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# On Jacobi Sums in $\mathbb{Q}(\zeta_p)$

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## Abstract

We study the  $p$ -adic behavior of Jacobi sums for  $\mathbb{Q}(\zeta_p)$  and link this study to the  $p$ -Sylow subgroup of the class group of  $\mathbb{Q}(\zeta_p)^+$  and to some properties of the jacobian of the Fermat curve  $X^p + Y^p = 1$  over  $\mathbb{F}_\ell$  where  $\ell$  is a prime number distinct from  $p$ .

Let  $p$  be a prime number,  $p \geq 5$ . Iwasawa has shown that the  $p$ -adic properties of Jacobi sums for  $\mathbb{Q}(\zeta_p)$  are linked to Vandiver's Conjecture (see [5]). In this paper, we follow Iwasawa's ideas and study the  $p$ -adic properties of the subgroup  $J$  of  $\mathbb{Q}(\zeta_p)^*$  generated by Jacobi sums.

Let  $A$  be the  $p$ -Sylow subgroup of the class group of  $\mathbb{Q}(\zeta_p)$ . If  $E$  denotes the group of units of  $\mathbb{Q}(\zeta_p)$ , then if Vandiver's Conjecture is true for  $p$ , by Kummer Theory, we must have  $\frac{A^-}{pA^-} \hookrightarrow \text{Gal}(\mathbb{Q}(\zeta_p)(^p\sqrt{E})/\mathbb{Q}(\zeta_p))$ . Note that  $J$  is analogous for the odd part to the group of cyclotomic units for the even part. We introduce a submodule  $W$  of  $\mathbb{Q}(\zeta_p)^*$  which was already considered

by Iwasawa ([6]). This module can be thought as the analogue for the odd part of the group of units for the even part. We observe that  $J \subset W$  and if the Iwasawa-Leopoldt Conjecture is true for  $p$  then  $W(Q(\zeta_p)^*)^p = J(Q(\zeta_p)^*)^p$ . We prove that if  $pA^- = \{0\}$  then (Corollary 4.8):

$$\frac{A^+}{pA^+} \hookrightarrow \text{Gal}(\mathbb{Q}(\zeta_p)(^p\sqrt{W})/\mathbb{Q}(\zeta_p)).$$

The last part of our paper is devoted to the study of the jacobian of the Fermat curve  $X^p + Y^p = 1$  over  $\mathbb{F}_\ell$  where  $\ell$  is a prime number,  $\ell \neq p$ . It is well-known that Jacobi sums play an important role in the study of that jacobian. Following ideas developped by Greenberg ([4]), we prove that Vandiver's Conjecture is equivalent to some properties of that jacobian (for the precise statement see Corollary 5.3).

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## 1 Notations

Let  $p$  be a prime number,  $p \geq 5$ . Let  $\zeta_p \in \mu_p \setminus \{1\}$ , and let  $L = \mathbb{Q}(\zeta_p)$ . Set  $\mathcal{O} = \mathbb{Z}[\zeta_p]$  and  $E = \mathcal{O}^*$ . Let  $\Delta = \text{Gal}(L/\mathbb{Q})$  and let  $\hat{\Delta} = \text{Hom}(\Delta, \mathbb{Z}_p^*)$ . Let  $\mathcal{I}$  be the group of fractional ideals of  $L$  which are prime to  $p$ , and let  $\mathcal{P}$  be the group of principal ideals in  $\mathcal{I}$ . Let  $A$  be the  $p$ -Sylow subgroup of the ideal class group of  $L$ .

Set  $\pi = \zeta_p - 1$ ,  $K = \mathbb{Q}_p(\zeta_p)$ ,  $U = 1 + \pi^2 \mathbb{Z}_p[\zeta_p]$ . Observe that if  $\mathcal{A} \in \mathcal{P}$ , then there exists  $\alpha \in L^* \cap U$  such that  $\mathcal{A} = \alpha \mathcal{O}$ . If  $H$  is a subgroup of  $U$ , we will denote the closure of  $H$  in  $U$  by  $\overline{H}$ . Let  $\omega \in \hat{\Delta}$  be the Teichmüller character, i.e. :

$$\forall \sigma \in \Delta, \sigma(\zeta_p) = \zeta_p^{\omega(\sigma)}.$$

For  $\rho \in \hat{\Delta}$ , we set:

$$e_\rho = \frac{1}{p-1} \sum_{\delta \in \Delta} \rho^{-1}(\delta) \delta \in \mathbb{Z}_p[\Delta].$$

If  $M$  is a  $\mathbb{Z}_p[\Delta]$ -module, for  $\rho \in \widehat{\Delta}$ , we set:

$$M(\rho) = e_\rho M.$$

For  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd, recall that:

$$B_{1,\psi} = \frac{1}{p} \sum_{a=1}^{p-1} a\psi(a).$$

Set:

$$\theta = \frac{1}{p} \sum_{a=1}^{p-1} a\sigma_a^{-1} \in \mathbb{Q}[\Delta],$$

where  $\sigma_a \in \Delta$  is such that  $\sigma_a(\zeta_p) = \zeta_p^a$ . Observe that we have the following equality in  $\mathbb{C}[\Delta]$  :

$$\theta = \frac{N}{2} + \sum_{\psi \in \widehat{\Delta}, \psi \text{ odd}} B_{1,\psi^{-1}} e_\psi,$$

where  $N = \sum_{\delta \in \Delta} \delta$ .

Let  $M$  be a  $\mathbb{Z}[\Delta]$ -module, we set:

$$M^- = \{m \in M, \sigma_{-1}(m) = -m\},$$

$$M^+ = \{m \in M, \sigma_{-1}(m) = m\}.$$

If  $M$  is an abelian group of finite type, we set:

$$M[p] = \{m \in M, pm = 0\},$$

$$d_p M = \dim_{\mathbb{F}_p} \frac{M}{pM}.$$

## 2 Background on Jacobi Sums

Let  $Cl(L)$  be the ideal class group of  $L$ , then:

$$Cl(L) \simeq \frac{\mathcal{I}}{\mathcal{P}}.$$

Note that we have a natural  $\mathbb{Z}[\Delta]$ -morphism (see [6], pages 102-103):

$$\phi : (\text{Ann}_{\mathbb{Z}[\Delta]} Cl(L))^- \rightarrow \text{Hom}_{\mathbb{Z}[\Delta]}(Cl(L), \frac{E^+}{(E^+)^2}).$$

For the convenience of the reader, we recall the construction of  $\phi$ . Let  $x \in (\text{Ann}_{\mathbb{Z}[\Delta]} Cl(L))^-$ . Let  $\mathcal{A} \in \mathcal{I}$ , we have:

$$\mathcal{A}^x = \gamma_a \mathcal{O},$$

where  $\gamma_a \in L^* \cap U$ . Now:

$$\overline{\gamma_a} = \varepsilon_a \gamma_a^{-1},$$

for some  $\varepsilon_a \in E^+ \cap U$ . One can prove that we obtain a well-defined morphism of  $\mathbb{Z}[\Delta]$ -modules:  $\phi(x) : Cl(L) \rightarrow \frac{E^+}{(E^+)^2}$ , class of  $\mathcal{A} \mapsto$  class of  $\varepsilon_a$ .

In this paragraph, we will study the kernel of the morphism  $\phi$ .

Let  $\mathcal{W}$  be the set of elements  $f \in \text{Hom}_{\mathbb{Z}[\Delta]}(\mathcal{I}, L^*)$  such that:

- $f(\mathcal{I}) \subset U$ ,
- there exists  $\beta(f) \in \mathbb{Z}[\Delta]$  such that for all  $\alpha \in L^* \cap U$ ,  $f(\alpha \mathcal{O}) = \alpha^{\beta(f)}$ .

One can prove that if  $f \in \mathcal{W}$  then  $\beta(f)$  is unique, the map  $\beta : \mathcal{W} \rightarrow \mathbb{Z}[\Delta]$  is an injective  $\mathbb{Z}[\Delta]$ -morphism and  $\beta(\mathcal{W}) \subset \text{Ann}_{\mathbb{Z}[\Delta]}(Cl(L))$  (see [2]). If  $\mathcal{B}$  denotes the group of Hecke characters of type  $(A_0)$  that have values in  $\mathbb{Q}(\zeta_p)$  (see [6]), then one can prove that  $\mathcal{B}$  is isomorphic to  $\mathcal{W}$ .

**Lemma 2.1**  $\text{Ker } \phi = \beta(\mathcal{W}^-)$ .

*Proof* We just prove the inclusion  $\text{Ker } \phi \subset \beta(\mathcal{W}^-)$ . Let  $x \in \text{Ker } \phi$ . Let  $\mathcal{A} \in \mathcal{I}$ , then there exists a unique  $\gamma_a \in L^* \cap U$  such that  $\overline{\gamma_a} \gamma_a = 1$  and:

$$\mathcal{A}^x = \gamma_a \mathcal{O}.$$

Let  $f : \mathcal{I} \rightarrow L^*$ ,  $\mathcal{A} \mapsto \gamma_a$ . It is not difficult to see that  $f \in \text{Hom}_{\mathbb{Z}[\Delta]}(\mathcal{I}, L^*)$  and  $f(\mathcal{I}) \subset U$ . Now, let  $\alpha \in L^* \cap U$ , we have:

$$f(\alpha \mathcal{O}) = \alpha^x u,$$

for some  $u \in E$ . Since  $x \in \mathbb{Z}[\Delta]^-$  and  $\alpha, f(\alpha \mathcal{O}) \in U$ , we must have  $u = 1$ . Therefore  $f \in \mathcal{W}^-$  and  $x = \beta(f)$ .  $\diamond$

Now, we recall some basic properties of Gauss and Jacobi sums (we refer the reader to [11], paragraph 6.1).

Let  $P$  be a prime ideal in  $\mathcal{I}$  and let  $\ell$  be the prime number such that  $\ell \in P$ . We fix  $\zeta_\ell \in \mu_\ell \setminus \{1\}$ . Set  $\mathbb{F}_P = \frac{\mathcal{O}}{P}$ . Let  $\chi_P : \mathbb{F}_P^* \rightarrow \mu_p$ , such that:

$$\forall \alpha \in \mathbb{F}_P^*, \chi_P(\alpha) \equiv \alpha^{\frac{1-NP}{p}} \pmod{P},$$

where  $NP = |\frac{\mathcal{O}}{P}|$ . For  $a \in \frac{\mathbb{Z}}{p\mathbb{Z}}$ , we set:

$$\tau_a(P) = - \sum_{\alpha \in \mathbb{F}_P} \chi_P^a(\alpha) \zeta_\ell^{\text{Tr}_{\mathbb{F}_P/\mathbb{F}_\ell}(\alpha)}.$$

We also set  $\tau(P) = \tau_1(P)$ . For  $a, b \in \frac{\mathbb{Z}}{p\mathbb{Z}}$ , we set:

$$j_{a,b}(P) = - \sum_{\alpha \in \mathbb{F}_P} \chi_P^a(\alpha) \chi_P^b(1 - \alpha).$$

Then:

- if  $a + b \equiv 0 \pmod{p}$ ,
  - i) if  $a \not\equiv 0 \pmod{p}$ ,  $j_{a,b}(P) = 1$ ,
  - ii) if  $a \equiv 0 \pmod{p}$ ,  $j_{a,b}(P) = 2 - NP$ ,
- if  $a + b \not\equiv 0 \pmod{p}$ , we have:

$$j_{a,b}(P) = \frac{\tau_a(P) \tau_b(P)}{\tau_{a+b}(P)}.$$

Observe that  $\tau(P) \equiv 1 \pmod{\pi}$ , and therefore (see [5], Theorem 1):

$$\forall a, b \in \frac{\mathbb{Z}}{p\mathbb{Z}}, j_{a,b}(P) \in U.$$

Let  $\Omega$  be the compositum of the fields  $\mathbb{Q}(\zeta_\ell)$  where  $\ell$  runs through the prime numbers distinct from  $p$ . The map  $P \mapsto \tau(P)$  induces by linearity a  $\mathbb{Z}[\Delta]$ -morphism:

$$\tau : \mathcal{I} \rightarrow \Omega(\zeta_p)^*.$$

Let  $\mathcal{G}$  be the sub- $\mathbb{Z}[\Delta]$ -module of  $\text{Hom}_{\mathbb{Z}[\Delta]}(\mathcal{I}, \Omega(\zeta_p)^*)$  generated by  $\tau$ . We set:

$$\mathcal{J} = \mathcal{G} \cap \text{Hom}_{\mathbb{Z}[\Delta]}(\mathcal{I}, L^*).$$

Let  $\mathcal{S}$  be the Stickelberger ideal of  $L$ , i.e.  $\mathcal{S} = \mathbb{Z}[\Delta]\theta \cap \mathbb{Z}[\Delta]$ . Then one can prove the following facts (see [2]):

- $\mathcal{J} \subset \mathcal{W}$ ,

- the map  $\beta : \mathcal{W} \rightarrow \mathbb{Z}[\Delta]$  induces an isomorphism of  $\mathbb{Z}[\Delta]$ -modules :

$$\mathcal{J} \simeq \mathcal{S}.$$

**Lemma 2.2** *Let  $\mathcal{N} \in \text{Hom}_{\mathbb{Z}[\Delta]}(I_L, L^*)$  be the ideal norm map. Then, as a  $\mathbb{Z}$ -module:*

$$\mathcal{J} = \mathcal{N}\mathbb{Z} \oplus \bigoplus_{n=1}^{(p-1)/2} j_{1,n}\mathbb{Z}.$$

*Proof* Recall that, for  $1 \leq n \leq p-2$ , for a prime  $P$  in  $\mathcal{I}$ , we have:

$$j_{1,n}(P) = - \sum_{\alpha \in \mathbb{F}_P} \chi_P(\alpha) \chi_P^n(1 - \alpha) = \frac{\tau(P)\tau_n(P)}{\tau_{n+1}(P)}.$$

Thus, for  $1 \leq n \leq p-2$ , we have:

$$j_{1,n} = \tau^{1+\sigma_n-\sigma_{1+n}} = \frac{\tau\tau_n}{\tau_{n+1}},$$

where for  $a \in \mathbb{F}_p^*$ ,  $\tau^{\sigma_a} = \tau_a$ . Observe that:

$$\forall a \in \mathbb{F}_p^*, \tau_a \tau_{-a} = N.$$

Thus  $\mathcal{N} \in \mathcal{J}$ . Since  $\mathcal{J} \simeq \mathcal{S}$ ,  $\mathcal{J}$  is a  $\mathbb{Z}$ -module of rank  $(p+1)/2$ . It is not difficult to show that (see [5], Lemma 2):

$$\mathcal{J} = \tau^p \mathbb{Z} \bigoplus_{a=1}^{(p-1)/2} \tau_{-a} \tau^a \mathbb{Z}.$$

Observe also that, for  $2 \leq n \leq p-2$ , we have:

$$j_{1,p-n} = j_{1,n-1}.$$

Let  $V$  be the sub- $\mathbb{Z}$ -module of  $\mathcal{J}$  generated by  $\mathcal{N}$  and the  $j_{1,n}$ ,  $1 \leq n \leq (p-1)/2$ . Then for  $1 \leq n \leq p-2$ ,  $j_{1,n} \in V$ . Furthermore:

$$\prod_{n=1}^{p-2} j_{1,n} = \frac{\tau^p}{\mathcal{N}}.$$

Therefore  $\tau^p \in V$ . Since  $\tau_{-1}\tau^1 = \mathcal{N}$ ,  $\tau_{-1}\tau^1 \in V$ . Now, let  $2 \leq r \leq (p-1)/2$  and assume that we have proved that  $\tau_{-(r-1)}\tau^{r-1} \in V$ . We have:

$$j_{1,r-1} = \frac{\tau\tau_{r-1}}{\tau_r} = \frac{\mathcal{N}\tau\tau_{1-r}^{-1}}{\mathcal{N}\tau_{-r}^{-1}}.$$

Thus:

$$\tau_{-r} = j_{1,r-1}^{-1}\tau_{1-r}\tau^{-1},$$

and

$$\tau_{-r}\tau^r = j_{1,r-1}^{-1}\tau_{-(r-1)}\tau^{r-1}.$$

Thus  $\tau_{-r}\tau^r \in V$  and the Lemma follows.  $\diamond$

**Lemma 2.3** *Let  $\ell$  be a prime number,  $\ell \neq p$ . Let  $P$  be a prime ideal of  $\mathcal{O}$  above  $\ell$  and let  $a \in \{1, \dots, p-2\}$ . Then  $\mathbb{Q}(j_{1,a}(P)) = L$  if and only if  $\ell \equiv 1 \pmod{p}$  and  $a^2 + a + 1 \not\equiv 0 \pmod{p}$  if  $p \equiv 1 \pmod{3}$ .*

*Proof* Since  $j_{1,a}(P) \equiv 1 \pmod{\pi^2}$  and  $j_{1,a}(P)j_{1,a}(P)^{\sigma^{-1}} = \ell^f$  where  $f$  is the order of  $\ell$  in  $(\mathbb{Z}/p\mathbb{Z})^*$ , we have:

$$\forall \sigma \in \Delta, j_{1,a}(P)^\sigma = j_{1,a}(P) \Leftrightarrow j_{1,a}(P)^\sigma \mathcal{O} = j_{1,a}(P) \mathcal{O}.$$

Recall that:

$$\forall \sigma \in \Delta, j_{1,a}(P)^\sigma \mathcal{O} = j_{1,a}(P) \mathcal{O} \Leftrightarrow P^{(\sigma-1)(1+\sigma_a-\sigma_{1+a})\theta} = \mathcal{O}.$$

Since  $j_{1,a}(P)^{\sigma_\ell} = j_{1,a}(P)$ , we can assume  $\ell \equiv 1 \pmod{p}$ . Let  $\sigma \in \Delta$ , we have to consider the following equation in  $\mathbb{C}[\Delta]$ :

$$(\sigma - 1)(1 + \sigma_a - \sigma_{1+a})\theta = 0.$$

This is equivalent to:

$$\forall \psi \in \widehat{\Delta}, \psi \text{ odd}, (\psi(\sigma) - 1)(1 + \psi(a) - \psi(1+a)) = 0.$$

Assume that  $\omega^3(\sigma) \neq 1$ . Then:

$$1 + \omega^3(a) - \omega^3(1+a) = 0.$$

This implies:

$$a^2 + a \equiv 0 \pmod{p},$$



which is a contradiction. Thus  $\omega^3(\sigma) = 1$ . Let's suppose that  $\sigma \neq 1$ . We get:

$$1 + \omega(a) = \omega(1 + a),$$

which is equivalent to:

$$a^2 + a + 1 \equiv 0 \pmod{p}.$$

Conversely, one can see that if  $p \equiv 1 \pmod{3}$ ,  $a^2 + a + 1 \equiv 0 \pmod{p}$ ,  $\omega^3(\sigma) = 1$ , then:

$$\forall \psi \in \widehat{\Delta}, \psi \text{ odd}, (\psi(\sigma) - 1)(1 + \psi(a) - \psi(1 + a)) = 0.$$

The Lemma follows.  $\diamond$

For  $x \in \mathbb{Z}_p$ , let  $[x] \in \{0, \dots, p-1\}$  such that  $x \equiv [x] \pmod{p}$ . We set:

$$\eta = \left( \prod_{n=1}^{p-2} j_{1,n}^{[n^{-1}]} \right)^{1-\sigma_{-1}} \in \mathcal{J}^-.$$

**Lemma 2.4**

a) Let  $\psi \in \widehat{\Delta}$ ,  $\psi \neq \omega$ ,  $\psi$  odd. Then:

$$e_\psi \left( \sum_{n=1}^{p-2} (1 + \sigma_n - \sigma_{1+n}) [n^{-1}] \right) \in \mathbb{Z}_p^* e_\psi.$$

b) We have:

$$\frac{1}{p} e_\omega \left( \sum_{n=1}^{p-2} (1 + \sigma_n - \sigma_{1+n}) [n^{-1}] \right) \in \mathbb{Z}_p^* e_\omega.$$

*Proof*

a) Write  $\psi = \omega^k$ ,  $k$  odd,  $k \in \{3, \dots, p-2\}$ . We have:

$$\sum_{n=2}^{p-2} (1 + \psi(n) - \psi(1+n)) [n^{-1}] \equiv \sum_{n=1}^{p-1} \frac{1 + n^k - (1+n)^k}{n} \equiv k \pmod{p}.$$

This implies a).

b) We have:

$$\forall a \in \mathbb{F}_p^*, \omega(a) \equiv a^p \pmod{p^2}.$$

Thus:

$$\frac{1}{p} \sum_{n=1}^{p-2} (1 + \omega(n) - \omega(1+n)) [n^{-1}] \equiv - \sum_{n=1}^{p-1} \sum_{k=1}^{p-1} \frac{p!}{(p-k)! k! p} n^{k-1} \pmod{p}.$$

And we get:

$$\frac{1}{p} \sum_{n=1}^{p-2} (1 + \omega(n) - \omega(1+n)) [n^{-1}] \equiv -1 \pmod{p}.$$

This implies b).  $\diamond$

**Lemma 2.5** *Let  $\ell$  be a prime number,  $\ell \neq p$ . Let  $V_\ell$  be the sub- $\mathbb{Z}[\Delta]$ -module of  $L^*/(L^*)^p$  generated by  $\{f(P), f \in \mathcal{J}\}$  where  $P$  is some prime of  $\mathcal{I}$  above  $\ell$ . Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd and  $\psi \neq \omega$ . Then:*

$$V_\ell(\psi) = \mathbb{F}_p e_\psi \eta(P).$$

*Proof* Let  $E = L(\zeta_\ell)$ . Then:

$$\frac{L^*}{(L^*)^p}(\psi) \hookrightarrow \frac{E^*}{(E^*)^p}(\psi).$$

Now, in  $\frac{E^*}{(E^*)^p}(\psi)$ , we have:

$$V_\ell(\psi) = \mathbb{F}_p e_\psi \tau(P).$$

It remains to apply Lemma 2.4.  $\diamond$

Finally, we mention the following Lemma:

**Lemma 2.6** *We have:*

$$(\mathcal{J}^- : \mathbb{Z}[\Delta]\eta) = 2^{\frac{p-3}{2}} \frac{1}{p} \prod_{\psi \in \widehat{\Delta}, \psi \text{ odd}} \left( \sum_{n=1}^{p-2} (1 + \psi(n) - \psi(1+n)) [n^{-1}] \right).$$

*Furthermore:*

$$(\mathcal{J}^- : \mathbb{Z}[\Delta]\eta) \not\equiv 0 \pmod{p}.$$

*Proof* Set  $\widetilde{\mathcal{J}}^- = (1 - \sigma_{-1})\mathcal{J} \subset \mathcal{J}^-$ . Ten (see [11], paragraph 6.4):

$$(\mathcal{J}^- : \widetilde{\mathcal{J}}^-) = 2^{\frac{p-3}{2}}.$$

Now, by the same kind of arguments as in [11], paragraph 6.4, we get:

$$(\widetilde{\mathcal{J}}^- : \mathbb{Z}[\Delta]\eta) = \frac{1}{p} \prod_{\psi \in \widehat{\Delta}, \psi \text{ odd}} \left( \sum_{n=1}^{p-2} (1 + \psi(n) - \psi(1+n)) [n^{-1}] \right).$$

It remains to apply Lemma 2.4. to conclude the proof of this Lemma.  $\diamond$

### 3 Jacobi Sums and the Ideal Class Group of $\mathbb{Q}(\zeta_p)$

Recall that the Iwasawa-Leopoldt Conjecture asserts that  $A$  is a cyclic  $\mathbb{Z}_p[\Delta]$ -module. This Conjecture is equivalent to:

$$\forall \psi \in \widehat{\Delta}, \psi \text{ odd}, \psi \neq \omega, A(\psi) \simeq \frac{\mathbb{Z}_p}{B_{1,\psi^{-1}}\mathbb{Z}_p}.$$

It is well-known (see [11], Theorem 10.9) that:

$$\forall \psi \in \widehat{\Delta}, \psi \text{ odd}, \psi \neq \omega, A(\omega\psi^{-1}) = \{0\} \Rightarrow A(\psi) \simeq \frac{\mathbb{Z}_p}{B_{1,\psi^{-1}}\mathbb{Z}_p}.$$

In this paragraph, we will study the links between Jacobi sums and the structure of  $A^-$ .

We fix  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd and  $\psi \neq \omega$ . We set:

$$m(\psi) = v_p(B_{1,\psi^{-1}}).$$

Recall that, by [11], paragraph 13.6, we have:

$$|A(\psi)| = p^{m(\psi)}.$$

Let  $p^{k(\psi)}$  be the exponent of the group  $A(\psi)$ . Then:

$$B_{1,\psi^{-1}} \equiv 0 \pmod{p^{k(\psi)}}.$$

**Lemma 3.1** *Let  $P$  be a prime ideal in  $\mathcal{I}$  above a prime number  $\ell$ . Then:*

$$e_\psi \eta(P)\mathcal{O} = 0 \text{ in } \frac{\mathcal{I}}{\mathcal{I}^p} \Leftrightarrow \psi(\ell) \neq 1 \text{ or } B_{1,\psi^{-1}} \equiv 0 \pmod{p}.$$

*Proof* First note that, if  $\rho \in \widehat{\Delta}$ , then  $e_\rho P = 0$  in  $\frac{\mathcal{I}}{\mathcal{I}^p}$  if and only if  $\rho(\ell) \neq 1$ . By the Stickelberger Theorem, we have:

$$\eta(P)\mathcal{O} = \left( \sum_{n=1}^{p-2} (1 + \sigma_n - \sigma_{1+n})[n^{-1}] \right) (1 - \sigma_{-1}) \theta P.$$

Recall that:

$$e_\psi \theta = B_{1,\psi^{-1}} e_\psi.$$

The Lemma follows.  $\diamond$

**Lemma 3.2** *Let  $f \in \mathcal{W}^-$ . Then  $f$  lies in  $\mathcal{W}^p$  if and only if for all prime ideal  $P \in \mathcal{I}$ ,  $f(P) \in (L^*)^p$ .*

*Proof* Let  $f \in \mathcal{W}^-$  such that for all prime ideal  $P \in \mathcal{I}$ ,  $f(P) \in (L^*)^p$ . Let  $\mathcal{A} \in \mathcal{I}$ . Then there exists  $\gamma_a \in L^* \cap U$  such that  $\gamma_a \overline{\gamma}_a = 1$  and:

$$f(\mathcal{A}) = \gamma_a^p.$$

Observe that  $\beta(f) \in p(\mathbb{Z}[\Delta])^-$ . Let  $g : \mathcal{I} \rightarrow L^*$ ,  $\mathcal{A} \mapsto \gamma_a$ . Then one can verify that  $f = g^p$  and  $g \in \mathcal{W}^-$ .  $\diamond$

Let  $m \geq 1$  such that  $p^m \mid |A|$ . Set  $n = |Cl(L)| / |A|$ . Let  $e_m(\psi) \in \mathbb{Z}[\Delta]^-$  such that:

$$e_m(\psi) \equiv e_\psi \pmod{p^m}.$$

Set:

$$\beta_\psi = 2np^{k(\psi)}e_m(\psi) \in \mathbb{Z}[\Delta]^-.$$

Since  $np^{k(\psi)}e_m(\psi) \in (\text{Ann}_{\mathbb{Z}[\Delta]Cl(L)}^-)$ , by Lemma 2.1, there exists a unique element  $f_\psi \in \mathcal{W}^-$  such that  $\beta(f_\psi) = \beta_\psi$ . Recall that:

$$(\text{Ann}_{\mathbb{Z}_p[\Delta]}A)(\psi) = p^{k(\psi)}\mathbb{Z}_pe_\psi.$$

Therefore, for  $0 \leq k \leq m$ ,  $\frac{\mathcal{W}^-}{(\mathcal{W}^-)^{p^k}}(\psi)$  is cyclic of order  $p^k$  generated by the image of  $f_\psi$ . We set:

$$W = \{f(\mathcal{A}), \mathcal{A} \in \mathcal{I}, f \in \mathcal{W}\},$$

and:

$$J = \{f(\mathcal{A}), \mathcal{A} \in \mathcal{I}, f \in \mathcal{J}\}.$$

Observe that  $J$  is a sub- $\mathbb{Z}[\Delta]$ -module of  $W$ , and it is called the module of Jacobi sums of  $\mathbb{Q}(\zeta_p)$ . Note that, by Lemma 3.2, we have:

$$\frac{W(L^*)^p}{(L^*)^p}(\psi) \neq \{0\}.$$

**Theorem 3.3** *The map  $f_\psi$  induces an isomorphism of groups:*

$$A(\psi) \simeq \frac{W(L^*)^{p^{k(\psi)}}}{(L^*)^{p^{k(\psi)}}}(\psi).$$

*Proof* First observe that  $m \geq k(\psi) + 1$ . Let  $P$  be a prime in  $\mathcal{I}$ . Then:

$$f_\psi(P)\mathcal{O} = P^{\beta_\psi}.$$

Let  $\rho \in \widehat{\Delta}$ ,  $\rho \neq \psi$ . Then:

$$e_m(\rho)e_m(\psi) \equiv 0 \pmod{p^m}.$$

Therefore, there exists  $\gamma \in L^* \cap U$  such that:

$$P^{(1-\sigma_{-1})ne_m(\rho)e_m(\psi)} = \left(\frac{\gamma}{\sigma_{-1}(\gamma)}\right)^p \mathcal{O}.$$

But  $(1 - \sigma_{-1})e_m(\psi) = 2e_m(\psi)$ . Thus, there exists  $\alpha \in L^* \cap U$ ,  $\alpha\sigma_{-1}(\alpha) = 1$ , and:

$$f_\psi(P)^{e_m(\rho)} = \alpha^{p^{k(\psi)+1}}.$$

Therefore,  $e_\rho f_\psi(\mathcal{I}) = 0$  in  $L^*/(L^*)^{p^{k(\psi)+1}}$ .

It is clear that  $f_\psi$  induces a morphism:

$$\frac{\mathcal{I}}{(\mathcal{I})^{p^m}\mathcal{P}}(\psi) \rightarrow \frac{L^*}{(L^*)^{p^{k(\psi)}}}(\psi).$$

Now, let  $P$  be a prime in  $\mathcal{I}$  such that  $e_\psi f_\psi(P) = 0$  in  $\frac{L^*}{(L^*)^{p^{k(\psi)}}}(\psi)$ . Then, by the above remark, we get:

$$f_\psi(P) = 0 \text{ in } L^*/(L^*)^{p^{k(\psi)}}.$$

Thus, there exists  $\gamma \in L^* \cap U$  such that:

$$P^{\beta_\psi} = \gamma^{p^{k(\psi)}} \mathcal{O}.$$

Thus:

$$P^{2ne_m(\psi)} = \gamma \mathcal{O}.$$

This implies:

$$e_\psi P = 0 \text{ in } \frac{\mathcal{I}}{(\mathcal{I})^{p^m}\mathcal{P}}(\psi).$$

Thus our map is injective. Now, observe that the image of the map induced by  $f_\psi$  is  $\frac{W(L^*)^{p^{k(\psi)}}}{(L^*)^{p^{k(\psi)}}}(\psi)$  and that:

$$A(\psi) \simeq \frac{\mathcal{I}}{(\mathcal{I})^{p^m}\mathcal{P}}(\psi).$$

The Theorem follows.  $\diamond$

Recall that:

$$\eta = \left( \prod_{n=1}^{p-2} j_{1,n}^{[n^{-1}]} \right)^{1-\sigma_{-1}} \in \mathcal{J}^-.$$

Set:

$$z = (1 - \sigma_{-1}) \sum_{n=1}^{p-2} (1 + \sigma_n - \sigma_{1+n})[n^{-1}] \in \mathbb{Z}[\Delta]^-.$$

We have:

$$\beta(\eta) = z\theta.$$

### Corollary 3.4

1) The map  $\eta$  induces an isomorphism of groups:

$$A(\psi) \simeq \frac{J(L^*)^{p^{m(\psi)}}}{(L^*)^{p^{m(\psi)}}}(\psi).$$

2)  $\frac{J(L^*)^p}{(L^*)^p}(\psi) \neq \{0\}$  if and only if  $A(\psi)$  is  $\mathbb{Z}_p$ -cyclic.

*Proof*

1) Let  $P$  be a prime in  $\mathcal{I}$ . Then one can show that:

$$f_\psi(P)^{z\theta} = \eta(P)^{2np^{k(\psi)}e_m(\psi)}.$$

The first assertion follows from Theorem 3.3.

2) Note that:

$$A(\psi) \text{ is } \mathbb{Z}_p\text{-cyclic} \Leftrightarrow m(\psi) = k(\psi).$$

Thus, if  $A(\psi)$  is  $\mathbb{Z}_p$ -cyclic, then:

$$\frac{J(L^*)^p}{(L^*)^p}(\psi) = \frac{W(L^*)^p}{(L^*)^p}(\psi) \neq \{0\}.$$

By the proof of assertion 1), if  $k(\psi) < m(\psi)$  and if  $P$  is a prime in  $\mathcal{I}$ , then:

$$\eta(P)^{e_m(\psi)} \in (L^*)^p.$$

Therefore, we get assertion 2).  $\diamond$

## 4 The $p$ -adic behavior of Jacobi Sums

Let  $M$  be a subgroup of  $L^*/(L^*)^p$ , we say that  $M$  is unramified if  $L(^p\sqrt{M})/L$  is an unramified extension. Note that Kummer's Lemma asserts that ([11], Theorem 5.36):

$$\forall \rho \in \widehat{\Delta}, \rho \text{ even}, \rho \neq 1, \frac{E}{E^p}(\rho) \text{ is unramified} \Rightarrow B_{1,\rho\omega^{-1}} \equiv 0 \pmod{p}.$$

It is natural to ask if this implication is in fact an equivalence (see [1], [3]). We will say that the converse of Kummer's Lemma is true for the character  $\rho$  if we have:

$$\frac{E}{E^p}(\rho) \text{ is unramified} \Leftrightarrow B_{1,\rho\omega^{-1}} \equiv 0 \pmod{p}.$$

In this paragraph, we will study this question with the help of Jacobi sums.

Let  $F/L$  be the maximal abelian  $p$ -extension of  $L$  which is unramified outside  $p$ . Set  $\mathcal{X} = \text{Gal}(F/L)$ . We have an exact sequence of  $\mathbb{Z}_p[\Delta]$ -modules ([11], Corollary 13.6):

$$0 \rightarrow \frac{U}{E} \rightarrow \mathcal{X} \rightarrow A \rightarrow 0.$$

Let  $\rho \in \widehat{\Delta}$ , observe that:

- if  $\rho = 1, \omega$  then  $\mathcal{X}(\rho) \simeq \mathbb{Z}_p$ ,
- if  $\rho$  is even,  $\rho \neq 1$ ,  $\mathcal{X}(\rho) \simeq \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\rho)$ ,
- if  $\rho$  is odd,  $\rho \neq \omega$ ,  $\mathcal{X}(\rho) \simeq \mathbb{Z}_p \oplus \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\rho)$ .

**Lemma 4.1** *Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . Then:*

$$d_p \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi) = d_p A(\omega\psi^{-1}).$$

*Proof* This is a consequence of the proof of Leopoldt's reflection Theorem ([11], Theorem 10.9). For the convenience of the reader, we give the proof of the above Lemma.

Let  $H$  be the Galois group of the maximal abelian extension of  $L$  which is unramified outside  $p$  and of exponent  $p$ . Then  $H$  is a  $\mathbb{Z}_p[\Delta]$ -module and we have:

- $H(1) \simeq \mathbb{F}_p$  and corresponds to  $L(\zeta_{p^2})/L$ ,
- $H(\omega) \simeq \mathbb{F}_p$  and corresponds to  $L(^p\sqrt{p})/L$ ,

- if  $\rho$  is even,  $\rho \neq 1$ ,  $d_p H(\rho) = d_p \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\rho)$ ,  
- if  $\rho$  is odd,  $\rho \neq \omega$ , then  $d_p H(\rho) = 1 + d_p \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\rho)$ .  
Let  $V$  be the sub- $\mathbb{Z}[\Delta]$ -module of  $L^*/(L^*)^p$  which corresponds to  $H$ , i.e.  $H = \text{Gal}(L(\sqrt[p]{V})/L)$ . Let  $M$  be the sub- $\mathbb{Z}[\Delta]$ -module of  $L^*/(L^*)^p$  generated by  $E$  and  $1 - \zeta_p$ . We have an exact sequence:

$$0 \rightarrow M \rightarrow V \rightarrow A[p] \rightarrow 0.$$

Soit  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . We have by Kummer theory :

$$1 + d_p \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi) = d_p V(\omega\psi^{-1}).$$

And, by the above exact sequence, we have:

$$d_p V(\omega\psi^{-1}) = 1 + d_p A(\omega\psi^{-1}).$$

The Lemma follows.  $\diamond$

**Lemma 4.2** *Let  $\rho \in \widehat{\Delta}$ ,  $\rho$  even and  $\rho \neq 1$ . If  $\frac{E}{E^p}(\rho)$  is ramified then  $d_p A(\rho) = d_p A(\omega\rho^{-1})$ .*

*Proof* We keep the notations of the proof of Lemma 4.1. Let  $V^{nr} \subset V$  which corresponds via Kummer theory to  $A/pA$ . Then:

$$V^{nr}(\rho) \simeq \frac{A}{pA}(\omega\rho^{-1}).$$

But we have:

$$\frac{E}{E^p}(\rho) \text{ is ramified if and only if } V^{nr}(\rho) \hookrightarrow A[p](\rho).$$

Now recall that:

$$d_p A(\rho) \leq d_p A(\omega\rho^{-1}).$$

The Lemma follows.  $\diamond$

**Lemma 4.3** *There exists an unique  $\mathbb{Z}[\Delta]$ -morphism  $\varphi : K^* \rightarrow \mathbb{Z}_p[\Delta]$  such that:*

$$\forall x \in K^*, \varphi(x)\zeta_p = \text{Log}_p(x).$$

*Furthermore, we have:*

$$\text{Im } \varphi = \bigoplus_{\rho=1,\omega} p\mathbb{Z}_p e_\rho \bigoplus_{\rho \neq 1,\omega} \mathbb{Z}_p e_\rho.$$



*Proof* Let  $\lambda \in K^*$  such that  $\lambda^{p-1} = -p$ . Then:

$$K^* = \lambda^{\mathbb{Z}} \times \mu_{p-1} \times \mu_p \times U.$$

Recall that:

- the kernel of  $\text{Log}_p$  on  $K^*$  is equal to  $\lambda^{\mathbb{Z}} \times \mu_{p-1} \times \mu_p$ ,
- $\text{Log}_p U = \pi^2 \mathbb{Z}_p[\zeta_p]$ .

For  $\rho \in \widehat{\Delta}$ , set:

$$\tau(\rho) = \sum_{a=1}^{p-1} \rho(a) \zeta_p \in \mathbb{Z}_p[\zeta_p].$$

Then:

$$e_\rho \zeta_p = \tau(\rho^{-1}).$$

But recall that  $\mathbb{Z}_p[\zeta_p] = \mathbb{Z}_p[\Delta] \zeta_p$ . Thus:

$$e_\rho \mathbb{Z}_p[\zeta_p] = \mathbb{Z}_p \tau(\rho^{-1}).$$

If  $\rho = \omega^k$ ,  $k \in \{0, \dots, p-2\}$ , we have:

$$v_p(\tau(\rho^{-1})) = \frac{k}{p-1}.$$

Therefore:

$$\pi^2 \mathbb{Z}_p[\zeta_p] = \bigoplus_{\rho=1, \omega} p \mathbb{Z}_p \tau(\rho^{-1}) \bigoplus_{\rho \neq 1, \omega} \mathbb{Z}_p \tau(\rho^{-1}).$$

The Lemma follows.  $\diamond$

Let  $P$  be a prime in  $\mathcal{I}$ . We fix a generator  $r_P \in \mathbb{F}_P^*$  such that:

$$\chi_P(r_P) = \zeta_p.$$

For  $x \in \mathbb{F}_P^*$ , let  $\text{Ind}(P, x) \in \{0, \dots, NP-2\}$  such that:

$$x = r_P^{\text{Ind}(P, x)}.$$

We recall the following Theorem (see also [9] for a statement similar but weaker than part 2) of the following Theorem):

**Theorem 4.4**

- 1)  $\varphi(1 - \zeta_p) = \sum_{\rho \in \widehat{\Delta}, \rho \neq 1, \rho \text{ even}} -(p-1)^{-1} L_p(1, \rho) e_\rho$ .
- 2) Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . Write  $\psi = \omega^k$ ,  $k \in \{2, \dots, p-2\}$ . We have:

$$e_\psi \varphi(\eta(P)) \equiv 2k \text{Ind}(P, \prod_{a=1}^{p-1} \left( \frac{1 - \zeta_p^{-a}}{1 - \zeta_p} \right)^{a^{k-1}}) e_\psi \pmod{p}.$$

*Proof*

1) Let  $\rho \in \widehat{\Delta}$ ,  $\rho$  even,  $\rho \neq 1$ . By [11], Theorem 5.18, we have:

$$L_p(1, \rho)\tau(\rho^{-1}) = -(p-1)e_\rho \text{Log}_p(1 - \zeta_p).$$

Thus the first assertion follows.

2) Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . By a beautiful result of Uehara ([10], Theorem1), we have:

$$e_\psi \text{Log}_p(\eta(P)) \equiv 2k \text{Ind}(P, \prod_{a=1}^{p-1} (\frac{1 - \zeta_p^{-a}}{1 - \zeta_p})^{a^{k-1}}) \tau(\psi^{-1}) \pmod{p}.$$

This implies the second assertion.  $\diamond$

**Theorem 4.5** *Let  $\psi \in \widehat{\Delta}$ ,  $\psi \neq \omega$ ,  $\psi$  odd. We have the following exact sequences:*

$$0 \rightarrow \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi) \rightarrow A(\psi) \rightarrow \frac{\overline{W}(\psi)}{Up^{k(\psi)}(\psi)} \rightarrow 0,$$

$$0 \rightarrow \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi) \rightarrow A(\psi) \rightarrow \frac{\overline{J}(\psi)}{Up^{m(\psi)}(\psi)} \rightarrow 0.$$

*Proof* This Theorem is a consequence of the method developped by Iwasawa in [5]. Let's recall briefly this method.

Let  $f \in \mathcal{W}$ . Set, for  $n \geq 2$ ,  $\mathcal{P}_n = \{\alpha \mathcal{O}, \alpha \equiv 1 \pmod{\pi^n}\}$ . Observe that:

$$f(\mathcal{P}_n) \subset 1 + \pi^n \mathbb{Z}_p[\zeta_p].$$

Let:

$$\tilde{\mathcal{X}} = \varprojlim \frac{\mathcal{I}}{\mathcal{P}_n}.$$

If  $\tilde{F}$  is the maximal abelian extension of  $L$  which is unramified outside  $p$ , then, we get by class field theory:

$$\tilde{\mathcal{X}} \simeq \text{Gal}(\tilde{F}/L).$$

By [11], Theorem 13.4, the natural surjective map  $\tilde{\mathcal{X}} \rightarrow \mathcal{X}$  has a finite kernel of order prime to  $p$ . Thus  $f$  induces a map:

$$\bar{f}: \mathcal{X} \rightarrow U.$$

Furthermore:

$$\overline{f}(U) = U^{\beta(f)} \subset \overline{f}(\mathcal{X}).$$

Now let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . We have a map:

$$\overline{f} : \mathcal{X}(\psi) \rightarrow U(\psi).$$

But:

$$\mathcal{X}(\psi) \simeq \mathbb{Z}_p \bigoplus \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi),$$

and:

$$U(\psi) \simeq \mathbb{Z}_p.$$

Thus, if  $e_\psi \beta(f) \neq 0$ , we get:

$$\text{Ker}(\overline{f} : \mathcal{X}(\psi) \rightarrow U(\psi)) = \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi).$$

Therefore, if  $e_\psi \beta(f) \neq 0$ , we get the following exact sequence induced by  $f$ :

$$0 \rightarrow \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi) \rightarrow A(\psi) \rightarrow \frac{\overline{f}(\mathcal{X})(\psi)}{U^{\beta(f)}(\psi)} \rightarrow 0.$$

It remains to apply this construction to  $f_\psi$  and  $\eta$  to get the desired exact sequences.  $\diamond$

#### Corollary 4.6

1) Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . Then:

$$d_p A(\psi) = 1 + d_p A(\omega\psi^{-1}) \Leftrightarrow B_{1,\psi^{-1}} \equiv 0 \pmod{p} \text{ and } \overline{W}(\psi) = U(\psi).$$

2) Let  $\rho \in \widehat{\Delta}$ ,  $\rho$  even and  $\rho \neq 1$ . Assume that  $B_{1,\rho\omega^{-1}} \equiv 0 \pmod{p}$  and that  $\overline{W}(\omega\rho^{-1}) = U(\omega\rho^{-1})$  then the converse of Kummer's Lemma is true for the character  $\rho$ .

*Proof*

1) We apply Theorem 4.5. We identify  $\text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi)$  with its image in  $A(\psi)$ . We can write:

$$A(\psi) = B \bigoplus C,$$

where  $C$  is cyclic of order  $p^{k(\psi)}$  and  $B \subset \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi)$ . Now:

$$(C : C \cap \text{Tor}_{\mathbb{Z}_p} \mathcal{X}(\psi)) = (\overline{W}(\psi) : U^{p^{k(\psi)}}(\psi)).$$

It remains to apply Lemma 4.1 to get the desired result.

2) We apply the first assertion and Lemma 4.1, we get:

$$d_p A(\rho) = d_p A(\omega \rho^{-1}) - 1.$$

It remains to apply Lemma 4.2.  $\diamond$

We set:

$$W^{nr} = \{\alpha \in W, \alpha \in U^p\}.$$

Let  $\psi \in \widehat{\Delta}$ ,  $\psi$  odd,  $\psi \neq \omega$ . We assume that  $B_{1,\psi^{-1}} \equiv 0 \pmod{p}$ . Write:

$$A(\psi) = \frac{\mathbb{Z}}{p^{e_1}\mathbb{Z}} \oplus \cdots \oplus \frac{\mathbb{Z}}{p^{e_t}\mathbb{Z}},$$

where  $t = d_p A(\psi)$  and  $1 \leq e_1 \leq \cdots \leq e_t = k(\psi)$ . Set:

$$n(\psi) = |\{i \in \{1, \dots, t\}, e_i = k(\psi)\}|.$$

**Corollary 4.7** *We have:*

$$n(\psi) - 1 \leq \dim_{\mathbb{F}_p} \frac{W^{nr}(L^*)^p}{(L^*)^p} \leq n(\psi).$$

*Furthermore:*

$$\dim_{\mathbb{F}_p} \frac{W^{nr}(L^*)^p}{(L^*)^p} = n(\psi) \Leftrightarrow \overline{W}(\psi) \neq U(\psi).$$

*Proof* By Theorem 4.5 and Theorem 3.3, we have:

$$\frac{W^{nr}(L^*)^{p^{k(\psi)}}}{(L^*)^{p^{k(\psi)}}} \simeq \text{Ker}(A(\psi) \rightarrow \frac{\overline{W}(\psi)}{Up^{k(\psi)}(\psi)}).$$

The Corollary follows.  $\diamond$

**Corollary 4.8** *Assume that  $pA^- = \{0\}$ . Then we have an isomorphism of groups:*

$$\text{Gal}(L(p\sqrt{W^{nr}})/L) \simeq \frac{A^+}{pA^+}.$$

*Proof* This result is a consequence of Kummer theory, Corollary 4.7 and Corollary 4.6.  $\diamond$

Note that the above results lead us to ask the following problem (which is a restatement of the converse of Kummer's Lemma):

do we have  $\varphi(\overline{W}^-) = (\text{Im } \varphi)^-$ ?

Observe that  $e_\omega \varphi(\overline{W}^-) = e_\omega (\text{Im } \varphi)^-$ , and since  $K_4(\mathbb{Z}) = \{0\}$ , we have  $A(\omega^{-2}) = \{0\}$  (see [7]) and therefore  $e_{\omega^3} \varphi(\overline{W}^-) = e_{\omega^3} (\text{Im } \varphi)^-$ .

## 5 Remarks on the Jacobian of the Fermat Curve over a finite field

First we fix some notations and recall some basic facts about global function fields.

Let  $\mathbb{F}_q$  be a finite field having  $q$  elements. Let  $\ell$  be the characteristic of  $\mathbb{F}_q$ ,  $\ell \neq p$ . Let  $\overline{\mathbb{F}_q}$  be a fixed algebraic closure of  $\mathbb{F}_q$  and let  $\widetilde{\mathbb{F}_q} = \bigcup_{n \geq 1, n \not\equiv 0 \pmod{p}} \mathbb{F}_{q^n} \subset \overline{\mathbb{F}_q}$ . Let  $k/\mathbb{F}_q$  be a global function field such that  $\mathbb{F}_q$  is algebraically closed in  $k$ . We set:

- $D_k$  : the group of divisors of  $k$ ,
- $D_k^0$  : the group of divisors of degree zero of  $k$ ,
- $P_k$  : the group of principal divisors of  $k$ ,
- $J_k$  : the jacobian of  $k$ , note that we have:

$$\forall n \geq 1, J_k(\mathbb{F}_{q^n}) \simeq \frac{D_{\mathbb{F}_{q^n}k}^0}{P_{\mathbb{F}_{q^n}k}},$$

- $g_k$  : the genus of  $k$ ,
- $L_k(Z) \in \mathbb{Z}[Z]$  : the numerator of the zeta function of  $k$ , we recall that:

$$\frac{L_k(Z)}{(1-Z)(1-qZ)} = \prod_{v \text{ place of } k} (1 - Z^{\deg v})^{-1},$$

furthermore  $\deg_Z L_k(Z) = 2g_k$  and  $L_k(1) = |J_k(\mathbb{F}_q)|$ ,

- $C_k(\mathbb{F}_{q^n}) = J_k(\mathbb{F}_{q^n}) \otimes_{\mathbb{Z}} \mathbb{Z}_p$ ,
- $\widetilde{d}_p J_k = d_p C_k(\widetilde{\mathbb{F}_q})$ , observe that there exists an integer  $m$ ,  $m \not\equiv 0 \pmod{p}$ , such that :

$$C_k(\widetilde{\mathbb{F}_q}) = C_k(\mathbb{F}_{q^m}).$$

Write:

$$L_k(Z) = \prod_{i=1}^{2g_k} (1 - \alpha_i Z).$$

For simplicity, we assume that  $v_p(\alpha_i - 1) > 0$  for  $i = 1, \dots, 2g_k$ . In this case, we have:

$$C_k(\tilde{\mathbb{F}}_q) = C_k(\mathbb{F}_q).$$

Set  $P_k(Z) = \prod_{i=1}^{2g_k} (Z - (\alpha_i - 1))$ . Let  $\gamma$  be the Frobenius of  $\mathbb{F}_q$ , and set:

$$C_n(k) = C_k(\mathbb{F}_{q^{p^n}}).$$

Let  $C_\infty(k) = \cup_{n \geq 0} C_n(k)$ , and set:

$$M_k = \text{Hom}\left(\frac{\mathbb{Q}_p}{\mathbb{Z}_p}, C_\infty(k)\right).$$

Then  $M_k$  is isomorphic to the  $p$ -adic Tate-module of  $J_k$ . Set  $\Lambda = \mathbb{Z}_p[[Z]]$  where  $Z$  corresponds to  $\gamma - 1$ . Then it is well-known that:

- $M_k$  is a  $\Lambda$ -module of finite type and of torsion,
- as a  $\mathbb{Z}_p$ -module  $M_k$  is isomorphic to  $\mathbb{Z}_p^{2g_k}$ ,
- $M_k/\omega_n M_k \simeq C_n(k)$ , where  $\omega_n = (1 + Z)^{p^n} - 1$ ,
- $\text{Char}_\Lambda M_k = P_k(Z)\Lambda$ ,
- the action of  $Z$  on  $M_k$  is semi-simple, i.e. the minimal polynomial of the action of  $Z$  on  $M_k$  has only simple roots.

Now, let  $\ell$  be a prime number,  $\ell \neq p$ . We fix a prime  $P$  of  $\mathcal{O}$  above  $\ell$  and we view  $\mathcal{O}/P$  as a subfield of  $\tilde{\mathbb{F}}_\ell$ , thus  $\mathbb{F}_q = \mathcal{O}/P \subset \tilde{\mathbb{F}}_\ell$ . We identify  $\zeta_p$  with its image in  $\mathbb{F}_q$ . Let  $X$  be an indeterminate over  $\mathbb{F}_q$ , we set  $k = \mathbb{F}_\ell(X, Y)$  where  $X^p + Y^p = 1$ , and we set:  $T = X^p$ . For  $a, b \in \mathbb{Z}$ , let  $\tau_{a,b} \in \text{Gal}(\overline{\mathbb{F}_\ell k}/\overline{\mathbb{F}_\ell}(T))$  such that:

$$\tau_{a,b}(X) = \zeta_p^a X \text{ and } \tau_{a,b}(Y) = \zeta_p^b Y.$$

Let  $a \in \{1, \dots, p-2\}$ . Let  $H_a$  be the subgroup of  $\text{Gal}(\overline{\mathbb{F}_\ell k}/\overline{\mathbb{F}_\ell}(T))$  generated by  $\tau_{1, [-a^{-1}]}$ . Set:

$$E_a = \mathbb{F}_\ell(T, XY^a).$$

We set:

$$E = \mathbb{F}_q E_a,$$

$$F = \mathbb{F}_q k,$$

and observe that:

$$\widetilde{\mathbb{F}}_\ell = \widetilde{\mathbb{F}}_q.$$

It is clear that:

$$F^{H_a} = E.$$

Finally, we set:

$$G = \text{Gal}(E/\mathbb{F}_q(T)).$$

Note that  $g_E = (p-1)/2$ .

**Lemma 5.1** *We have:*

$$L_E(Z) = \prod_{\sigma \in \Delta} (1 - j_{1,a}(P)^\sigma Z).$$

*Proof* Let  $\chi \in \widehat{G}$  such that:

$$\chi(g) = \zeta_p^{-1},$$

where  $g \in G$  is such that  $g(XY^a) = \zeta_p XY^a$ . Note that:

$$L_E(Z) = \prod_{\sigma \in \Delta} L(Z, \chi^\sigma),$$

where:

$$L(Z, \chi) = \prod_{v \text{ place of } \mathbb{F}_q(T)} (1 - \chi(v) Z^{\deg v})^{-1}.$$

Since  $2g_e = p-1$ , we get:

$$\deg_Z L(Z, \chi) = 1.$$

For  $b \in \mathbb{F}_q \setminus \{0, 1\}$ , we denote the Frobenius of  $T-b$  in  $E/\mathbb{F}_q(T)$  by  $Frob_b$ . We have:

$$Frob_b(XY^a) = (b(1-b)^a)^{(q-1)/p} XY^a.$$

But:

$$L(Z, \chi) \equiv 1 + \left( \sum_{b \in \mathbb{F}_q \setminus \{0, 1\}} \chi(Frob_b) \right) X \pmod{X^2}.$$

Thus:

$$L(Z, \chi) = 1 + \left( \sum_{b \in \mathbb{F}_q \setminus \{0, 1\}} \chi(Frob_b) \right) X.$$

But, we can write:

$$j_{1,a}(P) = - \sum_{i=0}^{p-1} N_i \zeta_p^{-i},$$

where  $N_i = |\{ \alpha \in \mathbb{F}_q \setminus \{0, 1\}, (\alpha(1 - \alpha)^a)^{(q-1)/p} \equiv \zeta_p^{-i} \pmod{P} \}|$ .  
Therefore:

$$j_{1,a}(P) = - \sum_{b \in \mathbb{F}_q \setminus \{0, 1\}} \chi(\text{Frob}_b).$$

The Lemma follows.  $\diamond$

**Theorem 5.2** *Let  $n$  be the smallest integer (if it exists) such that  $3 \leq n \leq p - 2$ ,  $n$  odd and  $e_{\omega^n} j_{1,a}(P) \notin U^p$ , then:*

$$J_k(\widetilde{\mathbb{F}}_\ell)^{H_a} \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq \left(\frac{\mathbb{Z}}{p\mathbb{Z}}\right)^n.$$

*If such an integer doesn't exist then:*

- 1)  $\widetilde{d}_p J_k^{H_a} = p - 1$ ,
- 2) *we have:*

$$J_k(\widetilde{\mathbb{F}}_\ell)^{H_a} \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq \left(\frac{\mathbb{Z}}{p\mathbb{Z}}\right)^{p-1} \Leftrightarrow \ell^{p-1} \not\equiv 1 \pmod{p^2}.$$

*Proof* The proof of this result is based on ideas developped by Greenberg in [4]. Set  $H = H_a$ . Let  $P_0$  be the prime of  $E$  above  $T$ ,  $P_1$  the prime of  $E$  above  $T - 1$  and  $P_\infty$  the prime of  $E$  above  $\frac{1}{T}$ . Recall that we have in  $D_E$  :

$$p(P_0 - P_\infty) = (T),$$

$$p(P_1 - P_\infty) = (T - 1),$$

$$P_0 - P_\infty + a(P_1 - P_\infty) = (XY^a).$$

Thus, by [4], paragraph 2, we get:

$$J_E(\mathbb{F}_q)^G \simeq \frac{\mathbb{Z}}{p\mathbb{Z}},$$

and  $J_E(\mathbb{F}_q)^G$  is generated by the class of  $P_0 - P_\infty$ . Observe also that  $F/E$  is unramified and cyclic of order  $p$ . Let's start by the following exact sequence:

$$0 \rightarrow \mathbb{F}_q^* \rightarrow F^* \rightarrow P_F \rightarrow 0.$$



We get:

$$\frac{P_F^H}{P_E} \simeq \frac{\mathbb{Z}}{p\mathbb{Z}},$$

and  $\frac{P_F^H}{P_E}$  is generated by the image of  $P_0 - P_\infty$  in  $D_F$ . In particular:

$$\frac{P_F^H}{P_E} \simeq J_E(\mathbb{F}_q)^G.$$

Note that we also have:

$$0 \rightarrow H^1(H, P_F) \rightarrow H^2(H, \mathbb{F}_q^*) \rightarrow H^2(H, F^*).$$

But  $F/E$  is unramified and cyclic, therefore every element of  $\mathbb{F}_q^*$  is a norm in the extension  $F/E$ . Thus:

$$H^1(H, P_F) \simeq \frac{\mathbb{Z}}{p\mathbb{Z}}.$$

Now, we look at the exact sequence:

$$0 \rightarrow P_F \rightarrow D_F^0 \rightarrow J_F(\mathbb{F}_q) \rightarrow 0.$$

Since  $F/E$  is unramified:

$$H^1(H, D_F^0) = \{0\}.$$

Therefore, we have obtained the following exact sequence:

$$0 \rightarrow J_E(\mathbb{F}_q)^G \rightarrow J_E(\mathbb{F}_q) \rightarrow J_F(\mathbb{F}_q)^H \rightarrow \frac{\mathbb{Z}}{p\mathbb{Z}} \rightarrow 0.$$

Now, it is not difficult to deduce that, for all  $n \geq 1$ , we have the following exact sequence:

$$0 \rightarrow \frac{\mathbb{Z}}{p\mathbb{Z}} \rightarrow J_E(\mathbb{F}_{q^n}) \rightarrow J_F(\mathbb{F}_{q^n})^H \rightarrow \frac{\mathbb{Z}}{p\mathbb{Z}} \rightarrow 0.$$

From this, we get the following exact sequence of  $\mathbb{Z}_p[G]$ -modules and  $\Lambda$ -modules:

$$0 \rightarrow M_E \rightarrow M_F^H \rightarrow \frac{\mathbb{Z}}{p\mathbb{Z}} \rightarrow 0.$$

Recall that in our situation, by Lemma 5.1, we have:

$$P_E(Z) = \prod_{\sigma \in \Delta} (Z - (j_{1,a}(P)^\sigma - 1)).$$

Furthermore the action of  $G$  and  $Z$  commute on  $M_F^H$ . Now, we have:

- $\text{Char}_\Lambda M_F^H = \text{Char}_\Lambda M_E = P_E(Z)\Lambda$ ,
- $M_F^H \simeq \mathbb{Z}_p^{p-1}$  as  $\mathbb{Z}_p$ -modules,
- $M_F^H/\omega_n \simeq C_n(F)^H$ .

Observe that:

$$C_0(F)^H = J_k(\widetilde{\mathbb{F}_\ell})^{H_a} \otimes_{\mathbb{Z}} \mathbb{Z}_p.$$

Note also that the minimal polynomial of the action of  $Z$  on  $M_F^H$  is:

$$\text{Irr}(j_{1,a}(P) - 1, \mathbb{Q}_p; Z) := G(Z).$$

Set  $N = \sum_{\delta \in G} \delta$ . Then one can see that:

$$NM_E = NM_F^H = \{0\}.$$

Thus  $M_F^H$  is a  $\mathbb{Z}_p[G]/N\mathbb{Z}_p[G]$ -module. Now, we identify  $\mathbb{Z}_p[G]/N\mathbb{Z}_p[G]$  with  $\mathbb{Z}_p[\zeta_p]$ . Since  $M_F^H \simeq \mathbb{Z}_p^{p-1}$ , there exists  $m \in M_F^H$  such that:

$$M_F^H \simeq \mathbb{Z}_p[\zeta_p].m,$$

i.e.  $M_F^H$  is a free  $\mathbb{Z}_p[\zeta_p]$ -module of rank one. Therefore there exists an element  $x \in \mathbb{Z}_p[\zeta_p]$  such that:

$$Zm = xm.$$

Now set:

$$D(Z) = \prod_{\sigma \in \Delta} (Z - x^\sigma) \in \Lambda.$$

Then:

$$D(Z)M_F^H = \{0\}.$$

Therefore  $G(Z)$  divides  $D(Z)$  in  $\Lambda$ . Thus there exists  $\sigma \in \Delta$  such that:

$$x^\sigma = j_{1,a}(P) - 1.$$

But:

$$C_0(F)^H \simeq \frac{M_F^H}{ZM_F^H} \simeq \frac{\mathbb{Z}_p[\zeta_p]}{x\mathbb{Z}_p[\zeta_p]}.$$

Therefore, we get:

$$J_k(\widetilde{\mathbb{F}}_\ell)^{H_a} \otimes_{\mathbb{Z}} \mathbb{Z}_p \simeq \frac{\mathbb{Z}_p[\zeta_p]}{(j_{1,a}(P) - 1)\mathbb{Z}_p[\zeta_p]}.$$

Recall that  $j_{1,a}(P) \equiv 1 \pmod{\pi^2}$ . Thus:

$$v_p(j_{1,a}(P) - 1) = v_p(\text{Log}_p(j_{1,a}(P))).$$

Now:

$$\text{Log}_p(j_{1,a}(P)) = \frac{1}{2}f\text{Log}_p(\ell) + \sum_{\psi \in \widehat{\Delta}, \psi \text{ odd}} e_\psi \text{Log}_p(j_{1,a}(P)),$$

where  $f$  is the order of  $\ell$  in  $(\mathbb{Z}/p\mathbb{Z})^*$ . Let  $\psi \in \widehat{\Delta}$ ,  $\psi = \omega^n$ ,  $n$  odd. If  $e_\psi \text{Log}_p(j_{1,a}(P)) \neq 0$ , then:

$$v_p(e_\psi \text{Log}_p(j_{1,a}(P))) \equiv \frac{n}{p-1} \pmod{\mathbb{Z}},$$

furthermore:

$$v_p(e_\psi \text{Log}_p(j_{1,a}(P))) > \frac{n}{p-1} \Leftrightarrow e_\psi j_{1,a}(P) \in U^p.$$

Note also that:

$$v_p(e_\omega \text{Log}_p(j_{1,a}(P))) > \frac{1}{p-1}.$$

The Theorem follows.  $\diamond$

**Corollary 5.3** *Let  $n \in \{3, \dots, p-2\}$ ,  $n$  odd. Let  $a \in \{1, \dots, p-2\}$  such that  $1+a^n - (1+a)^n \not\equiv 0 \pmod{p}$ . The following assertions are equivalent:*  
1)  $A(\omega^{1-n}) = \{0\}$ ,  
2) *there exists a prime number  $\ell$ ,  $\ell \neq p$ , such that  $\widetilde{d}_p J_k^{H_a} = n$ .*

*Proof* Observe that 2) implies 1) by the above Theorem and Theorem 4.5. Write  $\psi = \omega^n$ . Let  $\ell$  be a prime number,  $\ell \neq p$ . Write:

$$\mathbb{F}_{(\ell)} = \frac{\mathcal{O}}{\ell\mathcal{O}},$$

and:

$$D_\ell = \frac{\mathbb{F}_{(\ell)}^*}{(\mathbb{F}_{(\ell)}^*)^p}.$$

Observe that  $D_\ell$  is a  $\mathbb{Z}_p[\Delta]$ -module. Let  $Cyc$  be the group of cyclotomic units of  $L$ . We denote the image of  $Cyc$  in  $D_\ell$  by  $\overline{Cyc}^\ell$ . Then Theorem 4.4 asserts that  $e_\psi \overline{Cyc}^\ell = \{1\}$  in  $D_\ell$  if and only if  $e_\psi j_{1,a}(P) \in U^p$ , where  $P$  is a prime of  $\mathcal{O}$  above  $\ell$ . Let:

$$B = L(\sqrt[p]{Cyc}).$$

We assume that 1) holds. We apply the Chebotarev density theorem to the extension  $B/L$ , then there exist infinitely many primes  $\ell$  such that:

- $e_\rho \overline{Cyc}^\ell = \{1\}$  for  $\rho \neq \psi$ ,
- $e_\psi \overline{Cyc}^\ell \neq \{1\}$ .

It remains to apply Theorem 5.2 and the above remarks to get 2).  $\diamond$

Now, let  $\ell$  be a prime number. Let  $p$  be an odd prime number,  $p \neq \ell$ . Let  $T$  be an indeterminate over  $\mathbb{F}_\ell$  and let  $E_p/\mathbb{F}_\ell(T)$  be the imaginary quadratic extension defined by:

$$E_p = \mathbb{F}_\ell(T, X) \text{ where } X^2 - X + T^p = 0.$$

Let  $n$  be an odd integer,  $n \geq 3$ . Let  $S_n(\ell)$  denote the set of primes  $p$  such that  $\tilde{d}_p J_{E_p} = n$ . By our above results, we remark that if  $p \in S_n(\ell)$  then  $A(\omega^{1-n}) = \{0\}$ . Observe that if  $\ell^n \not\equiv 1 \pmod{p}$  then  $p \notin S_n(\ell)$ , and therefore  $S_n(\ell)$  is a finite set. Set  $S(\ell) = \cup_n S_n(\ell)$ , where  $n$  runs through the odd integers. Observe that if the order of  $\ell$  modulo  $p$  is even then  $p \notin S(\ell)$ . Therefore, by a classical result of Hasse (see [8]) there exist infinitely many prime  $p$  not in  $S(\ell)$  (in fact at least "2/3 of the prime numbers" are not in  $S(\ell)$ ). Thus, we ask the following question:

is  $S(\ell)$  infinite?

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