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José Ibrahim Villanueva Gutiérrez

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# ON THE MU AND LAMBDA INVARIANTS OF THE LOGARITHMIC CLASS GROUP.

JOSÉ-IBRAHIM VILLANUEVA-GUTIÉRREZ

ABSTRACT. Let  $\ell$  be a rational prime number. Assuming the Gross-Kuz'min conjecture along a  $\mathbb{Z}_\ell$ -extension  $K_\infty$  of a number field  $K$ , we show that there exist integers  $\tilde{\mu}$ ,  $\tilde{\lambda}$  and  $\tilde{\nu}$  such that the exponent  $\tilde{e}_n$  of the order  $\ell^{\tilde{e}_n}$  of the logarithmic class group  $\widetilde{C}\ell_n$  for the  $n$ -th layer  $K_n$  of  $K_\infty$  is given by  $\tilde{e}_n = \tilde{\mu}\ell^n + \tilde{\lambda}n + \tilde{\nu}$ , for  $n$  big enough. We show some relations between the classical invariants  $\mu$  and  $\lambda$ , and their logarithmic counterparts  $\tilde{\mu}$  and  $\tilde{\lambda}$  for some class of  $\mathbb{Z}_\ell$ -extensions. Additionally, we provide numerical examples for the cyclotomic and the non-cyclotomic case.

## 1. INTRODUCTION

Let  $K$  be a number field and  $\ell$  a prime integer. The logarithmic class group  $\widetilde{C}\ell_K$  of  $K$  is the  $\mathbb{Z}_\ell$ -module measuring the gap between the cyclotomic  $\mathbb{Z}_\ell$ -extension  $K^c$  of  $K$  and the maximal abelian pro- $\ell$ -extension  $K^{lc}$  of  $K$  which splits completely over  $K^c$ , i.e.  $\widetilde{C}\ell_K$  is isomorphic to the relative Galois group  $\text{Gal}(K^{lc}/K^c)$  [9]. The logarithmic class group is conjectured to be finite for every number field, this is equivalent to the Gross-Kuz'min conjecture [10]; its finiteness is verified in the abelian case and some other cases (e.g. [12, 11]). As an arithmetic invariant of a number field the logarithmic class group has importance in its own. The logarithmic class group is effective by computational methods [3, 2, 1] and it is surprisingly related to the wild kernels in  $K$ -theory [14]. In spite its tight relation to the  $\ell$ -class group  $C\ell_K$  of  $K$ , it behaves differently in several situations (see §5).

We are interested in the study of the logarithmic class group along  $\mathbb{Z}_\ell$ -extensions, in the spirit of Iwasawa's work for class groups [7, 8]. This has been done in the cyclotomic case by Jaulent in [9]; in this situation the logarithmic class group attached to the  $n$ -th layer of the cyclotomic  $\mathbb{Z}_\ell$ -extension has a nice interpretation as a quotient of Kuz'min-Tate modules [13]. This interpretation is no longer valid for non-cyclotomic  $\mathbb{Z}_\ell$ -extensions whenever the base field admits such an extension.

Assuming the Gross-Kuz'min conjecture, the main result of this work provides a method for the non-cyclotomic case, and therefore completes the study of the logarithmic class group along  $\mathbb{Z}_\ell$ -extensions:

**Theorem 1.1.** *Let  $K_\infty/K$  be a  $\mathbb{Z}_\ell$ -extension. Assume the Gross-Kuz'min conjecture is valid along the  $\mathbb{Z}_\ell$ -extension  $K_\infty$ . Let  $\widetilde{C}\ell_n$  be the logarithmic class group of  $K_n$  and*

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let  $\ell^{\tilde{e}_n}$  be its order. There exist integers  $\tilde{\lambda}, \tilde{\mu} \geq 0$  and  $\tilde{\nu}$  such that

$$\tilde{e}_n = \tilde{\mu}\ell^n + \tilde{\lambda}n + \tilde{\nu}, \quad \text{for } n \text{ big enough.}$$

This article is organized as follows. In Section 2 we recall briefly the basic definitions and properties of the logarithmic arithmetic that are helpful for our purposes, nonetheless, for more on logarithmic arithmetic we urge the reader to consult the seminal paper of Jaulent [10]. Then we show some results on logarithmic ramification in  $\mathbb{Z}_\ell$ -extensions.

In Section 3 we construct a  $\Lambda$ -module, which is the logarithmic analogue to the  $\Lambda$ -module  $X$  in [15, §1], to which we apply the codescent techniques. We show that this logarithmic  $\Lambda$ -module is noetherian and assuming the Gross-Kuz'min conjecture also torsion.

In Section 4 we prove Theorem 1.1 in the non-cyclotomic case as well as a set of results involving the  $\tilde{\mu}$  and  $\tilde{\lambda}$  logarithmic invariants for some class of  $\mathbb{Z}_\ell$ -extensions.

Finally, in section 5 we provide numerical examples, in both the cyclotmic and non-cyclotomic case, of logarithmic class groups in the first layers of  $\mathbb{Z}_\ell$ -extensions. Additionally we compare this information with the results in [6] to explicitly compute the  $\tilde{\mu}$ ,  $\tilde{\lambda}$  and  $\tilde{\nu}$  logarithmic invariants.

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## 2. LOGARITHMIC ARITHMETIC

From now on we fix a number field  $K$  and a prime number  $\ell$ . Let  $\text{Pl}_K^0$  be the set of finite places of  $K$ .

For any prime  $p$  let  $\widehat{\mathbb{Q}}_p^c$  be the cyclotomic  $\widehat{\mathbb{Z}}$ -extension of  $\mathbb{Q}_p$ . For a place  $\mathfrak{p}$  above  $p$  we define the logarithmic ramification index  $\tilde{e}_{\mathfrak{p}}$  and the logarithmic inertia degree  $\tilde{f}_{\mathfrak{p}}$  as

$$\tilde{e}_{\mathfrak{p}} = [K_{\mathfrak{p}} : K_{\mathfrak{p}} \cap \widehat{\mathbb{Q}}_p^c] \quad \text{and} \quad \tilde{f}_{\mathfrak{p}} = [K_{\mathfrak{p}} \cap \widehat{\mathbb{Q}}_p^c : \mathbb{Q}_p].$$

respectively. Similarly, for a local extension  $L_{\mathfrak{p}}/K_{\mathfrak{p}}$  we define the relative logarithmic ramification index  $\tilde{e}_{\mathfrak{p}|\mathfrak{p}}$  and relative logarithmic inertia degree  $\tilde{f}_{\mathfrak{p}|\mathfrak{p}}$  as

$$\tilde{e}_{\mathfrak{p}|\mathfrak{p}} = [L_{\mathfrak{p}} : L_{\mathfrak{p}} \cap \widehat{\mathbb{Q}}_p^c K_{\mathfrak{p}}] \quad \text{and} \quad \tilde{f}_{\mathfrak{p}|\mathfrak{p}} = [L_{\mathfrak{p}} \cap \widehat{\mathbb{Q}}_p^c K_{\mathfrak{p}} : K_{\mathfrak{p}}].$$

**Proposition 2.1.** *Let  $L_{\mathfrak{p}}/K_{\mathfrak{p}}$  be a local extension. The logarithmic ramification index and the logarithmic inertia degree satisfy the following properties:*

- (1) *Multiplicative relation:*  $n_{\mathfrak{p}} = [K_{\mathfrak{p}} : \mathbb{Q}_p] = e_{\mathfrak{p}} f_{\mathfrak{p}} = \tilde{e}_{\mathfrak{p}} \tilde{f}_{\mathfrak{p}}$ , where  $e_{\mathfrak{p}}$  and  $f_{\mathfrak{p}}$  are the usual ramification index and inertia degree.
- (2) *For all  $q \neq p$ :*  $v_q(e_{\mathfrak{p}}) = v_q(\tilde{e}_{\mathfrak{p}})$ .
- (3) *Multiplicative in towers:*  $\tilde{e}_{\mathfrak{p}} = \tilde{e}_{\mathfrak{p}|\mathfrak{p}} \tilde{e}_{\mathfrak{p}}$  and  $\tilde{f}_{\mathfrak{p}} = \tilde{f}_{\mathfrak{p}|\mathfrak{p}} \tilde{f}_{\mathfrak{p}}$ .

We endow  $K$  with a family of  $\ell$ -adic logarithmic valuations  $(\tilde{v}_{\mathfrak{p}})_{\mathfrak{p} \in \text{Pl}_K^0}$  defined as follows

$$\tilde{v}_{\mathfrak{p}}(x) = \begin{cases} v_{\mathfrak{p}}(x) & \text{if } \mathfrak{p} \nmid \ell, \\ -\frac{\text{Log}_{\ell}(N_{K_{\mathfrak{p}}/\mathbb{Q}_{\ell}}(x))}{\deg \mathfrak{p}} & \text{if } \mathfrak{p} \mid \ell, \end{cases} \quad \text{for } x \in K_{\mathfrak{p}}^{\times}.$$

Here  $v_{\mathfrak{p}}$  denotes the classical valuation,  $N_{K_{\mathfrak{p}}/\mathbb{Q}_{\ell}}$  is the local norm,  $\text{Log}_{\ell}$  is Iwasawa's logarithm and  $\deg \mathfrak{p}$  is a normalizing term defined as follows

$$\deg \mathfrak{p} = \tilde{f}_{\mathfrak{p}} \deg p \quad \text{where} \quad \deg p = \begin{cases} \text{Log}_{\ell}(p) & \text{if } p \neq \ell, \\ \text{Log}_{\ell}(1 + \ell) & \text{if } p = \ell. \end{cases}$$

We define the logarithmic divisors  $\mathcal{D}\ell_K$  as the free  $\mathbb{Z}_{\ell}$ -module  $\mathcal{D}\ell_K = \bigoplus_{\mathfrak{p} \in \text{Pl}_K^0} \mathbb{Z}_{\ell} \mathfrak{p}$  and we extend additively the mapping  $\deg$  to all of  $\mathcal{D}\ell_K$ , that is, for a logarithmic divisor  $\mathfrak{d}$ :

$$\deg(\mathfrak{d}) = \deg \left( \sum_{\mathfrak{p} \in \text{Pl}_K^0} a_{\mathfrak{p}} \mathfrak{p} \right) = \sum_{\mathfrak{p} \in \text{Pl}_K^0} a_{\mathfrak{p}} \deg \mathfrak{p}, \quad \text{with } a_{\mathfrak{p}} \in \mathbb{Z}_{\ell}.$$

Let us denote  $\mathcal{R}_K = \mathbb{Z}_{\ell} \otimes_{\mathbb{Z}} K^{\times}$ . The logarithmic divisor map

$$\tilde{\text{div}} : \mathcal{R}_K \longrightarrow \mathcal{D}\ell_K, \quad x \mapsto \sum_{\mathfrak{p} \in \text{Pl}_K^0} \tilde{v}_{\mathfrak{p}}(x) \mathfrak{p},$$

associates to each element in the tensor product a logarithmic divisor by means of the logarithmic valuation. It turns out that the image of an element in  $\mathcal{R}_K$  has degree 0 [10, Prop. & Def. 2.2]. The image  $\mathcal{P}\ell_K$  of all these elements is the subgroup of principal logarithmic divisors. Therefore it is natural to consider the following exact sequence:

$$1 \longrightarrow \tilde{\mathcal{E}}_K \longrightarrow \mathcal{R}_K \xrightarrow{\tilde{\text{div}}} \bigoplus_{\mathfrak{p} \in \text{Pl}_K^0} \mathbb{Z}_{\ell} \mathfrak{p} \longrightarrow \tilde{\mathcal{C}}\ell_K^* \longrightarrow 1,$$

we call  $\tilde{\mathcal{E}}_K$  the group of logarithmic units (defined in the obvious way) and  $\tilde{\mathcal{C}}\ell_K^* \simeq \mathcal{D}\ell_K / \mathcal{P}\ell_K$  the group of logarithmic classes of arbitrary degree.

**Definition 2.2.** The logarithmic class group  $\tilde{\mathcal{C}}\ell_K \subset \tilde{\mathcal{C}}\ell_K^*$  consists of the classes of degree 0.

The group  $\tilde{\mathcal{C}}\ell_K^*$  of logarithmic classes of arbitrary degree is isomorphic to the Galois group  $\text{Gal}(K^{\text{lc}}/K)$  of the maximal abelian  $\ell$ -extension of  $K$  which splits completely over the cyclotomic  $\mathbb{Z}_{\ell}$ -extension  $K^c$  of  $K$ . The logarithmic class group is isomorphic to the relative Galois group  $\text{Gal}(K^{\text{lc}}/K^c)$ . The Gross-Kuz'min conjecture asserts that the Galois group  $\text{Gal}(K^{\text{lc}}/K)$  is a  $\mathbb{Z}_{\ell}$ -module of dimension 1, equivalently, asserts the finiteness of the logarithmic class group.

*Logarithmic ramification.* Let  $\mathfrak{p}$  be a finite place of  $K$ . Let  $L/K$  be a finite extension, we say that  $\mathfrak{p}$  is logarithmically unramified if  $\tilde{e}_{\mathfrak{P}|\mathfrak{p}} = 1$  for every place  $\mathfrak{P}$  above  $\mathfrak{p}$ . Hence if  $L/K$  is infinite, we say that  $\mathfrak{p}$  is logarithmically unramified if and only if it is logarithmically unramified for every finite extension  $K'/K$  contained in  $L$ . In the Galois case it might be more convenient to work with inertia groups to study ramification, we

give the corresponding description in the logarithmic setting in the very special case when  $L$  is an abelian  $\ell$ -extension of  $K$ .

Let  $L/K$  be an abelian  $\ell$ -extension. Then  $\ell$ -adic class field theory establishes a correspondence between the decomposition group  $D_{\mathfrak{p}}$  of the maximal abelian  $\ell$ -extension  $K^{\text{ab}}$  of  $K$  with the pro- $\ell$ -completion  $\mathcal{R}_{\mathfrak{p}}$  of the groups  $K_{\mathfrak{p}}^{\times}$ , i.e.  $D_{\mathfrak{p}} \simeq \mathcal{R}_{\mathfrak{p}} = \varprojlim K_{\mathfrak{p}}^{\times} / K_{\mathfrak{p}}^{\times \ell^k}$ . We can extend the logarithmic valuations  $\tilde{v}_{\mathfrak{p}}$  to the  $\mathcal{R}_{\mathfrak{p}}$ ; in that sense we have an analogous decomposition  $\mathcal{R}_{\mathfrak{p}} = \tilde{\pi}_{\mathfrak{p}}^{\mathbb{Z}_{\ell}} \tilde{\mathcal{U}}_{\mathfrak{p}}$  to the classical decomposition  $\mathcal{R}_{\mathfrak{p}} = \pi_{\mathfrak{p}}^{\mathbb{Z}_{\ell}} \mathcal{U}_{\mathfrak{p}}$ , where  $\tilde{\pi}_{\mathfrak{p}}$  is a logarithmic uniformizer and  $\tilde{\mathcal{U}}_{\mathfrak{p}}$  is the subgroup of logarithmic units, i.e. the kernel under the corresponding logarithmic valuation. The image  $\tilde{I}_{\mathfrak{p}} \subset \text{Gal}(K^{\text{ab}}/K)$  of  $\tilde{\mathcal{U}}_{\mathfrak{p}}$  is said to be the subgroup of logarithmic inertia. Hence, we define the group of logarithmic inertia  $\tilde{I}_{\mathfrak{p}}(L/K)$  of the abelian  $\ell$ -extension  $L/K$  as the image of  $\tilde{\mathcal{U}}_{\mathfrak{p}}$  in the Galois group  $\text{Gal}(L/K)$ . We say  $\mathfrak{p}$  is logarithmically unramified in  $L/K$  if  $\tilde{I}_{\mathfrak{p}} \subseteq \text{Gal}(K^{\text{ab}}/L)$ . Notice that all the extensions we are considering are abelian, so we do not specify the place  $\mathfrak{P}$  above  $\mathfrak{p}$  since the logarithmic inertia subgroups are isomorphic.

In general,  $\ell$ -adic class field theory establishes a correspondence between the Galois group of the maximal abelian  $\ell$ -extension of  $K$  and the following quotient:

$$\text{Gal}(K^{\text{ab}}/K) \simeq \mathcal{J}_K / \mathcal{R}_K,$$

where  $\mathcal{J}_K$  is the restricted product  $\prod \mathcal{R}_{\mathfrak{p}}$  of the  $\ell$ -adic completions  $\mathcal{R}_{\mathfrak{p}}$  defined above.

**Remark 2.3.** Notice that in the finite case this characterisation of logarithmic ramification for abelian  $\ell$ -extensions in terms of inertia subgroups, coincides with the definition given at the beginning of the section.

In fact, as we have seen, if  $L/K$  is a finite abelian  $\ell$ -extension and  $\mathfrak{P}$  is a place of  $L$  above  $\mathfrak{p} \in \text{Pl}_K$ , the logarithmic inertia subgroup  $\tilde{I}_{\mathfrak{p}}(L/K)$  of the extension  $L/K$  is the image of  $\tilde{\mathcal{U}}_{\mathfrak{p}}$  inside the Galois group  $\text{Gal}(L/K) \simeq \mathcal{J}_K / N_{L/K}(\mathcal{J}_L) \mathcal{R}_K$ , hence:

$$\tilde{I}_{\mathfrak{p}}(L/K) \simeq \tilde{\mathcal{U}}_{\mathfrak{p}} / \tilde{\mathcal{U}}_{\mathfrak{p}} \cap N_{L/K}(\mathcal{J}_L) \mathcal{R}_K;$$

on the other hand, the logarithmic ramification index is defined as the degree  $\tilde{e}_{\mathfrak{P}|\mathfrak{p}} = [L_{\mathfrak{P}} : L_{\mathfrak{P}} \cap K_{\mathfrak{p}}^c]$ , which is equal to the order of the Galois group

$$\text{Gal}(L_{\mathfrak{P}}/L_{\mathfrak{P}} \cap K_{\mathfrak{p}}^c) = \tilde{\mathcal{U}}_{\mathfrak{p}} N_{L_{\mathfrak{P}}/K_{\mathfrak{p}}}(\mathcal{R}_{\mathfrak{P}}) / N_{L_{\mathfrak{P}}/K_{\mathfrak{p}}}(\mathcal{R}_{\mathfrak{P}}).$$

Since  $L/K$  is abelian ([9, Ch. 1 §2.a]) we have

$$N_{L_{\mathfrak{P}}/K_{\mathfrak{p}}}(\mathcal{R}_{\mathfrak{P}}) = \mathcal{R}_{\mathfrak{p}} \cap N_{L/K}(\mathcal{J}_L) \mathcal{R}_K$$

and so  $\tilde{I}_{\mathfrak{p}}(L/K) \simeq \text{Gal}(L_{\mathfrak{P}}/L_{\mathfrak{P}} \cap K_{\mathfrak{p}}^c)$ .

As a consequence of the classic case, logarithmic ramification behaves well at the tame places in  $\mathbb{Z}_{\ell}$ -extensions.

**Proposition 2.4.**  $\mathbb{Z}_{\ell}$ -extensions are logarithmically unramified at the tame places.

*Proof:* Let  $K_{\infty}$  be a  $\mathbb{Z}_{\ell}$ -extension and let  $\mathfrak{p}$  be a place over  $p$  with  $p \neq \ell$ . Let  $K_n$  be the  $n$ -th layer of  $K_{\infty}$ , i.e.  $K_{\infty}$  is the unique subfield of  $K_{\infty}$  with  $\text{Gal}(K_n/K) \simeq \mathbb{Z}/\ell^n \mathbb{Z}$ .

For every  $n$  we have that  $K_n$  is unramified at  $\mathfrak{p}$  [18, Prop. 13.2]. Let  $\mathfrak{P}$  be a place in  $K_n$  lying over  $\mathfrak{p} \in \text{Pl}_K$ . By 2. and 3. in Prop. 2.1 we have that  $v_q(e_{\mathfrak{P}|\mathfrak{p}}) = v_q(\tilde{e}_{\mathfrak{P}|\mathfrak{p}}) = 0$

for every  $q \neq p$ . Taking the  $p$ -adic valuation in the relative version of 1. Prop. 2.1 we have

$$v_p(\tilde{e}_{\mathfrak{P}|\mathfrak{p}}) + v_p(\tilde{e}_{\mathfrak{Q}|\mathfrak{p}}) = 0,$$

but both numbers are non-negative integers. We conclude that  $\tilde{e}_{\mathfrak{P}|\mathfrak{p}} = 1$  as desired.  $\square$

In terms of ramification, the locally cyclotomic extension  $K^{\text{lc}}$  of  $K$  corresponds to the maximal abelian extension of  $K$  which is logarithmically unramified. Unlike the classical case, this extension  $K^{\text{lc}}$  is infinite since it contains the cyclotomic  $\mathbb{Z}_\ell$ -extension  $K^c$  of  $K$ . Since  $K^{\text{lc}}$  is a subextension of the maximal abelian  $\ell$ -ramified  $\ell$ -extension of  $K$ , the Galois group  $\widetilde{\mathcal{C}\ell}_K^* \simeq \text{Gal}(K^{\text{lc}}/K)$  is a noetherian  $\mathbb{Z}_\ell$ -module, and assuming the Gross-Kuz'min Conjecture it has dimension 1. This yields the following result.

**Lemma 2.5.** *Let  $K$  be a number field verifying the Gross-Kuz'min conjecture for the prime  $\ell$ , let  $K_\infty/K$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension. Then at least one place  $\mathfrak{p}$  above  $\ell$  is logarithmically ramified in  $K_\infty/K$ .*

*Proof:* The torsion subgroup  $(\widetilde{\mathcal{C}\ell}_K^*)^{\text{tors}}$  is isomorphic to  $\widetilde{\mathcal{C}\ell}_K$ . Let us suppose that  $K_\infty$  is logarithmically unramified, hence it is contained in  $K^{\text{lc}}$ ; the mapping

$$\widetilde{\mathcal{C}\ell}_K^* \simeq \text{Gal}(K^{\text{lc}}/K) \rightarrow \Gamma = \text{Gal}(K_\infty/K)$$

is surjective and its kernel contains  $\widetilde{\mathcal{C}\ell}_K$ ; so  $K_\infty$  is fixed by  $\widetilde{\mathcal{C}\ell}_K$  which is absurd, for we assumed  $K_\infty$  was a non-cyclotomic  $\mathbb{Z}_\ell$ -extension.  $\square$

**Remark 2.6.** *The cyclotomic  $\mathbb{Z}_\ell$ -extension  $K^c$  of  $K$  is logarithmically unramified.*

Under the same assumptions and as a consequence of the preceding lemma we have the following corollary.

**Corollary 2.7.** *There is an integer  $d$  such that  $K_\infty/K_d$  is logarithmically totally ramified for a non-empty subset of places above  $\ell$  and logarithmically unramified (possibly inert) for the rest of the places.*

*Proof:* Let  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the places in  $K$  above  $\ell$  which are logarithmically ramified. The logarithmic inertia subgroups  $\tilde{I}_i$  are closed and non zero in  $\Gamma = \text{Gal}(K_\infty/K)$  ( $i = 1, \dots, s$ ), therefore we have

$$\tilde{I}_i \simeq \Gamma^{\ell^{d_i}},$$

for some  $d_i \in \mathbb{N}$  ( $i = 1, \dots, s$ ), taking  $d = \max d_i$ , it is clear that the extension  $K_\infty/K_d$  is logarithmically totally ramified at every logarithmically ramified place.  $\square$

**Definition 2.8.** We say that a  $\mathbb{Z}_\ell$ -extension  $K_\infty$  is locally disjoint of the cyclotomic  $\mathbb{Z}_\ell$ -extension  $K^c$  if there is a place  $\mathfrak{p} \in \text{Pl}_K$  such that  $\tilde{e}_{\mathfrak{P}|\mathfrak{p}} = 1$  for some  $\mathfrak{P} \in \text{Pl}_{K_1}$  above  $\mathfrak{p}$ , i.e. if  $K_1/K$  is logarithmically ramified, equivalently that  $K_\infty$  is globally disjoint from the locally cyclotomic extension  $K^{\text{lc}}$  of  $K$ , i.e.  $K^{\text{lc}} \cap K_\infty = K$ .

**Remark 2.9.** *In the above definition both conditions are equivalent, for if  $K_\infty \cap K^{\text{lc}} = K_n$  for some  $n > 0$ , then  $K_n/K$  is logarithmically unramified. In particular  $K_1/K$  is logarithmically unramified.*

Let  $K_\infty$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension and  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the places in  $K$  above  $\ell$  which ramify logarithmically. Define  $n_0 = \min\{d_i \mid \tilde{I}_i \simeq \Gamma^{\ell^{d_i}}\}$ . Then the  $\mathbb{Z}_\ell$ -extension  $K_\infty/K_{n_0}$  is locally disjoint of the cyclotomic extension  $K_{n_0}^c/K_{n_0}$  in the former sense.

### 3. THE LOGARITHMIC CLASS GROUP ALONG NON-CYCLOTOMIC $\mathbb{Z}_\ell$ -EXTENSIONS

Let  $K$  be a number field admitting a non-cyclotomic  $\mathbb{Z}_\ell$ -extension  $K_\infty$  with Galois group  $\Gamma = \text{Gal}(K_\infty/K)$ , and assume the Gross-Kuz'min conjecture is verified for  $K$ . We denote  $K_n$  the unique subextension of  $K_\infty$  such that  $\text{Gal}(K_n/K) \simeq \mathbb{Z}/\ell^n\mathbb{Z}$ .

Let  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the places of  $K$  above  $\ell$  which ramify logarithmically. There exist two integers  $n_0$  and  $d$  such that

- (1)  $0 \leq n_0 \leq d$ ,
- (2) for every  $n \geq n_0$  the  $\mathbb{Z}_\ell$ -extension  $K_\infty/K_n$  is locally disjoint of the cyclotomic  $\mathbb{Z}_\ell$ -extension  $K_n^c = K_n K^c$  of  $K_n$ ,
- (3)  $K_\infty/K_d$  is completely logarithmically-ramified for some non-empty subset of wild places in  $K_d$ .

Let  $\tilde{\mathcal{C}}^*$  be the inverse limit  $\varprojlim \tilde{\mathcal{C}}_{K_n}^*$  of the logarithmic classes of arbitrary degree of all the  $K_n$ . The group  $\tilde{\mathcal{C}}^*$  is isomorphic to the Galois group  $\text{Gal}(K_\infty^{\text{lc}}/K_\infty)$  of the maximal abelian logarithmically unramified extension of  $K_\infty$ . Hence  $K_n^{\text{lc}}$  is the maximal sub-extension of  $K_\infty^{\text{lc}}$  which is abelian over  $K_n$  and splits completely over  $K_n^c$ , equivalently  $K_n^{\text{lc}}$  is the maximal sub-extension of  $K_\infty^{\text{lc}}$  which is abelian and logarithmically unramified over  $K_n$ . Hence we have the following isomorphisms of Galois groups

$$\tilde{\mathcal{C}}_{K_n}^* = \text{Gal}(K_n^{\text{lc}}/K_n) \simeq \text{Gal}(K_\infty K_n^{\text{lc}}/K_\infty).$$

Fixing a pro-generator  $\gamma \in \Gamma$ , this defines an action on  $\tilde{\mathcal{C}}^*$  making it a  $\Lambda$ -module; where  $\Lambda$  is the Iwasawa algebra  $\mathbb{Z}_\ell[[\Gamma]]$ . This action is that of the product of the Galois group  $G = \text{Gal}(K_\infty^{\text{lc}}/K)$  corresponding to the semi-direct product  $\Gamma \ltimes \tilde{\mathcal{C}}^*$ .

**Proposition 3.1.**  *$\tilde{\mathcal{C}}^*$  is a noetherian  $\Lambda$ -module. Moreover, if the Gross-Kuz'min conjecture holds for every  $K_n$  in  $K_\infty$ , it is torsion.*

*Proof:* The locally cyclotomic extension  $K^{\text{lc}}$  of  $K$  is contained in the maximal abelian  $\ell$ -extension  $K^{\text{lr}}$  of  $K$  which is  $\ell$ -ramified. The  $\Lambda$ -module  $\tilde{\mathcal{C}}^*$  can be written as a quotient of the noetherian  $\Lambda$ -module  $X = \text{Gal}(K^{\text{lr}}/K_\infty)$  [8, Thm. 4]. This yields the noetherian property.

For  $n \geq 0$  let us denote  $L_{\infty/n}$  the maximal abelian extension of  $K_n$  which is logarithmically unramified over  $K_\infty$ , i.e. the maximal abelian extension of  $K_n$  contained in  $K_\infty^{\text{lc}}$ . Then

$$K_\infty \subseteq L_{\infty/0} \subseteq L_{\infty/1} \subseteq \dots \subseteq L_{\infty/n} \subseteq \dots \subseteq K_\infty^{\text{lc}},$$

and we have  $K_\infty^{\text{lc}} = \bigcup_{n \geq 0} L_{\infty/n}$ . Then we have the following identities of Galois groups

$$\omega_n \tilde{\mathcal{C}}^* = \text{Gal}(K_\infty^{\text{lc}}/L_{\infty/n}) \quad \tilde{\mathcal{C}}^*/\omega_n \tilde{\mathcal{C}}^* = \text{Gal}(L_{\infty/n}/K_\infty), \quad n \geq 0.$$

Let  $d$  be as in Corollary 2.7, for  $n \geq d$  let  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the primes of  $K_n$  which are logarithmically ramified in  $K_\infty$ ; the number of this primes is the same for all  $n \geq d$ . For

each  $i$  let  $\tilde{I}_i$  be the logarithmic inertia subgroup of the extension  $L_{\infty/n}/K_n$ . Since  $\mathfrak{p}_i$  is totally logarithmically ramified in  $K_{\infty}$  and the extension  $L_{\infty/n}/K_{\infty}$  is logarithmically unramified, the groups  $\tilde{I}_i$  are pro-cyclic isomorphic to  $\Gamma^{\ell^n} \simeq \mathbb{Z}_{\ell}$ , for  $i = 1, \dots, s$ . On the other hand, since none of the places apart of  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  are logarithmically ramified in  $L_{\infty/n}$ , it follows that  $\text{Gal}(L_{\infty/n}/K_n^{\text{lc}}) = \tilde{I}_1 \tilde{I}_2 \cdots \tilde{I}_s$  because  $K_n^{\text{lc}}$  is the maximal abelian extension of  $K_n$  which is logarithmically unramified contained in  $L_{\infty/n}$ . Assuming the Gross-Kuz'min conjecture,  $\widetilde{C\ell}_{K_n}^* = \text{Gal}(K_n^{\text{lc}}/K_n)$  is a noetherian  $\mathbb{Z}_{\ell}$ -module of dimension 1, then

$$\begin{aligned} \dim_{\mathbb{Z}_{\ell}} \text{Gal}(L_{\infty/n}/K) &= \dim_{\mathbb{Z}_{\ell}} \text{Gal}(K_n^{\text{lc}}/K_n) + \dim_{\mathbb{Z}_{\ell}}(\tilde{I}_1 \cdots \tilde{I}_s) \\ &\leq 1 + \sum_{i=1}^s [K_{\mathfrak{p}_i} : \mathbb{Q}_{\ell}] \end{aligned}$$

from which follows that

$$\dim_{\mathbb{Z}_{\ell}} \text{Gal}(L_{\infty/n}/K_{\infty}) = \dim_{\mathbb{Z}_{\ell}} \text{Gal}(L_{\infty/n}/K) - 1 \leq \sum_{i=1}^s [K_{\mathfrak{p}_i} : \mathbb{Q}_{\ell}],$$

so  $\dim_{\mathbb{Z}_{\ell}} \tilde{C}^*/\omega_n \tilde{C}^* \leq \sum_{i=1}^s [K_{\mathfrak{p}_i} : \mathbb{Q}_{\ell}]$ , for all  $n \geq d$ , therefore for all  $n \geq 0$ . Hence  $\tilde{C}^*$  is  $\Lambda$ -torsion (see [8, Lemme 3]).  $\square$

**Proposition 3.2.** *Assume the Gross-Kuz'min conjecture for all  $K_n$  in  $K_{\infty}$ . Let  $\tilde{C} = \varprojlim \tilde{C\ell}_{K_n}$  the inverse limit of the logarithmic class groups  $\tilde{C\ell}_{K_n}$ . Then*

$$(1) \quad \tilde{C}^* \simeq \tilde{C} \oplus \mathbb{Z}_{\ell}.$$

*Proof:* Consider the following exact sequence

$$0 \rightarrow \tilde{C\ell}_{K_n} \rightarrow \tilde{C\ell}_{K_n}^* \rightarrow \mathbb{Z}_{\ell} \rightarrow 0;$$

taking the inverse limit  $\varprojlim$  for the arithmetic norm maps in each of the terms. The modules  $\tilde{J}_{K_{n+1}}/\mathcal{R}_{K_{n+1}}$  are saturated by the arithmetic norms  $N_{K_{n+1}/K_n}$  [9, Thm. 1.1.26.] so the morphisms of the direct system are surjective. So we obtain exactness taking inverse limits

$$0 \rightarrow \tilde{C} \rightarrow \tilde{C}^* \rightarrow \mathbb{Z}_{\ell} \rightarrow 0.$$

$\square$

*Assumption on the logarithmic ramification.* Before approaching our problem in great generality, let us assume first that the places of  $K$  which ramify logarithmically are totally logarithmically ramified. We can always do so by rewriting the  $\mathbb{Z}_{\ell}$ -extension in order to have  $K = K_d$ , with  $d$  as in Corollary 2.7.

For each place  $\mathfrak{p}_i$  ramifying logarithmically, let  $\tilde{I}_i \subset G = \tilde{C}^* \rtimes \Gamma$  its logarithmic inertia subgroup. Since  $K_{\infty}^{\text{lc}}/K_{\infty}$  is logarithmically unramified, we have that each logarithmic inertia subgroup has trivial intersection with the group  $\tilde{C}^*$ :  $\tilde{I}_i \cap \tilde{C}^* = 1$ . Since  $K_{\infty}/K$  is totally logarithmically ramified over  $\mathfrak{p}_i$ , the groups of logarithmic inertia  $\tilde{I}_i$  are pro-cyclic isomorphic to  $\Gamma$ .

Since we are mainly interested in the study of the logarithmic class groups (of zero degree)  $\tilde{C\ell}_{K_n}$ , we consider the group  $H = \text{Gal}(K_{\infty}^{\text{lc}}/K^c)$ . For this we use the fact that

the logarithmic non-ramification spreads in the cyclotomic extensions. The group  $H$  is the semi-direct product of  $\Gamma$  and the normal subgroup  $\tilde{\mathcal{C}}$ , and can be written as

$$H = \tilde{I}_i \tilde{\mathcal{C}} = \tilde{\mathcal{C}} \tilde{I}_i \quad \text{for } i = 1, \dots, s.$$

Fixing pro-generators  $\tilde{\sigma}_i$  of  $\tilde{I}_i$ , there exists  $\tilde{a}_1, \dots, \tilde{a}_s \in \tilde{\mathcal{C}}$  such that

$$\tilde{\sigma}_i = \tilde{a}_i \tilde{\sigma}_1.$$

In particular we can make  $\tilde{\sigma}_1 = \gamma$  for a pro-generator  $\gamma$  of  $\Gamma$ .

For every  $n \geq 0$ , we set

$$(2) \quad \omega_n = \gamma^{\ell^n} - 1.$$

Let  $H'$  be the closure of the commutator subgroup of  $H$ . We know that  $H' = \omega_0 \tilde{\mathcal{C}} = T\tilde{\mathcal{C}}$ , the last equality being obtained from the isomorphism  $\mathbb{Z}_\ell[[\Gamma]] \simeq \mathbb{Z}_\ell[[T]]$  given by  $\gamma \mapsto T + 1$  [18, Lemma 13.14].

**Proposition 3.3.** *Let  $Y_0$  be the  $\mathbb{Z}_\ell$ -submodule of  $\tilde{\mathcal{C}}$  generated by  $\{\tilde{a}_i \mid 2 \leq i \leq s\}$  and  $\omega_0 \tilde{\mathcal{C}} = T\tilde{\mathcal{C}}$ . Let  $Y_n = \frac{\omega_n}{\omega_0} Y_0$ , where*

$$\frac{\omega_n}{\omega_0} = 1 + \gamma + \gamma^2 + \dots + \gamma^{\ell^n - 1} = \frac{(1 + T)^{\ell^n} - 1}{T}.$$

Then

$$\tilde{\mathcal{C}} \ell_{K_n} \simeq \tilde{\mathcal{C}} / Y_n \quad \text{for } n \geq 0.$$

*Proof:* Firstly, we show the case  $\tilde{\mathcal{C}} \ell_K \simeq \tilde{\mathcal{C}} / Y_0$ . The locally cyclotomic extension  $K^{\text{lc}}$  is the maximal abelian extension logarithmically unramified of  $K^c$  contained in  $K_\infty^{\text{lc}}$ . Its Galois group  $\text{Gal}(K^{\text{lc}}/K^c)$  is hence equal to  $\text{Gal}(K_\infty^{\text{lc}}/K^c)/Z_0$ , where  $Z_0$  is the smallest subgroup of  $H = \text{Gal}(K_\infty^{\text{lc}}/K)$  containing the commutator subgroup  $H'$  as well as the logarithmic inertia subgroups  $\tilde{I}_i$ ,  $1 \leq i \leq s$ . The decomposition of  $H$  in a semi-direct product of  $\tilde{I}_1$  and  $\tilde{\mathcal{C}}$  yields to

$$\begin{aligned} \tilde{\mathcal{C}} \ell_K = \text{Gal}(K^{\text{lc}}/K^c) &\simeq H / \text{Gal}(K_\infty^{\text{lc}}/K^{\text{lc}}) \\ &\simeq \tilde{\mathcal{C}} \tilde{I}_1 / \overline{\langle \tilde{I}_1, \tilde{a}_2, \dots, \tilde{a}_s, \omega_0 \tilde{\mathcal{C}} \rangle} \\ &\simeq \tilde{\mathcal{C}} / \overline{\langle \tilde{a}_2, \dots, \tilde{a}_s, \omega_0 \tilde{\mathcal{C}} \rangle} = \tilde{\mathcal{C}} / Y_0. \end{aligned}$$

Now let us assume  $n \geq 1$ . If we replace  $K^c$  by  $K_n^c$ , the extension  $K_\infty^c/K_n^c$  is also a  $\mathbb{Z}_\ell$ -extension. The above result can be applied by replacing the pro-generator  $\gamma$  by  $\gamma^{\ell^n}$  and the  $\tilde{\sigma}_i$  become  $\tilde{\sigma}_i^{\ell^n}$ . Notice that for every integer  $k$ , we have:

$$\begin{aligned} \tilde{\sigma}_i^k &= (\tilde{a}_i \tilde{\sigma}_1)^k \\ &= \tilde{a}_i (\tilde{\sigma}_1 \tilde{a}_i \tilde{\sigma}_1^{-1}) (\tilde{\sigma}_1^2 \tilde{a}_i \tilde{\sigma}_1^{-2}) \dots (\tilde{\sigma}_1^{k-1} \tilde{a}_i \tilde{\sigma}_1^{-(k-1)}) \tilde{\sigma}_1^k \\ &= \tilde{a}_i^{1 + \tilde{\sigma}_1 + \dots + \tilde{\sigma}_1^{k-1}} \tilde{\sigma}_1^k \end{aligned}$$

and particularly, for  $k = \ell^n$ , the isomorphism  $\tilde{I}_1 \simeq \Gamma$  gives  $\tilde{\sigma}_i^{\ell^n} = \tilde{a}_i^{\omega_n/\omega_0} (\tilde{\sigma}_1)^{\ell^n}$ . This implies that the groups of logarithmic inertia of  $H_n = \text{Gal}(K_\infty^{\text{lc}}/K_n^c)$  are generated by the  $\frac{\omega_n}{\omega_0} \tilde{a}_i$ . Finally, the commutator subgroup  $H'_n$  of  $H_n$  is generated by  $\omega_n$ . From which the result follows.  $\square$

*General case.* In what follows we come back to the general situation exposed in the beginning of the section. Let  $K_\infty/K$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension of  $K$ . Let  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the places of  $K$  which ramify logarithmically and let  $d$  the smallest integer such that the  $\mathbb{Z}_\ell$ -extension  $K_\infty/K_d$  is totally logarithmically ramified.

**Proposition 3.4.** *Let  $K_\infty/K$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension. There exists  $d \geq 0$  such that*

$$\widetilde{C}\ell_{K_n} \simeq \widetilde{C}/Y_n \quad \text{for } n \geq d.$$

*Proof:* We apply the Proposition 3.3 to the extension  $K_\infty/K_d$ , the group  $\widetilde{C}$  being the same of the original extension. The element  $\gamma^{\ell^d}$  generates  $\text{Gal}(K_\infty/K_d^c)$ , and naturally  $\omega_d \widetilde{C}$  generates the commutator subgroup of  $\text{Gal}(K_\infty/K_d)$ . For  $n \geq d$  we have

$$\frac{\omega_n}{\omega_d} = 1 + \gamma^{\ell^d} + \gamma^{2\ell^d} + \dots + \gamma^{\ell^n - \ell^d},$$

it comes that the commutator subgroup of  $\text{Gal}(K_\infty/K_n)$  is given by  $\frac{\omega_n}{\omega_d}(\omega_d \widetilde{C}) = \omega_n \widetilde{C}$ ; in general for the  $Y_n$  we have  $Y_n = \frac{\omega_n}{\omega_d} Y_d$ . □

The exact sequence

$$0 \rightarrow Y_d \rightarrow \widetilde{C} \rightarrow \widetilde{C}\ell_{K_d} \rightarrow 0$$

sets a pseudo-isomorphism  $Y_d \sim \widetilde{C}$ , that is a morphism  $Y_d \rightarrow \widetilde{C}$  of  $\Lambda$ -modules with finite kernel and cokernel.

#### 4. STRUCTURAL PARAMETERS

Let us recall a fundamental result (see [17, Cor 2.3], or [18, Thm 13.12] for an approach using matrices).

**Theorem 4.1** (Structure theorem of noetherian  $\Lambda$ -modules). *Let  $M$  be a noetherian  $\Lambda$ -module. There is a  $\Lambda$ -module morphism  $M \rightarrow E$  to a unique elementary  $\Lambda$ -module  $E$  with finite kernel and finite cokernel:*

$$M \sim E = \Lambda^\rho \oplus \left( \bigoplus_{i=1}^s \Lambda / \ell^{\mu_i} \Lambda \right) \oplus \left( \bigoplus_{j=1}^t \Lambda / P_j \Lambda \right)$$

with  $P_j$  distinguished polynomials, ordered by divisibility:  $P_1 | P_2 | \dots | P_t$ . The integer  $\rho$  is the dimension  $\dim_\Lambda M$  of the  $\Lambda$ -module  $M$ , and the polynomial

$$\chi = \prod_{i=1}^s \ell^{\mu_i} \prod_{j=1}^t P_j$$

is the characteristic polynomial of the torsion sub-module of  $M$ .

**Definition 4.2.** With the same notation of the above theorem lets set

$$\rho = \dim_\Lambda M, \quad \mu = \sum_{i=1}^s \mu_i \quad \text{and} \quad \lambda = \sum_{j=1}^t \deg(P_j);$$

we say that  $\rho$ ,  $\mu$  and  $\lambda$  are the structural invariants of the  $\Lambda$ -module  $M$ .

Assuming the Gross-Kuz'min conjecture, we have that  $\tilde{\mathcal{C}}$  is torsion 3.1, hence

$$Y_d \sim \tilde{\mathcal{C}} \sim E = \left( \bigoplus_{i=1}^s \Lambda / \ell^{n_i} \Lambda \right) \oplus \left( \bigoplus_{i=1}^t \Lambda / P_j \Lambda \right),$$

where  $E$  is the unique elementary  $\Lambda$ -module such that  $Y_d \sim E$ . To describe the growth of  $|\tilde{\mathcal{C}}\ell_{K_n}| = |\tilde{\mathcal{C}}/Y_n|$  we observe that for  $n \geq d$  we have  $|\tilde{\mathcal{C}}\ell_{K_n}| = |\tilde{\mathcal{C}}/Y_n| = |\tilde{\mathcal{C}}/Y_d| |Y_d/Y_n|$ , therefore it suffices to know the order of the quotients  $Y_d/Y_n$  since the left factor in the product is constant. Moreover, we know that for  $n$  big enough we have the equalities

$$|Y_d/Y_n| = |Y_d / \frac{\omega_n}{\omega_d} Y_d| = \ell^c |E / \frac{\omega_n}{\omega_d} E|,$$

for some constant  $c$ . Finally, the order of the quotient  $E / \frac{\omega_n}{\omega_d} E$  is given by the formula

$$|E / \frac{\omega_n}{\omega_d} E| = \ell^{m_0 \ell^n + l_0 n + c},$$

for  $n$  big enough and  $l_0, m_0, c$  constant integers.

Therefore, assuming the Gross-Kuz'min conjecture, we can apply Iwasawa theory to the non-cyclotomic case. Consequently, we obtain the following theorem.

**Theorem 4.3.** *Let  $K_\infty/K$  be a non cyclotomic  $\mathbb{Z}_\ell$ -extension. Let  $\tilde{\mathcal{C}}\ell_{K_n}$  be the logarithmic class group of  $K_n$ . Assuming the Gross-Kuz'min conjecture there exist integers  $\tilde{\lambda}, \tilde{\mu} \geq 0$  and  $\tilde{\nu}$ , such that*

$$|\tilde{\mathcal{C}}\ell_{K_n}| = \ell^{\tilde{\mu}\ell^n + \tilde{\lambda}n + \tilde{\nu}},$$

for  $n$  big enough.

**Remark 4.4.** *The above theorem together with Jaulent's results in the cyclotomic case yield Theorem 1.*

In order to compare the classical and logarithmic invariants, we recall the following definition.

**Definition 4.5.** We say that a sequence  $(X_n)_{n \in \mathbb{N}}$  of finite  $\mathbb{Z}_\ell$ -modules is parametrized by  $(\rho, \mu, \lambda)$  if the order  $\ell^{x(n)}$  of  $X_n$  is asymptotically given by the formula:

$$x(n) \approx (n+1)\rho\ell^n + \mu\ell^n + \lambda n,$$

where  $\approx$  means that the difference of the right and left side terms is bounded. Moreover, we say that it is strictly parametrized if the difference is eventually constant.

Let  $K_\infty/K$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension of  $K$ . Let  $\mathcal{C} = \varprojlim C\ell$  be the inverse limit of the  $\ell$ -class groups of the  $K_n$ , then  $\mathcal{C}$  is a torsion  $\Lambda$ -module corresponding to the Galois group  $\text{Gal}(K_\infty^{\text{nr}}/K_\infty)$  of the maximal abelian unramified  $\ell$ -extension  $K_\infty^{\text{nr}}$  of  $K_\infty$ , similarly the inverse limit  $\tilde{\mathcal{C}}^* = \varprojlim \tilde{\mathcal{C}}\ell_{K_n}^*$  of the logarithmic classes of arbitrary degree of the  $K_n$ , corresponds to the Galois group  $\text{Gal}(K_\infty^{\text{lc}}/K_\infty)$  of the maximal abelian logarithmically unramified  $\ell$ -extension  $K_\infty^{\text{lc}}$  of  $K_\infty$ ; after the propositions 3.1 and 3.2, assuming the Gross-Kuz'min conjecture  $\tilde{\mathcal{C}}^*$  is a noetherian torsion  $\Lambda$ -module, isomorphic to a direct sum  $\tilde{\mathcal{C}}^* \simeq \tilde{\mathcal{C}} \oplus \mathbb{Z}_\ell$ .

The characteristic polynomials associated to these  $\Lambda$ -modules satisfy

$$\chi_{\tilde{\mathcal{C}}^*} = \chi_{\tilde{\mathcal{C}}} \cdot (\gamma - 1),$$

and we have the following relations for their parameters

$$(3) \quad \tilde{\mu}^* = \tilde{\mu} \quad \text{and} \quad \tilde{\lambda}^* = \tilde{\lambda} + 1,$$

where  $\tilde{\mu}^*$  and  $\tilde{\lambda}^*$  (respectively  $\tilde{\mu}$  and  $\tilde{\lambda}$ ) are the parameters associated to the  $\Lambda$ -module  $\tilde{\mathcal{C}}^*$  (respectively  $\tilde{\mathcal{C}}$ ).

Let  $\mathfrak{p}_1, \dots, \mathfrak{p}_s$  be the places of  $K$  above  $\ell$ . We have the short exact sequence of  $\ell$ -groups

$$(4) \quad 0 \longrightarrow \tilde{\mathcal{C}}_{\ell_K}^{*[\ell]} \longrightarrow \tilde{\mathcal{C}}_{\ell_K}^* \xrightarrow{\Theta} \mathcal{C}_{\ell'} \longrightarrow 0,$$

where  $\tilde{\mathcal{C}}_{\ell_K}^{*[\ell]}$  is the subgroup of  $\tilde{\mathcal{C}}_{\ell_K}^*$  generated by the classes of the  $\mathfrak{p}_i$ , for  $i = 1, \dots, s$ ; and  $\Theta$  is defined as

$$\Theta : \sum_{\mathfrak{p}} m_{\mathfrak{p}} \mathfrak{p} \mapsto \prod_{\mathfrak{p} \nmid \ell} \mathfrak{p}^{m_{\mathfrak{p}}}.$$

We also have the following exact sequence by definition

$$(5) \quad 0 \longrightarrow \mathcal{C}_{\ell_K}^{[\ell]} \longrightarrow \mathcal{C}_{\ell_K} \longrightarrow \mathcal{C}_{\ell'_K} \longrightarrow 0,$$

recall that the group  $\mathcal{C}_{\ell'_K}$  is the  $\ell$ -subgroup of Sylow of the quotient of the class group of  $K$  and the subgroup generated by the classes associated to the primes  $\mathfrak{p}_i$  above  $\ell$ .

Taking the inverse limit in the short exact sequences (4) and (5) we still get short exact sequences, and the corresponding isomorphisms

$$(6) \quad \mathcal{C}' \simeq \tilde{\mathcal{C}}^* / \tilde{\mathcal{C}}^{*[\ell]} \simeq \mathcal{C} / \mathcal{C}^{[\ell]}.$$

Let us denote by  $\mu$  and  $\lambda$  (respectively  $\mu'$ ,  $\lambda'$ ) the parameters attached to the  $\Lambda$ -module  $\mathcal{C}$  (respectively  $\mathcal{C}'$ ). We have the following obvious relations

$$(7) \quad \begin{array}{lll} \tilde{\mu}^* = \tilde{\mu} & \tilde{\mu}^* = \mu' + \tilde{\mu}^{*[\ell]} & \tilde{\lambda}^* = \lambda' + \tilde{\lambda}^{*[\ell]} \\ \tilde{\lambda}^* = \tilde{\lambda} + 1 & \mu = \mu' + \mu^{[\ell]} & \lambda = \lambda' + \lambda^{[\ell]} \end{array}$$

with  $\mu^{[\ell]}$  and  $\lambda^{[\ell]}$  (respectively  $\tilde{\mu}^{*[\ell]}$  and  $\tilde{\lambda}^{*[\ell]}$ ) as the associated parameters to  $\mathcal{C}^{[\ell]}$  (respectively  $\tilde{\mathcal{C}}^{*[\ell]}$ ).

The following definition, if verified, allows us to have some control on the characteristic polynomials of the preceding modules.

**Definition 4.6.** Let  $K_{\infty}/K$  be a  $\mathbb{Z}_{\ell}$ -extension. We say that a place  $\mathfrak{p}$  of  $K$  splits finitely in the tower  $K_{\infty}/K$ , if its decomposition group in  $\text{Gal}(K_{\infty}/K)$  is open, equivalently, if there is an integer  $n_{\mathfrak{p}}$  such that the layer  $K_{n_{\mathfrak{p}}}$  corresponds to the decomposition field of  $\mathfrak{p}$  in  $K_{\infty}/K$ .

**Remark 4.7.** The preceding definition holds for every wild place in the cyclotomic  $\mathbb{Z}_{\ell}$ -extension.

With the notation of (7) we state the following theorem:

**Theorem 4.8.** *Let  $K_\infty/K$  be a non-cyclotomic  $\mathbb{Z}_\ell$ -extension. Assume that the places of  $K$  above  $\ell$  split finitely in the extension  $K_\infty/K$ . Then the structural invariants  $(\rho, \mu, \lambda)$  attached to the sequence  $(C\ell_n)_{n \in \mathbb{N}}$  of  $\ell$ -class groups and the invariants  $(\tilde{\rho}, \tilde{\mu}, \tilde{\lambda})$  attached to the sequence  $(\tilde{C}\ell_n)_{n \in \mathbb{N}}$  of logarithmic class groups along the extension  $K_\infty/K$  satisfy the following relations:*

$$\rho = \tilde{\rho} = 0, \quad \mu = \tilde{\mu} \quad \text{but} \quad \lambda \text{ might be different of } \tilde{\lambda}.$$

*And the characteristic polynomials of the torsion  $\Lambda$ -modules  $\mathcal{C}$  and  $\tilde{\mathcal{C}}$  just differ by cyclotomic factors.*

*Proof:* The first relation is trivial since  $\mathcal{C}$  and  $\tilde{\mathcal{C}}^*$  are torsion modules.

Let  $D_i$  be the decomposition subgroup for the place  $\mathfrak{p}_i$ ; since the  $D_i$  are open they are isomorphic to  $\Gamma^{\ell^{m_i}}$  for some  $m_i$ . Take  $m = \max_{1 \leq i \leq s} \{m_i\}$ , then  $\Gamma^{\ell^m}$  acts trivially on  $\mathcal{C}^{[\ell]}$  and  $\tilde{\mathcal{C}}^{*[\ell]}$ . Hence  $\omega_m = \gamma^{\ell^m} - 1$  annihilates them, we have the decomposition into cyclotomic factors

$$\omega_m = \omega_0 \frac{\omega_1}{\omega_0} \frac{\omega_2}{\omega_1} \cdots \frac{\omega_m}{\omega_{m-1}}.$$

Since the minimal polynomial and the characteristic polynomials must have the same factors, the characteristic polynomials of  $\mathcal{C}$  and  $\tilde{\mathcal{C}}^*$  differ just by cyclotomic factors, in particular they have the same  $\mu$  invariants by (7). Finally from (3) we recover the relations for the logarithmic class group.  $\square$

**Remark 4.9.** *We deduced that  $\tilde{\lambda}^* = \tilde{\lambda} + 1$  from Proposition 3.2. In fact we can apply an analogous argument to the groups  $\tilde{\mathcal{C}}\ell^{[\ell]}$  and  $\tilde{\mathcal{C}}\ell^{*[\ell]}$ , from which we deduce that  $\tilde{\lambda}^{*[\ell]} = \tilde{\lambda}^{[\ell]} + 1$ .*

The following table summarizes the our results.

| Invariants attached to parametrized sequences of finite $\mathbb{Z}_\ell$ -modules. |   |            |   |        |
|---|---|------------|---|--------|
| Modules   | Definition  | Parameters |   |        |
|   |   | $\rho$     | $\lambda$   | $\mu$  |
| $C\ell'_n$  | $C\ell'_n$ is the $\ell$ -group of $\ell$ -classes of $K_n$ | 0          | $\lambda'$  | $\mu'$ |
| $\tilde{C}\ell_n$   | $\tilde{C}\ell_n$ is the logarithmic class group of $K_n$   | 0          | $\tilde{\lambda} = \lambda' + \tilde{\lambda}^{[\ell]}$ | $\mu'$ |
| $C\ell_n$   | $C\ell_n$ is the $\ell$ -class group of $K_n$               | 0          | $\lambda = \lambda' + \lambda^{[\ell]}$                 | $\mu'$ |

We give an example for which we can apply our results.

**Example 4.10.** Let  $K$  be a quadratic imaginary number field and  $\ell$  a prime number splitting in  $K$ , say  $(\ell) = \bar{\ell}\ell$ . The maximal abelian  $\ell$ -ramified  $\ell$ -extension  $M_\ell$  contains a non-cyclotomic  $\mathbb{Z}_\ell$ -extension, say  $K_\infty$ . For consider the  $\ell$ -Hilbert class field  $H$  of  $K$ ,

then

$$\begin{aligned}
\text{Gal}(M_{\mathfrak{l}}/H) &= \prod_{\mathfrak{p}} \mathcal{U}_{\mathfrak{p}} \mathcal{R}_K / \prod_{\mathfrak{p} \neq \mathfrak{l}} \mathcal{U}_{\mathfrak{p}} \mathcal{R}_K \\
&= \mathcal{U}_{\mathfrak{l}} / \mathcal{U}_{\mathfrak{l}} \cap \left( \prod_{\mathfrak{p} \neq \mathfrak{l}} \mathcal{U}_{\mathfrak{p}} \mathcal{R}_K \right) \\
&= \mathcal{U}_{\mathfrak{l}} / s_{\mathfrak{l}}(\mu_K) \\
&= \mathbb{Z}_{\ell},
\end{aligned}$$

where  $s_{\mathfrak{l}}(\mu_K)$  is the image of the generalized units  $\mu_K$  of  $K$  under the localisation map  $s_{\mathfrak{l}}$  [9, Thm. & Def. 1.1.22]. Therefore  $\text{Gal}(M_{\mathfrak{l}}/K) \simeq \mathbb{Z}_{\ell} \times \ell$ -finite group.

In particular, since  $K/\mathbb{Q}$  is abelian, the Lemma 2.5 states that at least one place  $\mathfrak{l}$  over  $\ell$  ramifies logarithmically in  $K_{\infty}$ . Finally, the image of the decomposition subgroup  $D_{\mathfrak{l}}$  inside  $\text{Gal}(M_{\mathfrak{l}}/K)$  is isomorphic to  $\mathbb{Z}_{\ell} \times \ell$ -finite group, hence it has finite index in  $\text{Gal}(M_{\mathfrak{l}}/K)$ . For the image of  $D_{\mathfrak{l}}$  is

$$\mathcal{R}_{\mathfrak{l}} / \mathcal{R}_{\mathfrak{l}} \cap \left( \prod_{\mathfrak{p} \neq \mathfrak{l}} \mathcal{U}_{\mathfrak{p}} \mathcal{R}_K \right).$$

Therefore both places  $\mathfrak{l}$  and  $\bar{\mathfrak{l}}$  split finitely.

## 5. NUMERICAL EXAMPLES

**5.1. Quadratic fields.** We use the functions and algorithms implemented by Belabas and Jaulent in [1] to compute the logarithmic class group of a number field. These algorithms are available in PARI/GP [16], so we are in position of computing the first layers of  $\mathbb{Z}_{\ell}$ -extensions.

Let  $K$  be a quadratic field of the form  $\mathbb{Q}(\sqrt{d})$ . For now we will restrict to the computation of the 3-group of logarithmic classes in the layers  $K = K_0, K_1$  and  $K_2$  of the cyclotomic tower of  $K$ .

In the next table we take  $-100 < d < 100$ . For sake of space, we just show the cases for which the logarithmic class group is not trivial and for which 3 splits in  $\mathbb{Q}(\sqrt{d})$ .

|     | $\mathbb{Q}(\sqrt{d})$ |                                |            | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/9))$ |                                    |                | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/27))$ |                                    |                |
|-----|------------------------|--------------------------------|------------|--------------------------------------|------------------------------------|----------------|---------------------------------------|------------------------------------|----------------|
| $d$ | $\widetilde{C}\ell_K$  | $\widetilde{C}\ell_K^{[\ell]}$ | $C\ell'_K$ | $\widetilde{C}\ell_{K_1}$            | $\widetilde{C}\ell_{K_1}^{[\ell]}$ | $C\ell'_{K_1}$ | $\widetilde{C}\ell_{K_2}$             | $\widetilde{C}\ell_{K_2}^{[\ell]}$ | $C\ell'_{K_2}$ |
| -86 | [3]                    | [3]                            | $\square$  | [9, 9]                               | [3]                                | [9, 3]         | [27, 27]                              | [3]                                | [27, 9]        |
| -74 | [9]                    | [9]                            | $\square$  | [27]                                 | [9]                                | [3]            | [81]                                  | [9]                                | [9]            |
| -65 | [3]                    | [3]                            | $\square$  | [9]                                  | [3]                                | [3]            | [27]                                  | [3]                                | [9]            |
| -47 | [9]                    | [9]                            | $\square$  | [27]                                 | [9]                                | [3]            | [81]                                  | [9]                                | [9]            |
| -41 | [27]                   | [27]                           | $\square$  | [81, 3]                              | [27]                               | [3, 3]         | [243, 9]                              | [27]                               | [9, 9]         |
| -35 | [3]                    | [3]                            | $\square$  | [9]                                  | [3]                                | [3]            | [27]                                  | [3]                                | [9]            |
| -14 | [3]                    | [3]                            | $\square$  | [9]                                  | [3]                                | [3]            | [27]                                  | [3]                                | [9]            |
| 67  | [3]                    | [3]                            | $\square$  | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |

In the next table we present further computations with  $d < 3000$  for which the  $C\ell'_K$  groups are not trivial.

|      | $\mathbb{Q}(\sqrt{d})$ |                                |            | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/9))$ |                                    |                | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/27))$ |                                    |                |
|------|------------------------|--------------------------------|------------|--------------------------------------|------------------------------------|----------------|---------------------------------------|------------------------------------|----------------|
| $d$  | $\widetilde{C}\ell_K$  | $\widetilde{C}\ell_K^{[\ell]}$ | $C\ell'_K$ | $\widetilde{C}\ell_{K_1}$            | $\widetilde{C}\ell_{K_1}^{[\ell]}$ | $C\ell'_{K_1}$ | $\widetilde{C}\ell_{K_2}$             | $\widetilde{C}\ell_{K_2}^{[\ell]}$ | $C\ell'_{K_2}$ |
| 1129 | [3]                    | $\square$                      | [3]        | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |
| 1654 | [3]                    | $\square$                      | [3]        | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |
| 1954 | [3]                    | $\square$                      | [3]        | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |
| 2419 | [3]                    | $\square$                      | [3]        | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |
| 2713 | [3]                    | $\square$                      | [3]        | [9]                                  | $\square$                          | [9]            | [9]                                   | $\square$                          | [9]            |
| 2971 | [3]                    | $\square$                      | [3]        | [3]                                  | $\square$                          | [3]            | [3]                                   | $\square$                          | [3]            |

Finally, for  $d < 50\,000$  we ask both  $\widetilde{C}\ell_K^{[\ell]}$  and  $C\ell'_K$  non trivial.

|       | $\mathbb{Q}(\sqrt{d})$ |                                |            | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/9))$ |                                    |                | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/27))$ |                                    |                |
|-------|------------------------|--------------------------------|------------|--------------------------------------|------------------------------------|----------------|---------------------------------------|------------------------------------|----------------|
| $d$   | $\widetilde{C}\ell_K$  | $\widetilde{C}\ell_K^{[\ell]}$ | $C\ell'_K$ | $\widetilde{C}\ell_{K_1}$            | $\widetilde{C}\ell_{K_1}^{[\ell]}$ | $C\ell'_{K_1}$ | $\widetilde{C}\ell_{K_2}$             | $\widetilde{C}\ell_{K_2}^{[\ell]}$ | $C\ell'_{K_2}$ |
| 3739  | [9]                    | [3]                            | [3]        | [27]                                 | [3]                                | [9]            | [81]                                  | [3]                                | [27]           |
| 7726  | [3,3]                  | [3]                            | [3]        | [9,3,3]                              | $\square$                          | [9,3,3]        | [27,3,3]                              | $\square$                          | [27,3,3]       |
| 11545 | [9]                    | [3]                            | [3]        | [9]                                  | $\square$                          | [9]            | [9]                                   | $\square$                          | [9]            |
| 17134 | [9]                    | [3]                            | [3]        | [9]                                  | $\square$                          | [9]            | [9]                                   | $\square$                          | [9]            |
| 19330 | [9]                    | [3]                            | [3]        | [9]                                  | $\square$                          | [9]            | [9]                                   | $\square$                          | [9]            |

**5.2. Logarithmic invariants: Cyclotomic case.** We are now interested in explicitly knowing the values of the logarithmic invariants  $\widetilde{\mu}$  et  $\widetilde{\lambda}$ . In [9] Jaulent showed that the invariant  $\widetilde{\mu}$  attached to the logarithmic class group equals its classical counterpart  $\mu$ . Hence we can state the following result.

**Theorem 5.1** (Logarithmic Ferrero-Washington). *Let  $K$  be an abelian number field over  $\mathbb{Q}$ , and let  $K^c/K$  be its cyclotomic  $\mathbb{Z}_\ell$ -extension. Then*

$$\widetilde{\mu} = 0.$$

**Remark 5.2.** *We have  $\widetilde{\mu} = 0$  for the examples given in the preceding section 5.1.*

Also in [9] is shown that  $\lambda' = \widetilde{\lambda}$ , where  $\lambda'$  is the invariant attached to the  $\ell$ -subgroup of  $\ell$ -classes  $C\ell'_n$ . Furthermore Gold's papers [4] and [5] allow us to compute explicitly the value of  $\widetilde{\lambda}$  for imaginary quadratic fields:

**Theorem 5.3** ([5]). *Let  $K$  be an imaginary quadratic number field and let  $K_n$  be the  $n$ -th layer of the cyclotomic  $\mathbb{Z}_\ell$ -extension of  $K$ . Let  $e'_n$  the power of the order of the  $\ell$ -subgroup of  $\ell$ -classes  $C\ell'_n$  attached to  $K_n$ . If there is  $n \geq 1$ , such that  $e'_n - e'_{n-1} < \varphi(\ell^n)$ , then*

$$\lambda' = e'_n - e'_{n-1}.$$

We use these facts to compute  $\widetilde{\mu}$  and  $\widetilde{\lambda}$  for the layers  $K$ ,  $K_1$  and  $K_2$  of the cyclotomic  $\mathbb{Z}_3$ -extension of the imaginary quadratic number field  $\mathbb{Q}(\sqrt{d})$  for  $-100 \leq d \leq -1$ .

|     | $\mathbb{Q}(\sqrt{d})$ |           | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/9))$ |             | $\mathbb{Q}(\sqrt{d}, \cos(2\pi/27))$ |             | $\varphi(3) = 2$ | $\varphi(9) = 6$ | $\tilde{\mu} = 0$ |               |
|-----|------------------------|-----------|--------------------------------------|-------------|---------------------------------------|-------------|------------------|------------------|-------------------|---------------|
| $d$ | $\widetilde{Cl}_K$     | $Cl'_K$   | $\widetilde{Cl}_{K_1}$               | $Cl'_{K_1}$ | $\widetilde{Cl}_{K_2}$                | $Cl'_{K_2}$ | $e'_1 - e'_0$    | $e'_2 - e'_1$    | $\tilde{\lambda}$ | $\tilde{\nu}$ |
| -87 | [3]                    | [3]       | [9]                                  | [9]         | [27]                                  | [27]        | 1                | 1                | 1                 | 1             |
| -86 | [3]                    | $\square$ | [9, 9]                               | [9, 3]      | [27, 27]                              | [27, 9]     | 3                | 2                | 2                 | 2             |
| -74 | [9]                    | $\square$ | [27]                                 | [3]         | [81]                                  | [9]         | 1                | 1                | 1                 | 2             |
| -65 | [3]                    | $\square$ | [9]                                  | [3]         | [27]                                  | [9]         | 1                | 1                | 1                 | 1             |
| -61 | [3]                    | [3]       | [9]                                  | [9]         | [27]                                  | [27]        | 1                | 1                | 1                 | 1             |
| -47 | [9]                    | $\square$ | [27]                                 | [3]         | [81]                                  | [9]         | 1                | 1                | 1                 | 2             |
| -41 | [27]                   | $\square$ | [81, 3]                              | [3, 3]      | [243, 9]                              | [9, 9]      | 2                | 2                | 2                 | 3             |
| -35 | [3]                    | $\square$ | [9]                                  | [3]         | [27]                                  | [9]         | 1                | 1                | 1                 | 1             |
| -31 | [3]                    | [3]       | [9]                                  | [9]         | [27]                                  | [27]        | 1                | 1                | 1                 | 1             |
| -14 | [3]                    | $\square$ | [9]                                  | [3]         | [27]                                  | [9]         | 1                | 1                | 1                 | 1             |

We now compute the logarithmic class groups for the layers  $K$  and  $K_1$  of the cyclotomic  $\mathbb{Z}_5$  and  $\mathbb{Z}_7$  extensions of the imaginary quadratic number fields  $\mathbb{Q}(\sqrt{d})$  for  $-100 \leq d \leq -1$ . In all these cases, it suffices to compute  $Cl_K$  and  $Cl_{K_1}$  to know the logarithmic invariants.

Case  $\ell = 5$ .

|     | $K = \mathbb{Q}(\sqrt{d})$ |           | $K_1$                  |             | $\varphi(5) = 4$ | $\tilde{\mu} = 0$ |               |
|-----|----------------------------|-----------|------------------------|-------------|------------------|-------------------|---------------|
| $d$ | $\widetilde{Cl}_K$         | $Cl'_K$   | $\widetilde{Cl}_{K_1}$ | $Cl'_{K_1}$ | $e'_1 - e'_0$    | $\tilde{\lambda}$ | $\tilde{\nu}$ |
| -51 | [125]                      | $\square$ | [625]                  | [5]         | 1                | 1                 | 3             |
| -47 | [5]                        | [5]       | [25]                   | [25]        | 1                | 1                 | 1             |
| -41 | [5]                        | $\square$ | [25]                   | [5]         | 1                | 1                 | 1             |
| -34 | [5]                        | $\square$ | [25]                   | [5]         | 1                | 1                 | 1             |
| -26 | [5]                        | $\square$ | [25]                   | [5]         | 1                | 1                 | 1             |
| -11 | [5]                        | $\square$ | [25]                   | [5]         | 1                | 1                 | 1             |

Case  $\ell = 7$ .

|     | $K = \mathbb{Q}(\sqrt{d})$ |           | $K_1$                  |             | $\varphi(7) = 6$ | $\tilde{\mu} = 0$ |               |
|-----|----------------------------|-----------|------------------------|-------------|------------------|-------------------|---------------|
| $d$ | $\widetilde{Cl}_K$         | $Cl'_K$   | $\widetilde{Cl}_{K_1}$ | $Cl'_{K_1}$ | $e'_1 - e'_0$    | $\tilde{\lambda}$ | $\tilde{\nu}$ |
| -89 | [7]                        | $\square$ | [49]                   | [7]         | 1                | 1                 | 1             |
| -73 | [7]                        | $\square$ | [49]                   | [7]         | 1                | 1                 | 1             |
| -71 | [7]                        | [7]       | [49]                   | [49]        | 1                | 1                 | 1             |
| -34 | [7]                        | $\square$ | [49]                   | [7]         | 1                | 1                 | 1             |

**5.3. Logarithmic invariants: Non-cyclotomic case.** We now compute logarithmic invariants of some non-cyclotomic extensions. For that we extrapolate the computations made by Hubbard and Washington [6].

Let  $K = \mathbb{Q}(\sqrt{-3})$  and  $\ell = 3$ . Let  $K_\infty$  the non-cyclotomic  $\mathbb{Z}_\ell$ -extension of  $K$ . Let  $K_1$  be the first layer of  $K_\infty$ , i.e.  $K_1 = K(\sqrt[3]{3})$ . The extension  $L = \mathbb{Q}(\sqrt{-3}, \sqrt[3]{d})$  is an extension of degree 3 of  $K$ . Let  $L_n$  be such that

$$L_n = LK_n,$$

therefore  $L_\infty/L$  is a non-cyclotomic  $\mathbb{Z}_\ell$ -extension.

All places of  $L$  above 3 are totally ramified and split finitely. Hence Theorem 4.8 is valid for our examples.

|     | $L_0 = \mathbb{Q}(\sqrt{-3}, \sqrt[3]{d})$ |             | $L_1$                     |                         | Invariants              |                       |                   |           |       |
|-----|--|-------------|---------------------------|-------------------------|-------------------------|-----------------------|-------------------|-----------|-------|
| $d$ | $\widetilde{C}\ell_K$                      | $C\ell'_K$  | $\widetilde{C}\ell_{K_1}$ | $C\ell'_{K_1}$          | $\mu = \widetilde{\mu}$ | $\widetilde{\lambda}$ | $\widetilde{\nu}$ | $\lambda$ | $\nu$ |
| 10  | $\square$                                  | $\square$   | $[3, 3, 3]$               | $[3, 3]$                | 1                       | 1                     | -1                | 0         | -1    |
| 22  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 34  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 44  | $\square$                                  | $\square$   | $[9, 3, 3]$               | $[3, 3]$                | 1                       | 2                     | -1                | 0         | -1    |
| 46  | $\square$                                  | $\square$   | $[3, 3, 3]$               | $[3, 3]$                | 1                       | 1                     | -1                | 0         | -1    |
| 58  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 68  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 85  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 92  | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 110 | $[3, 3, 3]$                                | $[3, 3, 3]$ | $[3, 3, 3, 3, 3, 3, 3]$   | $[3, 3, 3, 3, 3, 3, 3]$ | 2                       | 0                     | 1                 | 0         | 2     |
| 164 | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 170 | $[3]$                                      | $[3]$       | $[3, 3, 3, 3, 3]$         | $[3, 3, 3, 3, 3]$       | 2                       | 0                     | -1                | 0         | 0     |
| 230 | $[3, 3, 3]$                                | $[3, 3, 3]$ | $[3, 3, 3, 3, 3, 3, 3]$   | $[3, 3, 3, 3, 3, 3, 3]$ | 2                       | 0                     | 1                 | 0         | 2     |
| 236 | $[3]$                                      | $[3]$       | $[3, 3, 3]$               | $[3, 3, 3]$             | 1                       | 0                     | 0                 | 0         | 1     |
| 253 | $\square$                                  | $\square$   | $[3, 3, 3]$               | $[3, 3]$                | 1                       | 1                     | -1                | 0         | -1    |

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UNIVERSITÉ DE BORDEAUX, INSTITUT DE MATHÉMATIQUES, 351, COURS DE LA LIBRATION, F 33 405 TALENCE, FRANCE.

*E-mail address:* [jovillan@math.u-bordeaux.fr](mailto:jovillan@math.u-bordeaux.fr)

*URL:* <http://www.math.u-bordeaux.fr/~jovillan/>