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EXTENDING KATO'S RESULT TO ELLIPTIC CURVES WITH p-ISOGENIES

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Abstract. Let E be an elliptic curve without complex multiplication defined over $\mathbb{Q}$ and let p be an odd prime number at which E has good and ordinary reduction. Kato has proved in [Kat04] half of the main conjecture for E under the condition that the representation $\rho_p \colon G_{\mathbb{Q}} \longrightarrow \operatorname{Aut}(T_pE)$ of the absolute Galois group of $\mathbb{Q}$ attached to the Tate module T_pE is surjective. We prove here that the result still holds if E admits an isogeny of degree p. As a by-product, we show that the p-adic L-functions attached to an elliptic curve with good ordinary reduction at p is always an integral series.

1. Introduction

Let E be an elliptic curve without complex multiplication defined over $\mathbb{Q}$ and let $p > 2$ be a prime number. Suppose that E has good ordinary reduction at p. We denote by $\rho_p \colon G_{\mathbb{Q}} \longrightarrow \operatorname{Aut}(T_pE)$ the representation of the absolute Galois group of $\mathbb{Q}$ attached to the Tate module T_pE.

Let E_{p^∞} be the group of all points on E whose order is a power of p. Let $\mathbb{Q}_\infty$ be the cyclotomic $\mathbb{Z}_p$-extension and $\mathbb{Q}_n$ its n-th layer. The Selmer group of E is defined as the kernel of the map

$$\mathcal{S}(E/\mathbb{Q}_n) = \ker\bigl(\mathrm{H}^1(\mathbb{Q}_n, E_{p^\infty}) \longrightarrow \prod_v \mathrm{H}^1(\mathbb{Q}_{n,v}, E)\bigr),$$

where the product runs over all places v in $\mathbb{Q}_n$. The Pontryagin dual of the direct limit of these groups under the restriction maps

$$X(E/\mathbb{Q}_\infty) = \operatorname{Hom}\bigl(\varinjlim \mathcal{S}(E/\mathbb{Q}_n), {}^{\mathbb{Q}_p}\!/\!{}_{\mathbb{Z}_p}\bigr)$$

has naturally the structure of a finitely generated Λ-module, if Λ denotes the Iwasawa algebra of the $\mathbb{Z}_p$-extension $\mathbb{Q}_\infty/\mathbb{Q}$. By Theorem 17.4 of [Kat04], we know that $X(E/\mathbb{Q}_\infty)$ is Λ-torsion. The characteristic ideal $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ in Λ is an important algebraic object attached to E and p.

On the analytic side, Mazur and Swinnerton-Dyer have constructed in [MSD74] a p-adic L-function $\mathcal{L}_p(E/\mathbb{Q}, T)$ in $\Lambda \otimes \mathbb{Q}_p$. See section 3 for more details. It was conjectured that this series has integral coefficients. We will prove the following extension of Proposition 3.7 in [GV00].

Theorem 5. *The analytic p-adic L-function $\mathcal{L}_p(E/\mathbb{Q}, T)$ belongs to Λ for all elliptic curves $E/\mathbb{Q}$ with good ordinary reduction at $p > 2$.*

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The conclusion can certainly not be extended to the supersingular case since the p-adic L-functions in this case will never be integral. The supersingular case is well explained in [Pol03] where it is shown how one can extract integral power series.

The main conjecture asserts that the element $\mathcal{L}_p(E/\mathbb{Q},T)$ generates the characteristic ideal $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$. Kato has proved in [Kat04] half of the main conjecture under the assumption that the representation ρ_p is surjective. Our aim is to extend his result to curves where the $G_\mathbb{Q}$-module $E[p]$ is reducible.

Theorem 4. *Let $E/\mathbb{Q}$ be an elliptic curve without complex multiplication and let $p > 2$ be a prime. Suppose that E has good ordinary reduction at p and that the representation ρ_p is either surjective or that $E[p]$ is reducible. Then* $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ *divides the ideal generated by $\mathcal{L}_p(E/\mathbb{Q},T)$.*

The same argument does not extend to the remaining cases; for them we only obtain a conditional result. See Proposition 7.

In special cases, Greenberg and Vatsal have proved in [GV00] the full main conjecture. Namely if the E admits an isogeny of degree p whose kernel is either ramified at p and odd or unramified at p and even.

The paper consists of two parts. The first part concerns tha so-called fine Selmer group. The existence of Kato's Euler system gives directly a bound on this group. We use a result of Coates and Sujatha in [CS05] to strengthen the usual bound.

The second part transfers the bound from the fine Selmer group to the Selmer group using global duality. The proof of theorem 4 is first done on the so-called optimal curve where one knows already that the p-adic L-function is integral.

2. The fine Selmer group

Let E be an elliptic curve defined over $\mathbb{Q}$ and let p be any odd prime. We define the fine[1] Selmer group to be the subgroup of $\mathcal{S}(E/\mathbb{Q}_n)$ defined by imposing stronger conditions at the completion $\mathbb{Q}_{n,\mathfrak{p}}$ of $\mathbb{Q}_n$ at the unique prime $\mathfrak{p}$ above p :

$$0 \longrightarrow \mathcal{R}(E/\mathbb{Q}_n) \longrightarrow \mathcal{S}(E/\mathbb{Q}_n) \longrightarrow \mathrm{H}^1(\mathbb{Q}_{n,\mathfrak{p}}, E_{p^\infty})$$

The dual of the direct limit of the groups $\mathcal{R}(E/\mathbb{Q}_n)$ will be denoted by $Y(E/\mathbb{Q}_\infty)$; it is again a finitely generated Λ-module. Theorem 12.4.1 in [Kat04] proves that $Y(E/\mathbb{Q}_\infty)$ is Λ-torsion. Denote by $\operatorname{char}_\Lambda(Y(E/\mathbb{Q}_\infty))$ the characteristic ideal of $Y(E/\mathbb{Q}_\infty)$ in Λ.

Kato constructs an Euler system $\mathbf{c}$ attached to E and p. This is a collection of cohomology classes $\mathbf{c}_K \in H^1(K, T_pE)$ for sufficiently many abelian extensions K of $\mathbb{Q}$, including $K = \mathbb{Q}(\mu[p^k])$ for all $k \geqslant 0$. The norm compatibility imposed on an Euler system, provides us with an element $\mathbf{c}_\infty$ in the projective limit

$$\mathbf{c}_\infty \in \varprojlim_n \mathrm{H}^1(\mathbb{Q}_n, T_pE) = \mathrm{H}^1_\infty(\mathbb{Q}, T_pE)$$

where the limit follows the corestriction map. We also recall that $\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)$ is a Λ-module of rank 1. The ideal

$$\operatorname{ind}_\Lambda(\mathbf{c}_\infty) = \{\psi(\mathbf{c}_\infty) \mid \psi \in \operatorname{Hom}_\Lambda(\mathrm{H}^1_\infty(\mathbb{Q}, T_pE), \Lambda)\}$$

in Λ measures the Λ-divisibility of $\mathbf{c}_\infty$ in $\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)$.

[1] This group is sometimes called the "strict" or "restricted" Selmer group.

Lemma 1. *Let E be an elliptic curve and p an odd prime such that E admits an isogeny of degree p. Then the fine Selmer group $Y(E/\mathbb{Q}_\infty)$ is a finitely generated $\mathbb{Z}_p$-module, i.e. its μ-invariant vanishes.*

Proof. Let $\phi\colon E \longrightarrow E'$ be an isogeny with cyclic kernel $E[\phi]$ of order p defined over $\mathbb{Q}$. The extension K of $\mathbb{Q}$ fixed by the kernel of $\rho_\phi\colon G_\mathbb{Q} \longrightarrow \mathrm{Aut}(E[\phi])$ is a cyclic extension of degree dividing $p-1$. Let Δ be the Galois group of $K/\mathbb{Q}$. Over the abelian field K, the curve admits a p-torsion point. We can therefore apply Corollary 3.6 in [CS05] (a consequence of the theorem of Ferrero-Washington) to $Y(E/K_\infty)$ where K_∞ is the cyclotomic $\mathbb{Z}_p$-extension of K. This proves that $Y(E/K_\infty)$ is a finitely generated $\mathbb{Z}_p$-module. Write $\mathcal{R}(E/\mathbb{Q}_\infty)$ and $\mathcal{R}(E/K_\infty)$ for the dual of $Y(E/\mathbb{Q}_\infty)$ and $Y(E/K_\infty)$ respectively. Then we have the following diagram

$$\begin{tikzcd}
0 \arrow[r] & \mathcal{R}(E/K_\infty)^\Delta \arrow[r] & \mathrm{H}^1(K_\infty, E_{p^\infty})^\Delta \\
0 \arrow[r] & \mathcal{R}(E/\mathbb{Q}_\infty) \arrow[r] \arrow[u] & \mathrm{H}^1(\mathbb{Q}_\infty, E_{p^\infty}) \arrow[u] \\
 & & \mathrm{H}^1(\Delta, E(K_\infty)_{p^\infty}) \arrow[u, hook]
\end{tikzcd}$$

and since the group Δ is of order prime to p, the kernel on the right is trivial. We deduce that the left hand side is injective, too, and hence that the dual map $Y(E/K_\infty) \longrightarrow Y(E/\mathbb{Q}_\infty)$ is surjective. Therefore $Y(E/\mathbb{Q}_\infty)$ is a finitely generated $\mathbb{Z}_p$-module. □

Theorem 2. *If $E/\mathbb{Q}$ is an elliptic curve without complex multiplication and $p > 2$ a prime such that the representation $\rho_p\colon G_\mathbb{Q} \longrightarrow \mathrm{Aut}(T_pE)$ is either surjective or that $E[p]$ is reducible then* $\mathrm{char}_\Lambda(Y(E/\mathbb{Q}_\infty))$ *divides* $\mathrm{ind}_\Lambda(\mathbf{c}_\infty)$.

Proof. If we are in the surjective case, then the theorem is a known consequence of Kato's Euler system. See Theorem 2.3.3 and Proposition 3.5.8 in [Rub00]. In the latter case when ρ_p is not surjective, we know that there exists an isogeny $\phi\colon E \longrightarrow E'$ of degree p defined over $\mathbb{Q}$. The Euler system argument gives us only a divisibility of the form

$$\mathrm{char}_\Lambda(Y(E/\mathbb{Q}_\infty)) \bigm| p^t \cdot \mathrm{ind}_\Lambda(\mathbf{c}_\infty)$$

for some integer $t \geqslant 0$, see Theorem 2.3.4 in [Rub00]. The previous lemma shows now that $\mathrm{char}_\Lambda(Y(E/\mathbb{Q}_\infty))$ is not divisible by p and hence we can take t to be equal to 0. □

3. The Selmer group

Suppose now that the curve E has good and ordinary reduction at the odd prime p. It is known that there exists an element $\mathcal{L}_p(E/\mathbb{Q}, T) \in \Lambda \otimes \mathbb{Q}_p$, called the analytic p-adic L-function, which interpolates in a certain precise way the Hasse-Weil L-function associated to E which we are going to recall now. Let γ be a topological generator of $\Gamma = \mathrm{Gal}(\mathbb{Q}_\infty/\mathbb{Q})$. Let $\chi\colon \Gamma \longrightarrow \mu_{p^\infty}$ be a Dirichlet character of conductor p^{k+1}.

It is determined by its image $\chi(\gamma) = \zeta$ which is a primitive root of unity of order p^k. Then $\mathcal{L}_p(E/\mathbb{Q}, T)$ is characterised by

$$\mathcal{L}_p(E/\mathbb{Q}, \zeta - 1) = \frac{1}{\alpha^{k+1}} \cdot \frac{p^{k+1}}{\tau(\chi^{-1})} \cdot \frac{L_E(\chi^{-1}, 1)}{\Omega_E}. \tag{1}$$

Here $\tau(\chi^{-1})$ is the usual Gauss sum and α is the unit root of the characteristic polynomial of Frobenius acting on T_pE. The real Néron period of E is denoted by Ω_E and $L_E(\chi^{-1}, s)$ is the Hasse-Weil L-function attached to E twisted by the character χ^{-1}.

We recall from [Ste89] that an elliptic curve $E/\mathbb{Q}$ is called *optimal* among the curves in the isogeny class of E if the map $\varphi^* \colon \operatorname{Pic}^0(E) \longrightarrow \operatorname{Pic}^0(X_1(N))$ induced by the modular parametrisation $\varphi \colon X_1(N) \longrightarrow E$ is injective. It is conjectured that the optimal curve is a curve with minimal analytic μ-invariant. It is also conjectured that the μ-invariant of the optimal curve is zero. Greenberg and Vatsal have shown in Proposition 3.7 of [GV00] that the p-adic L-series of an optimal curve is integral, i.e. $\mathcal{L}_p(E/\mathbb{Q}, T) \in \Lambda$.

Lemma 3. *Let $p > 2$ be a prime. Let $E/\mathbb{Q}$ be an elliptic curve without complex multiplication with good ordinary reduction at p and such that $E[p]$ is reducible. Suppose E is the optimal curve in the isogeny class. Then* $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ *divides the ideal $\mathcal{L}_p(E/\mathbb{Q}, T) \cdot \Lambda$.*

Proof. We follow the proof of Theorem 2.3.8 in [Rub00].

Let $\mathbb{Q}_{\infty,\mathfrak{p}}$ be the cyclotomic $\mathbb{Z}_p$-extension of $\mathbb{Q}_p$. Define the singular local cohomology group $Z(E/\mathbb{Q}_\infty) = \mathrm{H}^1_{\infty,s}(\mathbb{Q}_p, T_pE)$ to be the dual of $E(\mathbb{Q}_{\infty,\mathfrak{p}}) \otimes \mathbb{Q}_p/\mathbb{Z}_p$. It is a Λ-module of rank 1. By global duality (see Proposition 1.3.2 in [PR95]), we have the following exact sequence

$$0 \longrightarrow \mathrm{H}^1_\infty(\mathbb{Q}, T_pE) \longrightarrow Z(E/\mathbb{Q}_\infty) \longrightarrow X(E/\mathbb{Q}_\infty) \longrightarrow Y(E/\mathbb{Q}_\infty) \longrightarrow 0. \tag{2}$$

Write $\mathbf{c}_{\infty,s}$ for the image of $\mathbf{c}_\infty$ in $Z(E/\mathbb{Q}_\infty)$. Theorem 16.6.2 in [Kat04] states that the image of $\mathbf{c}_{\infty,s}$ via the Perrin-Riou–Coleman map $\mathrm{Col}\colon Z(E/\mathbb{Q}_\infty) \rightarrowtail \Lambda$ is up to a p-adic unit the analytic p-adic L-function $\mathcal{L}_p(E/\mathbb{Q}, T)$. Here we use that Greenberg and Vatsal [GV00, Theorem 3.1] have shown that the canonical period associated to the newform corresponding to E differs from Ω_E by a p-adic unit, if E is the optimal curve.

Rohrlich [Roh84] has shown that $\mathcal{L}_p(E/\mathbb{Q}, T)$ is non-zero. Hence $\mathbf{c}_{\infty,s}$ is not torsion and the characteristic ideal of the Λ-torsion module $Z(E/\mathbb{Q}_\infty)/\mathbf{c}_{\infty,s}\Lambda$, which is equal to $\mathrm{Col}(Z(E/\mathbb{Q}_\infty))/\mathcal{L}_p(E/\mathbb{Q}, T)\,\Lambda$ contains $\mathcal{L}_p(E/\mathbb{Q}, T)\,\Lambda$.

The sequence (2) induces an exact sequence of Λ-modules

$$0 \longrightarrow \frac{\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)}{\mathbf{c}_\infty\,\Lambda} \longrightarrow \frac{Z(E/\mathbb{Q}_\infty)}{\mathbf{c}_{\infty,s}\Lambda} \longrightarrow X(E/\mathbb{Q}_\infty) \longrightarrow Y(E/\mathbb{Q}_\infty) \longrightarrow 0$$

in which all terms are known to be torsion Λ-modules. We know that $\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)$ is a Λ-module of rank 1 and hence there is a Λ-morphism ψ from $\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)$ to Λ whose kernel is Λ-torsion and whose cokernel is pseudo-null. Since $\mathbf{c}_\infty$ cannot be torsion, the quotient on the right hand side of the above sequence is Λ-torsion and its characteristic ideal is contained in $\psi(\mathbf{c}_\infty)\,\Lambda$. The latter is contained in $\operatorname{ind}_\Lambda(\mathbf{c}_\infty)$.

So, using theorem 2, we conclude that

$$\begin{aligned}\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty)) &= \operatorname{char}_\Lambda(Y(E/\mathbb{Q}_\infty)) \cdot \operatorname{char}_\Lambda\Bigl(\frac{Z(E/\mathbb{Q}_\infty)}{\mathbf{c}_{\infty,s}\Lambda}\Bigr) \cdot \operatorname{char}_\Lambda\Bigl(\frac{\mathrm{H}^1_\infty(\mathbb{Q}, T_pE)}{\mathbf{c}_\infty\,\Lambda}\Bigr)^{-1} \\ &\supset \operatorname{ind}_\Lambda(\mathbf{c}_\infty) \cdot \mathcal{L}_p(E/\mathbb{Q},T)\,\Lambda \cdot \bigl(\operatorname{ind}_\Lambda(\mathbf{c}_\infty)\bigr)^{-1} \\ &= \mathcal{L}_p(E/\mathbb{Q},T)\,\Lambda\end{aligned}$$

□

Theorem 4. *Let $E/\mathbb{Q}$ be an elliptic curve without complex multiplication and let $p > 2$ be a prime. Suppose that E has good ordinary reduction at p and that the representation ρ_p is either surjective or that $E[p]$ is reducible. Then* $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ *divides the ideal generated by $\mathcal{L}_p(E/\mathbb{Q},T)$.*

Proof. If the representation ρ_p is surjective, then this is Theorem 17.4. in [Kat04].

Suppose now that $E[p]$ is reducible. Then there is an isogeny ϕ from E to the optimal curve E^{opt} in the isogeny class of E. Note that (1) and the formula for the change of the μ-invariant by Perrin-Riou [PR87, Appendice] show that the statement that $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ contains $\mathcal{L}_p(E/\mathbb{Q},T)\,\Lambda$ is invariant under isogeny. So the conclusion drawn for E^{opt} in the previous lemma applies also to E. □

Theorem 5. *The analytic p-adic L-function $\mathcal{L}_p(E/\mathbb{Q},T)$ belongs to Λ for all elliptic curves $E/\mathbb{Q}$ with good ordinary reduction at $p > 2$.*

Proof. If the elliptic curve E admits no isogenies of degree dividing p this is well-known by [GV00, Proposition 3.7]. If this is not the case, then $E[p]$ is reducible and we have seen in the previous theorem 4 that the ideal generated by $\mathcal{L}_p(E/\mathbb{Q},T)$ is divisible by an integral ideal $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$. □

Corollary 6. *If $E/\mathbb{Q}$ is a semi-stable elliptic curve and $p > 3$ a prime of good ordinary reduction, then* $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ *divides the ideal generated by $\mathcal{L}_p(E/\mathbb{Q},T)$.*

Proof. By a theorem of Serre ([Ser96, Proposition 1] and [Ser72, Proposition 21]), we know that the image of the representation $\bar\rho_p\colon G_\mathbb{Q} \longrightarrow \operatorname{Aut}(E[p])$ is either the whole of $\mathrm{GL}_2(\mathbb{F}_p)$ or it is contained in a Borel subgroup. In the latter case the representation ρ_p is reducible and in the first case the representation $\rho_p\colon G_\mathbb{Q} \longrightarrow \operatorname{Aut}(T_pE)$ is surjective by another result of Serre [Ser81, Lemme 15]. □

Unfortunately, the hypothesis that E is semi-stable can not be dropped. There are curves $E/\mathbb{Q}$ such that $\bar\rho_p$ has its image in the normaliser of a Cartan subgroup. In this case there are no p-torsion points defined over an abelian extension of $\mathbb{Q}$. Similarly there are also curves without complex multiplications for $p = 5$ such that the image of ρ_5 maps to the exceptional subgroup S_4 in $\mathrm{PGL}(\mathbb{F}_5)$.

The methods in this article are not sufficient to extend the main theorem 4 to these cases. The best we can do is the following

Proposition 7. *Let $E/\mathbb{Q}$ be an elliptic curve without complex multiplication, with good and ordinary reduction at $p > 13$ or $p = 7$. If the conjecture of Iwasawa on the vanishing of the classical μ-invariant in cyclotomic $\mathbb{Z}_p$-extensions is valid for abelian extensions of imaginary quadratic fields, then* $\operatorname{char}_\Lambda(X(E/\mathbb{Q}_\infty))$ *divides the ideal generated by $\mathcal{L}_p(E/\mathbb{Q},T)$.*

Proof. By theorem 4, we may assume that the image of $\bar{\rho}_p$ is contained in the normaliser of a Cartan subgroup. The case of the exceptional subgroups is excluded by the hypothesis on p by Lemme 18 in [Ser81].

The idea of the proof is the same as for the proofs of Theorem 2 and Theorem 4, but we replace the Corollary 3.6 in [CS05] by the previous Corollary 3.5 with L being the field $\mathbb{Q}(E[p])$. In our case L is an abelian extension of an imaginary quadratic field. □

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