

THE HESSE PENCIL OF PLANE CUBIC CURVES

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ABSTRACT. This is a survey of the classical geometry of the Hesse configuration of 12 lines in the projective plane related to inflection points of a plane cubic curve. We also study two K3 surfaces with Picard number 20 which arise naturally in connection with the configuration.

1. INTRODUCTION

In this paper we discuss some old and new results about the widely known *Hesse configuration* of 9 points and 12 lines in the projective plane $\mathbb{P}^2(k)$: each point lies on 4 lines and each line contains 3 points, giving an abstract configuration $(12_3, 9_4)$. Through most of the paper we will assume that k is the field of complex numbers \mathbb{C} although the configuration can be defined over any field containing three cubic roots of unity. The Hesse configuration can be realized by the 9 inflection points of a nonsingular projective plane curve of degree 3. This discovery is attributed to Colin Maclaurin (1698-1746) (see [44], p. 384), however the configuration is named after Otto Hesse who was the first to study its properties in [24], [25]¹. In particular, he proved that the nine inflection points of a plane cubic curve form one orbit with respect to the projective group of the plane and can be taken as common inflection points of a pencil of cubic curves generated by the curve and its Hessian curve. In appropriate projective coordinates the *Hesse pencil* is given by the equation

$$(1) \quad \lambda(x^3 + y^3 + z^3) + \mu xyz = 0.$$

The pencil was classically known as the *syzygetic pencil*² of cubic curves (see [9], p. 230 or [16], p. 274), the name attributed to L. Cremona. We do not know who is responsible for the renaming the pencil, but apparently the new terminology is widely accepted in modern literature (see, for example, [4]).

Recently Hesse pencils have become popular among number-theorists in connection with computational problems in arithmetic of elliptic curves (see, for example, [49]), and also among theoretical physicists, for example in connection with homological mirror symmetry for elliptic curves (see [54]).

The group of projective automorphisms which transform the Hesse pencil to itself is a group G_{216} of order 216 isomorphic to the group of affine transformations with determinant 1 of the plane over the field \mathbb{F}_3 . This group was discovered by C. Jordan in 1878 [30] who called it the *Hessian group*. Its invariants were described in 1889 by H. Maschke in [35]. A detailed historical account and the first figure of the Hesse pencil can be found in [21].

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¹Not to be confused with another Hesse's configuration $(12_4, 16_3)$, also related to plane cubic curves, see [15].

²The term "syzygy" originates in astronomy where three planets are in syzygy when they are in line. Sylvester used this word to express a linear relation between a form and its covariant. We will see later that the pencil contains the Hesse covariant of each of its members.

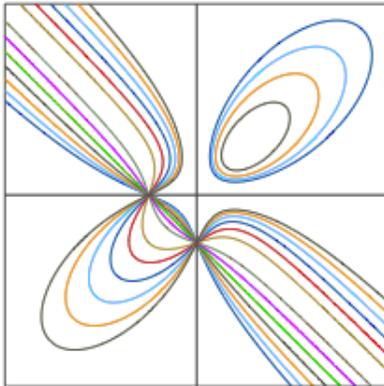


FIGURE 1. The Hesse pencil

The projective action of the Hessian group comes from a linear action of a complex reflection group \overline{G}_{216} of order 648 (n.25 in the Shephard-Todd list [46]) whose set of reflection hyperplanes consists of the 12 inflection lines of the Hesse configuration. The algebra of invariant polynomials of the group \overline{G}_{216} is freely generated by three polynomials of degrees 6, 9, 12 (see [35]). An invariant polynomial of degree 6 defines a nonsingular plane sextic curve C_6 . The double cover of the plane branched along the sextic curve C_6 is a K3 surface X on which G_{216} acts as a group of automorphisms. Its subgroup $H = \mathbb{F}_3^2 \rtimes Q_8$, where Q_8 is the Sylow 2-subgroup of $\mathrm{SL}(2, \mathbb{F}_3)$ isomorphic to the quaternion group of order 8, acts on the surface as a group of symplectic automorphisms. In fact, the group $\mathbb{F}_3^2 \rtimes Q_8$ can be found in Mukai's list [39] of finite groups which can be realized as a maximal finite group of symplectic automorphisms of a complex K3 surface.

The linear system of plane sextics with double points at 8 inflection points of a plane cubic is of projective dimension 3. The stabilizer H of the ninth remaining inflection point in G_{216} is isomorphic to $\mathrm{SL}(2, \mathbb{F}_3)$ and acts on this space by projective transformations. There is a unique invariant sextic C'_6 for this action, having cuspidal singularities at the inflection points. The double cover of the plane branched along C'_6 is birational to another K3 surface Y and the action of H can be lifted to Y . We show that Y is birationally isomorphic to the quotient of X by the subgroup \mathbb{F}_3^2 and the induced action of the quotient group $G_{216}/\mathbb{F}_3^2 \cong \mathrm{SL}(2, \mathbb{F}_3)$ coincides with the action of H on Y . Both K3 surfaces X and Y are singular in the sense of Shioda, i.e. the subgroup of algebraic cycles in the second cohomology group is of maximal possible rank equal to 20. We compute the intersection form defined by the cup-product on these subgroups.

The invariant sextic C_6 cuts out a set of 18 points on each nonsingular member of the pencil. We explain its geometric meaning, a result which we were unable to find in the classical literature.

It is a pleasure to thank Bert van Geemen who was kind to provide us with his informal notes on this topic and to make many useful comments on our manuscript. We are also indebted to Thierry Vust for his numerous suggestions for improving the exposition of the paper.

2. THE HESSE PENCIL

Let k be an algebraically closed field of characteristic different from 3 and E be a nonsingular cubic in the projective plane $\mathbb{P}^2(k)$ defined by a homogeneous equation $F(x, y, z) = 0$ of degree 3. The *Hessian curve* $\text{He}(E)$ of E is the plane cubic curve defined by the equation $\text{He}(F) = 0$, where $\text{He}(F)$ is the determinant of the matrix of the second partial derivatives of F . The nine points in $E \cap \text{He}(E)$ are the *inflection points* of E . Fixing one of the inflection points p_0 defines a commutative group law \oplus on E with p_0 equal to the zero: $p \oplus q$ is the unique point r such that p_0, r and the third point of intersection in $\overline{p, q} \cap E$ lie on a line. It follows from this definition of the group law that each inflection point is a 3-torsion point and that the group $E[3]$ of 3-torsion points on E is isomorphic to $(\mathbb{Z}/3\mathbb{Z})^2$. Any line $\overline{p, q}$ through two inflection points intersects E at another inflection point r such that p, q, r form a coset with respect to some subgroup of $E[3]$. Since we have 4 subgroups of order 3 in $(\mathbb{Z}/3\mathbb{Z})^2$ we find 12 lines, each containing 3 inflection points. They are called the *inflection lines* (or the *Maclaurin lines* [16]) of E . Since each element in $(\mathbb{Z}/3\mathbb{Z})^2$ is contained in 4 cosets, we see that each inflection point is contained in four inflection lines. This gives the famous *Hesse configuration* $(12_3, 9_4)$ of 12 lines and 9 points in the projective plane. It is easy to see that this configuration is independent of the choice of the point p_0 .

The *Hesse pencil* is the one-dimensional linear system of plane cubic curves given by

$$(2) \quad E_{t_0, t_1} : t_0(x^3 + y^3 + z^3) + t_1xyz = 0, \quad (t_0, t_1) \in \mathbb{P}^1.$$

We use the affine parameter $\lambda = t_1/t_0$ and denote $E_{1, \lambda}$ by E_λ ; the curve $xyz = 0$ is denoted by E_∞ . Since the pencil is generated by the Fermat cubic E_0 and its Hessian, its nine base points are in the Hesse configuration. In fact, they are the inflection points of any smooth curve in the pencil. In coordinates they are:

$$\begin{aligned} p_0 &= (0, 1, -1), \quad p_1 = (0, 1, -\epsilon), \quad p_2 = (0, 1, -\epsilon^2), \\ p_3 &= (1, 0, -1), \quad p_4 = (1, 0, -\epsilon^2), \quad p_5 = (1, 0, -\epsilon), \\ p_6 &= (1, -1, 0), \quad p_7 = (1, -\epsilon, 0), \quad p_8 = (1, -\epsilon^2, 0), \end{aligned}$$

where ϵ denotes a primitive third root of 1.

If we fix the group law by choosing the point p_0 to be the zero point, then the set of inflection points is the group of 3-torsion points of each member of the Hesse pencil. Hence we can define an isomorphism

$$\alpha : E_\lambda[3]_{p_0} \rightarrow (\mathbb{Z}/3\mathbb{Z})^2$$

by sending the point $p_1 = (0, 1, -\epsilon)$ to $(1, 0)$ and the point $p_3 = (1, 0, -1)$ to $(0, 1)$. Under this isomorphism we can identify the nine base points with elements of $(\mathbb{Z}/3\mathbb{Z})^2$ as follows

$$(3) \quad \begin{array}{cccccc} p_0 & p_1 & p_2 & (0, 0) & (1, 0) & (2, 0) \\ p_3 & p_4 & p_5 & (0, 1) & (1, 1) & (2, 1) \\ p_6 & p_7 & p_8 & (0, 2) & (1, 2) & (2, 2). \end{array}$$

It is now easy to see that any triple of base points which represents a row, a column, or a term in the expansion of the determinant of the matrix (3) spans an inflection line (cf. [37], p. 335).

The existence of an isomorphism α not depending on the member of the pencil can be interpreted by saying that the Hesse pencil is a family of elliptic curves together with a 3-level structure (i.e. a basis in its subgroup of 3-torsion points). In fact, in the following lemma we will prove that any smooth plane cubic is projectively isomorphic to a member of the Hesse pencil. It follows (see [4]) that its parameter space can be naturally identified with a smooth compactification of the fine moduli space $\mathcal{A}_1(3)$ of elliptic curves with a 3-level structure (when $k = \mathbb{C}$ this is the *modular curve* $X(3)$ of *principal level 3*).

Lemma 1. *Any smooth plane cubic is projectively equivalent to a member of the Hesse pencil i.e. it admits a Hesse canonical form³:*

$$x^3 + y^3 + z^3 + \lambda xyz = 0.$$

Proof. We will follow the arguments from [53]. Let E be a nonsingular plane cubic. Given two inflection tangent lines for E we can choose projective coordinates such that their equations are $x = 0$ and $y = 0$. Then it is easy to see that the equation of E can be written in the form

$$(4) \quad F(x, y, z) = xy(ax + by + cz) + dz^3 = 0,$$

where $ax + by + cz = 0$ is a third inflection tangent line. Suppose $c = 0$, then $ab \neq 0$ since otherwise the curve would be singular. Since a binary form of degree 3 with no multiple roots can be reduced, by a linear change of variables, to the form $x^3 + y^3$, the equation takes the form $x^3 + y^3 + dz^3 = 0$. After scaling the coordinate z , we arrive at a Hesse equation. So we may assume $c \neq 0$ and, after scaling the coordinate z , that $c = 3$. Let ϵ be a primitive 3rd root of unity and define new coordinates u, v by the formulae

$$ax + z = \epsilon u + \epsilon^2 v, \quad by + z = \epsilon^2 u + \epsilon v.$$

Then

$$\begin{aligned} abF(x, y, z) &= (\epsilon u + \epsilon^2 v - z)(\epsilon^2 u + \epsilon v - z)(-u - v + z) + dz^3 \\ &= -u^3 - v^3 + (d + 1)z^3 - 3uvz = 0. \end{aligned}$$

Since the curve is nonsingular we have $d \neq -1$. Therefore, after scaling the coordinate z , we get a Hesse equation for E :

$$(5) \quad x^3 + y^3 + z^3 + \lambda xyz = 0.$$

□

Assume additionally that the characteristic of the field k is not equal to 2. Recall that a plane nonsingular cubic also admits the Weierstrass canonical form

$$y^2 z = x^3 + axz^2 + bz^3, \quad 4a^3 + 27b^2 \neq 0.$$

Projecting from the point p_0 we exhibit each curve of the Hesse pencil as a double cover of \mathbb{P}^1 branched at 4 points. By a standard procedure, this allows one to compute the Weierstrass form of any curve from the Hesse pencil:

$$(6) \quad y^2 z = x^3 + A(t_0, t_1)xz^2 + B(t_0, t_1)z^3,$$

where

$$(7) \quad A(t_0, t_1) = 12u_1(u_0^3 - u_1^3),$$

$$(8) \quad B(t_0, t_1) = 2(u_0^6 - 20u_0^3u_1^3 - 8u_1^6),$$

³called the *second canonical form* in [45], the first one being the Weierstrass form.

and $(t_0, t_1) = (u_0, 6u_1)$. The discriminant of the cubic curve given by (6) is

$$\Delta = 4A^3 + 27B^2 = 2^2 3^3 u_0^3 (u_0^3 + 8u_1^3)^3,$$

its zeroes describe the singular members of the pencil. The zeroes of the binary form $A(t_0, t_1)$ define the curves from the Hesse pencil which admit an automorphism of order 6 with a fixed point (*equianharmonic cubics*). For example, the Fermat curve $E_0 : x^3 + y^3 + z^3 = 0$ is one of them. The zeroes of the binary form $B(t_0, t_1)$ define the curves from the Hesse pencil which admit an automorphism of order 4 with a fixed point (*harmonic cubics*). The map

$$j : \mathbb{P}^1 \rightarrow \mathbb{P}^1, (t_0, t_1) \mapsto (4A^3, 4A^3 + 27B^2)$$

coincides (up to a scalar factor) with the map assigning to the elliptic curve E_λ its j -invariant, which distinguishes the projective equivalence classes of cubic curves.

The Hesse pencil naturally defines a rational map

$$\mathbb{P}^2 - \rightarrow \mathbb{P}^1, (x, y, z) \mapsto (xyz, x^3 + y^3 + z^3)$$

which is not defined at the nine base points. Let

$$\pi : S(3) \rightarrow \mathbb{P}^2$$

be the blowing up of the base points. This is a rational surface such that the composition of rational maps $S(3) \rightarrow \mathbb{P}^2 - \rightarrow \mathbb{P}^1$ is a regular map

$$(9) \quad \phi : S(3) \rightarrow \mathbb{P}^1$$

whose fibres are isomorphic to the members of the Hesse pencil. The map ϕ defines a structure of a minimal elliptic surface on $S(3)$. Here and later we refer to [17], [38] or [10] for the theory of elliptic fibrations on algebraic surfaces. The surface $S(3)$ is a special case of an *elliptic modular surface* $S(n)$ of level n (see [4], [47]), giving the universal family of elliptic curves with a n -level.

There are four singular members in the Hesse pencil, each one is the union of three lines:

$$\begin{aligned} E_\infty : & \quad xyz = 0, \\ E_{-3} : & \quad (x + y + z)(x + \epsilon y + \epsilon^2 z)(x + \epsilon^2 y + \epsilon z) = 0, \\ E_{-3\epsilon} : & \quad (x + \epsilon y + z)(x + \epsilon^2 y + \epsilon^2 z)(x + y + \epsilon z) = 0, \\ E_{-3\epsilon^2} : & \quad (x + \epsilon^2 y + z)(x + \epsilon y + \epsilon z)(x + y + \epsilon^2 z) = 0. \end{aligned}$$

We will call these singular members the *triangles* and denote them by T_1, \dots, T_4 , respectively. The singular points of the triangles, referred to as the *vertices* of the triangles, are

$$(10) \quad \begin{aligned} v_0 &= (1, 0, 0), & v_1 &= (0, 1, 0), & v_2 &= (0, 0, 1), \\ v_3 &= (1, 1, 1), & v_4 &= (1, \epsilon, \epsilon^2), & v_5 &= (1, \epsilon^2, \epsilon), \\ v_6 &= (\epsilon, 1, 1), & v_7 &= (1, \epsilon, 1), & v_8 &= (1, 1, \epsilon), \\ v_9 &= (\epsilon^2, 1, 1), & v_{10} &= (1, \epsilon^2, 1), & v_{11} &= (1, 1, \epsilon^2). \end{aligned}$$

The 12 lines forming the triangles are the inflection lines of the Hesse configuration. If we fix a point p_i as the origin in the group law of a nonsingular member of the pencil, then the side of a triangle T_i passing through p_i contains 3 base points forming a subgroup of order 3, while the other sides of T_i contain the cosets with respect to this subgroup. The triangles obviously give four singular fibres of Kodaira's type I_3 in the elliptic fibration ϕ .

Remark 2.1. The Hesse pencil makes sense over a field of any characteristic and is popular in number-theory and cryptography for finding explicit algorithms for computing the number of points of an elliptic curve over a finite field of characteristic 3 (see [22], [49]). We are grateful to Kristian Ranestad for this comment.

The proof of the existence of a Hesse equation for an elliptic curve E over a field of characteristic 3 goes through if we assume that E is an ordinary elliptic curve with rational 3-torsion points. We find the equation (4) and check that it defines a nonsingular curve only if $abc \neq 0$. By scaling the variables we may assume that $a = b = -1, c = 1$. Next we use the variable change $z = u + x + y$ to transform the equation to the Hesse form

$$xyu + d(u + x + y)^3 = xyu + d(u^3 + x^3 + y^3) = 0$$

The Hesse pencil (2) in characteristic 3 has two singular members: $(x + y + z)^3 = 0$ and $xyz = 0$. It has three base points $(1, -1, 0), (0, 1, -1), (1, 0, -1)$, each of multiplicity 3, which are the inflection points of all nonsingular members of the pencil. Blowing up the base points, including infinitely near base points, we get a rational elliptic surface. It has two singular fibres of Kodaira's types IV^* and I_2 . The fibre of type IV^* has the invariant δ of wild ramification equal to 1. This gives an example of a rational elliptic surface in characteristic 3 with finite Mordell-Weil group of sections (these surfaces are classified in [34]). For our surface the Mordell-Weil group is of order 3.

3. THE HESSIAN AND THE CAYLEYAN OF A PLANE CUBIC

The first polar of a plane curve E with equation $F = 0$ with respect to a point $q = (a, b, c) \in \mathbb{P}^2$ is the curve $P_q(E)$ defined by $aF'_x + bF'_y + cF'_z = 0$. It is easy to see that the Hessian curve $\text{He}(E)$ of a plane cubic E coincides with the locus of points q such that the polar conic $P_q(E) = 0$ is reducible.

If E_λ is a member of the Hesse pencil, we find that $\text{He}(E_\lambda)$ is the member $E_{\mathfrak{h}(\lambda)}$ of the Hesse pencil, where

$$(11) \quad \mathfrak{h}(\lambda) = -\frac{108 + \lambda^3}{3\lambda^2}.$$

Let $p_i = (a, b, c)$ be one of the base points of the Hesse pencil. By computing the polar $P_{p_i}(E_\lambda)$ we find that it is equal to the union of the inflection tangent line $\mathbb{T}_{p_i}(E_\lambda)$ to the curve at the point p_i and the line $L_i : ax + by + cz = 0$. The lines L_0, \dots, L_8 are called the *harmonic polars*. It follows easily from the known properties of the first polars (which can be checked directly in our case) that the line L_i intersects the curve E_λ at 3 points q_j such that the tangent to the curve at q_j contains p_i . Together with p_i they form the group of 2-torsion points in the group law on the curve in which the origin is chosen to be the point p_i .

The harmonic polars, considered as points in the dual plane $\check{\mathbb{P}}^2$, give the set of base points of a Hesse pencil in $\check{\mathbb{P}}^2$. Its inflection lines are the lines dual to the vertices of the inflection triangles given in (10). If we identify the plane with its dual by means of the quadratic form $x^2 + y^2 + z^2$, the equation of the dual Hesse pencil coincides with the equation of the original pencil. For any nonsingular member of the Hesse pencil its nine tangents at the inflection points, considered as points in the dual plane, determine uniquely a member of the dual Hesse pencil.

Remark 3.1. In the theory of line arrangements, the Hesse pencil defines two different arrangements (see [6] and [26]). The *Hesse arrangement* consists of 12 lines

(the inflection lines), it has 9 points of multiplicity 4 (the base points) and no other multiple points. The second arrangement is the dual of the Hesse arrangement, denoted by $A_3^0(3)$. It consists of 9 lines (the harmonic polars) and has 12 multiple points of multiplicity 3. Together these two arrangements form an abstract configuration $(12_3, 9_4)$ which is a special case of a modular configuration (see [15]). In [26] Hirzebruch constructs certain finite covers of the plane with abelian Galois groups ramified over the lines of the Hesse configuration or its dual configuration. One of them, for each configuration, is a surface of general type with universal cover isomorphic to a complex ball.

Proposition 3.2. *Let E_λ be a nonsingular member of the Hesse pencil. Let $L_i \cap E_\lambda = \{q_1, q_2, q_3\}$ and E_{λ_j} , $j = 1, 2, 3$, be the curve from the Hesse pencil whose tangent at p_i contains q_j . Then $\text{He}(E_\mu) = E_\lambda$ if and only if $\mu \in \{\lambda_1, \lambda_2, \lambda_3\}$.*

Proof. It is a straightforward computation. Because of the symmetry of the Hesse configuration, it is enough to consider the case when $i = 0$, i.e. $p_i = (0, 1, -1)$. We have that $L_0 : y - z = 0$ and $L_0 \cap E_\lambda$ is equal to the set of points $q_j = (1, y_j, y_j)$ satisfying $1 + 2y_j^3 + \lambda y_j^2 = 0$. The line $\overline{p_0, q_j}$ has the equation $-2y_j x + y + z = 0$. The curve E_μ from the Hesse pencil is tangent to this line at the point $(0, 1, -1)$ if and only if $(-\mu, 3, 3) = (-2y_j, 1, 1)$, i.e. $y_j = \mu/6$. Thus

$$\lambda = -\frac{1 + 2y_j^3}{y_j^2} = -\frac{108 + \mu^3}{3\mu^2}.$$

Comparing with the formula (11), we see that $\mathfrak{h}(\mu) = \lambda$. This proves the assertion. \square

Let E be a smooth cubic which is not equianharmonic. Then $\text{He}(E)$ is smooth and for any $q \in \text{He}(E)$ the polar conic $P_q(E)$ has one isolated singular point s_q . In fact s_q lies on $\text{He}(E)$ and the map $q \mapsto s_q$ is a fixed point free involution on $\text{He}(E)$ (see, for example, [14]). If we fix a group law on $\text{He}(E)$ with zero at p_i , then the map $q \mapsto s_q$ is the translation by a non-trivial 2-torsion point η . In the previous proposition this 2-torsion point is one of the intersection points of the harmonic polar L_i with $\text{He}(E)$ such that E is tangent to the line connecting this point with the inflection point p_i .

The quotient $\text{He}(E)/\langle \eta \rangle$ is isomorphic to the cubic curve in the dual plane $\check{\mathbb{P}}^2$ parametrizing the lines $\overline{q, s_q}$. This curve is classically known as the *Cayleyan curve* of E . One can show that the Cayleyan curve also parametrizes the line components of reducible polar conics of E . In fact, the line $\overline{q, s_q}$ is a component of the polar conic $P_a(E)$, where a is the intersection point of the tangents of $\text{He}(E)$ at q and s_q .

Proposition 3.3. *If $E = E_\lambda$ is a member of the Hesse pencil, then its Cayleyan curve $\text{Ca}(E_\lambda)$ is the member of the dual Hesse pencil corresponding to the parameter*

$$(12) \quad \mathfrak{c}(\lambda) = \frac{54 - \lambda^3}{9\lambda}.$$

Proof. To see this, following [9], p. 245, we write the equation of the polar conic $P_q(E_{6\mu})$ with respect to a point $q = (u, v, w)$

$$u(x^2 + 2\mu yz) + v(y^2 + 2\mu xz) + w(z^2 + 2\mu xy) = 0.$$

It is a reducible conic if the equation decomposes into linear factors

$$u(x^2 + 2\mu yz) + v(y^2 + 2\mu xz) + w(z^2 + 2\mu xy) = (ax + by + cz)(\alpha x + \beta y + \gamma z).$$

This happens if and only if

$$\begin{pmatrix} u & 2\mu w & 2\mu v \\ 2\mu w & v & 2\mu u \\ 2\mu v & 2\mu u & w \end{pmatrix} = \begin{pmatrix} a\alpha & a\beta + b\alpha & a\gamma + c\alpha \\ a\beta + b\alpha & b\beta & c\beta + b\gamma \\ a\gamma + c\alpha & c\beta + b\gamma & c\gamma \end{pmatrix}.$$

Considering this as a system of linear equations in the variables u, v, w, a, b, c we get the condition of solvability as the vanishing of the determinant

$$\begin{vmatrix} -1 & 0 & 0 & \alpha & 0 & 0 \\ 0 & -1 & 0 & 0 & \beta & 0 \\ 0 & 0 & -1 & 0 & 0 & \gamma \\ -2\mu & 0 & 0 & 0 & \gamma & \beta \\ 0 & -2\mu & 0 & \gamma & 0 & \alpha \\ 0 & 0 & -2\mu & \beta & \alpha & 0 \end{vmatrix} = \mu(\alpha^3 + \beta^3 + \gamma^3) + (1 - 4\mu^3)\alpha\beta\gamma = 0.$$

If we take (α, β, γ) as the coordinates in the dual plane, this equation represents the equation of the Cayleyan curve because the line $\alpha x + \beta y + \gamma z$ is an irreducible component of a singular polar conic. Plugging in $\mu = \lambda/6$, we get (12). \square

Note that the Cayleyan curve $\text{Ca}(E_\lambda) = \text{He}(E_\lambda)/\langle \eta \rangle$ comes with a distinguished nontrivial 2-torsion point, which is the image of the nontrivial coset of 2-torsion points on $\text{He}(E_\lambda)$. This shows that $\text{Ca}(E_\lambda) = \text{He}(E'_\mu)$ for a uniquely defined member E'_μ of the dual Hesse pencil. The map $\alpha : \mathbb{P}^1 \rightarrow \mathbb{P}^1, \lambda \mapsto \mu$, gives an isomorphism between the spaces of parameters of the Hesse pencil and its dual pencil such that $\mathfrak{h}(\alpha(\lambda)) = \mathfrak{c}(\lambda)$. One checks that

$$\mathfrak{h}(-18/\lambda) = \mathfrak{c}(\lambda).$$

Remark 3.4. The Hesse pencil in the dual plane should not be confused with the (non-linear) pencil of the dual curves of members of the Hesse pencil. The dual curve of a nonsingular member $E_m = E_{m_0, 3m_1}$ of the Hesse pencil is a plane curve of degree 6 with 9 cusps given by the equation

$$(13) \quad m_0^4(X_0^6 + X_1^6 + X_2^6) - m_0(2m_0^3 + 32m_1^3)(X_0^3X_1^3 + X_0^3X_2^3 + X_2^3X_1^3) - 24m_0^2m_1^2X_0X_1X_2(X_0^3 + X_1^3 + X_2^3) - (24m_0^3m_1 + 48m_1^4)X_0^2X_1^2X_2^2 = 0.$$

This equation defines a surface V in $\mathbb{P}^1 \times \check{\mathbb{P}}^2$ of bi-degree $(4, 6)$, the universal family of the pencil. The projection to the first factor has fibres isomorphic to the dual curves of the members of the Hesse pencil, where the dual of a triangle becomes a triangle taken with multiplicity 2. The base points p_i of the Hesse pencil define 9 lines ℓ_{p_i} in the dual plane and each of the 9 cusps of an irreducible member from (13) lies on one of these lines. The unique cubic passing through the nine cusps is the Cayleyan curve of the dual cubic. If $(m, x) \in V$, then the curve E_m has the line ℓ_x (dual to x) as its tangent line. For a general point x , there will be 4 curves in the Hesse pencil tangent to this line, in fact the degree of the second projection $V \rightarrow \check{\mathbb{P}}^2$ is equal to 4. Each line ℓ_{p_i} lies in the branch locus of this map and its pre-image in V has a component $\bar{\ell}_{p_i}$ contained in the ramification locus. The surface V is singular along the curves $\bar{\ell}_{p_i}$ and at the points corresponding to vertices of the double triangles. One can show that a nonsingular minimal relative model of the elliptic surface $V \rightarrow \mathbb{P}^1$ is a rational elliptic surface isomorphic to $S(3)$. Thus, the dual of the Hesse pencil is the original Hesse pencil in disguise.

Remark 3.5. The iterations of the maps $\mathfrak{h} : \mathbb{P}^1 \rightarrow \mathbb{P}^1$ and $\mathfrak{c} : \mathbb{P}^1 \rightarrow \mathbb{P}^1$ given by (11) and (12) were studied in [27]. They give interesting examples of complex dynamics in one complex variable. The critical points of \mathfrak{h} are the four equianharmonic cubics and its critical values correspond to the four triangles. Note that the set of triangles is invariant under this map. The set of critical points of \mathfrak{c} is the set of triangles and it coincides with the set of critical values. The equianharmonic cubics are mapped to critical points. This shows that both maps are critically finite maps in the sense of Thurston (see [36]).

4. THE HESSIAN GROUP

The *Hessian group* is the subgroup G_{216} of $\text{Aut}(\mathbb{P}^2) \cong \text{PGL}(3, \mathbb{C})$ preserving the Hesse pencil.⁴ The Hessian group acts on the space \mathbb{P}^1 of parameters of the Hesse pencil, hence defines a homomorphism

$$(14) \quad \alpha : G_{216} \longrightarrow \text{Aut}(\mathbb{P}^1).$$

Its kernel K is generated by the transformations

$$(15) \quad \begin{aligned} g_0(x, y, z) &= (x, z, y), \\ g_1(x, y, z) &= (y, z, x), \\ g_2(x, y, z) &= (x, \epsilon y, \epsilon^2 z). \end{aligned}$$

and contains a normal subgroup of index 2

$$\Gamma = \langle g_1, g_2 \rangle \cong (\mathbb{Z}/3\mathbb{Z})^2.$$

If we use the group law with zero p_0 on a nonsingular member of the pencil, then g_1 induces the translation by the 3-torsion point p_3 and g_2 that by the point p_1 .

The image of the homomorphism (14) is clearly contained in a finite subgroup of $\text{Aut}(\mathbb{P}^1)$ isomorphic to the permutation group S_4 . Note that it leaves the zeroes of the binary forms $A(t_0, t_1), B(t_0, t_1)$ from (7) invariant. It is known that the group S_4 acts on \mathbb{P}^1 as an octahedral group, with orbits of cardinalities 24, 12, 8, 6, so it cannot leave invariant the zeroes of a binary form of degree 4. However, its subgroup A_4 acts as a tetrahedral group with orbits of cardinalities 12, 6, 4, 4. This suggests that the image of (14) is indeed isomorphic to A_4 . In order to see it, it is enough to exhibit transformations from G_{216} which are mapped to generators of A_4 of orders 2 and 3. Here they are

$$g_3 = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \epsilon & \epsilon^2 \\ 1 & \epsilon^2 & \epsilon \end{pmatrix}, \quad g_4 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & \epsilon \end{pmatrix}.$$

The group generated by g_0, g_3, g_4 is a central extension of degree two of A_4 . It is isomorphic to the binary tetrahedral group and to the group $\text{SL}(2, \mathbb{F}_3)$. Note that $g_3^2 = g_0$ so

$$G_{216} = \langle g_1, g_2, g_3, g_4 \rangle.$$

It is clear that the order of G_{216} is equal to the order of K times the order of A_4 making it equal to 216 that explains the notation.

⁴Not to be confused with the Hesse group isomorphic to $\text{Sp}(6, \mathbb{F}_2)$ and related to the 28 bitangents of a plane quartic.

Proposition 4.1. *The Hessian group G_{216} is isomorphic to the semi-direct product*

$$\Gamma \rtimes \mathrm{SL}(2, \mathbb{F}_3)$$

where $\mathrm{SL}(2, \mathbb{F}_3)$ acts on $\Gamma \cong (\mathbb{Z}/3\mathbb{Z})^2$ via the natural linear representation.

The Hessian group clearly acts on the set of nine points p_i , giving a natural homomorphism from G_{216} to $\mathrm{Aff}_2(3)$, the affine group of \mathbb{F}_3^2 . In fact, the Hessian group is the subgroup of index 2 of $\mathrm{Aff}_2(3)$ of transformations with linear part of determinant 1. In this action the group G_{216} is realized as a 2-transitive subgroup of the permutation group S_9 on $\{0, 1, \dots, 8\}$ generated by permutations

$$T = (031)(475)(682) \quad \text{and} \quad U = (147)(285)$$

(see [11], 7.7). The stabilizer subgroup of the point p_0 is generated by U and $TUT^{-1} = (354)(678)$ and coincides with $\langle g_3, g_4 \rangle$.

Remark 4.2. The group $\mathrm{Aff}_2(3)$ of order 432 that contains G_{216} as a subgroup of order 2 is isomorphic to the Galois group of the equation of degree 9 defining the first coordinates of the inflection points of a cubic with general coefficients in the affine plane [13], [53].

The Hessian group G_{216} , considered as a subgroup $\mathrm{PGL}(3, \mathbb{C})$, admits two different extensions to a subgroup of $\mathrm{GL}(3, \mathbb{C})$ generated by complex reflections. The first group \overline{G}_{216} is of order 648 and is generated by reflections of order 3 (n.25 in Shephard-Todd's list [46]). The second group \overline{G}'_{216} is of order 1296 and is generated by reflections of order 3 and reflections of order 2 (n.26 in Shephard-Todd's list). The images of the reflection hyperplanes of \overline{G}_{216} in the projective plane are the inflection lines, while the images of the reflection hyperplanes of \overline{G}'_{216} are the inflection lines and the harmonic polars.

The algebra of invariants of \overline{G}_{216} is generated by three polynomials of degrees 6, 9 and 12 (see [35], [50])

$$\begin{aligned} \Phi_6 &= x^6 + y^6 + z^6 - 10(x^3y^3 + x^3z^3 + y^3z^3), \\ \Phi_9 &= (x^3 - y^3)(x^3 - z^3)(y^3 - z^3), \\ \Phi_{12} &= (x^3 + y^3 + z^3)[(x^3 + y^3 + z^3)^3 + 216x^3y^3z^3]. \end{aligned}$$

Note that the curve $\Phi_9 = 0$ is the union of the nine harmonic polars L_i and the curve $\Phi_{12} = 0$ is the union of the four equianharmonic members of the pencil. The union of the 12 inflection lines is obviously invariant with respect to G_{216} , however the corresponding polynomial Φ'_{12} of degree 12 is not an invariant but a relative invariant (i.e. the elements of \overline{G}_{216} transform the polynomial to a constant multiple).

The algebra of invariants of the second complex reflection group \overline{G}'_{216} is generated by Φ_6, Φ'_{12} and a polynomial of degree 18

$$\Phi_{18} = (x^3 + y^3 + z^3)^6 - 540x^3y^3z^3(x^3 + y^3 + z^3)^3 - 5832x^6y^6z^6.$$

The curve $\Phi_{18} = 0$ is the union of the six harmonic cubics in the pencil. We will give later a geometric meaning to the 18 intersection points of the curve defined by $\Phi_6 = 0$ with nonsingular members of the pencil.

A third natural linear extension of the group G_{216} is the pre-image G'_{216} of the group under the projection $\mathrm{SL}(3, \mathbb{C}) \rightarrow \mathrm{PGL}(3, \mathbb{C})$. This is a group of order 648 isomorphic to the central extension $3G_{216}$ of G_{216} , however it is not isomorphic to \overline{G}_{216} . The pre-image of the subgroup Γ in $3G_{216}$ is a non-abelian group of order 27

isomorphic to the *Heisenberg group* $\mathcal{H}_3(3)$ of unipotent 3×3 -matrices with entries in \mathbb{F}_3 . The group G'_{216} is then isomorphic to the semi-direct product $\mathcal{H}_3(3) \rtimes \mathrm{SL}(2, \mathbb{F}_3)$ and it is generated by $g_1, g_2, \frac{1}{\epsilon - \epsilon^2} g_3, e^{2\pi i/9} g_4$ considered as linear transformations.

Remark 4.3. Classical geometers were used to define a projective transformation as a pair consisting of a nondegenerate quadric in the projective space and a nondegenerate quadric in the dual projective space. If $\mathbb{P}^n = \mathbb{P}(V)$, then the first quadric is given by a quadratic form on V which defines a linear map $\phi : V \rightarrow V^*$. The second quadric defines a linear map $V^* \rightarrow V$ and the composition with the first one is a linear map $V \rightarrow V$. In [21] the Hessian group is given by a set of 36 conics which are identified with conics in the dual plane $\check{\mathbb{P}}^2$ by means of an isomorphism $\mathbb{P}^2 \rightarrow \check{\mathbb{P}}^2$ defined by the conic $x_0^2 + x_1^2 + x_2^2 = 0$. These conics are the polars of four equianharmonic cubics in the pencil with respect to the 12 vertices of the inflection triangles. The 12 of them which are double lines have to be omitted.

It is known that the simple group $G = \mathrm{PSp}(4, \mathbb{F}_3)$ of order 25,920 has two maximal subgroups of index 40. One of them is isomorphic to the complex reflection group \overline{G}_{216} of order 648. It has the following beautiful realization in terms of complex reflection groups in dimensions 4 and 5.

It is known that the group $\mathbb{Z}/3\mathbb{Z} \times \mathrm{Sp}(4, \mathbb{F}_3)$ is isomorphic to a complex reflection group in \mathbb{C}^4 with 40 reflection hyperplanes of order 3 (n.32 in Shephard-Todd's list). This defines a projective representation of G in \mathbb{P}^3 and the their stabilizer subgroups of the reflection projective planes are isomorphic to \overline{G}_{216} . The reflection planes cut out on each fixed reflection plane the extended Hesse configuration of 12 inflection lines and 9 harmonic polars [35], p. 334.

Also is known that the group $\mathbb{Z}/2\mathbb{Z} \times G \cong \mathrm{Sp}(4, \mathbb{F}_3)$ is isomorphic to a complex reflection group in \mathbb{C}^5 with 45 reflections hyperplanes of order 2 (n.33 in Shephard-Todd's list). This defines a projective representation of G in \mathbb{P}^4 . The algebra of invariant polynomials with respect to the complex reflection group $\mathbb{Z}/2\mathbb{Z} \times G$ was computed by Burkhardt [8]. The smallest degree invariant is of degree 4. Its zero locus in \mathbb{P}^4 is the famous Burkhardt quartic hypersurface with 45 nodes where 12 reflection hyperplanes meet. There are 40 planes forming one orbit, each containing 9 nodes. Each such plane contains 12 lines cut out by the reflection hyperplanes. They form the Hesse configuration with the 9 points equal to the set of base points of the Hesse pencil.

One can find an excellent exposition of the results of Maschke and Burkhardt in [28]. There is also a beautiful interpretation of the geometry of the two complex reflection groups in terms of the moduli space $\mathcal{A}_2(3)$ of principally polarized abelian surfaces with some 3-level structure (see [18], [20]). For example, one can identify $\mathcal{A}_2(3)$ with an open subset of the Burkhardt quartic whose complement is equal to the union of the 40 planes.

5. THE QUOTIENT PLANE

Consider the blowing up $\pi : S(3) \rightarrow \mathbb{P}^2$ of the base points p_i of the Hesse pencil and the elliptic fibration (9)

$$\phi : S(3) \rightarrow \mathbb{P}^1, \quad (x, y, z) \mapsto (xyz, x^3 + y^3 + z^3).$$

The action of the group Γ on \mathbb{P}^2 lifts to an action on $S(3)$. Fixing one section of ϕ (i.e. one point p_i), the group Γ is identified with the Mordell-Weil group of the

elliptic surface and its action with the translation action. Let

$$\bar{\phi} : S(3)/\Gamma \longrightarrow \mathbb{P}^1, \quad \bar{\pi} : S(3)/\Gamma \longrightarrow \mathbb{P}^2/\Gamma,$$

be the morphisms induced by ϕ and π , respectively.

Proposition 5.1. *The quotient surfaces \mathbb{P}^2/Γ and $S(3)/\Gamma$ have 4 singular points of type A_2 given by the orbits of the vertices (10). The minimal resolution of singularities are isomorphic to a Del Pezzo surface S of degree 1 and to $S(3)$, respectively. Up to these resolutions, $\bar{\phi}$ is isomorphic to ϕ and $\bar{\pi}$ is the blowing up of S in one point, the Γ -orbit of the points p_i .*

Proof. The group Γ preserves each singular member of the Hesse pencil and any of its subgroups of order 3 leaves invariant the vertices of one of the triangles. Without loss of generality we may assume that the triangle is $xyz = 0$. Then the subgroup of Γ stabilizing its vertices is generated by the transformation g_2 , which acts locally at the point $y = z = 0$ by the formula $(y, z) \mapsto (\epsilon y, \epsilon^2 z)$. It follows that the orbits of the vertices give 4 singular points of type A_2 in \mathbb{P}^2/Γ and $S(3)/\Gamma$, locally given by the equation $uv + w^3 = 0$.

Let E be an elliptic curve with a group law and $[n] : E \rightarrow E$ be the map $x \mapsto nx$. It is known that this map is a surjective map of algebraic groups with kernel equal to the group of n -torsion points. Its degree is equal to n^2 if n is coprime to the characteristic. In our case the quotient map by Γ acts on each member of the Hesse pencil as the map [3]. This implies that the quotient of the surface $S(3)$ by the group Γ is isomorphic to $S(3)$ over the open subset $U = \mathbb{P}^1 \setminus \{\Delta(t_0, t_1) = 0\}$.

The map $\bar{\phi} : S(3)/\Gamma \rightarrow \mathbb{P}^1$ induced by the map ϕ has four singular fibres given by rational curves with a double point and on each such fibre lies a singular point of type A_2 . Let $\sigma : S(3)' \rightarrow S(3)/\Gamma$ be a minimal resolution of the four singular points of $S(3)/\Gamma$. The composition $\bar{\phi} \circ \sigma : S(3)' \rightarrow \mathbb{P}^1$ is an elliptic surface isomorphic to $\phi : S(3) \rightarrow \mathbb{P}^1$ over the open subset U of the base \mathbb{P}^1 . Moreover, $\bar{\phi} \circ \sigma$ and ϕ have singular fibres of the same types, thus $S(3)'$ is a minimal elliptic surface. Since it is known that a birational isomorphism of minimal elliptic surfaces is an isomorphism, this implies that $\bar{\phi} \circ \sigma$ is isomorphic to ϕ .

The minimal resolution S of \mathbb{P}^2/Γ contains a pencil of cubic curves intersecting in one point q_0 , the orbit of the points p_i . Hence it follows easily (see for example [10]) that S is isomorphic to a Del Pezzo surface of degree one and $\bar{\pi}$ is the blowing up of the point q_0 . □

Let $\pi' : S(3)' \rightarrow \mathbb{P}^2$ be the contraction of the 9 sections E_0, \dots, E_8 of the elliptic fibration $\bar{\phi} \circ \sigma$ to the points q_0, \dots, q_8 in \mathbb{P}^2 , the base points of the Hesse pencil in the second copy of \mathbb{P}^2 .

By Proposition 8.1 the following diagram is commutative:

$$(16) \quad \begin{array}{ccccc} S(3) & \xrightarrow{r} & S(3)/\Gamma & \xleftarrow{\sigma} & S(3)' \\ \pi \downarrow & & \downarrow \bar{\pi} & & \downarrow \alpha \quad \searrow \pi' \\ \mathbb{P}^2 & \xrightarrow{p} & \mathbb{P}^2/\Gamma & \xleftarrow{\beta} & S \xrightarrow{\gamma} \mathbb{P}^2. \end{array}$$

Here p is the quotient map by Γ , β is a minimal resolution of singularities of the orbit space \mathbb{P}^2/Γ , α is the blow-up of the point q_0 on S and γ is the blow-up of q_1, \dots, q_8 (see the notation in the proof of Proposition 8.1).

Proposition 5.2. *The curves $B_i = p^{-1}(\beta(\alpha(E_i)))$, $i = 1, \dots, 8$, are plane cubic curves with equations*

$$\begin{aligned} B_1 : x^3 + \epsilon y^3 + \epsilon^2 z^3 &= 0, & B_5 : x^3 + \epsilon^2 y^3 + \epsilon z^3 &= 0, \\ B_2 : x^2 y + y^2 z + z^2 x &= 0, & B_6 : x^2 z + y^2 x + z^2 y &= 0, \\ B_3 : x^2 y + \epsilon^2 y^2 z + \epsilon z^2 x &= 0, & B_7 : x^2 z + \epsilon y^2 x + \epsilon^2 z^2 y &= 0, \\ B_4 : x^2 y + \epsilon y^2 z + \epsilon^2 z^2 x &= 0, & B_8 : x^2 z + \epsilon^2 y^2 x + \epsilon z^2 y &= 0. \end{aligned}$$

The union of the eight cubics B_i cuts out on each nonsingular member of the Hesse pencil the set of points of order 9 in the group law with the point p_0 as the origin.

Each of them has one of the triangles of the Hesse pencil as inflection triangle and it is inscribed and circumscribed to the other three triangles (i.e. is tangent to one side of the triangle at each vertex).

Proof. Recall that the sections E_1, \dots, E_8 on $S(3)'$ are non-trivial 3-torsion sections (the zero section is equal to E_0). The pre-image \bar{B}_i of E_i under the map $r^{-1} \circ \sigma$ cuts out on each nonsingular fibre the Γ -orbit of a point of order 9. Thus the image B_i of \bar{B}_i in \mathbb{P}^2 is a plane cubic cutting out the Γ -orbit of a point of order 9 on each nonsingular member of the Hesse pencil.

Let E be a plane nonsingular cubic from the Hesse pencil. Take a point $p \in E$ and let $q \neq p$ be the intersection of E with the tangent line at p . Let $r \neq q$ be the intersection of E with the tangent line at q . Finally, let $s \neq r$ be the intersection of E with the tangent line at r . It follows from the definition of the group law that we have $2p \oplus q = 2q \oplus r = 2r \oplus s = 0$. This immediately implies that $9p = 0$ if and only if $p = s$ (this explains why the classics called a point of order 9 a *coincidence point*). The triangle formed by the lines $\bar{p}, \bar{q}, \bar{r}, \bar{r}, \bar{p}$ is inscribed and circumscribed to E . Following Halphen [23], we will use this observation to find the locus of points of order 9.

The tangent line of E at $p = (x_0, y_0, z_0)$ has the equation

$$(x_0^2 + ty_0 z_0)x + (y_0^2 + tx_0 z_0)y + (z_0^2 + tx_0 y_0)z = 0,$$

where we assume that $E = E_{3t}$. The point $q = (x_0, \epsilon y_0, \epsilon^2 z_0)$ lies on E because $(x_0, y_0, z_0) \in E$ and it also lies on the tangent line at p if $p = (x_0, y_0, z_0)$ satisfies the equation

$$(17) \quad B_1 : x^3 + \epsilon y^3 + \epsilon^2 z^3 = 0.$$

If p satisfies this equation, then q also satisfies this equation, hence $r = (x_0, \epsilon^2 y_0, \epsilon z_0)$ lies on the tangent at q and again satisfies (17). Next time we repeat this procedure we get back to the original point p . Hence we see that any point in $B_1 \cap E$ is a point of order 9. Now we apply the elements of the Hessian group to the curve B_1 to get the remaining cubic curves B_2, \dots, B_8 . Notice that the stabilizer of B_1 in the Hessian group is generated by Γ and g_4 . It is a Sylow 3-subgroup of the Hessian group isomorphic to a semi-direct product $\Gamma \rtimes \mathbb{Z}/3\mathbb{Z}$.

To check the last assertion it is enough, using the G_{216} -action, to consider one of the curves B_i . For example, we see that the triangle T_1 of equation $xyz = 0$ is an inflection triangle of the curve B_1 and the triangles T_2, T_3, T_4 are inscribed and circumscribed to B_1 . More precisely we have the following configuration:

- i) B_i and B_{i+4} have T_i as a common inflection triangle and they intersect in the 9 vertices of the other triangles;
- ii) B_i and B_j , $i \neq j$, $i, j \leq 4$, intersect in the 3 vertices of a triangle T_k and they are tangent in the 3 vertices of T_ℓ with $k, \ell \notin \{i, j\}$;

iii) B_i and B_{j+4} , $i \neq j$, $i, j \leq 4$, intersect similarly with k and ℓ interchanged. For example, B_1 and B_2 intersect in the vertices of T_3 and are tangent in the vertices of T_4 , while B_1 and B_6 intersect transversally on T_4 and are tangent on T_3 . \square

We will call the cubics B_i the *Halphen cubics*. Observe that the element g_0 from the Hessian group sends B_i to B_{i+4} . We will call the pairs $(B_i, B'_i = B_{i+4})$ the *pairs of Halphen cubics* and we will denote with $q_i, q'_i = q_{i+4}$ the corresponding pairs of points in \mathbb{P}^2 .

It can be easily checked that the projective transformations g_3, g_4 act as follows on the Halphen cubics (with the obvious notation):

$$g_3 : (121'2')(434'3'), \quad g_4 : (243)(2'4'3').$$

Remark 5.3. The linear representation of Γ on the space of homogeneous cubic polynomials decomposes into the sum of one-dimensional eigensubspaces. The cubic polynomials defining B_i together with the polynomials xyz , $x^3 + y^3 + z^3$ form a basis of eigenvectors. Moreover, note that the cubics B_i are equianharmonic cubics. In fact, they are all projectively equivalent to B_1 , which is obviously isomorphic to the Fermat cubic. We refer to [2], [3] where the Halphen cubics play a role in the construction of bielliptic surfaces in \mathbb{P}^4 .

Remark 5.4. According to G. Halphen [23] the rational map $\gamma \circ \beta^{-1} \circ \rho : \mathbb{P}^2 - \rightarrow \mathbb{P}^2$ can be given explicitly by

$$(x, y, z) \mapsto (P'_2 P'_3 P'_4, P_2 P_3 P_4, xyz P_1 P'_1),$$

where P_i, P'_i are the polynomials defining B_i, B'_i as in Proposition 5.2. His paper [23], besides many other interesting results, describes the locus of m -torsion points of nonsingular members of the Hesse pencil (see [19] for a modern undertaking of this problem)

Remark 5.5. In characteristic 3 the cyclic group of projective transformations generated by g_1 acts on nonsingular members of the Hesse pencil as translation by 3-torsion points with the zero point taken to be $(1, -1, 0)$. The polynomials

$$(X, Y, Z, W) = (x^2 y + y^2 z + z^2 x, xy^2 + yz^2 + zx^2, x^3 + y^3 + z^3, xyz)$$

are invariant with respect to g_1 and map \mathbb{P}^2 onto a cubic surface in \mathbb{P}^3 given by the equation (see [22], (3.1))

$$(18) \quad X^3 + Y^3 + Z^2 W = XYZ.$$

Among the singular points of the cubic surface, $(0, 0, 0, 1)$ is a rational double point of type $E_6^{(1)}$ in Artin's notation [1]. The image of the member E_λ of the Hesse pencil is the plane section $Z + \lambda W = 0$. Substituting in equation (18), we find that the image of this pencil of plane sections under the projection from the singular point is the Hesse pencil. The parameter λ of the original pencil and the new parameter λ' are related by $\lambda = \lambda'^3$.

6. THE 8-CUSPIDAL SEXTIC

Let C_6 be the sextic curve with equation $\Phi_6 = 0$ where Φ_6 is the degree 6 invariant of the Hessian group. This is a smooth curve and it is immediately checked that it does not contain the 12 vertices of the inflection triangles T_1, \dots, T_4 given in (10) as well as the base points of the Hesse pencil.

This shows that the pre-image $\bar{C}_6 = \pi^{-1}(C_6)$ of C_6 in $S(3)$ is isomorphic to C_6 and the group Γ acts on \bar{C}_6 freely. The orbit space \bar{C}_6/Γ is a smooth curve of genus 2 on $S(3)/\Gamma$ which does not pass through the singular points and does not contain the orbit of the section $\pi^{-1}(p_0)$. Its pre-image under σ is a smooth curve \bar{C}'_6 of genus 2 on $S(3)'$ that intersects a general fibre of the Hesse pencil at 2 points. Observe that the curve C_6 is tangent to each Halphen cubic B_i, B'_i at a Γ -orbit of 9 points. In fact, it is enough to check that C_6 is tangent to one of them, say B_1 , at some point. We have

$$\begin{aligned} x^6 + y^6 + z^6 - 10(x^3y^3 + x^3z^3 + y^3z^3) &= (x^3 + y^3 + z^3)^2 - 12(x^3y^3 + x^3z^3 + y^3z^3) \\ &= -3(x^3 + y^3 + z^3)^2 + 4(x^3 + \epsilon y^3 + \epsilon^2 z^3)(x^3 + \epsilon^2 y^3 + \epsilon z^3). \end{aligned}$$

This shows that the curves B_1 and B'_1 are tangent to C_6 at the points where C_6 intersects the curve $E_0 : x^3 + y^3 + z^3 = 0$. The map $\pi' : S(3)' \rightarrow \mathbb{P}^2$ blows down the curves $B_i, i = 1, \dots, 8$ to the base points q_1, \dots, q_8 of the Hesse pencil. Hence the image C'_6 of \bar{C}'_6 in \mathbb{P}^2 is a curve of degree 6 with cusps at the points q_1, \dots, q_8 .

Proposition 6.1. *The 8-cuspidal sextic C'_6 is projectively equivalent to the sextic curve defined by the polynomial*

$$\Phi'_6(x, y, z) = (x^3 + y^3 + z^3)^2 - 36y^3z^3 + 24(z^4y^2 + z^2y^4) - 12(z^5y + zy^5) - 12x^3(z^2y + zy^2).$$

Proof. In an appropriate coordinate system the points q_i have the same coordinates as the p_i 's. By using the action of the group Γ , we may assume that the sextic has cusps at p_1, \dots, p_8 . Let V be the vector space of homogeneous polynomials of degree 6 vanishing at p_1, \dots, p_8 with multiplicity ≥ 2 . If S is the blowing up of q_1, \dots, q_8 and K_S is its canonical bundle, then $\mathbb{P}(V)$ can be identified with the linear system $| -2K_S |$. It is known that the linear system $| -2K_S |$ is of dimension 3 (see [12]) and defines a regular map of degree 2 from S to \mathbb{P}^3 with the image a singular quadric.

A basis of V can be found by considering the product of six lines among the 12 inflection lines. In this way one finds the following sextic polynomials

(19)

$$\begin{aligned} A_1 &= yz(x + \epsilon y + z)(x + y + \epsilon z)(x + \epsilon^2 y + z)(x + y + \epsilon^2 z), \\ A_2 &= yz(x + \epsilon y + \epsilon^2 z)(x + \epsilon^2 y + \epsilon z)(x + y + \epsilon z)(x + \epsilon y + z), \\ A_3 &= yz(x + \epsilon^2 y + z)(x + y + \epsilon^2 z)(x + \epsilon y + \epsilon^2 z)(x + \epsilon^2 y + \epsilon z), \\ A_4 &= (x + \epsilon y + \epsilon^2 z)(x + \epsilon^2 y + \epsilon z)(x + y + \epsilon z)(x + \epsilon y + z)(x + \epsilon^2 y + z)(x + y + \epsilon^2 z). \end{aligned}$$

A polynomial $P(x, y, z)$ defining the curve C'_6 is invariant with respect to the linear representation of the binary tetrahedral group $\bar{T} \cong \text{SL}(2, \mathbb{F}_3)$ in V . This decomposes into the direct sum of the 3-dimensional representation isomorphic to the second symmetric power of the standard representation of $2.A_4$ in \mathbb{C}^2 and a one-dimensional representation spanned by $P(x, y, z)$. Applying g_4 we find that

$$(A_1, A_2, A_3, A_4) \mapsto (\epsilon^2 A_2, \epsilon^2 A_3, \epsilon^2 A_1, A_4).$$

Thus $P(x, y, z) = \lambda(A_1 + \epsilon^2 A_2 + \epsilon A_3) + \mu A_4$ for some constants λ, μ . Now we apply g_3 and find λ, μ such that $P(x, y, z)$ is invariant. A simple computation gives the equation of C'_6 .

□

Remark 6.2. The geometry of the surface S , the blow-up of \mathbb{P}^2 in q_1, \dots, q_8 , is well-known. We now present several birational models of this surface and relations between them.

The surface S is a Del Pezzo surface of degree 1 and admits a birational morphism $\psi : S \rightarrow \bar{S}$ onto a surface in the weighted projective space $\mathbb{P}(1, 1, 2, 3)$ given by an equation

$$(20) \quad -u_3^2 + u_2^3 + A(u_0, u_1)u_2 + B(u_0, u_1) = 0,$$

where (u_0, u_1, u_2, u_3) have weights 1, 1, 2, 3 (see [12]). The morphism ψ is an isomorphism outside of the union of the 8 lines ℓ_1, \dots, ℓ_8 which correspond to factors of the polynomials A_1, \dots, A_4 from (19). In fact the map ψ is a resolution of indeterminacy points of the rational map $\bar{\psi} : \mathbb{P}^2 \dashrightarrow \mathbb{P}(1, 1, 2, 3)$ given by the formulas

$$(x, y, z) \mapsto (u_0, u_1, u_2, u_3) = (-xyz, x^3 + y^3 + z^3, \Phi'_6(x, y, z), P_9(x, y, z)),$$

where $P_9(x, y, z) = 0$ is the union of the line $\ell_0 : y - z = 0$ and the 8 lines ℓ_1, \dots, ℓ_8 . Explicitly,

$$P_9(x, y, z) = yz(y - z)(x^6 + x^3(2y^3 - 3y^2z - 3yz^2 + 2z^3) + (y^3 - yz + z^2)^3).$$

Up to some constant factors, the polynomials A, B are the same as in (7). The 8 lines are blown down to singular points of the surface.

The composition of $\bar{\psi}$ with the projection $(u_0, u_1, u_2, u_3) \mapsto (u_0^2, u_0u_1, u_1^2, u_2)$ gives the rational map $\mathbb{P}^2 \dashrightarrow \mathbb{P}^3$ defined by

$$(x, y, z) \mapsto (u_0, u_1, u_2, u_3) = (x^2y^2z^2, xyz(x^3 + y^3 + z^3), (x^3 + y^3 + z^3)^2, \Phi'_6).$$

This is a $2.A_4$ -equivariant map of degree 2 onto the quadric cone $u_0u_2 - u_1^2 = 0$. The ramification curve is the line $y - z = 0$ and the branch curve is the intersection of the quadric cone and a cubic surface. This is a curve W of degree 6 with 4 ordinary cuspidal singularities lying on the hyperplane $u_3 = 0$.

Consider the rational map $\phi = \gamma \circ \beta^{-1} \circ p : \mathbb{P}^2 \dashrightarrow \mathbb{P}^2$ from the diagram (16). It follows from the description of the maps in the diagram that the pre-image of the Hesse pencil is a Hesse pencil, the pre-image of the curve C'_6 is the curve C_6 , and the pre-image of the union of the lines $\ell_0, \ell_1, \dots, \ell_8$ is the union of harmonic polars. This shows that the composition $\psi \circ \phi : \mathbb{P}^2 \dashrightarrow \mathbb{P}(1, 1, 2, 3)$ can be given by the formulas

$$(x, y, z) \mapsto (xyz, x^3 + y^3 + z^3, \Phi_6(x, y, z), \Phi_9(x, y, z)),$$

where $\Phi_9(x, y, z)$ is the invariant of degree 9 for the group \bar{G}_{216} given in (4). This agrees with a remark of van Geemen in [51] that the polynomials $xyz, x^3 + y^3 + z^3, \Phi_6(x, y, z), \Phi_9(x, y, z)$ satisfy the same relation (20) as the polynomials $xyz, x^3 + y^3 + z^3, \Phi'_6(x, y, z), P_9(x, y, z)$. Standard techniques of invariant theory of finite groups show that the polynomials $xyz, x^3 + y^3 + z^3, \Phi_6(x, y, z), \Phi_9(x, y, z)$ generate the algebra of invariants of the Heisenberg group $\mathcal{H}_3(3)$, the pre-image of Γ in $\text{SL}(3, \mathbb{F}_3)$. The equations of S have been given with respect to different sets of generators in [7] and [52].

Finally we explain the geometric meaning of the intersection points of the sextic curve C_6 with a nonsingular member E_λ of the Hesse pencil. This set of intersection points is invariant with respect to the translation group Γ and the involution g_0 , thus its image on $C'_6 = C_6/\Gamma$ consists of two points on the curve E_λ . These points lie on the line through the point p_0 because they differ by the negation involution g_0 on E_λ in the group law with the zero point p_0 .

Proposition 6.3. *The curves C'_6 and E_λ intersect at two points p, q outside the base points p_1, \dots, p_8 . These points lie on a line through p_0 which is the tangent line to the Hessian cubic $\text{He}(E_\lambda)$ at p_0 . The 18 points in $C_6 \cap E_\lambda$ are the union of the two Γ -orbits of p and q .*

Proof. This is checked by a straightforward computation. By using MAPLE we find that the curves C'_6 , E_λ and the tangent line to $E_{\mathfrak{h}(\lambda)}$ at p_0 have two intersection points. \square

7. A $K3$ SURFACE WITH AN ACTION OF G_{216}

In the previous sections we introduced two plane sextics, C_6 and C'_6 which are naturally related to the Hesse configuration. The double cover of \mathbb{P}^2 branched along any of these curves is known to be birationally isomorphic to a $K3$ surface, i.e. a simply connected compact complex surface with trivial canonical bundle. In the following sections we will study the geometry of the $K3$ surfaces associated to C_6 and C'_6 , in particular we will show how the symmetries of the Hesse configuration can be lifted to the two surfaces. We start giving some basic properties of $K3$ surfaces and their automorphisms (see for example [5]).

Since the canonical bundle is trivial, the vector space $\Omega^2(X)$ of holomorphic 2-forms on a $K3$ surface X is one-dimensional. Moreover, the group $L = H^2(X, \mathbb{Z})$ is known to be a free abelian group equipped with the quadratic form induced by the cup-product. In fact it is an even unimodular quadratic lattice of signature $(3, 19)$. The sublattice $S_X \subset L$ generated by the fundamental cocycles of algebraic curves on X is called the *Picard lattice* and its orthogonal complement T_X in L is the *transcendental lattice* of X .

Any automorphism g on X clearly acts on $\Omega^2(X)$ and also induces an isometry g^* on L which preserves S_X and T_X . If g acts identically on $\Omega^2(X)$, then it is called *symplectic*. We recall here a result given in [41].

Theorem 7.1. *Let g be an automorphism of finite order on a $K3$ surface X .*

- i) *If g is symplectic then g^* acts trivially on T_X and its fixed locus is a finite union of points.*
- ii) *If g is not symplectic then g^* acts on $\Omega^2(X)$ as the multiplication by a primitive r -th root of unity and its eigenvalues on T_X are the primitive r -th roots of unity.*

Let $q : X \rightarrow \mathbb{P}^2$ be the double cover branched along C_6 . We now prove that the action of the Hessian group on the projective plane lifts to an action on X . We denote by Q_8 be the 2-Sylow subgroup of $\text{SL}(2, \mathbb{F}_3)$, isomorphic to the quaternion group.

Proposition 7.2. *The Hessian group G_{216} is isomorphic to a group of automorphisms of the $K3$ surface X . Under this isomorphism, any automorphism in the normal subgroup $H_{72} = \Gamma \rtimes Q_8$ is symplectic.*

Proof. The double cover $q : X \rightarrow \mathbb{P}^2$ branched along C_6 can be defined by the equation

$$w^2 + \Phi_6(x, y, z) = 0,$$

considered as a weighted homogeneous polynomial with weights $(1, 1, 1, 3)$. Thus we can consider X as a hypersurface of degree 6 in the weighted projective space $\mathbb{P}(1, 1, 1, 3)$.

Let G'_{216} be the pre-image of G_{216} in $\mathrm{SL}(3, \mathbb{C})$ considered in section 4 and $g'_i, i = 1, \dots, 4$, be the lifts of the generators g_i in G'_{216} . It is checked immediately that the generators g'_1, g'_2, g'_3 leave the polynomial Φ_6 invariant and g'_4 multiplies Φ_6 by ϵ^2 . Thus the group G'_{216} acts on X by the formula

$$g_i(x, y, z, w) = (g'_i(x, y, z), w), \quad i \neq 4, \quad g_4(x, y, z, w) = (g'_4(x, y, z), \epsilon w).$$

The kernel of $G'_{216} \rightarrow G_{216}$ is generated by the scalar matrix $(\epsilon, \epsilon, \epsilon)$, which acts as the identity transformation on X . Then it is clear that the induced action of G_{216} on X is faithful.

The subgroup H_{72} of G_{216} is generated by the transformations $g_1, g_2, g_3, g_4 g_3 g_4^{-1}$. To check that it acts symplectically on X we recall that the space of holomorphic 2-forms on a hypersurface $F(x_0, \dots, x_n)$ of degree d in \mathbb{P}^n is generated by the residues of the meromorphic n -forms on \mathbb{P}^n of the form

$$\omega = \frac{P}{F} \sum_{i=0}^n (-1)^i x_i dx_1 \wedge \dots \wedge \widehat{dx}_i \wedge \dots \wedge dx_n,$$

where P is a homogeneous polynomial of degree $d - n - 1$. This is easily generalized to the case of hypersurfaces in a weighted projective space $\mathbb{P}(q_0, \dots, q_n)$. In this case the generating forms are

$$\omega = \frac{P}{F} \sum_{i=0}^n (-1)^i q_i x_i dx_1 \wedge \dots \wedge \widehat{dx}_i \wedge \dots \wedge dx_n,$$

where $\deg P = d - q_0 - \dots - q_n$. In our case there is only one form up to proportionality (in fact $d = q_0 + q_1 + q_2 + q_3 = 6$):

$$\omega = \frac{xdy \wedge dz \wedge dw - ydx \wedge dz \wedge dw + zdx \wedge dy \wedge dw - 3wdx \wedge dy \wedge dz}{w^2 + \Phi_6(x, y, z)}.$$

It is straightforward to check that the generators of H_{72} leave this form invariant (cf. [39], p. 193). □

Remark 7.3. The action of $\Gamma \rtimes Q_8$ appears as Example 0.4, n.10. in the paper of S. Mukai [39] containing the classification of maximal finite symplectic groups of automorphisms of complex $K3$ surfaces.

Let $P_i, P'_i, i = 1, \dots, 4$ be the polynomials defining the cubics B_i, B'_i as given in section 5 and F_i be the equations of the equianharmonic cubics in the Hesse pencil:

$$F_i(x, y, z) = x^3 + y^3 + z^3 + \alpha_i xyz, \quad i = 1, \dots, 4,$$

where $\alpha_1 = 0$ and $\alpha_i = 6\epsilon^{2-i}$ for $i = 2, 3, 4$ (see section 2).

Proposition 7.4. *The $K3$ surface X is isomorphic to the divisor of bidegree $(2, 3)$ in $\mathbb{P}^1 \times \mathbb{P}^2$ with equation*

$$(21) \quad u^2 P_i(x, y, z) + v^2 P'_i(x, y, z) + \sqrt{3}uv F_i(x, y, z) = 0$$

for any $i = 1, \dots, 4$.

Proof. As noticed in the previous section we can write

$$\Phi_6 = \det \begin{pmatrix} 2P_1 & \sqrt{3}F_0 \\ \sqrt{3}F_1 & 2P'_1 \end{pmatrix} = -3F_1^2 + 4P_1P'_1.$$

The $K3$ surface Y given by the bihomogeneous equation of bidegree $(2, 3)$ in $\mathbb{P}^1 \times \mathbb{P}^2$

$$(22) \quad u^2P_1(x, y, z) + v^2P'_1(x, y, z) + \sqrt{3}uvF_1(x, y, z) = 0$$

is a double cover of \mathbb{P}^2 with respect to the projection to the second factor and its branch curve is defined by $\Phi_6 = 0$. Thus Y is isomorphic to the $K3$ surface X . By acting on equation (22) with the Hessian group G_{216} we find analogous equations for X in $\mathbb{P}^1 \times \mathbb{P}^2$ in terms of the polynomials P_i, P'_i and F_i for $i = 2, 3, 4$. \square

An important tool for understanding the geometry of $K3$ surfaces is the study of their *elliptic fibrations* i.e. holomorphic maps from the surface to \mathbb{P}^1 whose general fibers are smooth elliptic curves (see [10]). We recall that the *multisection index* of an elliptic fibration is the minimum positive intersection number between a fibre and a divisor. If this index is equal to 1, then the corresponding divisor is a *section* and the fibration is called *jacobian*.

Proposition 7.5. *The $K3$ surface X has 4 pairs of elliptic fibrations*

$$\mathfrak{h}_i, \mathfrak{h}'_i : X \rightarrow \mathbb{P}^1, \quad i = 1, \dots, 4$$

with the following properties:

- a) \mathfrak{h}_i and \mathfrak{h}'_i are exchanged by the covering involution of q and G_{216} acts transitively on $\mathfrak{h}_1, \dots, \mathfrak{h}_4$;
- b) the j -invariant of any smooth fibre of the elliptic fibration \mathfrak{h}_i or \mathfrak{h}'_i is equal to zero;
- c) each fibration has 6 reducible fibres of Kodaira's type IV , i.e. the union of three smooth rational curves intersecting at one point. The singular points in the reducible fibers of \mathfrak{h}_i and \mathfrak{h}'_i are mapped by q to the vertices of the triangle T_i ;
- d) each fibration has multisection index equal to 3.

Proof. Consider the equations (21) for X in $\mathbb{P}^1 \times \mathbb{P}^2$. The projections on the first factor $\mathfrak{h}_i : X \rightarrow \mathbb{P}^1$, $i = 1, \dots, 4$ are elliptic fibrations on X since the fibre over a generic point (u, v) is a smooth plane cubic. A second set of elliptic fibrations on X is given by $\mathfrak{h}'_i = \mathfrak{h}_i \circ \sigma$, where σ is the covering involution of q . Since all these fibrations are equivalent modulo the group generated by σ and G_{216} , it will be enough to prove properties b), c) and d) for \mathfrak{h}_1 .

The fibre of \mathfrak{h}_1 over a point (u, v) is the plane cubic defined by equation (22). This can be written also as

$$(u^2 + v^2 + \sqrt{3}uv)x^3 + (\epsilon u^2 + \epsilon^2 v^2 + \sqrt{3}uv)y^3 + (\epsilon^2 u^2 + \epsilon v^2 + \sqrt{3}uv)z^3 = 0.$$

Hence it is clear that all smooth fibres of \mathfrak{h}_1 are isomorphic to a Fermat cubic i.e. they are equianharmonic cubics. This system of plane cubics contains exactly 6 singular members which are the union of 3 lines meeting in one point (corresponding to the vanishing of the coefficients of x^3 , y^3 and z^3), giving 6 fibres of \mathfrak{h}_1 of type IV . The meeting points of the three lines in these reducible fibers are the inverse images by q of the vertices v_0, v_1, v_2 of the triangle T_1 (see section 2, (10)). This gives b) and c).

Let R be a curve on X intersecting each fibre B of \mathfrak{h}_1 in n points. The projection $q(R)$ to \mathbb{P}^2 is not a point since otherwise the polynomials P_1, P'_1 and F_1 would have a common zero (an easy computation shows that this is not the case). Hence $q(R)$ is a curve and

$$(q(R), q(B)) \leq (R, B) = n.$$

Since $q(B)$ is a plane cubic this implies that $n \geq 3$. Note that the fibration \mathfrak{h}_1 has 3-sections i.e. there are curves on X intersecting each fibre in 3 points, for example $X \cap \{x = 0\}$. Hence the multisection index of \mathfrak{h}_1 is 3, proving c). \square

Remark 7.6.

i) It is easy to notice that the degree 9 morphism

$$\mathbb{P}^2 \longrightarrow \mathbb{P}^2, (x, y, z) \longmapsto (x^3, y^3, z^3)$$

sends the sextic C_6 to a conic K such that everywhere tangent cubics to C_6 correspond to tangent lines to K . This induces a degree 9 morphism from X to the double cover of \mathbb{P}^2 branched along K isomorphic to $\mathbb{P}^1 \times \mathbb{P}^1$. The projections to the two factors give the fibrations $\mathfrak{h}_1, \mathfrak{h}'_1$.

ii) Each family of everywhere tangent cubics to C_6 corresponds to an even theta characteristic θ on C_6 with $h^0(\theta) = 2$.

The Picard lattice of X clearly contains the components of reducible fibers and the 3-sections of the elliptic fibrations in Corollary 7.5. In fact, we will prove that these curves generate a sublattice of S_X of finite index.

We first recall that the *discriminant group* A_M of a lattice M is the finite abelian group M^*/M , where $M^* = \text{Hom}(M, \mathbb{Z})$ is the dual lattice of L (see [40]). It can be easily proved that the order of A_M equals the absolute value of the determinant of the intersection matrix of M . Moreover, it is known that if M is a sublattice of a unimodular lattice and M^\perp is its orthogonal complement then $A_M \cong A_{M^\perp}$.

Lemma 7.7. *The Picard lattice S_X contains a proper sublattice M of rank 20 with*

$$A_M \cong \mathbb{Z}/3\mathbb{Z}^2 \oplus \mathbb{Z}/6\mathbb{Z} \oplus \mathbb{Z}/18\mathbb{Z}.$$

In particular $\text{rank } S_X = 20$ and $\text{rank } T_X = 2$.

Proof. We will denote by f_i, f'_i the singular fibres of the elliptic fibration \mathfrak{h}_1 corresponding to the vertex $v_i, i = 0, \dots, 2$ (see Corollary 7.5, c)). Let M be the sublattice of S_X generated by the following 20 divisor classes

$$h, l_i (i = 1, \dots, 7), l'_1, l'_2, l'_4, l'_5, l'_6, l'_7, m_1, m_2, m_3, m'_1, m'_2, n_1,$$

where:

h is the pull-back of a line by the double cover q ,

$$l_1 + l_2 + l_3 = f_1,$$

$l'_i = g_0(l_i), i = 1, 2$ are irreducible components of f'_1 ,

$l_i = g_1(l_{i-3}), l'_i = g_1(l'_{i-3}), i = 4, 5$ are irreducible components of $f_2 (f'_2)$,

$l_i = g_1^2(l_{i-5}), l'_i = g_1^2(l'_{i-5}), i = 6, 7$ are irreducible components of $f_3 (f'_3)$,

$m_i = g_3(l_i), i = 1, 2, 3$ are irreducible components of the fibre $g_3(f_1)$ of \mathfrak{h}_2 ,

$m'_i = g_3(l'_i), i = 1, 2$ are irreducible components of $g_3(f'_1)$,

$n_1 = g_5 g_4 g_1(l_1)$ is a irreducible component of a fibre of \mathfrak{h}_3 .

A MAPLE computation shows that the intersection matrix of the lattice M has determinant $d = -2^2 \cdot 3^5$. This implies that the 20 classes above are independent, i.e. M has rank 20, which is the maximum possible rank for the Picard lattice of

an algebraic $K3$ surface (see [5]). Hence S_X has rank 20, T_X has rank 2 and M is a sublattice of S_X of finite index. In particular, it follows that the discriminant group $A_{S_X} \cong A_{T_X}$ is generated by at most two elements.

It is not difficult to prove that a set of generators for M^* is given by the rows of the inverse of the intersection matrix of M . A direct computation of this matrix shows that A_M is isomorphic to $\mathbb{Z}/3\mathbb{Z}^2 \oplus \mathbb{Z}/6\mathbb{Z} \oplus \mathbb{Z}/18\mathbb{Z}$. Since this group has more than two generators, then A_M is not equal to A_{S_X} , i.e. M does not coincide with S_X . \square

It is known that two $K3$ surfaces with transcendental lattices of rank 2 are isomorphic if and only if their transcendental lattices are isomorphic (see [48]). Hence it is interesting to determine the structure of T_X .

The following result will be a useful tool in the proof (see [10], [31]).

Lemma 7.8. *Let $f : X \rightarrow \mathbb{P}^1$ be an elliptic fibration on a $K3$ surface X with multisection index l . Then there exists a jacobian fibration $J(f) : J(X) \rightarrow \mathbb{P}^1$ on a $K3$ surface $J(X)$ with singular fibres of the same type and*

$$\text{rank } T_{J(X)} = \text{rank } T_X, \quad \det T_X = l^2 \det T_{J(X)}.$$

Theorem 7.9. *The intersection matrix of the transcendental lattice of the $K3$ surface X with respect to a suitable basis is:*

$$T_X = \begin{pmatrix} 12 & 6 \\ 6 & 12 \end{pmatrix}.$$

Proof. By Lemma 7.7 the rank of T_X is equal to 2, we now determine its quadratic form.

The automorphism $g_4(x, y, z, w) = (x, \epsilon y, \epsilon z, \epsilon w)$ on $X = \{w^2 + \Phi_6(x, y, z) = 0\}$ clearly fixes the curve $\{x = 0\}$ pointwisely. Hence, by Theorem 7.1, g_4 has a non-symplectic action on X and g_4^* acts on T_X as an isometry with eigenvalues ϵ, ϵ^2 . Let $e \in T_X$, $e \neq 0$, then

$$0 = (e + g_4^*(e) + (g_4^*)^2(e), g_4^*(e)) = 2(e, g_4^*(e)) + (e, e).$$

Note that $e^2 = 2m$ for some positive integer m because the lattice $T_X \subset L$ is even and positive definite. Then the intersection matrix of T_X with respect to the basis $e, -g_4^*(e)$ is given by

$$(23) \quad \begin{pmatrix} 2m & m \\ m & 2m \end{pmatrix},$$

for some $m \in \mathbb{Z}$, $m > 0$ (see also Lemma 2.8, [43]). In particular, a direct computation shows that the discriminant group of the lattice T_X is isomorphic to $\mathbb{Z}/m\mathbb{Z} \oplus \mathbb{Z}/3m\mathbb{Z}$. We will now determine the integer m .

Let M be the proper sublattice of S_X as in Lemma 7.7. Since M has finite index in S_X , then it follows easily from the definition of discriminant group that there is an inclusion of $A_{S_X} \cong A_{T_X}$ in $A_M \cong \mathbb{Z}/3\mathbb{Z}^2 \oplus \mathbb{Z}/6\mathbb{Z} \oplus \mathbb{Z}/18\mathbb{Z}$. This implies that m is a proper divisor of 6.

Moreover, since the elliptic fibration \mathfrak{h}_1 on X has multisection index 3, it follows from Lemma 7.8 that 3 divides m .

Assume that $m = 3$ and let $J(\mathfrak{h}_1) : J(X) \rightarrow \mathbb{P}^1$ be the jacobian fibration associated to \mathfrak{h}_1 . By Lemma 7.8, $J(X)$ is a $K3$ surface, $\text{rank } T_{J(X)} = 2$ and $\det T_{J(X)} = 3$. According to [48] there exists a unique $K3$ surface with transcendental lattice of

this type and all its jacobian elliptic fibrations are classified in Theorem 3.1, [42]. Since no one of these fibrations has the same configuration of singular fibers as \mathfrak{h}_1 (see Proposition 7.5), this contradicts Lemma 7.8. Hence the only possible case is $m = 6$. \square

We conclude this section giving another model for the surface X .

Proposition 7.10. *The K3 surface X is birational to the double cover of \mathbb{P}^2 branched along a sextic with 8 nodes which admits a group of linear automorphisms isomorphic to A_4 .*

Proof. The lift of the involution g_0 to the cover $X = \{w^2 + \Phi_6(x, y, z) = 0\}$ given by

$$\tilde{g}_0(x, y, z, w) = (x, z, y, w)$$

is a non-symplectic involution. The fixed locus of \tilde{g}_0 is the genus two curve \tilde{L}_0 which is the double cover of the harmonic polar $L_0 = \{y - z = 0\}$ branched along $L_0 \cap C_6$. The quotient surface $R = X/(\tilde{g}_0)$ is a Del Pezzo surface of degree 1, the double cover of $\mathbb{P}^2/(g_0) \cong Q$, where Q is the quadratic cone with vertex equal to the orbit of the fixed point $p_0 = (0, 1, -1)$ of g_0 .

Let $b : R \rightarrow \mathbb{P}^2$ be the blowing-down of 8 disjoint (-1) -curves on R to points s_1, \dots, s_8 in \mathbb{P}^2 . The pencil of cubic curves through the eight points is the image of the elliptic pencil $|-K_R|$ on R . Note that the stabilizer of the point p_0 in the Hessian group is isomorphic to $2.A_4$ with center equal to (g_0) , thus the group A_4 acts naturally on R and on the elliptic pencil $|-K_R|$. The curve $B \in |-2K_R|$ is an A_4 -invariant member of the linear system $|-2K_R|$ and $b(B)$ is a plane sextic with 8 nodes at the points s_1, \dots, s_8 . Thus we see that X admits 9 isomorphic models as a double cover of the plane branched along a 8-nodal sextic with a linear action of A_4 . \square

Remark 7.11. In [33] the authors study a K3 surface birationally isomorphic to the double cover of \mathbb{P}^2 branched along the union of two triangles from the Hesse pencil. This surface has transcendental lattice of rank 2 with intersection matrix $diag(6, 6)$ and it admits a group of automorphisms isomorphic to $A_6 \rtimes \mathbb{Z}/4\mathbb{Z}$.

8. A K3 SURFACE WITH AN ACTION OF $SL(2, \mathbb{F}_3)$

We now study the K3 surface which is birational to the double cover of \mathbb{P}^2 branched along the sextic C'_6 defined by $\Phi'_6 = 0$.

We recall that C'_6 has 8 cusps in the base points q_1, \dots, q_8 of the Hesse pencil. The double cover of \mathbb{P}^2 branched along C'_6 is locally isomorphic to $z^2 + x^2 + y^3 = 0$ over each cusp of C'_6 , hence it has 8 singular points of type A_2 (see [5]). It is known that the minimal resolution of singularities of this surface is a K3 surface and that the exceptional curve over each singular point of type A_2 is the union of two rational curves intersecting in one point.

In this section we will study the properties of this K3 surface, which will be denoted by X' .

Proposition 8.1. *The K3 surface X' is birationally isomorphic to the quotient of the K3 surface X by the subgroup Γ of G_{216} . In particular, the group $SL(2, \mathbb{F}_3)$ is isomorphic to a group of automorphisms of X' .*

Proof. The minimal resolution of the double cover of \mathbb{P}^2 branched along C'_6 can be obtained by first resolving the singularities of C'_6 through the morphism $\gamma : S \rightarrow \mathbb{P}^2$ from diagram (16) and then taking the double cover $q' : X' \rightarrow S$ branched over the proper transform \bar{C}'_6 of C'_6 ([5]). Since $\beta^{-1}(p(C_6)) = \bar{C}'_6$ we have the following commutative diagram

$$(24) \quad \begin{array}{ccccc} X & \xrightarrow{\tilde{r}} & X/\Gamma & \xleftarrow{\tilde{\sigma}} & X' \\ q \downarrow & & \downarrow & & \downarrow \bar{q}' \\ \mathbb{P}^2 & \xrightarrow{p} & \mathbb{P}^2/\Gamma & \xleftarrow{\beta} & S \xrightarrow{\gamma} \mathbb{P}^2, \end{array}$$

where q and q' are the double covers branched along C_6 and C'_6 respectively, \tilde{r} and p are the natural quotient maps, $\tilde{\sigma}$ is the minimal resolution of singularities and the bottom maps are as in diagram (16). This gives the first statement. The second one follows from the isomorphism $G_{216}/\Gamma \cong SL(2, \mathbb{F}_3)$. \square

Remark 8.2. The points in X with non trivial stabilizer for the action of Γ are exactly the 24 preimages by q of the vertices of the triangles in the Hesse pencil. In fact these points belong to 8 orbits for the action of Γ and give 8 singular points of type A_2 in the quotient surface X/Γ (see Proposition 8.1).

We now describe some natural elliptic fibrations on the surface X' .

Proposition 8.3. *The pencil of lines through each of the cusps of C'_6 induces a jacobian fibration on X' with 3 singular fibres of Kodaira's type I_6 and one of type I_3 (i.e. cycles of 6 and 3 rational curves respectively).*

Proof. Let p be a cusp of C'_6 and h_p be the pencil of lines through p . The generic line in the pencil intersects C'_6 in p and 4 other distinct points, hence its preimage in X' is an elliptic curve. Thus h_p induces an elliptic fibration \tilde{h}_p on X' .

The pencil h_p contains 3 lines through 3 cusps and one line through 2 cusps of C'_6 since the cusps of C'_6 are 8 points in the Hesse configuration. The proper transform of a line containing 3 cusps is a disjoint union of two smooth rational curves. Together with the preimages of the cusps, the full preimage of such line in X' gives a fibre of \tilde{h}_p of Kodaira's type I_6 , described by the affine Dynkin diagram \tilde{A}_5 . Similarly, the preimage of a line containing 2 cusps gives a fibre of \tilde{h}_p of type I_3 (in this case the proper transform of the line does not split). Thus \tilde{h}_p has three fibers of type I_6 and one of type I_3 .

The exceptional divisor over the cusp p splits in two rational curves e_1, e_2 on X' and each of them intersect each fibre of \tilde{h}_p in one point i.e. it is a section of \tilde{h}_p . \square

Proposition 8.4. *The elliptic fibrations $\mathfrak{h}_i, \mathfrak{h}'_i, i = 1, \dots, 4$ on X induce 8 elliptic fibrations $\bar{\mathfrak{h}}_i, \bar{\mathfrak{h}}'_i$ on X' such that*

- $\bar{\mathfrak{h}}_i$ and $\bar{\mathfrak{h}}'_i$ are exchanged by the covering involution of q' and $SL(2, \mathbb{F}_3)$ acts transitively on $\bar{\mathfrak{h}}_1, \dots, \bar{\mathfrak{h}}_4$;
- the j -invariant of a smooth fibre of the elliptic fibration $\bar{\mathfrak{h}}_i$ or $\bar{\mathfrak{h}}'_i$ is equal to zero;
- each fibration has two fibres of Kodaira's type IV^* (i.e. 7 rational curves in the configuration described by the affine Dynkin diagram \tilde{E}_6) and two of type IV .

Proof. It will be enough to study the case of the fibration \mathfrak{h}_1 , since all other fibrations are projectively equivalent to this one by the action of G_{216} and σ .

Let g_1, g_2 be the generators of Γ as in section 4. The polynomials P_1, P'_1 and F_1 are eigenvectors for the action of Γ (Remark 5.3), hence it is clear from equation (22) that Γ preserves the elliptic fibration \mathfrak{h}_1 . In fact, g_1 acts on the basis of the fibration as an order three automorphism and fixes exactly the two fibers E_1, E'_1 such that $q(E_1) = B_1$ and $q(E'_1) = B'_1$. The automorphism g_2 preserves each fiber of \mathfrak{h}_1 and acts on it as an order 3 automorphism without fixed points. Hence it follows that the image of the elliptic fibration \mathfrak{h}_1 by the map $\tilde{\sigma}^{-1}\tilde{r}$ in diagram (24) is an elliptic fibration on X' . We will denote it by $\bar{\mathfrak{h}}_1$.

Now statements *a), b), c)* are easy consequences of the analogous statements in Proposition 7.5.

According to Proposition 5.2 the cubics B_1 and B'_1 contain the 9 vertices of the triangles T_2, T_3, T_4 in the Hesse pencil. Hence the fibers E_1, E'_1 contain each 9 points in the preimage of the 9 vertices by q . It follows from Remark 8.2 that the images of E_1 and E'_1 in X/Γ contain each 3 singular points of type A_2 . The preimage of one of these fibers in the minimal resolution X' is a fibre of type IV^* in the elliptic fibration $\bar{\mathfrak{h}}_1$ on X' (the union of 3 exceptional divisors of type A_2 and the proper transform of E_1 or E'_1).

It can be easily seen that the 6 singular fibers of \mathfrak{h}_1 of type IV belong to two orbits for the action of Γ . In fact, the singular points in each of these fibers are the preimages by q of the vertices of T_1 (see Proposition 7.5). The image of a singular fiber of type IV in X/Γ is a rational curve containing a singular point of type A_2 and its preimage in X' is again a fiber of type IV . Hence $\bar{\mathfrak{h}}_1$ has two fibers of type IV . \square

Remark 8.5. It can be proved that the image of any of these fibrations by the cover q' is a one-dimensional family of curves of degree 9 in \mathbb{P}^2 with 8 triple points in q_1, \dots, q_8 and 3 cusps on C'_6 . In fact, q' sends the fibre $\tilde{\sigma}^{-1}\tilde{r}(F_1)$ of $\bar{\mathfrak{h}}_1$ to the union of the 6 inflection lines through q_1 and q'_1 not containing q_0 , where the 3 lines through q_1 are double. Clearly, the similar statement is true for F'_1 (now the lines through p'_1 are double). Hence the image of a fibre of $\bar{\mathfrak{h}}_1$ is a plane curve D of degree 9 with 8 triple points at q_1, \dots, q_8 . Moreover, the curve D intersects the sextic C'_6 in 6 more points and since its inverse image in X' has genus one, then D must also have three cusps at smooth points of C'_6 which are resolved in the double cover q' .

Theorem 8.6. *The K3 surface X' is birationally isomorphic to the Kummer surface*

$$\text{Kum}(E_\epsilon \times E_\epsilon) = (E_\epsilon \times E_\epsilon)/(x \mapsto -x),$$

where E_ϵ is the elliptic curve with fundamental periods $1, \epsilon$. In particular its transcendental lattice has rank two and its intersection matrix with respect to a suitable basis is

$$T_{X'} = \begin{pmatrix} 4 & 2 \\ 2 & 4 \end{pmatrix}.$$

Proof. We will consider one of the jacobian fibrations on X' described in Proposition 8.3. Let M be the lattice generated by the two sections e_1, e_2 , the components of the 3 singular fibres of type I_6 not intersecting e_2 and the components of the

fibre of type I_3 . The intersection matrix of M has determinant $-2^2 \cdot 3^5$, hence $\text{rank } M = \text{rank } S_{X'} = 20$ and $\text{rank } T_{X'} = 2$.

The non-symplectic automorphism g_4 of order 3 on X induces an automorphism g'_4 on X' . Recall that g_4 fixes the curve $R = \{x = 0\}$ on X , hence g'_4 fixes the proper transform of $\tilde{r}(R)$ on X' . Thus by Theorem 7.1 g'_4 is a non-symplectic automorphism of order three on X' . This implies, as in the proof of Theorem 7.9, that the intersection matrix of $T_{X'}$ is of the form (23) with respect to a proper choice of generators, in particular its discriminant group is isomorphic to $\mathbb{Z}/3\mathbb{Z} \oplus \mathbb{Z}/3m\mathbb{Z}$.

A direct computation of M^* shows that the $A_M \cong \mathbb{Z}/3\mathbb{Z}^3 \oplus \mathbb{Z}/6\mathbb{Z}^2$. Since M is a sublattice of finite index of $S_{X'}$, then the discriminant group $A_{T_{X'}} \cong A_{S_{X'}}$ is a subgroup of A_M . This implies that $m \leq 2$.

By Theorem 3.1 (Table 1.1), [42] the unique $K3$ surface with transcendental lattice as in (23) with $m = 1$ has no jacobian elliptic fibration as in Proposition 8.3. Hence $m = 2$ and by [29] X' is isomorphic to the Kummer surface of the abelian surface $E_\epsilon \times E_\epsilon$. \square

Remark 8.7.

i) The general fibre of an elliptic fibration can be considered as a smooth elliptic curve E over the field K of rational functions of the basis and a section of the fibration corresponds to a K -rational point on E . Thus the general fibre of a jacobian fibration is an elliptic curve with a K -rational point, i.e. an abelian variety of dimension 1. The group of K -rational points is called *Mordell-Weil group* and it is known to be a finitely generated abelian group unless the fibration is trivial (this never happens for an elliptic fibration on a $K3$ surface).

In [31] it is proved that all elliptic fibrations on the Kummer surface $\text{Kum}(E_\epsilon \times E_\epsilon)$ are jacobian. All these fibrations and their Mordell-Weil groups are described in [42]. In particular it is proved that the Mordell-Weil group of the elliptic fibration in Proposition 8.3 is isomorphic to $\mathbb{Z} \oplus \mathbb{Z}/3\mathbb{Z}$ and those of the 8 elliptic fibrations in Proposition 8.4 are isomorphic to $\mathbb{Z}^2 \oplus \mathbb{Z}/3\mathbb{Z}$ (see Theorem 3.1, Table 1.3, No. 19, 30).

ii) The full automorphism group of X' has been computed in [32] while the full automorphism group of X is not known at present.

REFERENCES

- [1] M. Artin, *Coverings of the rational double points in characteristic p* , Complex analysis and algebraic geometry, pp. 11–22. Iwanami Shoten, Tokyo, (1977).
- [2] A. Aure, W. Decker, S. Popescu, K. Hulek, K. Ranestad, *The geometry of bielliptic surfaces in P^4* , Internat. J. Math., **4** (1993), 873–902.
- [3] A. Aure, W. Decker, S. Popescu, K. Hulek, K. Ranestad, *Szyzygies of abelian and bielliptic surfaces in P^4* , Internat. J. Math. **8** (1997), 849–919.
- [4] W. Barth, K. Hulek, *Projective models of Shioda modular surfaces*, Manuscripta Math., **50** (1985), 73–132.
- [5] W. Barth, K. Hulek, C. Peters, A. Van de Ven, *Compact complex surfaces* 2nd edition. Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge, Springer-Verlag, Berlin, 2004.
- [6] G. Barthel, F. Hirzebruch, T. Hofer, *Geradenkonfigurationen und Algebraische Flächen*, Vieweg Aspekte der Mathematik, Bd. 4. (1987).
- [7] S. Benvenuti, B. Feng, A. Hanany, Y.-H. He, *Counting BPS operators in gauge theories: quivers, syzygies and plethystics*, hep-th/0608050.
- [8] H. Burkhardt, *Untersuchungen aus dem Gebiete der hyperelliptischen Modulfunctionen. II*, Math. Ann., **38** (1890), 161–224.
- [9] A. Clebsch, F. Lindemann, *Vorlesungen über Geometrie*, B. 2, Leipzig, 1906.

- [10] F. Cossec, I. Dolgachev, *Enriques surfaces. I*, Progress in Mathematics, 76. Birkhuser Boston, Inc., Boston, MA, 1989.
- [11] H. S. M. Coxeter, W. O. J. Moser, *Generators and relations for discrete groups*, 4th edition, Ergebnisse der Mathematik und ihrer Grenzgebiete, 14. Springer-Verlag, Berlin-New York, 1980.
- [12] M. Demazure, *Surfaces de Del Pezzo-V, Modèles anticanoniques*, in “Séminaire sur les Singularités des Surfaces”, Lect. Notes in Math., vol. 777, Springer-Verlag, (1980), 61–70.
- [13] L. Dickson, *The points of inflexion of a plane cubic curve*, Ann. Math. **16** (1914), 50–66.
- [14] I. Dolgachev, V. Kanev, *Polar covariants of plane cubics and quartics*, Adv. Math., **98** (1993), no. 2, 216–301.
- [15] I. Dolgachev, *Abstract configurations in algebraic geometry*, in “The Fano Conference, Proceedings”, Univ. Torino, Torino, 2004, pp. 423–462.
- [16] F. Enriques, O. Chisini, *Lezioni sulla teoria geometrica delle equazioni e delle funzioni algebriche*, vol. I-IV, Bologna, Zanichelli, 1918 (New edition, 1985).
- [17] R. Friedman, *Algebraic surfaces and holomorphic vector bundles*, Universitext. Springer-Verlag, New York, 1998.
- [18] E. Freitag, R. Salvati Manni, *The Burkhardt group and modular forms*, Transform. Groups **9** (2004), 25–45.
- [19] H. Frium, *The group law on elliptic curves on Hesse form*, in “Finite fields with applications to coding theory, cryptography and related areas (Oaxaca, 2001)”, 123–151, Springer, Berlin, 2002.
- [20] G. van der Geer, *Note on abelian schemes of level three*. Math. Ann. , **278**, (1987), 401–408.
- [21] C. Grove, *I. The syzygetic pencil of cubics with a new geometrical development of its Hesse Group, G_{216} ; II. The complete Pappus hexagon*, Dissertation, Baltimore, Md., (1906).
- [22] T. Gustavsen, K. Ranestad, *A simple point counting algorithm for Hessian elliptic curves in characteristic three*, Appl. Algebra Engrg. Comm. Comput., **17** (2006), no. 2, 141–150.
- [23] G. Halphen, *Recherches sur les courbes planes du troisieme degre*, Math. Ann., **15** (1879), 359–379.
- [24] O. Hesse, *Über die Elimination der Variablen aus drei algebraischen Gleichungen vom zweiten Grade mit zwei Variablen*, J. Reine Angew. Math., **28** (1844), 68–96.
- [25] O. Hesse, *Über die Wendepunkte der Curven dritter Ordnung*, J. Reine Angew. Math., **28** (1844), 97–102.
- [26] F. Hirzebruch, *Arrangements of lines and algebraic surfaces. Arithmetic and geometry*, Vol. II, Progr. Math., 36, Birkhuser, Boston, Mass., (1983), 113–140.
- [27] T. Holcroft, *Harmonic cubics*, Ann. Math., **27** (1926), 568–576.
- [28] B. Hunt, *The geometry of some special arithmetic quotients*, Lect. Notes in Math., 1637. Springer-Verlag, Berlin, 1996.
- [29] H. Inose, T. Shioda, *On singular $K3$ surfaces*, Complex Analysis and Algebraic Geometry, Iwanami Shoten, (1977).
- [30] C. Jordan, *Mémoire sur les équations différentielles linéaires á intégrale algébrique*, Journal für Reine und Angew. Math. , **84** (1877), 89–215.
- [31] J. Keum, *A note on elliptic $K3$ surfaces*, Trans. of the AMS, **352**(1999), 2077–2086.
- [32] J. Keum, S. Kondō, *The automorphism groups of Kummer surfaces associated with the product of two elliptic curves*, Trans. of the AMS, **353**, (2000), 1469–1487.
- [33] J. Keum, K. Oguiso, D.-Q. Zhang, *Extensions of the alternating group of degree 6 in geometry of $K3$ surfaces*, European J. Combinatorics: Special issue on Groups and Geometries (in press). math.AG/0408105.
- [34] W. Lang, *Extremal rational elliptic surfaces in characteristic p . II. Surfaces with three or fewer singular fibres*, Ark. Mat. **32** (1994), no. 2, 423–448.
- [35] H. Maschke, *Aufstellung des vollen Formensystems einer quaternären Gruppe von 51840 linearen Substitutionen*, Math. Ann, **33** (1889), 317–344.
- [36] C. McMullen, *Complex dynamics and renormalization*, Annals of Mathematics Studies, 135. Princeton University Press, Princeton, NJ, (1994).
- [37] G. Miller, H. Blichfeldt, L. Dickson, *Theory and applications of finite groups*, Dover Publ. , New York, 1916 (reprinted in 1961).
- [38] R. Miranda, *The basic theory of elliptic surfaces* Dottorato di Ricerca in Matematica, ETS Editrice, Pisa, 1989.

- [39] S. Mukai, *Finite groups of automorphisms of K3 surfaces and the Mathieu group*, Invent. Math., **94** (1988), 183–221.
- [40] V. V. Nikulin, *Integral symmetric bilinear forms and its applications*, Math. USSR Izv., **14** (1980), 103–167.
- [41] V. V. Nikulin, *Finite automorphism groups of Kähler K3 surfaces*, Trudy Moskov. Mat. Obshch. **38** (1979), 73–137 [English translation *Trans. Moscow Math. Soc.* (1980), no. 2, 71–135].
- [42] K. Nishiyama, *The Jacobian fibrations on some K3 surfaces and their Mordell-Weil groups*, Japan. J. Math. (N.S.), **22** (1996), no. 2, 293–347.
- [43] K. Oguiso and D. Zhang, *The simple group of order 168 and K3 surfaces*, on “Complex Geometry (Göttingen, 2000)”, Springer, Berlin, 2002, pp. 165–184.
- [44] E. Pascal, *Repertorium der Höheren Mathematik, Bd.2: Geometrie*, Teubniger, Leipzig, 1910.
- [45] J. Semple, L. Roth, *Introduction to Algebraic Geometry*, Oxford University Press, 1949 (reprinted in 1987).
- [46] G. Shephard, J. Todd, *Finite unitary reflection groups* Canadian J. Math. **6**, (1954) 274–304.
- [47] T. Shioda, *On elliptic modular surfaces*, J. Math. Soc. Japan, **24** (1972), 20–59.
- [48] T. Shioda, H. Inose, *On Singular K3 surfaces*, Complex Analysis and Algebraic Geometry, Iwanami Shoten, (1977), 119–136.
- [49] N. Smart, *The Hessian form of an elliptic curve*, Cryptographic hardware and embedded systems—CHES 2001 (Paris), 118–125, Lecture Notes in Comput. Sci., 2162, Springer, Berlin, (2001).
- [50] T. Springer, *Invariant Theory*, Lect. Notes in Math., v. 585, Springer-Verlag, (1977).
- [51] B. van Geemen, *private notes*.
- [52] H. Verlinde, M. Wijnholt, *Building the Standard Model on a D3 brane*, hep-th/0508089.
- [53] H. Weber, *Lehrbuch der Algebra*, vol. 2, Braunschweig, F. Vieweg and Sohn, (1898) (reprinted by Plenum Publ. Co., New-York, 1961).
- [54] E. Zaslow, *Seidel’s mirror map for the torus*, Adv. Theor. Math. Phys., **9** (2005), no. 6, 999–1006.

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