_{2}\right)^{2}  \tag{2.1}\\
& s_{4}=-\left(\alpha_{1} \alpha_{2} \alpha_{3} \alpha_{4}\right)^{2}
\end{align*}
$$

Then, we have

$$
Y^{2}=X^{8}+s_{1} X^{6}+s_{2} X^{4}+s_{3} X^{2}+s_{4}
$$

with $s_{1}, s_{2}, s_{3}, s_{4} \in k, s_{4} \neq 0$. Furthermore, $E=k\left(X^{2}, Y\right)$ and $C=k\left(X^{2}, Y X\right)$ are the two subfields corresponding to $\varepsilon$ of genus 1 and 2 respectively.

Preserving the condition $\varepsilon(X)=-X$ we can further modify $X$ such that $s_{4}=1$. Then, we have the following:
Theorem 1. Let $K$ be a genus 3 hyperelliptic field and $F$ an elliptic subfield of degree 2.
i) Then, $K=k(X, Y)$ such that

$$
\begin{equation*}
Y^{2}=X^{8}+a X^{6}+b X^{4}+c X^{2}+1 \tag{2.2}
\end{equation*}
$$

for $a, b, c \in k$ such that $\Delta \neq 0$, where

$$
\begin{align*}
\Delta= & 256\left(-256+80 b^{2} a c-18 b a^{3} c-18 a c^{3} b-b^{2} a^{2} c^{2}+6 a^{2} c^{2}-144 c^{2} b+4 a^{3} c^{3}\right. \\
& \left.+4 b^{3} a^{2}+4 b^{3} c^{2}+128 b^{2}-144 b a^{2}+192 a c-16 b^{4}+27 c^{4}+27 a^{4}\right)^{2} \tag{2.3}
\end{align*}
$$

ii) $F=k(U, V)$ where

$$
U=X^{2}, \quad \text { and } \quad V=Y
$$

and

$$
\begin{equation*}
V^{2}=U^{4}+a U^{3}+b U^{2}+c U+1 \tag{2.4}
\end{equation*}
$$

iii) There is a genus 2 subfield $L=k(x, y)$ where

$$
x=X^{2}, \quad \text { and } \quad y=Y X
$$

and

$$
\begin{equation*}
y^{2}=x\left(x^{4}+a x^{3}+b x^{2}+c x+1\right) \tag{2.5}
\end{equation*}
$$

Proof. The proof follows from the above remarks. To show that the genus 2 subfield is generated by $X^{2}, Y X$ it is enough to show that they are fixed by $\omega_{2}$. In cases ii) and iii) we are again assuming that Eq. (2.3) holds.

These conditions determine $X$ up to coordinate change by the group $\left\langle\tau_{1}, \tau_{2}\right\rangle$ where

$$
\tau_{1}: X \rightarrow \zeta_{8} X, \quad \text { and } \quad \tau_{2}: X \rightarrow \frac{1}{X}
$$

and $\zeta_{8}$ is a primitive 8 -th root of unity in $k$. Hence,

$$
\tau_{1}:(a, b, c) \rightarrow\left(\zeta_{8}^{6} a, \zeta_{8}^{4} b, \zeta^{2} c\right)
$$



Figure 1. The lattice of a genus 3 hyperelliptic field with an extra involution
and

$$
\tau_{2}:(a, b, c) \rightarrow(c, b, a)
$$

Then, $\left|\tau_{1}\right|=4$ and $\left|\tau_{2}\right|=2$. The group generated by $\tau_{1}$ and $\tau_{2}$ is the dihedral group of order 8 . Invariants of this action are

$$
\begin{equation*}
\mathfrak{s}_{2}=a c, \quad \mathfrak{s}_{3}=\left(a^{2}+c^{2}\right) b, \quad \mathfrak{s}_{4}=a^{4}+c^{4} \tag{2.6}
\end{equation*}
$$

since

$$
\begin{aligned}
& \tau_{1}(a c)=\cdot \zeta_{8}^{6} a \cdot \zeta_{8}^{2} c=a c \\
& \tau_{1}\left(\left(a^{2}+c^{2}\right) b\right)=\left(\zeta_{8}^{4} a^{2}+\zeta_{8}^{4} c^{2}\right) \cdot\left(\zeta_{8}^{4} b\right)=\left(a^{2}+c^{2}\right) b \\
& \tau_{1}\left(a^{4}+c^{4}\right)=\left(\zeta_{8}^{6} a\right)^{4}+\left(\zeta_{8}^{2} c\right)^{4}=a^{4}+c^{4}
\end{aligned}
$$

Since the above transformations are automorphisms of the projective line $\mathbb{P}^{1}(k)$ then the $S L_{2}(k)$ invariants must be expressed in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}$, and $\mathfrak{s}_{4}$.

If $\mathfrak{s}_{4}+2 \mathfrak{s}_{2}^{2}=0$ then this implies that the curve has automorphism group $\mathbb{Z}_{2} \times \mathbb{Z}_{4}$, continue to Theorem 2 for details. From now on we assume that $\mathfrak{s}_{4}+2 \mathfrak{s}_{2}^{2} \neq 0$.

In these parameters, the discriminant of the octavic polynomial on the right hand side of Eq. (2.2) equals

$$
\begin{align*}
\Delta= & 16 s_{2}{ }^{7}+24 s_{2}{ }^{6}-72 s_{3} s_{2}{ }^{5}+16 s_{4} s_{2}{ }^{5}+768 s_{2}{ }^{5}-1024 s_{2}{ }^{4}-2 s_{3}{ }^{2} s_{2}{ }^{4}+132 s_{4} s_{2}{ }^{4}  \tag{2.7}\\
& -576 s_{3} s_{2}{ }^{4}+768 s_{4} s_{2}{ }^{3}-72 s_{4} s_{3} s_{2}{ }^{3}+160 s_{3}{ }^{2} s_{2}{ }^{3}+4 s_{4}{ }^{2} s_{2}{ }^{3}-576 s_{4} s_{3} s_{2}{ }^{2}+8 s_{3}{ }^{3} s_{2}{ }^{2} \\
& -1024 s_{4} s_{2}{ }^{2}-s_{3}{ }^{2} s_{4} s_{2}{ }^{2}+256 s_{3}{ }^{2} s_{2}{ }^{2}+114 s_{4}{ }^{2} s_{2}{ }^{2}+192 s_{4}{ }^{2} s_{2}-18 s_{4}{ }^{2} s_{3} s_{2}+80 s_{3}{ }^{2} s_{4} s_{2} \\
& -256 s_{4}{ }^{2}+27 s_{4}{ }^{3}+128 s_{3}{ }^{2} s_{4}-16 s_{3}{ }^{4}-144 s_{4}{ }^{2} s_{3}+4 s_{3}{ }^{3} s_{4}
\end{align*}
$$

From now forward we will assume that $\Delta\left(\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}\right) \neq 0$ since in this case the corresponding triple $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ does not correspond to a genus 3 curve. The map $(a, b, c) \mapsto\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ is a branched Galois covering with group $D_{4}$ of the set

$$
\left\{\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) \in k^{3}: \Delta\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) \neq 0\right\}
$$

by the corresponding open subset of $(a, b, c)$-space. In any case, it is true that if $a, b, c$ and $a^{\prime}, b^{\prime}, c^{\prime}$ have the same $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$-invariants then they are conjugate under $\left\langle\tau_{1}, \tau_{2}\right\rangle$.

Lemma 1. For $(a, b, c) \in k^{3}$ with $\Delta \neq 0$, equation (2.2) defines a genus 3 hyperelliptic field $K_{a, b, c}=k(X, Y)$. Its reduced automorphism group contains the
non-hyperelliptic involution $\varepsilon_{a, b, c}: X \mapsto-X$. Two such pairs $\left(K_{a, b, c}, \varepsilon_{a, b, c}\right)$ and $\left(K_{a^{\prime}, b^{\prime}, c^{\prime}}, \varepsilon_{a^{\prime}, b^{\prime}, c^{\prime \prime}}\right)$ are isomorphic if and only if

$$
\mathfrak{s}_{4}=\mathfrak{s}_{4}^{\prime}, \quad \mathfrak{s}_{3}=\mathfrak{s}_{3}^{\prime}, \quad \text { and } \quad \mathfrak{s}_{2}=\mathfrak{s}_{2}^{\prime}
$$

where $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ and $\mathfrak{s}_{4}^{\prime}, \mathfrak{s}_{3}^{\prime}, \mathfrak{s}_{2}^{\prime}$ are associated with $a, b, c$ and $a^{\prime}, b^{\prime}, c^{\prime}$, respectively, by (2.6)).

Proof. An isomorphism $\alpha$ between these two pairs yields $K=k(X, Y)=k\left(X^{\prime}, Y^{\prime}\right)$ with $k(X)=k\left(X^{\prime}\right)$ such that $X, Y$ satisfy $(2.2)$ and $X^{\prime}, Y^{\prime}$ satisfy the corresponding equation with $a, b, c$ replaced by $a^{\prime}, b^{\prime}, c^{\prime}$. Further, $\varepsilon_{a, b, c}\left(X^{\prime}\right)=-X^{\prime}$. Thus $X^{\prime}$ is conjugate to $X$ under $\left\langle\tau_{1}, \tau_{2}\right\rangle$ by the above remarks. This proves the condition is necessary. It is clearly sufficient.

The following theorem determines relations among $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ for each group $G$ such that $V_{4} \hookrightarrow G$.
Theorem 2. Let $\mathcal{X}$ be a curve in $\mathcal{S}=\mathcal{M}_{3}^{b} \cap \mathcal{H}_{3}$. Then, the following hold
i) Aut $(\mathcal{X}) \cong \mathbb{Z}_{2}^{3}$ if and only if $\mathfrak{s}_{4}-2 \mathfrak{s}_{2}^{2}=0$
ii) Aut $(\mathcal{X}) \cong \mathbb{Z}_{2} \times D_{8}$ if and only if $\mathfrak{s}_{2}=\mathfrak{s}_{4}=0$
iii) Aut $(\mathcal{X}) \cong \mathbb{Z}_{2} \times \mathbb{Z}_{4}$ if and only if $\mathfrak{s}_{4}+2 \mathfrak{s}_{2}^{2}=0$ and $\mathfrak{s}_{3}=0$.
iv) Aut $(\mathcal{X}) \cong D_{12}$ if and only if

$$
\begin{align*}
\mathfrak{s}_{3} & =\frac{1}{75}\left(9 \mathfrak{s}_{2}-224\right)\left(\mathfrak{s}_{2}-196\right) \\
\mathfrak{s}_{4} & =-\frac{9}{125} \mathfrak{s}_{2}{ }^{3}+\frac{1962}{125} \mathfrak{s}_{2}^{2}-\frac{840448}{1125} \mathfrak{s}_{2}+\frac{9834496}{1125} \tag{2.8}
\end{align*}
$$

See [21] for the proof.
Remark 1. Any genus 3 hyperelliptic curve is determined uniquely (up to isomorphism) by the tuple $\left(t_{1}, \ldots, t_{6}\right)$ as defined in [20]. Such invariants can be expressed in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ as in [21]. The correctness of the result can be checked by substituting the expressions in the equation of the moduli space $\mathcal{H}_{3}$, which is computed explicitly in [20].

## 3. Decomposition of Jacobians

In this section we give a brief description of the decomposition of Jacobians of genus 3 curves when such decomposition is induced by the automorphisms of the curve.

Let $\mathcal{X}$ be a genus $g$ algebraic curve with automorphism group $G:=\operatorname{Aut}(\mathcal{X})$. Let $H \leq G$ such that $H=H_{1} \cup \cdots \cup H_{t}$ where the subgroups $H_{i} \leq H$ satisfy $H_{i} \cap H_{j}=\{1\}$ for all $i \neq j$. Then,

$$
\operatorname{Jac}^{t-1}(\mathcal{X}) \times \operatorname{Jac}^{|H|}(\mathcal{X} / H) \cong \operatorname{Jac}^{\left|H_{1}\right|}\left(\mathcal{X} / H_{1}\right) \times \cdots \operatorname{Jac}^{\left|H_{t}\right|}\left(\mathcal{X} / H_{t}\right)
$$

The group $H$ satisfying these conditions is called a group with partition. Elementary abelian $p$-groups, the projective linear groups $P S L_{2}(q)$, Frobenius groups, dihedral groups are all groups with partition.

Let $H_{1}, \ldots, H_{t} \leq G$ be subgroups with $H_{i} \cdot H_{j}=H_{j} \cdot H_{i}$ for all $i, j \leq t$, and let $g_{i j}$ denote the genus of the quotient curve $\mathcal{X} /\left(H_{i} \cdot H_{j}\right)$. Then, for $n_{1}, \ldots, n_{t} \in \mathbb{Z}$ the conditions

$$
\sum n_{i} n_{j} g_{i j}=0, \quad \sum_{j=1}^{t} n_{j} g_{i j}=0
$$

imply the isogeny relation

$$
\prod_{n_{i}>0} \operatorname{Jac}^{n_{i}}\left(\mathcal{X} / H_{i}\right) \cong \prod_{n_{j}<0} \operatorname{Jac}^{\left|n_{j}\right|}\left(\mathcal{X} / H_{j}\right)
$$

In particular, if $g_{i j}=0$ for $2 \leq i<j \leq t$ and if

$$
g=g_{\mathcal{X} / H_{2}}+\cdots+g_{\mathcal{X} / H_{t}}
$$

then

$$
\operatorname{Jac}(\mathcal{X}) \cong \operatorname{Jac}\left(\mathcal{X} / H_{2}\right) \times \cdots \times \operatorname{Jac}\left(\mathcal{X} / H_{t}\right)
$$

The reader can check $[1,2,12]$ for the proof of the above statements.
3.1. Non-hyperelliptic curves. We will use the above facts to decompose the Jacobians of genus 3 non-hyperelliptic curves. $\mathcal{X}$ denotes a genus 3 non-hyperelliptic curve unless otherwise stated and $\mathcal{X}_{2}$ denotes a genus 2 curve.
3.1.1. The group $C_{2}$. Then the curve $\mathcal{X}$ has an elliptic involution $\mathfrak{s} \in$ Aut $(\mathcal{X})$. Hence, there is a Galois covering $\pi: \mathcal{X} \rightarrow \mathcal{X} /\langle\sigma\rangle=: E$. We can assume that this covering is maximal. The induced map $\pi^{*}: E \rightarrow \operatorname{Jac}(\mathcal{X})$ is injective. Then, the kernel projection $\operatorname{Jac}(\mathcal{X}) \rightarrow E$ is a dimension 2 abelian variety. Hence, there is a genus 2 curve $\mathcal{X}_{2}$ such that

$$
\operatorname{Jac}\left(\mathcal{X}_{2}\right) \cong E \times \operatorname{Jac}\left(\mathcal{X}_{2}\right)
$$

3.1.2. The Klein 4-group. Next, we focus on the automorphism groups $G$ such that $V_{4} \hookrightarrow G$. In this case, there are three elliptic involutions in $V_{4}$, namely $\sigma, \tau, \sigma \tau$. Obviously they form a partition. Hence, the Jacobian of $\mathcal{X}$ is the product

$$
\operatorname{Jac}^{2}(\mathcal{X}) \cong E_{1}^{2} \times E_{2}^{2} \times E_{3}^{2}
$$

of three elliptic curves. By applying the Poincare duality we get

$$
\operatorname{Jac}(\mathcal{X}) \cong E_{1} \times E_{2} \times E_{3}
$$

3.1.3. The dihedral group $D_{8}$. In this case, we have 5 involutions in $G$ in 3 conjugacy classes. No conjugacy class has three involutions. Hence, we can pick three involutions such that two of them are conjugate to each other in $G$ and all three of them generate $V_{4}$. Hence, $\operatorname{Jac}(\mathcal{X}) \cong E_{1}^{2} \times E_{2}$, for some elliptic curves $E_{1}, E_{2}$.
3.1.4. The symmetric group $S_{4}$. The Jacobian of such curves splits into a product of elliptic curves since $V_{4} \hookrightarrow S_{4}$. Below we give a direct proof of this.

We know that there are 9 involutions in $S_{4}$, six of which are transpositions. The other three are product of two 2 -cycles and we denote them by $\sigma_{1}, \sigma_{2}, \sigma_{3}$. Let $H_{1}, H_{2}, H_{3}$ denote the subgroups generated by $\sigma_{1}, \sigma_{2}, \sigma_{3}$. They generate $V_{4}$ and are all isomorphic in $G$. Hence, $\operatorname{Jac}(\mathcal{X}) \cong E^{3}$, for some elliptic curve $E$.
3.1.5. The symmetric group $S_{3}$. We know from above that the Jacobian is a direct product of three elliptic curves. Here we will show that two of those elliptic curves are isomorphic. Let $H_{1}, H_{2}, H_{3}$ be the subgroups generated by transpositions and $H_{4}$ the subgroup of order 3. Then

$$
\operatorname{Jac}^{3}(\mathcal{X}) \cong E_{1}^{2} \times E_{2}^{2} \times E_{3}^{2} \times \operatorname{Jac}^{3}(\mathcal{Y})
$$

for three elliptic curves $E_{1}, E_{2}, E_{3}$ fixed by involutions and a curve $\mathcal{Y}$ fixed by the element of order 3. Simply by counting the dimensions we have $\mathcal{Y}$ to be another elliptic curve $E_{4}$. Since all the transpositions of $S_{3}$ are in the same conjugacy class
then $E_{1}, E_{2}, E_{3}$ are isomorphic. Then by applying the Poincare duality we have that

$$
\operatorname{Jac}(X) \cong E^{2} \times E^{\prime}
$$

Summarizing, we have the following:
Theorem 3. Let $\mathcal{X}$ be a genus 3 curve and $G$ its automorphism group. Then, a) If $\mathcal{X}$ is hyperelliptic, then the following hold:
i) If $G$ is isomorphic to $V_{4}$ or $C_{2} \times C_{4}$, then $J a c(X)$ is isogenous to the product of and elliptic curve $E$ and the Jacobian of a genus 2 curve $\mathcal{X}_{2}$,

$$
\operatorname{Jac}(\mathcal{X}) \cong E \times J a c\left(\mathcal{X}_{2}\right)
$$

ii) If $G$ is isomorphic to $C_{2}^{3}$ then $J a c(X)$ is isogenous to the product of three elliptic curves,

$$
\operatorname{Jac}(\mathcal{X}) \cong E_{1} \times E_{2} \times E_{3} .
$$

iii) If $G$ is isomorphic to $D_{12}, C_{2} \times S_{4}$ or any of the groups of order 24 or 32, then Jac ( $X$ ) is isogenous to the product of three elliptic curve such that two of them are isomorphic

$$
\operatorname{Jac}(\mathcal{X}) \cong E_{1}^{2} \times E_{2}
$$

b) If $\mathcal{X}$ is non-hyperelliptic then the following hold:
i) If $G$ is isomorphic to $C_{2}$ then Jac $(X)$ is isogenous to the product of an elliptic curve and the Jacobian of some genus 2 curve $\mathcal{X}_{2}$

$$
J a c(\mathcal{X}) \cong E \times J a c\left(\mathcal{X}_{2}\right)
$$

ii) If $G$ is isomorphic to $V_{4}$ then $\operatorname{Jac}(X)$ is isogenous to the product of three elliptic curves

$$
\operatorname{Jac}(\mathcal{X}) \cong E_{1} \times E_{2} \times E_{3}
$$

iii) If $G$ is isomorphic to $S_{3}, D_{8}$ or has order 16 or 48 then Jac $(X)$ is isogenous to the product of three elliptic curves such that two of them are isomorphic to each other

$$
J a c(\mathcal{X}) \cong E_{1}^{2} \times E_{2}
$$

iv) If $G$ is isomorphic to $S_{4}, L_{3}(2)$ or $C_{2}^{3} \rtimes S_{3}$ then Jac $(X)$ is isogenous to the product of three elliptic curves such that all three of them are isomorphic to each other

$$
J a c(\mathcal{X}) \cong E^{3}
$$

Proof. The proof of the hyperelliptic case is similar and we skip the details. The reader interested in details can check [16].

Part b): When $G$ is isomorphic to $C_{2}, V_{4}, D_{8}, S_{4}, S_{3}$ the result follows from the remarks above. The rest of the theorem is an immediate consequence of the list of groups as in the Table 1 of [10]. If $|G|=16,48$ then $D_{8} \hookrightarrow G$. Then, from the remarks at the beginning of this section the results follows. If $G$ is isomorphic to $L_{3}(2)$ or $C_{4}^{2} \rtimes S_{3}$ then $S_{4} \hookrightarrow G$. Hence the Jacobian splits as in the case of $S_{4}$. This completes the proof.

It is possible that given the equation of $\mathcal{X}$ one can determine the equations of the elliptic or genus 2 components in all cases of the theorem.

The reader interested in decomposition of Jacobians of curves with large automorphism group can check [11], where an algorithm is provided. Indeed, the method suggested in [11] works for all curves $C$ which have an element $\tau \in \operatorname{Aut}(C)$ such that $C /\langle\tau\rangle$ has genus 0 . This includes all superelliptic curves. The automorphism
groups of such curves (including positive characteristic) were determined in [17] and their equations in [18].

The above theorem gives the splitting of the Jacobian based on automorphisms. Next we will focus on the $(2,4,4)$ splitting for hyperelliptic curves. We will explicitly determine the elliptic components for a given genus 3 curve $\mathcal{X}$.

## 4. Subcovers of genus 2

Next we study in detail the complement $C$ of $E$ in $\operatorname{Jac}(\mathcal{X})$. From the above theorem, $C$ has equation as in Eq. (2.5). Its absolute invariants $i_{1}, i_{2}, i_{3}$, as defined in [33], can be expressed in terms of the dihedral invariants $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ as follows:

$$
\begin{align*}
i_{1}= & 144 \frac{M}{D^{2}}\left(2 \mathfrak{s}_{2}{ }^{4}+2 \mathfrak{s}_{2}{ }^{3}-6 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}+\mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}-40 \mathfrak{s}_{2}{ }^{2}+\mathfrak{s}_{2} \mathfrak{s}_{4}+9 \mathfrak{s}_{3}{ }^{2}-3 \mathfrak{s}_{3} s_{4}-20 \mathfrak{s}_{4}\right)  \tag{4.1}\\
i_{2}= & 432 \frac{M^{2}}{D^{3}}\left(8 \mathfrak{s}_{2}{ }^{5}+12 \mathfrak{s}_{2}{ }^{4}-36 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}+4 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}+1248 \mathfrak{s}_{2}{ }^{3}-558 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}+114 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}\right. \\
& \left.+81, \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{2}-18 \mathfrak{s}_{2} \mathfrak{s}_{3} \mathfrak{s}_{4}-2240 \mathfrak{s}_{2}{ }^{2}+624 \mathfrak{s}_{2} \mathfrak{s}_{4}+216 \mathfrak{s}_{3}{ }^{2}-279 \mathfrak{s}_{3} \mathfrak{s}_{4}+54 \mathfrak{s}_{4}{ }^{2}-1120 \mathfrak{s}_{4}\right) \\
i 3= & \frac{243}{16} \frac{M^{3}}{D^{5}}\left(16 \mathfrak{s s}_{2}{ }^{7}+24 \mathfrak{s}_{2}{ }^{6}-72 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}+16 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{4}-2 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{2}+768 \mathfrak{s}_{2}{ }^{5}-576 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}\right. \\
& +132 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{4}+160 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{2}-72 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3} \mathfrak{s}_{4}+4 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}{ }^{2}+8 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{3}-\mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-1024 \mathfrak{s}_{2}{ }^{4} \\
& +768 \mathfrak{s}_{2}{ }_{5} \mathfrak{s}_{4}+256 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2}-576 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3} \mathfrak{s}_{4}+114 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}{ }^{2}+80 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-18 \mathfrak{s}_{2} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{2}-16 s_{3}{ }^{4} \\
& \left.+4 \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}-1024 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}+192 \mathfrak{s}_{2} \mathfrak{s}_{4}{ }^{2}+128 \mathfrak{s}_{3}{ }_{5} \mathfrak{s}_{4}-144 \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{2}+27 \mathfrak{s}_{4}{ }^{3}-256 \mathfrak{s}_{4}{ }^{2}\right)
\end{align*}
$$

where $M=\mathfrak{s}_{4}+2 \mathfrak{s}_{2}^{2}$ and $D=16 s_{2}^{3}-40 s_{2}^{2}+8 s_{2} s_{4}-3 s_{3}^{2}-20 s_{4}$. For the rest of the paper we assume that $D=J_{2} \neq 0$.

We are interested in the case when the Jacobian of $C$ splits. Splitting of such Jacobians of genus 2 has been studied in our previous work at [22,33]. We only consider the case when $\mathrm{Jac}(C)$ is $(2,2)$ decomposable. The locus $\mathcal{L}_{2}$ of such genus two curves is computed in [33] in terms of the invariants $i_{1}, i_{2}, i_{3}$. Substituting the expressions in Eq. (4.1) in the equation of $\mathcal{L}_{2}$ from [33] we have the following:

$$
\begin{equation*}
\left(2 \mathfrak{s}_{2}^{2}-\mathfrak{s}_{4}\right) \cdot\left(2 \mathfrak{s}_{2}^{2}+\mathfrak{s}_{4}\right) \cdot F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0 \tag{4.2}
\end{equation*}
$$

where $F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ is an irreducible polynomial of degree $13,8,6$ in given in $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ respectively. The expression of $F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ is given in the Appendix.

Let the locus of genus 3 hyperelliptic curves whose Jacobian is $(2,4,4)$-split be denoted by $\mathcal{T}$. There are three components of $\mathcal{T}$ which we denote them by $\mathcal{T}_{i}$, $i=1,2,3$ as seen by Eq. (4.2).

Two of these components are well known and the correspond to the cases when $V_{4}$ is embedded in the reduced automorphism group of $\mathcal{X}$. These cases correspond to the singular locus of $\mathcal{S}_{2}$ and are precisely the locus $\operatorname{det}(\operatorname{Jac}(\phi))=0$, see [24]. This happens for all genus $g \geq 2$ as noted by Geyer [8], Shaska/Völklein [33], and shown in [24].

Lemma 2. Let $\mathcal{X}$ be a genus 3 curve with (2,2,4)-split Jacobian. Then, one of the following occurs
i) $\mathbb{Z}_{2}^{3} \hookrightarrow \operatorname{Aut}(\mathcal{X})$
ii) $\mathbb{Z}_{2} \times \mathbb{Z}_{4} \hookrightarrow$ Aut (X)
iii) $\mathcal{X}$ is in the locus $\mathcal{T}_{3}$

Proof. The proof is an immediate consequence of Theorem 2 and Eq. (4.2).
The third component $\mathcal{T}_{3}$ is more interesting to us. It is the moduli space of pairs of degree 4 non-Galois covers $\psi_{i}: \mathcal{X}_{3} \rightarrow E_{i}, i=1,2$.

One of the main goals of this paper is to determine explicitly the family $\mathcal{T}_{3}$ of genus 3 curves and relations among its elliptic subcovers. We have the maps

$$
\begin{align*}
\mathcal{T}_{3} & \xrightarrow{\psi} \mathcal{L}_{2} \xrightarrow{\psi_{0}} k^{2} \\
\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) & \rightarrow(u, v) \rightarrow\left(j_{1}, j_{2}\right) \tag{4.3}
\end{align*}
$$

where $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ satisfy $F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0$ and $u, v$ are given explicitly by Eq. (4.1) and Thm. (3) in [33].

The expressions of $u$ and $v$ are computed explicitly in terms of $\mathfrak{s}_{2}, \mathfrak{F}_{3}, \mathfrak{s}_{4}$ by substituting the expressions of Eq. (4.1) expressions for $u$ and $v$ as rational functions of $i_{1}, i_{2} i_{3}$ as computed in Shaska/Völklein [33]. As rational functions $u$ and $v$ have degrees 35 and 70 respectively (in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ ). The $j$-invariants $j_{1}$ and $j_{2}$ will be determined in the next section.

Since $\mathcal{T}_{3}$ is a subvariety of $\mathcal{H}_{3}$ it would be desirable to express its equation in terms of a coordinate in $\mathcal{H}_{3}$. One can use the absolute invariants of the genus 3 hyperelliptic curves $t_{1}, \ldots, t_{6}$ as defined in [20] and the expressions of $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ in terms of these invariants as computed in [21].
Remark 2. $\mathcal{T}_{3}$ is a 2-dimensional subvariety of $\mathcal{H}_{3}$ determined by the equations

$$
\left\{\begin{array}{r}
F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0  \tag{4.4}\\
t_{i}-T_{i}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right), \quad i=1, \ldots, 6
\end{array}\right.
$$

where $T_{i}$ is the function $t_{i}$ evaluated for the triple $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$.
The equations of $\mathcal{T}_{3}$ can be explicitly determined in terms of $t_{1}, \ldots, t_{6}$ by eliminating $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ from the above equations. Normally, when we talk about $\mathcal{T}_{3}$ we will think of it given in terms of $t_{1}, \ldots, t_{6}$.
Example 1 (Automorphism group $\mathbb{Z}_{2}^{3}$ ). Consider the genus 3 curves $\mathcal{X}$ with Aut $(\mathcal{X}) \cong \mathbb{Z}_{2}^{3}$. Then, $\mathfrak{s}_{4}=2 s_{2}^{2}$ and

$$
\begin{aligned}
u= & \frac{1}{P}\left(-9 s_{3}^{2}+120 s_{2} s_{3}-400 s_{2}^{2}+16 s_{2}^{3}\right) \\
v= & -\frac{2}{P^{2}}\left(432 s_{2} s_{3}{ }^{3}-27 s_{3}{ }^{4}-1440 s_{2}^{2} s_{3}^{2}-6400 s_{2}^{3} s_{3}+32000 s_{2}^{4}+288 s_{2}^{3} s_{3}^{2}\right. \\
& \left.-5376 s_{2}{ }^{4} s_{3}+23040 s_{2}{ }^{5}+256 s_{2}{ }^{6}\right)
\end{aligned}
$$

where $P=-s_{3}^{2}-8 s_{2} s_{3}-16 s_{2}^{2}+16 s_{2}^{3}$.
For the rest of this section we will see if we can invert the map $\psi$. Given an ordered pair $(u, v) \in \mathcal{L}_{2}$ there is a unique genus two curve corresponding to this pair. Indeed, an explicit equation can be found in terms of $u$ and $v$ from the following.
Proposition 1. Let $(u, v) \in k^{2}$ such that

$$
\left(u^{2}-4 v+18 u-27\right)\left(v^{2}-4 u^{3}\right)\left(4 v-u^{2}+110 u-1125\right) \neq 0 .
$$

Then, the curve of genus 2 defined over $k$ given by

$$
\begin{equation*}
y^{2}=a_{0} x^{6}+a_{1} x^{5}+a_{2} x^{4}+a_{3} x^{3}+t a_{2} x^{2}+t^{2} a_{1} x+t^{3} a_{0}, \tag{4.5}
\end{equation*}
$$

corresponds to the moduli point $(u, v) \in \mathcal{L}_{2} \hookrightarrow \mathcal{M}_{2}$, where one of the following holds:
i) If $u \neq 0$, then

$$
\begin{aligned}
t & =v^{2}-4 u^{3}, \\
a_{0} & =v^{2}+u^{2} v-2 u^{3}, \\
a_{1} & =2\left(u^{2}+3 v\right)\left(v^{2}-4 u^{3}\right), \\
a_{2} & =\left(15 v^{2}-u^{2} v-30 u^{3}\right)\left(v^{2}-4 u^{3}\right), \\
a_{3} & =4\left(5 v-u^{2}\right)\left(v^{2}-4 u^{3}\right)^{2},
\end{aligned}
$$

ii) If $u=0$, then

$$
t=1, a_{0}=1+2 v, a_{1}=2(3-4 v), a_{2}=15+14 v, a_{3}=4(5-4 v)
$$

A proof of this is provided in [32] together with other computational aspects of genus 2 curves.

Hence, corresponding to the pair $(u, v)$ there is a unique genus 2 curve $C_{u, v}$. The following Lemma addresses the rest of our question.

Lemma 3. i) Any genus two curve $C$ defined over an algebraically closed field $k$ can be written as

$$
\begin{equation*}
y^{2}=x\left(x^{4}+a x^{3}+b x^{2}+c x+1\right) \tag{4.6}
\end{equation*}
$$

for some $a, b, c \in k$ such that

$$
\begin{aligned}
\Delta(a, b, c)= & 256-192 c a-6 c^{2} a^{2}-4 c^{3} a^{3}-27 c^{4}-27 a^{4}-80 b^{2} c a-128 b^{2} \\
& +18 b c a^{3}+18 c^{3} a b+144 b a^{2}+144 c^{2} b+c^{2} b^{2} a^{2}-4 b^{3} a^{2}-4 c^{2} b^{3}+16 b^{4} \neq 0
\end{aligned}
$$

ii) Let $C$ be a genus 2 curve with equation as in Eq. (4.6). Then, there exists a genus 3 curve $\mathcal{X}$ with equation

$$
Y^{2}=X^{8}+a X^{6}+b X^{4}+C X^{2}+1
$$

and a degree 2 map $f: \mathcal{X} \rightarrow C$ such that

$$
x=X^{2} \quad \text { and } \quad y=Y X
$$

Proof. i) Let $C$ be a genus 2 curve defined over $k$. Then, the equation of $C$ is given by

$$
y^{2}=\Pi_{i=1}^{6}\left(x-\alpha_{i}\right)
$$

where $\alpha_{i}$ are all distinct for all $i=1 \ldots 6$. Since $k$ is algebraically closed, then we can pick a change of transformation in $\mathbb{P}^{1}(k)$ such that $\alpha_{1} \rightarrow 0$ and $\alpha_{2} \rightarrow \infty$. We can also pick a coordinate such that $\alpha_{3} \cdots a_{6}=1$. Then, the curve $C$ as equation as claimed. The condition that $\Delta(a, b, c) \neq 0$ simply assures that not two roots of the sextic coalesce.
ii) This genus 3 curve is a covering of $C$ from Thm. 1 .

Hence, the curve $C_{u, v}$ can be written as in Eq. (4.6). This would mean that we can explicitly compute $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ in terms of $u$ and $v$. Finding a general formula for $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ in terms of $(u, v)$ is computationally difficult. Under some additional restrictions this ca be done, as we will see in the next section.

## 5. Elliptic subfields

In this section we will determine the elliptic subcovers of the genus 3 curves $\mathcal{X} \in \mathcal{T}_{3}$. We will describe how this can be explicitly done, but will skip displaying the computations here.

A point $\mathfrak{p}=\left(t_{1}, \ldots, t_{6}\right) \in \mathcal{T}_{3}$ satisfies equations Eq. (4.4). Our goal is to determine the $j$-invariants of $E, E_{1}, E_{2}$ in terms of $t_{1}, \ldots t_{6}$. The $j$-invariant of $E$ is

$$
\begin{align*}
j= & 256 \frac{\left(-\mathfrak{s}_{3}{ }^{2}-12 \mathfrak{s}_{4}-24 \mathfrak{s}_{2}{ }^{2}+3 \mathfrak{s}_{2} \mathfrak{s}_{4}+6 \mathfrak{s}_{2}{ }^{3}\right)^{3}}{\left(\mathfrak{s}_{4}+2 \mathfrak{s}_{2}{ }^{2}\right)}\left(4 \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}-256 \mathfrak{s}_{4}{ }^{2}-1024 \mathfrak{s}_{2}{ }^{4}\right.  \tag{5.1}\\
& -72 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}-144 \mathfrak{s}_{4}{ }^{2} \mathfrak{s}_{3}+8 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{3}-576 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}+114 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}{ }^{2}+132 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{4}-2 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{2} \\
& +160 \mathfrak{s}_{2}{ }_{5}{ }_{5}{ }^{2}+4 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}{ }^{2}+16 \mathfrak{s}_{2} \mathfrak{s}_{4}-16 \mathfrak{s}_{3}{ }^{4}+192 \mathfrak{s}_{2} \mathfrak{s}_{4}{ }^{2}+128 \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-1024 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4} \\
& +768 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}+24 \mathfrak{s}_{2}{ }^{6}+16 \mathfrak{s}_{2}{ }^{7}+27 \mathfrak{s}_{4}^{3}+768 \mathfrak{s}_{2}{ }^{5}-18 \mathfrak{s}_{2} \mathfrak{s}_{4}{ }^{2} \mathfrak{s}_{3}-72 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4} \mathfrak{s}_{3} \\
& \left.-576 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3} \mathfrak{s}_{4}-\mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}+80 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}+256 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2}\right)
\end{align*}
$$

We denote the degree 2 elliptic subcovers of $C$ by $E_{1}$ and $E_{2}$ and their $j$-invariants by $j_{1}$ and $j_{2}$. These $j$ invariants are the roots of the quadratic

$$
\begin{equation*}
j^{2}+256 \frac{2 u^{3}-54 u^{2}+9 u v-v^{2}+27 v}{u^{2}+18 u-4 v-27} j+65536 \frac{u^{2}+9 u-3 v}{\left(u^{2}+18 u-4 v-27\right)^{2}} \tag{5.2}
\end{equation*}
$$

see Eq. (4) in [33].


Figure 2. A genus 3 curve $\mathcal{X}$ with its three elliptic subcovers

Since these $j$-invariants are determined explicitly in terms of $u$ and $v$, then via the map $\psi: \mathcal{T}_{3} \rightarrow \mathcal{L}_{2}$ we express such coefficients in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$. Moreover, the maps

$$
\begin{align*}
& \mathcal{T}_{3} \rightarrow k^{3} \backslash\left\{\Delta\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0\right\} \rightarrow k^{2} \backslash\left\{\Delta_{u, v}=0\right\} \rightarrow k^{2} \\
& \left(t_{1}, \ldots, t_{6}\right) \rightarrow\left(\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}\right) \xrightarrow{\psi}(u, v) \rightarrow\left(j_{1}, j_{2}\right) \tag{5.3}
\end{align*}
$$

are all explicitly determined.
Remark 3. Given a tuple $\left(t_{1}, \ldots, t_{6}\right)$ which satisfies the equations of $\mathcal{T}_{3}$ does not necessarily represent a genus 3 hyperelliptic curve. We have to check that such tuple satisfies the equation of the genus 3 hyperelliptic moduli, as described in [20].

Example 2. Let be given a 6-tuple

$$
\left(t_{1}, \ldots, t_{6}\right)=\left(\frac{8767521}{6224272}, \frac{152464}{5329}, \frac{8116}{3431},-\frac{3343532}{695617},-\frac{91532}{148117},-\frac{50448727768}{28398241}\right)
$$

which satisfies the Eq. (17) in [20]. Then, this tuple correspond to a genus 3 hyperelliptic curve, more precisely the curve $\mathcal{X}$ with equation

$$
Y^{2}=X^{8}+X^{6}+X^{4}+X^{2}+1
$$

Then, the corresponding invariants are

$$
\mathfrak{s}_{2}=1, \quad \mathfrak{s}_{3}=2, \quad s_{4}=2
$$

The genus 2 subcover has invariants

$$
i_{1}=-\frac{48}{5}, \quad i_{2}=\frac{432}{5}, \quad i_{3}=\frac{1}{400}
$$

and the corresponding dihedral invariants $u$ and $v$ are

$$
u=9, \quad v=-\frac{754}{5}
$$

The $j$-invariants of the three elliptic subcover are

$$
j=2048, \quad j_{1}=\frac{32768}{5}+\frac{2}{5} \sqrt{268435081}, \quad j_{2}=\frac{32768}{5}-\frac{2}{5} \sqrt{268435081}
$$

Next we will study a very special subvariety of $\mathcal{T}_{3}$, such as the locus of curves in $\mathcal{T}_{3}$ when $E_{1}$ is isomorphic to $E_{2}$.
5.1. Isomorphic elliptic subfields. The two elliptic curves $E_{1}$ and $E_{2}$ are isomorphic when their $j$-invariants are equal, which happens when the discriminant of the quadratic in Eq. (5.2) is zero. From Remark (1) in [33] this occurs if and only if

$$
\left(v^{2}-4 u^{3}\right)(v-9 u+27)=0
$$

The first condition is equivalent to $D_{8} \hookrightarrow A u t(C)$. The later condition gives

$$
u=9-\frac{\lambda}{256}, \quad \text { and } \quad v=9\left(6-\frac{\lambda}{256}\right)
$$

where $\lambda:=j_{1}=j_{2}$. Both of these loci can be explicitly computed given enough computing power.

Substituting $u$ and $v$ in terms of $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ in the equation

$$
v-9 u+27=0
$$

we get an equation of degree 68,42 , and 29 in $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ respectively. We denote it by

$$
\begin{equation*}
F_{2}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0 \tag{5.4}
\end{equation*}
$$

and do not display it here because of its size. This equation and the Eq. (4.2) define the locus $\mathfrak{T}$ in terms of $\mathfrak{s}_{4}, \mathfrak{F}_{3}, \mathfrak{s}_{2}$.

Let $\mathfrak{T}$ denote the algebraic variety defined by by the equations

$$
\left\{\begin{array}{l}
F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0  \tag{5.5}\\
F_{2}\left(\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}\right)=0
\end{array}\right.
$$

Lemma 4. The algebraic variety $\mathfrak{T}$ is a 1-dimensional subvariety, it has 5 genus 0 components as in Eq. (5.6). Every point $\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right) \in \mathfrak{T}$ correspond to a genus 3 hyperelliptic curve with $(2,4,4)$-split Jacobian such that the degree 4 elliptic subcovers are isomorphic to each other.

Proof. From the equations above we can eliminate $\mathfrak{s}_{3}$ via resultants and get the following. In this case we get

$$
\left(2 \mathfrak{s}_{2}^{2}-\mathfrak{s}_{4}\right)^{16}\left(\mathfrak{s}_{4}+2 \mathfrak{s}_{2}^{2}\right)^{172} g_{1}^{12} g_{2}^{12} g_{3}^{10} g_{4}^{8} g_{5}=0
$$

where
(5.6)

$$
\begin{aligned}
& g_{1}=s_{4}+2 s_{2}^{2}-100 s_{2}+625 \\
& g_{2}=-27 s_{4}+s_{2}{ }^{3}+6 s_{2}{ }^{2}+768 s_{2}-4096 \\
& g_{3}=-16777216+5242880 s_{2}-450560 s_{2}{ }^{2}+7680 s_{2}{ }^{3}-340 s_{2}{ }^{4}+8 s_{2}{ }^{5}-102400 s_{4} \\
& +16640 s_{2} s_{4}-220 s_{2}{ }^{2} s_{4}+4 s_{4} s_{2}{ }^{3}-125 s_{4}{ }^{2} \\
& g_{4}=3515625-937500 s_{2}+62500 s_{2}^{2}+64 s_{2}{ }^{4}+15000 s_{4}-2000 s_{2} s_{4} \\
& g_{5}=35153041-16173862 s_{4}+2926323 s_{4}{ }^{2}+131244344 s_{2}-11788512 s_{2}{ }^{4}+133698380 s_{2}{ }^{2} \\
& +41050 s_{4}{ }^{3}+1792 s_{2}{ }^{7}+22764 s_{4}{ }^{2} s_{2}{ }^{3}-21768 s_{2}{ }^{5} s_{4}+136952 s_{2}{ }^{6}-134208 s_{2}{ }^{5} \\
& +16762008 s_{2}{ }^{3}-57934 s_{2}{ }^{2} s_{4}{ }^{2}-111744 s_{4} s_{2}{ }^{4}-1040380 s_{2} s_{4}{ }^{2}+1987608 s_{4} s_{2}{ }^{3}+2559786 s_{2}{ }^{2} s_{4} \\
& -27622208 s_{2} s_{4}-16 s_{2}{ }^{7} s_{4}-316 s_{2}{ }^{6} s_{4}+16 s_{2}{ }^{5} s_{4}{ }^{2}-4 s_{2}{ }^{3} s_{4}{ }^{3}-530 s_{2}{ }^{2} s_{4}{ }^{3}-6180 s_{2} s_{4}{ }^{3} \\
& +685 s_{2}{ }^{4} s_{4}{ }^{2}+132 s_{2}{ }^{8}+125 s_{4}{ }^{4}
\end{aligned}
$$

We have $\left(2 \mathfrak{s}_{4}-\mathfrak{s}_{2}^{2}\right)\left(2 \mathfrak{s}_{4}+\mathfrak{s}_{2}^{2}\right) \neq 0$, as noted before. All other components are genus zero curves.

Remark 4. The equation of $\mathfrak{T}$ can be expressed in the absolute invariants $t_{1}, \ldots, t_{6}$ by eliminating $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ from expressions in Eq. (4.1). Such expressions are large and we do not display them here.

Let be given a parameterization of $\mathfrak{T}$. Then we have the following maps

$$
\begin{align*}
k \rightarrow \mathfrak{T} & \rightarrow L_{2} \rightarrow k \\
t \rightarrow\left(\mathfrak{s}_{4}(t), \mathfrak{s}_{3}(t), \mathfrak{s}_{2}(t)\right) & \rightarrow(u(t), v(t)) \rightarrow j(t) \tag{5.7}
\end{align*}
$$

This map gives us the possibility to construct a family of curves defined over $\mathbb{Q}$ such that all their subcovers, namely $C, E, E_{1}$, and $E_{2}$ are also defined over $\mathbb{Q}$. For example, for $t \in \mathbb{Q}$ we have the corresponding $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{3} \in \mathbb{Q}$. Hence, there is a genus 3 curve $\mathcal{X}$ defined over $\mathbb{Q}$. The invariants $u, v$ are rational functions of $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ and therefore of $t$. Thus, $u, v \in \mathbb{Q}$. Form Prop. 1 there a genus 2 curve $C$ such that $C$ is defined over $\mathbb{Q}$. Moreover, the $j$-invariants for all elliptic subcovers are rational functions in $\mathfrak{s}_{4}, \mathfrak{s}_{3}, \mathfrak{s}_{2}$ and therefore in $t$. Hence, $E, E_{1}, E_{2}$ are also defined over $\mathbb{Q}$.

Theorem 4. Let $\mathcal{X}$ be a curve in $\mathfrak{T}$ and $\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}$ its corresponding dihedral invariants. Then

$$
\operatorname{Jac}(\mathcal{X}) \cong E \times E^{\prime} \times E^{\prime}
$$

where $E$ and $E^{\prime}$ are elliptic curves with $j$-invariants $j(E)$ as in $E q$. (5.1) and $j\left(E^{\prime}\right)$ as

$$
j^{\prime}=-128 \frac{2 u^{3}-54 u^{2}+9 u v-v^{2}+27 v}{u^{2}+18 u-4 v-27}
$$

where $u$ and $v$ are given as rational functions of $i_{1}, i_{2}, i_{3}$ as in [33]. Moreover, there is only a finite number of genus 3 curves $\mathcal{X}$ such that $E \cong E^{\prime}$.

Proof. The equation of $j(E)$ was computed in Eq. (5.1). Since the other two elliptic subcovers have the same $j$-invariants then this invariant is given by the double root of the quadratic in Eq. (5.2). Thus,

$$
j^{\prime}=-128 \frac{2 u^{3}-54 u^{2}+9 u v-v^{2}+27 v}{u^{2}+18 u-4 v-27}
$$

Substituting the values for $u$ and $v$ we get the expression as claimed.
We have $E \cong E^{\prime}$ if and only if $j=j^{\prime}$. This gives a third equation $G\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0$ as claimed in the theorem. By Bezut's theorem, the number of solutions of the system of equations $F_{i}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0$, for $i=1,2$ and $G\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)=0$ is finite.

The family above could be significant in number theory in constructing genus 3 curves with many rational points. Similar techniques have been used for genus 2 in [26] and by various other authors.

## Appendix

The polynomial $F_{1}\left(\mathfrak{s}_{2}, \mathfrak{s}_{3}, \mathfrak{s}_{4}\right)$ from Eq. (4.2).

$$
\begin{aligned}
& F_{1}\left(\mathfrak{s}_{2}, \mathfrak{F}_{3} \mathfrak{s}_{4}\right)=1024 \mathfrak{s}_{2}{ }^{13}-256 \mathfrak{s}_{2}{ }^{12} \mathfrak{s}_{3}+1536 \mathfrak{s}_{2}{ }^{12}-8448 \mathfrak{s}_{2}{ }^{11} \mathfrak{s}_{3}+2560 \mathfrak{s}_{2}{ }^{11} \mathfrak{s}_{4}+1664 \mathfrak{s}_{2}{ }^{10} \mathfrak{s}_{3}{ }^{2} \\
& -512 \mathfrak{s}_{2}{ }^{10} \mathfrak{s}_{3} \mathfrak{s}_{4}+64 \mathfrak{s}_{2}{ }^{9} \mathfrak{s}_{3}{ }^{3}+33600 \mathfrak{s}_{2}{ }^{11}-48720 \mathfrak{s}_{2}{ }^{10} \mathfrak{s}_{3}+10752 \mathfrak{s}_{2}{ }^{10} \mathfrak{s}_{4}+37696 \mathfrak{s}_{2}{ }^{9} \mathfrak{s}_{3}{ }^{2} \\
& -20928 \mathfrak{s}_{2}{ }^{9} \mathfrak{s}_{3} \mathfrak{s}_{4}+2560 \mathfrak{s}_{2}{ }^{9} \mathfrak{s}_{4}{ }^{2}-4448 \mathfrak{s}_{2}{ }^{8}{ }_{\mathfrak{S}_{3}}{ }^{3}+3008 \mathfrak{s}_{2}{ }^{8} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-384 \mathfrak{s}_{2}{ }^{8} \mathfrak{S}_{3} \mathfrak{s}_{4}{ }^{2}-432 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3}{ }^{4} \\
& +96 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}-4 \mathfrak{s}_{2}{ }^{6} \mathfrak{S}_{3}{ }^{5}+20000 \mathfrak{s}_{2}{ }^{10}-140000 \mathfrak{s}_{2}{ }^{9} \mathfrak{s}_{3}+84000 \mathfrak{s}_{2}{ }^{9} \mathfrak{S}_{4}+172600 \mathfrak{s}_{2}{ }^{8} \mathfrak{s}_{3}{ }^{2} \\
& -139200 \mathfrak{s}_{2}{ }^{8} \mathfrak{S}_{3} \mathfrak{s}_{4}+21120 \mathfrak{s}_{2}{ }^{8} \mathfrak{S}_{4}{ }^{2}-71680 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3}{ }^{3}+78368 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3}{ }^{2} \mathfrak{S}_{4}-20736 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{2} \\
& +1280 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{4}{ }^{3}+2288 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3}{ }^{4}-6200 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}+2016 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{2}-128 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{3}+1256 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{5} \\
& -568 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}+48 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{2}+26 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{6}-4 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4}+50000 \mathfrak{s}_{2}{ }^{8} \mathfrak{s}_{4}+80000 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3}{ }^{2} \\
& -280000 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{3} \mathfrak{s}_{4}+84000 \mathfrak{s}_{2}{ }^{7} \mathfrak{s}_{4}{ }^{2}-140000 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3}{ }^{3}+345500 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-156600 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{2} \\
& +19200 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{4}{ }^{3}+30000 \mathfrak{s}_{2}{ }^{5} \mathfrak{S}_{3}{ }^{4}-107520 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}+61008 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{2} \mathfrak{S}_{4}{ }^{2}-10272 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{3} \\
& +320 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{4}{ }^{4}+8060 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{5}-204 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}-2628 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{2}+592 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{3}-16 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{4} \\
& -1464 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{6}+1256 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4}-244 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{2}+8 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}{ }^{3}-72 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{7}+21 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{6} \mathfrak{S}_{4} \\
& -\mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4}{ }^{2}+50000 \mathfrak{s}_{2}{ }^{6} \mathfrak{s}_{4}{ }^{2}+120000 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}-210000 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{2}+42000 \mathfrak{s}_{2}{ }^{5} \mathfrak{s}_{4}{ }^{3}+40000 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{4} \\
& -210000 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}+259350 \mathfrak{s}_{2}{ }^{4} \mathfrak{S}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{2}-87000 \mathfrak{s}_{2}{ }^{4} \mathfrak{S}_{3} \mathfrak{s}_{4}{ }^{3}+9120 \mathfrak{s}_{2}{ }^{4} \mathfrak{S}_{4}{ }^{4}+30000 \mathfrak{s}_{2}{ }^{3} \mathfrak{S}_{3}{ }^{4} \mathfrak{S}_{4} \\
& -53760 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{2}+21080 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{3}-2544 \mathfrak{s}_{2}{ }^{3} \mathfrak{S}_{3} \mathfrak{s}_{4}{ }^{4}+32 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}{ }^{5}-3600 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{6}+8060 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4} \\
& -1920 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{2}-202 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{3}+64 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{4}-732 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{6} \mathfrak{s}_{4}+314 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4}{ }^{2}-34 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{3} \\
& +81 \mathfrak{s}_{3}{ }^{8}-36 \mathfrak{s}_{3}{ }^{7} \mathfrak{s}_{4}+4 \mathfrak{s}_{3}{ }^{6} \mathfrak{s}_{4}{ }^{2}+25000 \mathfrak{s}_{2}{ }^{4} \mathfrak{s}_{4}{ }^{3}+60000 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{2}-70000 \mathfrak{s}_{2}{ }^{3} \mathfrak{S}_{3} \mathfrak{s}_{4}{ }^{3}+10500 \mathfrak{s}_{2}{ }^{3} \mathfrak{s}_{4}{ }^{4} \\
& +40000 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}-105000 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{2}+86525 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{S}_{4}{ }^{3}-23925 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{4}+2208 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}{ }^{5} \\
& +7500 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{2}-8960 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}{ }^{3}+2728 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{4}-252 \mathfrak{s}_{2} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{5}-1800 \mathfrak{s}_{3}{ }^{6} \mathfrak{s}_{4}+2015 \mathfrak{s}_{3}{ }^{5} \mathfrak{s}_{4}{ }^{2} \\
& -623 \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{3}+59 \mathfrak{s}_{3}{ }^{3} \mathfrak{S}_{4}{ }^{4}+6250 \mathfrak{s}_{2}{ }^{2} \mathfrak{s}_{4}{ }^{4}+10000 \mathfrak{s}_{2} \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{3}-8750 \mathfrak{s}_{2} \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{4}+1050 \mathfrak{s}_{2} \mathfrak{s}_{4}{ }^{5}+10000 \mathfrak{s}_{3}{ }^{4} \mathfrak{s}_{4}{ }^{2} \\
& -17500 \mathfrak{s}_{3}{ }^{3} \mathfrak{s}_{4}{ }^{3}+10825 \mathfrak{s}_{3}{ }^{2} \mathfrak{s}_{4}{ }^{4}-2610 \mathfrak{s}_{3} \mathfrak{s}_{4}{ }^{5}+216 \mathfrak{s}_{4}{ }^{6}+625 \mathfrak{s}_{4}{ }^{5}
\end{aligned}
$$

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