Compositio Math. 140 (2004) 1432–1438
DOI: 10.1112/S0010437X04000533

Torsion on theta divisors of hyperelliptic Fermat Jacobians

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Abstract

We generalize a result of Anderson by showing that torsion points of certain orders cannot lie on a theta divisor in the Jacobians of hyperelliptic images of Fermat curves. The proofs utilize the explicit geometry of hyperelliptic Jacobians and their formal groups at the origin.

Introduction

Let ℓ be an odd prime, ζ a primitive ℓth-root of unity, $K = \mathbb{Q}(\zeta)$, and $\lambda = 1 - \zeta$, a generator for the lone prime of the ring of integers $\mathbb{Z}[\zeta]$ of K that lies over ℓ. For any $1 \leqslant a \leqslant \ell - 2$, let C_a be the non-singular projective curve defined over $\mathbb{Q}$ by the affine model $x^\ell = y(1-y)^a$. We let ∞ denote the lone point on C_a which is at infinity on this model. Note that C_a is an image of the ℓth Fermat curve, and has genus $g = (\ell-1)/2$. Let J_a denote the Jacobian of C_a, and $\phi : C_a \to J_a$ be the embedding sending a point $P \in C_a$ to the point of J_a corresponding to the divisor class of $P - \infty$. For any $m \geqslant 1$ we extend ϕ to a map on the mth-symmetric product $C_a^{(m)}$ of C_a, and let $\Theta = \phi(C_a^{(g-1)})$.

The automorphism $(x, y) \to (\zeta x, y)$ of C_a extends to an automorphism ξ of J_a, so we can endow J_a with complex multiplication (CM) by $\mathbb{Z}[\zeta]$ by defining an embedding $\iota : \mathbb{Z}[\zeta] \to \mathrm{End}(J_a)$ such that $\iota(\zeta) = \xi$. We write $[\alpha]$ for $\iota(\alpha)$. Let $\overline{K}$ be an algebraic closure of K. For any $\alpha \in \mathbb{Z}[\zeta]$, we let $J_a[\alpha]$ denote the kernel of $[\alpha]$ in $J_a(\overline{K})$, and for any ideal $\mathfrak{a} \subseteq \mathbb{Z}[\zeta]$, we let $J_a[\mathfrak{a}] = \bigcap_{\alpha \in \mathfrak{a}} J_a[\alpha]$. The following was proved in [And94].

Theorem (Anderson). *Let $\mathfrak{p}$ be a first degree prime of $\mathbb{Z}[\zeta]$. Then $J_a[\lambda\mathfrak{p}] \cap \Theta = J_a[\lambda] \cap \Theta$.*

For any $\mathfrak{a} \subseteq \mathbb{Z}[\zeta]$, let $J_a[\mathfrak{a}]'$ denote the non-trivial elements of $J_a[\mathfrak{a}]$, and for any point $Q \in J_a(\overline{K})$, let T_Q denote the translation-by-Q map on J_a. Let Z be the point $(0, 0)$ on C and $P = \phi(Z)$. Since $J_a[\lambda]$ is generated by P, Anderson's theorem is equivalent to the statement that $J_a[\mathfrak{p}]' \cap T^*_{vP}\Theta$ is empty for all $0 \leqslant v \leqslant \ell - 1$. The goal of this paper is to extend Anderson's result as best as we can to powers of primes of $\mathbb{Z}[\zeta]$ of arbitrary degree, at least in the case that C_a is hyperelliptic, when the geometry of J_a is more tractable. We note that for $1 \leqslant a \leqslant \ell - 2$, the only C_a which are hyperelliptic are C_1, $C_{(\ell-1)/2}$, and $C_{\ell-2}$. Since there are isomorphisms from $C_{(\ell-1)/2}$ and $C_{\ell-2}$ to C_1 which induce isomorphisms from Θ on $J_{(\ell-1)/2}$ and $J_{\ell-2}$ to Θ on J_1 translated by a λ-torsion point, we will lose no generality by concentrating on C_1.

Let $C = C_1$ and $J = J_1$. For any $i \in (\mathbb{Z}/\ell\mathbb{Z})^*$, let $\sigma_i \in G = \mathrm{Gal}(K/\mathbb{Q})$ be such that $\sigma_i(\zeta) = \zeta^i$. It is well known (and we will see in § 2) that the CM-type of J is $\Phi = \{\sigma_1, \ldots, \sigma_g\}$.

We prove two theorems.

Received 27 November 2002, accepted in final form 31 July 2003, published online 15 October 2004.
2000 Mathematics Subject Classification 11G10, 14K12.
Keywords: Fermat curves, torsion.

Theorem 1. *Let $\mathfrak{p}$ be a first or second degree prime of $\mathbb{Z}[\zeta]$. Then for any $n \geqslant 1$, $J[\lambda\mathfrak{p}^n] \cap \Theta = J[\lambda] \cap \Theta$.*

The theorem is proved in § 2 by showing that certain functions h_v on J, $1 \leqslant v \leqslant g$, which vanish on $T^*_{(g-v)P}\Theta$, have non-zero $\mathfrak{p}$-adic absolute value when evaluated at $J[\mathfrak{p}^n]'$. Since $J[\mathfrak{p}^n]$ lies in the kernel of reduction of J mod $\mathfrak{p}$, this is achieved by using the formal group $\mathcal{F}$ on the kernel of reduction mod $\mathfrak{p}$ to compute the $\mathfrak{p}$-adic absolute values of certain parameters s_i at the origin of J evaluated at $J[\mathfrak{p}^n]$, $1 \leqslant i \leqslant g$, and then by expanding h_v in the local ring at the origin in terms of the s_i.

The formal group calculation crucially depends on the assumption that $\mathfrak{p}$ is a first or second degree prime. Indeed, if $\pi \in \mathbb{Z}[\zeta]$ is a uniformizer at $\mathfrak{p}$ and prime to all of its other conjugates, then the $\mathfrak{p}^n$-torsion in $\mathcal{F}$ coincides with π^n-torsion, and we compute the $\mathfrak{p}$-adic absolute value of s_i evaluated at π^n-torsion by applying the formal implicit function theorem to $[\pi^n]$, thought of as an endomorphism of $\mathcal{F}$. This requires that the rank of the Jacobian of $[\pi]$ mod $\mathfrak{p}$ is $g-1$, which only happens when the intersection of Φ and the decomposition group G_0 of $\mathfrak{p}$ in G is the identity.

The assumption that C is hyperelliptic is used only to explicitly produce the s_i and the h_v, and in § 1 to compute the expansions of the h_v in terms of the s_i. It may well be that a more clever geometric argument will produce analogous results in the case that C_a is not hyperelliptic. Indeed, since this paper was written, using Galois-theoretic techniques, Simon has shown that Theorem 1 holds for any J_a as long as $\mathfrak{p}$ has norm greater than some explicit function of ℓ and the CM-type of J_a is non-degenerate. Simon also has some remarkable results constraining the orders of torsion points on the theta divisor of J_a when the orders are not necessarily the power of a single prime [Sim03].

There are, however, some cases when we can use formal groups to generalize Theorem 1 to primes of arbitrary degree. Let $\mathfrak{p} \neq (\lambda)$ be any prime of $\mathbb{Z}[\zeta]$, p the rational prime it lies over, and $f = \#(G_0)$. Let s be the number of cosets of G_0 in G which have non-trivial intersection with Φ, let W_r, $1 \leqslant r \leqslant s$, denote these intersections, and $d_r = \#(W_r)$. We arbitrarily choose an element $\sigma_{m_r} \in W_r$ for each $1 \leqslant r \leqslant s$. Given these choices we form a double indexed permutation $\omega(r,j)$, $1 \leqslant r \leqslant s$, $j \in \mathbb{Z}/d_r\mathbb{Z}$, of $(1,\ldots,g)$, by picking $\omega(r,j)$ such that $\sigma_{\omega(r,j)} \in W_r$, and if $\omega(r,j) \equiv m_r p^{e_{r,j}} \mod \ell$, with $0 \leqslant e_{r,j} < f$, then $0 = e_{r,1} < \cdots < e_{r,d_r}$.

For any integer i, let $\langle i \rangle$ denote the least non-negative residue of i modulo f. For each $1 \leqslant r \leqslant s$ and $j \in \mathbb{Z}/d_r\mathbb{Z}$, we set $E_{r,j} = \sum_{i \in \mathbb{Z}/d_r\mathbb{Z}} p^{\langle e_{r,j} - e_{r,i} \rangle}$. If r is such that there is a unique $j' \in \mathbb{Z}/d_r\mathbb{Z}$ such that $E_{r,j'}$ is minimal, we say that $\omega(r,j')$ is *admissible* for p. Let $[\cdot]$ denote the greatest integer function. If $0 \leqslant q \leqslant g-1$ is such that $[(g+q+1)/2] = \omega(r,j')$ for some $\omega(r,j')$ admissible for p, then we call q *good* for p. Let A_p denote the set of all q which are good for p, which depends only on the residue class of p mod ℓ.

Theorem 2. *$J[\mathfrak{p}]' \cap T^*_{vP}\Theta$ is empty for all $v \in \pm(A_p \cup \{g\})$.*

Note that when $\mathfrak{p}$ is a first or second degree prime, then Theorem 2 reduces to Theorem 1 in the case $n = 1$. The first improvement comes when $\ell = 5$, but in this case $J[\mathfrak{p}] \cap \Theta$ has been explicitly determined (see [BG00] or [Col86]). When $\ell = 7$, we get that $J[\mathfrak{p}]' \cap T^*_{vP}\Theta$ is empty for: all v when $p \equiv 2 \mod 7$; $v = 0, \pm1, \pm3$ when $p \equiv 3 \mod 7$; $v = \pm2, \pm3$ when $p \equiv 4 \mod 7$; and $v = \pm3$ when $p \equiv 5 \mod 7$.

The reason for the rather arcane hypotheses for Theorem 2 is that the $\mathfrak{p}$-adic absolute values of the s_i evaluated at $[\pi]$-torsion can no longer be calculated via the implicit function theorem, and are instead calculated (in [Gra]) for parameters S_i of a p-typical formal group isomorphic to $\mathcal{F}$ (see [Haz78]). The hypotheses are necessary to ensure that we can glean information on the $\mathfrak{p}$-adic absolute values of the s_i evaluated at $[\pi]$-torsion from the absolute values of the S_i.

To the author's taste, the proofs given here have some of the same flavor as Anderson's proof, without sharing many of the ingredients.

1. Expansions of functions on J

Let k be any field of characteristic other than ℓ, so that C defines a hyperelliptic curve of genus $g=(\ell-1)/2$ over k, with hyperelliptic involution $\gamma(x,y)=(x,\bar{y})$, where $\bar{y}=1-y$. We will identify points of J with the corresponding divisor classes in $\mathrm{Pic}^0(C)$. We write $\mathcal{D}_1 \sim \mathcal{D}_2$ to denote that two divisors on a variety are linearly equivalent, and let $cl(\mathcal{D})$ be the class of a divisor $\mathcal{D}$ modulo linear equivalence. It is well known that for any $Q \in C$, $Q+\gamma(Q) \sim 2\infty$, and that every divisor class $\mathcal{D} \in \mathrm{Pic}^0(C)$ can be uniquely represented by a divisor of the form $P_1+\cdots+P_r-r\infty$ for some $r \leqslant g$, where $P_i \neq \infty$, and for $i \neq j$, $P_i \neq \gamma(P_j)$. In particular, $[-1](P_1+\cdots+P_r-r\infty)=\gamma(P_1)+\cdots+\gamma(P_r)-r\infty$. Hence, Θ consists of divisor classes of the form $cl(P_1+\cdots+P_r-r\infty)$ for $r \leqslant g-1$, so is symmetric, and $J-\Theta$ consists of divisor classes of the form $cl(P_1+\cdots+P_g-g\infty)$, where $P_i \neq \infty$ and $P_i \neq \gamma(P_j)$ for $i \neq j$.

Via the surjective birational map $\phi : C^{(g)} \to J$, we identify symmetric functions on C^g with functions on J. Since $Z=(0,0) \in C$ is not fixed by γ, gZ is not a special divisor on C, and if $P=\phi(Z)$, $gP \notin \Theta$. So if $E \in C^{(g)}$ is the image of the g-tuple $(Z,\ldots,Z)$ under the natural projection from C^g to $C^{(g)}$, then ϕ is an isomorphism in a neighborhood of E, and induces an isomorphism between completed local rings $\hat{\mathcal{O}}_{J,gP}$ and $\hat{\mathcal{O}}_{C^{(g)},E}$. As in [Mil86], the latter is generated as a power series ring over k by the elementary symmetric functions $e_1,\ldots,e_g$ in any local parameter τ of C at Z. We always take $\tau=x$, and if $P_i=(x_i,y_i)$, $1 \leqslant i \leqslant g$, are independent generic points of C, we set $t_i=e_i(x_1,\ldots,x_g)$, so that $t_1,\ldots,t_g$ form a set of local parameters of J at gP. Our goal in this section is to write down functions B_v on J, $1 \leqslant v \leqslant g$ (determined up to constant multiples), with divisors $vT_P^*\Theta+T_{-vP}^*\Theta-(v+1)\Theta$, and to calculate the lead term of the expansion of B_v in $\hat{\mathcal{O}}_{J,gP}$ in terms of $t_1,\ldots,t_g$. We employ the techniques and some of the results of [AG01].

Let $H \subset J$ be the irreducible divisor on J representing divisor classes in $\mathrm{Pic}^0(C)$ of the form $\{cl(2Q_1+Q_2+\cdots+Q_{g-1}-g\infty) \mid Q_i \in C\}$. If $g=1$, we take H to be the zero divisor.

For any functions $F_i \in k(C)$, and points $Q_i \in C$, $1 \leqslant i \leqslant g$, let

$$D(F_1,\ldots,F_g)(Q_1,\ldots,Q_g)$$

denote the determinant $\det(F_i(Q_j))_{1\leqslant i,j\leqslant g}$.

As before, let $P_i=(x_i,y_i)$, $1 \leqslant i \leqslant g$, denote independent generic points on C, so $U = P_1+\cdots+P_g-g\infty$ is a generic point on J. For any $1 \leqslant v \leqslant g$, let

$$\begin{aligned} M_v &= D(x^v,\ldots,x^a,y,\ldots,yx^b)(P_1,\ldots,P_g), \\ N_v &= D(x^v,\ldots,x^a,y,\ldots,yx^b)(\gamma(P_1),\ldots,\gamma(P_g)) \\ &= D(x^v,\ldots,x^a,\bar{y},\ldots,\bar{y}x^b)(P_1,\ldots,P_g), \end{aligned}$$

where $a=[g+(v-1)/2]$, $b=[(v-2)/2]$. If $b=-1$, then $v=1$, and by convention the function y is omitted from the definitions of M_1 and N_1.

Proposition 1. *For any $1 \leqslant v \leqslant g$, we can take $B_v = N_v/\prod_{1\leqslant i<j\leqslant g}(x_i-x_j)$.*

In the case $v=1$, we have $N_1/\prod_{1\leqslant i<j\leqslant g}(x_i-x_j)=\pm t_g$, in which case the result follows from [AG01, Proposition 5]. So we assume now that $b \geqslant 0$. We need a few lemmas. We first investigate where M_v and N_v vanish when we specialize $P_1,\ldots,P_g$.

Lemma 1. *If $U \in J-\Theta-H-T_P^*\Theta-T_{-P}^*\Theta$, then $M_v(P_1,\ldots,P_g)=0$ if and only if $U \in T_{vP}^*\Theta$, and $N_v(P_1,\ldots,P_g)=0$ if and only if $U \in T_{-vP}^*\Theta$.*

Proof. If $U \in T^*_{vP}\Theta$, then $U + vP \in \Theta$, so there exist $Q_1, \dots, Q_{g-1} \in C$ such that $P_1 + \dots + P_g + Q_1 + \dots + Q_{g-1} \sim (2g+v-1)\infty - vZ$, hence a function $f \in \mathcal{L}((2g+v-1)\infty - vZ)$ which vanishes at $P_1, \dots, P_g$. Since $x^v, \dots, x^a, y, \dots, yx^b$ form a basis for $\mathcal{L}((2g+v-1)\infty - vZ)$, there is a non-trivial linear combination of $x^v, \dots, x^a, y, \dots, yx^b$ which vanishes at $P_1, \dots, P_g$, so $M_v(P_1, \dots, P_g) = 0$. The converse and the corresponding results for $N_v(P_1, \dots, P_g)$ are similar. □

Since the function M_vN_v is symmetric in $P_1, \dots, P_g$, we can consider it as a function $F(U)$ on J. Since it is regular on $C^{(g)}$ except where some P_i is specialized to ∞, on J it is regular on $J - \Theta$. The precise order of its pole at Θ can be read off by the recipe of [AG01, Lemma 1], and is computed to be $4g + 2v - 2$. Since Θ, H, and F are invariant under $[-1]^*$, we get that the divisor (F) of F is of the form

$$(F) = m(T^*_{vP}\Theta + T^*_{-vP}\Theta) + j(T^*_P\Theta + T^*_{-P}\Theta) + nH - (4g + 2v - 2)\Theta, \tag{1}$$

for some $m \geqslant 1$, $j \geqslant 0$, and $n \geqslant 0$. It is clear that M_vN_v vanishes on H, so $n \geqslant 1$, and if the characteristic of k is 2, then each of M_v and N_v are functions on J that vanish at H, so $n \geqslant 2$.

LEMMA 2. *We have $j \geqslant v$.*

Proof. Again, it follows from [AG01, Proposition 5] that the divisor of $t_g = x_1 \cdots x_g$ is $T^*_P\Theta + T^*_{-P}\Theta - 2\Theta$, so is a uniformizer for $T^*_P\Theta$ and $T^*_{-P}\Theta$. Expanding M_vN_v in $\hat{\mathcal{O}}_{J,gP}$ using $y_i = x_i^\ell + \cdots$, $1 \leqslant i \leqslant g$, in $\hat{\mathcal{O}}_{C,Z}$, we get that F/t_g^v is a power series in $t_1, \dots, t_g$, and hence is regular at gP, which gives the lemma. □

Let $\Delta(U) = \prod_{1 \leqslant i < j \leqslant g}(x_i - x_j)^2$. It is shown in [AG01, Proposition 7] that the divisor of Δ is $n'H - 4(g-1)\Theta$, where $n' = 2$ if the characteristic of k is 2 and $n' = 1$ otherwise.

LEMMA 3. *We have $(F/\Delta) = T^*_{vP}\Theta + T^*_{-vP}\Theta + v(T^*_P\Theta + T^*_{-P}\Theta) - (2v+2)\Theta$.*

Proof. It follows from (1) and Lemma 2 that

$$(F/\Delta) = m(T^*_{vP}\Theta + T^*_{-vP}\Theta) + j(T^*_P\Theta + T^*_{-P}\Theta) + I - (2v+2)\Theta,$$

for some $m \geqslant 1$ and $j \geqslant v$, where I is some effective divisor. However, by the theorem of the square, $T^*_{vP}\Theta + T^*_{-vP}\Theta \sim T^*_P\Theta + T^*_{-P}\Theta \sim 2\Theta$, so $I = 0$, $j = v$, and $m = 1$. □

Proof of Proposition 1. Lemma 3 states that

$$F_M(U) = M_v \Big/ \prod_{1 \leqslant i < j \leqslant g}(x_i - x_j), F_N(U) = N_v \Big/ \prod_{1 \leqslant i < j \leqslant g}(x_i - x_j),$$

are functions on J, such that the sum of the divisors $(F_M) + (F_N)$ is

$$T^*_{vP}\Theta + T^*_{-vP}\Theta + v(T^*_P\Theta + T^*_{-P}\Theta) - 2(v+1)\Theta.$$

Note that $F_N = [-1]^*F_M$. We get immediately that the polar divisors of F_M and F_N are each $(v+1)\Theta$, and by Lemma 1, using the irreducibility of Θ and the theorem of the square, that

$$(F_N) = vT^*_P + T^*_{-vP} - (v+1)\Theta, \tag{2}$$

so we can take $B_v = F_N$. □

PROPOSITION 2. *Take $1 \leqslant v \leqslant g$. Let $c = a - v + 1 = [g + (1-v)/2]$ and $d = v - b - 1 = [(v+1)/2]$. The lead term in the expansion of B_v in $\hat{\mathcal{O}}_{J,gP}$ in terms of $t_1, \dots, t_g$ is*

$$\pm\det(t_{c-i+j})_{1 \leqslant i,j \leqslant d},$$

so is of degree d, and includes the monomial $\pm t_c^d$.

Proof. Note that the statement of the theorem makes sense, since for $1 \leqslant i,j \leqslant d$, we have $1 \leqslant c-i+j \leqslant g$. Note also that the case $v=1$ follows from the choice $B_1 = \pm t_g$, so we can assume $b \geqslant 0$.

Recall that if $\nu = (\nu_1, \dots, \nu_g)$ is a g-tuple of exponents, then the generalized Vandermonde determinant a_ν in variables $z_1, \dots, z_g$ is $\det(z_i^{\nu_j})_{1 \leqslant i,j \leqslant g}$, and permuting the entries of ν changes a_ν by at most a sign. In particular, if δ is the g-tuple $(g-1, g-2, \dots, 1, 0)$, then a_δ is the standard Vandermonde determinant. An L-tuple of positive integers $\eta = (\eta_1, \dots, \eta_L)$, $\eta_1 \geqslant \cdots \geqslant \eta_L$, is called a partition of length L. If $L \leqslant g$, we can append zeros to η to make it a g-tuple, and define $s_\eta = a_{\eta+\delta}/a_\delta$, which is called the Schur function corresponding to η (see [Mac79]). Recall that the conjugate partition of η is defined to be the partition $\mu = (\mu_1, \dots, \mu_m)$, where $m = \eta_1$, and $\mu_i = \#\{1 \leqslant j \leqslant L | \eta_j \geqslant i\}$. It is shown in [Mac79, p. 41], that

$$s_\eta = \det(e_{\mu_i - i + j})_{1 \leqslant i,j \leqslant m}, \tag{3}$$

where e_ϵ denotes the ϵth-elementary symmetric function in $z_1, \dots, z_g$, with the convention that $e_0 = 1$, and $e_\epsilon = 0$ for $\epsilon < 0$ or $\epsilon > g$.

Using that $y = \sum_{i \geqslant 1} \kappa_i x^{\ell i}$ in $\hat{\mathcal{O}}_{C,Z}$, with $\kappa_i = (2(i-1))!/i!(i-1)!$, we get that N_v can be expanded as an infinite sum of generalized Vandermonde determinants in $x_1, \dots, x_g$, with exponent vectors

$$(v, v+1, \dots, a, i_0\ell, i_1\ell + 1, \dots, i_b\ell + b), \tag{4}$$

$i_j \geqslant 0$, $0 \leqslant j \leqslant b$, and coefficients $\pm \prod_{j=0}^{b} \kappa_{i_j}$ (where we set $\kappa_0 = 1$). Hence, B_v can be expanded as an infinite sum of Schur functions s_η in $x_1, \dots, x_g$, with coefficients $\pm \prod_{j=0}^{b} \kappa_{i_j}$, where η depends on the choice of $i_0, \dots, i_b$. Let us first calculate s_η when $i_0 = \cdots = i_b = 0$. Ordering (4) from largest to smallest gives $(a, \dots, v, b, \dots, 0)$ for $\eta + \delta$, so η is the partition $(d, \dots, d)$ of length c. Hence, the conjugate μ of η is the partition $(c, \dots, c)$ of length d. So by (3), $\pm s_\eta$ is the determinant in the statement of the proposition. It remains to be shown that the total degree of every monomial in s_η for the η corresponding to any other choice of $i_0, \dots, i_b$ is greater than d.

Suppose now that for some $0 < r \leqslant b+1$, r of the i_j are positive, and we have reordered (4) from largest to smallest, so for some permutation $j_1, \dots, j_{b+1}$ of $0, \dots, b$, we get that $\eta + \delta$ is

$$(i_{j_1}\ell + j_1, \dots, i_{j_r}\ell + j_r, a, \dots, v, j_{r+1}, \dots, j_{b+1}).$$

Subtracting δ to find η shows that $\eta_i \geqslant d + r$ for all $1 \leqslant i \leqslant c + r$. Hence, the conjugate partition μ to η has $\mu_i \geqslant c + r$ for all $1 \leqslant i \leqslant d + r$. In particular, if $m = \eta_1$, since $c \geqslant d$, e_0 does not appear in the first $d + r$ columns of the matrix $[e_{\mu_i + i - j}]_{1 \leqslant i,j \leqslant m}$. Hence, by (3), every monomial in s_η has total degree at least $d + r > d$, so we are done. □

2. Proofs of the theorems

From the results of § 1, we see that $s_i = T_{gP}^* t_i$, $1 \leqslant i \leqslant g$, form a system of parameters for J at the origin O, for J defined over K, or for J defined over any residue field $\mathbb{Z}[\zeta]/\mathfrak{p}$, for any prime $\mathfrak{p} \subseteq \mathbb{Z}[\zeta]$ other than (λ). As a result, s_i, $1 \leqslant i \leqslant g$, are a set of parameters for the formal group $\mathcal{F}$ of J at the origin defined over $\mathbb{Z}[1/\ell][\zeta]$. Furthermore, for any $\alpha \in \mathbb{Z}[\zeta]$, we have power series $\rho(\alpha)_i$, $1 \leqslant i \leqslant g$, with coefficients in $\mathbb{Z}[1/\ell][\zeta]$, such that $[\alpha]^* s_i = \rho(\alpha)_i(s_1, \dots, s_g)$ in $\hat{\mathcal{O}}_{J,O}$. The map $\alpha \to \rho(\alpha) = (\rho(\alpha)_1, \dots, \rho(\alpha)_g)$ gives an embedding of $\mathbb{Z}[\zeta]$ into the endomorphism ring of $\mathcal{F}$. Since gP is fixed by $[\zeta]$, we see that $[\zeta]^* s_i = \zeta^i s_i$, confirming that Φ is the CM-type of J. Therefore,

$$\rho(\alpha)_i(s_1, \dots, s_g) = \sigma_i(\alpha) s_i + (d^o \geqslant 2), \tag{5}$$

where $(d^o \geqslant n)$ denotes a power series, all of whose terms have total degree at least n.

Let $\mathfrak{p} \neq (\lambda)$ be a prime of K, and for all $i \in (\mathbb{Z}/\ell\mathbb{Z})^*$, let $\mathfrak{p}_i = \sigma_i(\mathfrak{p})$, and let $K_{\mathfrak{p}_i}$ be the completion of K at $\mathfrak{p}_i$. Let $\mathfrak{m}_i$ be the maximal ideal in the valuation ring $\mathcal{O}_i$ of an algebraic closure of $K_{\mathfrak{p}_i}$. For any $i \in (\mathbb{Z}/\ell\mathbb{Z})^*$, we can consider $\mathcal{F}$ to be defined over $R_i = \mathbb{Z}[\zeta]_{\mathfrak{p}_i}$, in which case we can identify $\mathcal{F}(\mathfrak{m}_i)$ with the kernel of reduction of $J(\mathcal{O}_i)$ mod $\mathfrak{m}_i$.

By (5), for any $1 \leqslant i \leqslant g$ and any $\alpha \in \mathfrak{p}$, the isogeny $[\alpha]$ is not separable mod $\mathfrak{p}_i$, so $J[\mathfrak{p}^n]$ is in the kernel of reduction mod $\mathfrak{m}_i$ for any $n \geqslant 1$. Now fix any i, $1 \leqslant i \leqslant g$. For any $\alpha \in \mathbb{Z}[\zeta]$, let $\mathcal{F}[\alpha]$ denote the kernel of $\rho(\alpha)$ in $\mathcal{F}(\mathfrak{m}_i)$, and for any ideal $\mathfrak{a} \subseteq \mathbb{Z}[\zeta]$, let $\mathcal{F}[\mathfrak{a}] = \bigcap_{\alpha\in\mathfrak{a}} \mathcal{F}[\alpha]$. Hence, for any $n \geqslant 1$ we can identify $J[\mathfrak{p}^n] = \mathcal{F}[\mathfrak{p}^n]$. Let $\pi \in \mathbb{Z}[\zeta]$ be a uniformizer at $\mathfrak{p}$ which is prime to all other conjugates of $\mathfrak{p}$. It is easy to see that

$$\mathcal{F}[\mathfrak{p}^n] = \mathcal{F}[\pi^n]. \tag{6}$$

Indeed, the containment of the left-hand side of (6) in the right-hand side follows by definition, and since for any $a \leqslant b$, $(\mathfrak{p}^b, \pi^a) = \mathfrak{p}^a$, it suffices to show the reverse inclusion for those n which are a multiple of the class number h of K. However, if $(\alpha) = \mathfrak{p}^h$, then $\pi^h = \beta\alpha$, for some $\beta \in \mathbb{Z}[\zeta]$ prime to $\mathfrak{p}$, so $\rho(\beta)$ is an automorphism of $\mathcal{F}$ over R_i.

Proof of Theorem 1. We now assume that $\mathfrak{p}$ is a first or second degree prime and that $n \geqslant 1$. As above, fix an i, $1 \leqslant i \leqslant g$. Note that $\mathcal{F}[\pi^n]$ is precisely the set of solutions in $\mathcal{O}_i$ to the simultaneous equations

$$0 = \rho(\pi^n)_j(s_1, \ldots, s_g) = \sigma_j(\pi^n)s_j + (d^o \geqslant 2), \tag{7}$$

for $1 \leqslant j \leqslant g$. Since for any $1 \leqslant j \leqslant g$, $j \neq i$, $\sigma_j(\pi^n)$ is a unit in R_i, by the formal implicit function theorem (see, e.g., [Gra]), there are power series χ_j, $j \neq i$, over R_i, without constant or linear term, such that the solutions to (7) are precisely the same as those of the system

$$s_j = \chi_j(s_i), j \neq i; V(s_i) = 0,$$

where V is obtained by substituting $s_j = \chi_j(s_i)$ for all $j \neq i$ into the equation $0 = \rho(\alpha)_i(s_1, \ldots, s_g)$. Hence, s_i takes on different values at every point of $J[\mathfrak{p}^n]$, and since it vanishes at the origin, for every $Q \in J[\mathfrak{p}^n]'$, we have $s_i(Q) \neq 0$. Since χ_j is without constant or linear term, $|s_i(Q)| > |s_j(Q)|$ for any $j \neq i$, where $|\cdot|$ denotes an absolute value on $\mathcal{O}_i$. Now pick any $1 \leqslant v \leqslant g$. Let $h_v = T^*_{gP}B_v$, and let $c = [g + (1-v)/2]$. Then by Proposition 2, the lead term in the expansion of h_v at O in terms $s_1, \ldots, s_g$, is of degree $d = [(v+1)/2]$ and contains the monomial $\pm s_c^d$. Hence, $h_v(Q) \neq 0$, since taking $i = c$, there is a unique term in the expansion of $h_v(Q)$ in terms of $s_j(Q)$, $1 \leqslant j \leqslant g$, of maximal absolute value over $\mathcal{O}_i$.

Note that the divisor of h_v is

$$vT^*_{(g+1)P}\Theta + T^*_{(g-v)P}\Theta - (v+1)T^*_{gP}\Theta.$$

Since $h_v(Q) \neq 0$,

$$Q \notin T^*_{(g-v)P}\Theta \tag{8}$$

for all $1 \leqslant v \leqslant g$. Since Θ is symmetric, replacing Q by $[-1]Q$ also gives (8) for $g+1 \leqslant v \leqslant 2g-1$. Finally, note that $Q \notin T^*_{\pm gP}\Theta$, since the origin does not lie on $T^*_{\pm gP}\Theta$ mod $\mathfrak{m}_i$, and Q is in the kernel of reduction mod $\mathfrak{m}_i$. This shows that (8) also holds for $v = 0, 2g$, and gives us the theorem. $\square$

Proof of Theorem 2. Assume now that $\mathfrak{p}$ is a prime of K of arbitrary residue degree f that lies over the rational prime $p \neq \ell$. As above, fix an i, $1 \leqslant i \leqslant g$, and set $\mathfrak{p}_i = \sigma_i(\mathfrak{p})$.

It is now a seemingly hard problem in general to compute $|s_j(Q)|$ for some $1 \leqslant j \leqslant g$, $Q \in \mathcal{F}[\mathfrak{p}]'$, and $|\cdot|$ an absolute value on $\mathcal{O}_i$. However, in [Gra] such a problem is solved under the assumptions that $\mathcal{F}$ has 'complex multiplication' by $\mathbb{Z}[\zeta]$ with CM-type Φ (i.e. (5) holds), that there is an $\alpha \in \mathbb{Z}[\zeta]$ such that $[\alpha]$ reduces to the Frobenius endomorphism of $\mathcal{F}$ mod $\mathfrak{p}_i$, with the factorization $(\alpha) = \prod_{\phi\in\Phi} \phi^{-1}(\mathfrak{p}_i)$ (which is just the congruence relation from the theory of complex multiplication of abelian varieties), that $\mathcal{F}[\phi^{-1}(\mathfrak{p}_i)^m] \cong \mathbb{Z}[\zeta]/\phi^{-1}(\mathfrak{p}_i)^m$ for every $m \geqslant 1$ and every $\phi \in \Phi$ (which follows since J has full complex multiplication by $\mathbb{Z}[\zeta]$), and also that $\mathcal{F}$ is a p-typical group (see [Haz78]), which $\mathcal{F}$ is not.

However, as described in [Gra, § 2], there is a p-typical formal group $\mathcal{G}$ over R_i (called the 'p-typification' of $\mathcal{F}$), and a strict isomorphism $\psi = (\psi_m)_{1\leqslant m\leqslant g}$ over R_i from $\mathcal{F}$ to $\mathcal{G}$, so that if S_m, $1 \leqslant m \leqslant g$, are the parameters of $\mathcal{G}$, then

$$S_m = \psi_m(s_1, \dots, s_g) = s_m + (d^o \geqslant 2). \tag{9}$$

It follows from [Gra, Lemma 4] that $\mathcal{G}$ is now a formal group over R_i with complex multiplication by $\mathbb{Z}[\zeta]$ with CM-type Φ, and it follows from the existence of ψ that for the same α as for $\mathcal{F}$, the endomorphism $[\alpha]$ on $\mathcal{G}$ reduces to the Frobenius endomorphism of $\mathcal{G}$ mod $\mathfrak{p}_i$, and that $\mathcal{G}[\phi^{-1}(\mathfrak{p}_i)^m] \cong \mathbb{Z}[\zeta]/\phi^{-1}(\mathfrak{p}_i)^m$ for every $m \geqslant 1$ and every $\phi \in \Phi$. Hence, $\mathcal{G}$ satisfies the hypotheses of [Gra, Proposition 1], whose conclusion gives us the following proposition.

Proposition 3. *Let $\omega(r, j)$ and $E_{r,j}$ be as in the Introduction, and let $S_1, \dots, S_g$ be the parameters for $\mathcal{G}$. Let w be the normalized $\mathfrak{p}_i$-adic valuation extended to $\mathcal{O}_i$. Then for any $Q \in J[\mathfrak{p}]'$, $w(S_{\omega(r,j)}(Q)) = (1/(p^f - 1))E_{r,j}$.*

Hence, if $\omega(r, j')$ is admissible for p and $Q \in J[\mathfrak{p}]'$, $w(S_{\omega(r,j')}(Q))$ is the unique minimal valuation among all $w(S_{\omega(r,j)}(Q))$, $j \in \mathbb{Z}/d_rZ$. Furthermore, by [Gra, Remark 2], $w(S_{\omega(r,j')}(Q))$ is the unique minimal valuation among $w(S_m(Q))$ for all $1 \leqslant m \leqslant g$. So by (9), the same must be true for $w(s_{\omega(r,j')}(Q))$. Therefore, as in the proof of Theorem 1, if $[g + (1 - v)/2] = \omega(r, j')$, that is, if $q = g - v$ is good for p, then $h_v(Q) \neq 0$. We conclude as in (8) that $Q \notin T^*_{qP}\Theta$. Again replacing Q by $[-1]Q$ shows that $Q \notin T^*_{-qP}\Theta$. Finally, by the same reason as in the proof of Theorem 1, $Q \notin T^*_{\pm gP}\Theta$. □

Remark. See [GS] for a complete determination of the torsion of J that lies on $\phi(C)$.

References

And94 G. Anderson, *Torsion points on Jacobians of quotients of Fermat curves and p-adic soliton theory*, Invent. Math. **118** (1994), 475–492.

AG01 J. Arledge and D. Grant, *An explicit theorem of the square for hyperelliptic Jacobians*, Michigan Math. J. **49** (2001), 485–492.

BG00 J. Boxall and D. Grant, *Examples of torsion points on genus 2 curves*, Trans. Amer. Math. Soc. **352** (2000), 4533–4555.

Col86 R. F. Coleman, *Torsion points on Fermat curves*, Compositio Math. **58** (1986), 191–208.

Gra D. Grant, *Geometric proofs of reciprocity laws*, J. reine angew. Math., to appear.

GS D. Grant and D. Shaulis, *The cuspidal torsion packet on hyperelliptic Fermat quotients*, J. Théor. Nombres Bordeaux, to appear.

Haz78 M. Hazewinkel, *Formal groups and applications* (Academic Press, New York, 1978).

Mac79 I. G. Macdonald, *Symmetric functions and Hall polynomials* (Oxford University Press, Oxford, 1979).

Mil86 J. Milne, *Jacobian varieties*, in *Arithmetic Geometry*, eds G. Cornell and J. Silverman (Springer, New York, 1986).

Sim03 B. Simon, *Torsion points on a theta divisor in the Jacobian of a Fermat quotient*, Thesis, University of Colorado at Boulder (2003).

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