On elliptic curves with everywhere good reduction over certain number fields

Shun’ichi Yokoyama (Kyushu University)

September 14th, 2012

Abstract We prove the existence and non-existence of elliptic curves having good reduction everywhere over some real quadratic fields \( \mathbb{Q}(\sqrt{m}) \) for \( m \leq 200 \). These results of computations give best-possible data including structures of Mordell-Weil groups over some real quadratic fields via two-descent. We also prove similar results for the case of certain cubic fields. Especially, we give the first example of elliptic curve having everywhere good reduction over a pure cubic field using our method.

Contents

1 Introduction

2 Strategy

2.1 For the case of admissible curves

2.2 For the case of non-admissible curves

2.3 Computing Mordell-Weil basis and integral points

2.4 Computation I: Admissible curves for real quadratic case

2.5 Computation II: Non-admissible curves for real quadratic case

2.6 Computation III: Non-admissible curves for pure cubic case

3 Tables

3.1 The case of real quadratic fields

3.2 The case of pure cubic fields

4 Conclusion

1 Introduction

Tables of elliptic curves over \( \mathbb{Q} \) have been of great value in mathematical research. In particular, some databases are very famous and useful, and Cremona’s index (classification of elliptic curves over \( \mathbb{Q} \)) becomes popular. Nowadays, modularity theorem that explains correspondence between elliptic curves and modular forms becomes one of the most important facts in number theory and arithmetic geometry.

Meanwhile, computing elliptic curves (rank of curves, Mordell-Weil groups etc.) over general number fields is still hard. There are only a few databases of such curves and these databases use Cremona-Lingham’s general algorithm over
number fields. It seems ideal from the viewpoint of computational approach, and we can also observe the case of elliptic curves over cubic fields that are not totally real. However, updating of this algorithm with supplementary tables had been stopped since September 2005. In addition, though we apply this general algorithm, we have to determine many Mordell-Weil groups (= sets of rational points) and this task is the most difficult in creating databases.

Therefore, we have to find a more efficient way (reducing the number of Mordell-Weil groups that we have to determine) to achieve this project and also easy-to-read sorted tables of such curves, including information (with references) which case is already known and which case is still open.

Let $K_m$ be the real quadratic field $\mathbb{Q}(\sqrt{m})$ where $m$ is a square-free positive integer with $m \leq 200$ and $\mathcal{O}_{K_m}$ the ring of integers of $K_m$. We already know the following results concerning elliptic curves with everywhere good reduction over real quadratic fields ([3], [4], [5], [6], [7], [8], [9], [13], [14], [15], [16], [17], [19], [21], [29] and [30]):

Theorem 1.1. 1. There are no elliptic curves with everywhere good reduction over $K_m$ if

$m = 2, 3, 5, 10, 11, 13, 15, 17, 19, 21, 23, 30, 31, 34, 35, 39, 42, 47, 53, 55, 57, 58, 61, 66, 69, 70, 73, 74, 78, 82, 83, 85, 89, 93, 94, 95$ and 97.

2. The elliptic curves with everywhere good reduction over $K_m$ are determined completely for $m = 6, 7, 14, 22, 29, 33, 37, 38, 41, 65$ and 77.

3. There are elliptic curves with everywhere good reduction over $K_m$ if $m = 26, 79$ and 86 (cf. [5], [19] and Cremona’s table [4]).

We can also consider the pure cubic field case. Let $L_m$ be the cubic field $\mathbb{Q}(\sqrt[3]{m})$ where $m$ is cube-free, positive integer with $m \leq 200$ and $\mathcal{O}_{L_m}$ the ring of integers of $L_m$. The first known result is given by Bertolini-Canuto [1]:

Theorem 1.2 (Bertolini-Canuto, 1988). Let $L$ be the field $\mathbb{Q}(\sqrt[3]{2})$ where $\sqrt[3]{2}$ is the real cube root of 2 (i.e. $L = L_2$). Then there are no elliptic curves over $L$ with good reduction everywhere.

Recently, N. Takeshi applied Bertolini-Canuto’s method and showed the following criterion in her master’s thesis [28]:

Theorem 1.3 (Takeshi, 2012). Let $L$ be the cubic field (not only pure cubic) satisfying the following conditions:

1. 2 does not split on $L/\mathbb{Q}$,

2. The narrow class number of $L$ is coprime to 6.

Then there are no elliptic curves with everywhere good reduction over $L$ which have $L$-rational point of order 2.

In this paper, we extend Theorem 1.1 and apply our method to determine the existence and non-existence of elliptic curves having good reduction everywhere over certain pure cubic fields. The following two theorems are our main result:
Theorem 1.4. Let $K_m$ be the real quadratic field $\mathbb{Q}(\sqrt{m})$ where $m$ is a square-free positive integer with $m \leq 200$.

1. There are no elliptic curves with everywhere good reduction over $K_m$ if $m = 43, 46, 59, 62, 67, 71, 103, 107, 127, 137, 139, 151$ and $163$.

2. The elliptic curves with everywhere good reduction over $K_m$ are determined completely for $m = 109$.

3. There are admissible curves over $K_m$ if $m = 118, 134, 161$ and $166$.

4. There are no admissible curves over $K_m$ if $m = 131, 179$ and $199$.

5. There is an elliptic curve $E$ with everywhere good reduction and not admissible over $K_m$ if $m = 158$ and $161$. Explicit forms of $E$ are determined.

Theorem 1.5. Let $L_m$ be the pure cubic field $\mathbb{Q}(\sqrt[3]{m})$ where $m$ is a cube-free positive integer with $m \leq 200$.

1. There are no elliptic curves with everywhere good reduction over $L_m$ if $m = 3, 5, 6, 10, 12, 17, 18, 29, 116, 137, 173$ and $197$.

2. If $m = 23, 44, 45, 75$ and $87$, there are no admissible curves and elliptic curves with everywhere good reduction over $L_m$ which have cubic discriminant.

3. There is an elliptic curve $E$ with everywhere good reduction and not admissible over $L_m$ if $m = 46$. An explicit form of $E$ is determined.

We would like to remark that this result is an extension of the author’s previous result [32].

2 Strategy

In this section, we introduce the strategy to prove our results. Our strategy for the proof is close to that of T. Kagawa [9]. However, we use different kinds of computer softwares and computational techniques.

Important processes of our result are the following: At first, we divide all elliptic curves having everywhere good reduction into two types. One is “admissible case”, and the other is “non-admissible case”. Next we consider some criteria of S. Comalada to determine whether admissible curves exist or not (Section 2.1). After that, we observe (non-)existence of all non-admissible curves using some criteria from algebraic number theory (Section 2.2). Using this method, we can get the list of important invariants having constraint condition, and this condition can be expressed using certain elliptic curves over $K_m$ or $L_m$. Finally, we directly compute Mordell-Weil groups of specific elliptic curves (Section 2.3). Explicit data are given from Section 2.4 to 2.6. We note that easy-to-read sorted tables will be given in Chapter 3.
2.1 For the case of admissible curves

First of all, Comalada [2] determines all admissible curves (i.e., elliptic curves having good reduction everywhere and a $K_m$-rational point of order 2) defined over $K_m$ with $m \leq 100$. [2] also gives some criteria to find admissible curves over $K_m$ for an arbitrary $m$.

**Definition 2.1.** An elliptic curve defined over $K_m$ is called $g$-admissible if it is admissible and has a global minimal model.

**Proposition 2.2** ([2], Thm. 1). The following three conditions are equivalent:

1. There exists a $g$-admissible elliptic curve defined over $K_m$.
2. Either of the following equations has a solution in integers $u, v \in \mathcal{O}_m^X, X, Y \in \mathcal{O}_m$:
   - (a) $u + 64v = X^2$, $X$ a square (mod 4),
   - (b) $u + v = X^2$, $u \equiv v \equiv 1 + 2\sqrt{m}$ (mod 4) and $m \equiv 2$ (mod 4),
   - (c) $4Y + uY^2 = X^2$, $2 \mid Y$, $N(Y) = \pm 16$, $N(X) \equiv -2$ (mod 8) and $m \equiv 1$ (mod 8), where the symbol $N$ denotes the norm.
3. $m = 1023$ or either of these sets of diophantine equations has a solution:
   - (a) $x^2 - 4my^2 = -7$, $7 \mid m$,
   - (b) $x^2 - 4my^2 = 65$, $65 \mid m$,
   - (c) $x^2 - my^2 = -2$, $m \equiv -2$ (mod 8),
   - (d) $x^2 - my^2 = -8$ and $r^4 - ms^2 = \pm 256$, $r$ is odd, $m \equiv 1$ (mod 8),
   - (e) $r^4 - ms^2 = -16384$ and $t^2 - mw^2 = 8r$, $r \equiv 3$ (mod 4), $(t, r) = 1$, $128w \equiv st$ (mod $r$), $m \equiv 1$ (mod 8).

Thus we can find some admissible curves appearing Theorem 1.4 using Comalada’s method.

2.2 For the case of non-admissible curves

Next we assume that a number field $K$ is $K_m$ or $L_m$. We also assume that the class number of $K$ is 1 and every elliptic curve $E$ with everywhere good reduction over $K$ has no $K$-rational point of order 2. For our convenience, we say “non-admissible” if $E$ has everywhere good reduction over $K$ with no $K$-rational point of order 2. First we use the following result:

**Proposition 2.3** (Setzer [23]). Let $E$ be an elliptic curve over a number field $K$. If the class number of $K$ is prime to 6 then $E$ has a global minimal model.
Let $E$ be an elliptic curve with everywhere good reduction over a number field $K$. By Proposition 2.3, $E$ has a global minimal model

$$E : y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6$$

with coefficients $a_i \in O_K$ ($i = 1, 2, 3, 4, 6$). The discriminant of $E$ (denoted by $\Delta(E)$) is

$$\Delta(E) = \frac{c_4^3 - c_6^2}{1728}$$

where $c_4, c_6 \in O_K$ are, as in [25] (Chapter III, p.42), written as polynomials in the $a_i$’s with integer coefficients. Moreover, the following conditions are equivalent (cf. [25], Chapter VII, Prop. 5.1):

- $E$ has everywhere good reduction over $K$,
- $\Delta(E) \in O_K^\times$.

In our case, all elements of $O_K^\times$ are written in the form $\pm \varepsilon^n$ where $\varepsilon$ is a fundamental unit of $K$ (let us fix $\varepsilon$ for each $m$). Thus to determine the elliptic curves with everywhere good reduction over $K$, we shall compute the sets

$$E_n^\pm(O_K) = \{ (x, y) \in O_K \times O_K \mid y^2 = x^3 \pm 1728\varepsilon^n \}, \quad 0 \leq n < 12.$$  

However, the set of coefficients $(a_1, a_2, a_3, a_4, a_6) \in O_K^{10}$, which gives rise to $(c_4, c_6) \in O_K^{12}$, does not necessarily exist. Therefore, we check whether the curve

$$E_C : y^2 = x^3 - 27c_4x - 54c_6,$$

which is isomorphic to $E$ over $K$, has trivial conductor for each $(c_4, c_6) \in E_n^\pm(O_K)$.

Actually, it is very hard to compute all $E_n^\pm(O_K)$ because of the limitation of efficiency of equipments. To reduce the amount of computation, we show that some values of $n$ are irrelevant by using Kagawa’s results. Before that, we can easily reduce for the cases of $6 \leq n < 12$ because the map

$$E_n^\pm(O_K) \to E_{n+6}^\pm(O_K), \quad (x, y) \mapsto (x, \varepsilon^2y, \varepsilon^3)$$

is a bijection. Hence, we observe $E_n^\pm(O_K)$ only for $0 \leq n < 6$.

In [9], Kagawa shows a criterion whether the discriminant of an elliptic curve with everywhere good reduction over $K_m$ is a cube in $K_m$:

**Lemma 2.4** ([9], Prop. 1). If the following five conditions hold, then the discriminant of every elliptic curve with everywhere good reduction over $K_m$ is a cube in $K_m$:

1. The class number of $K_m$ is prime to 6;
2. $K_m/\mathbb{Q}$ is unramified at 3;
3. The class number of $K_m(\sqrt{-3})$ is prime to 3;

4. The class number of $K_m(\sqrt{\varepsilon})$ is odd;

5. For some prime ideal $\mathfrak{p}$ of $K_m$ dividing 3, the congruence $X^3 \equiv \varepsilon \pmod{\mathfrak{p}^2}$ does not have a solution in $\mathcal{O}_{K_m}$.

Using the criterion, Kagawa shows the following:

**Lemma 2.5** ([11]). If $m = 107, 127, 161, 166$ or $193$, every elliptic curve with everywhere good reduction over $K_m$ has a global minimal model whose discriminant is a cube in $K_m$.

Therefore, we have $\Delta(E) = \pm \varepsilon^{3n}$ for some $n \in \mathbb{Z}$.

By applying the next lemma, we can further discard some cases:

**Lemma 2.6** ([9], Prop. 4). Let $K$ be a number field and $E$ an elliptic curve defined over $K$. If $E$ has good reduction outside 2 and has no $K$-rational point of order 2, then $K(E[2])/K(\sqrt{\Delta(E)})$ is a cyclic cubic extension unramified outside 2. In particular, the ray class number of $K(\sqrt{\Delta(E)})$ modulo $\prod_{\mathfrak{p}|2} \mathfrak{p}$ is a multiple of 3.

Note that $K(\sqrt{\Delta(E)}) = K(\sqrt{\pm \varepsilon^n})$ is either $K$, $K(\sqrt{-1})$ or $K(\sqrt{1})$. Thus we compute the ray class number of $K(\sqrt{\Delta(E)})$ modulo $\prod_{\mathfrak{p}|2} \mathfrak{p}$. The following computations are carried out by using Pari/GP [20] (Same type results were obtained in [10] by using KASH [12]). The bold-faced numbers in this table are the ones divisible by 3.

**Remark 2.7.** Using Lemma 2.6 with some arguments, we conclude that if the class number of $K$ is 2 and the ray class numbers of $K$, $K(\sqrt{-1})$ and $K(\sqrt{\varepsilon})$ are all prime to 3 then each elliptic curve with everywhere good reduction over $K$ is admissible (See [10], Cor. 2.3). In this way, we compute them for $K_m$ with $m = 118, 134, 158, 166$ and we conclude that the it cannot be determined for these 4 cases whether there is an elliptic curve with everywhere good reduction over $K_m$ which have no $K_m$-rational point of order 2. Meanwhile, we can show the (non-)existence of an admissible curve (see the next section).

| $m$ | $K_m$ | $K_m(\sqrt{-1})$ | $K_m(\sqrt{\varepsilon})$ | $K_m(\sqrt{-\varepsilon})$ |
|-----|-------|-----------------|-----------------|-----------------|
| 43  | 1     | 3               | 10              | 1               |
| 46  | 1     | 4               | 1               | 3               |
| 59  | 1     | 9               | 6               | 1               |
| 62  | 1     | 8               | 3               | 1               |
| 67  | 1     | 3               | 14              | 1               |
| 71  | 1     | 7               | 3               | 4               |

Ray class number of $K_m(\sqrt{\Delta(E)})$ modulo $\prod_{\mathfrak{p}|2} \mathfrak{p}$
2.3 Computing Mordell-Weil basis and integral points

To compute $E_n^\pm(O_K)$, we first compute the Mordell-Weil group

$$E_n^\pm(K) = \{(x, y) \in K \times K \mid y^2 = x^3 \pm 1728E^n\}, \quad 0 \leq n < 6.$$
It is decomposed into a direct-sum of $E_n^\pm(K)_{\text{tors}}$ (torsion part) and $E_n^\pm(K)_{\text{free}} \simeq \mathbb{Z}^{\oplus r}$ (free part, which is not canonical, with $r \geq 0$). The torsion part can be determined by observing reduction at good primes and decomposition of division polynomials. On the other hand, the free part can be computed by applying two-descent and infinite descent (the process of decompression from $E_n^\pm(K)/2E_n^\pm(K)$ to $E_n^\pm(K)$). We used Denis Simon’s two-descent program (cf. [26]) on Pari-GP [20]. To compute some related data efficiently, we executed the Pari-GP program on Sage [22] as a built-in software.

The procedure of explicit computation of $E(K)$ is the following:

1. Determine $P_1, ..., P_r$ whose images in $E(K)/E(K)_{\text{tors}}$ generate a subgroup of finite index of $E(K)/E(K)_{\text{tors}}$. Usually, these are obtained by performing an $m$-descent for some $m \geq 2$, especially we often choose $m = 2$.

2. Compute an upper bound on the index $[E(K)/E(K)_{\text{tors}} : \langle P_1, ..., P_r \rangle]$.

3. A sieving procedure (See [24], Section 4) is then used to deduce a Mordell-Weil basis for $E(K)$.

We certainly wish to have an upper bound for $[E(K)/E(K)_{\text{tors}} : \langle P_1, ..., P_r \rangle]$ as small as possible. In particular, $P_1, ..., P_r$ will certainly be a Mordell-Weil basis of $E(K)$ if the value is equal to 1.

To compute the subset $E_n^\pm(O_K)$ of integral points in $E_n^\pm(K)$, we use the method of elliptic logarithm to compute the linear form:

$$P = \sum_{i=1}^{r} m_i P_i + nT \in E_n^\pm(O_K) \quad (m_1, ..., m_r, n \in \mathbb{Z})$$

where $P_i$’s and $T$ are generators of the free part and the torsion part. Moreover, the maximum of the absolute values of the coefficients of the linear form

$$M := \max \{|m_1|, ..., |m_r|, |n|\}$$

can be bounded using the LLL-algorithm (by Lenstra-Lenstra-Lovász, cf. [27]). Finally, we compute that the elliptic curve

$$E_C : y^2 = x^3 - 27c_4x - 54c_6$$

has trivial conductor.

### 2.4 Computation I: Admissible curves for real quadratic case

First we prove the (non-)existence of $g$-admissible curves:

**Proposition 2.8.** 1. There are no $g$-admissible curves over $K_m$ if $m = 103, 107, 109, 127, 131, 137, 139, 151, 158, 163, 179$ and $199$.

2. There are $g$-admissible curves over $K_m$ if $m = 118, 134, 161$ and $166$. 

8
Proof. For all $m$’s appearing in 1., the third equivalent condition (a)–(e) of Proposition 2.2 does not be satisfied. For $m = 118, 134$ and $166$, we need to check whether $x^2 - my^2 = -2$ has a solution in $\mathcal{O}_{K_m}$. As a result, we get the following results:

- (Case $m = 118$) $554^2 - 118 \cdot 51^2 = -2$,
- (Case $m = 134$) $382^2 - 134 \cdot 33^2 = -2$,
- (Case $m = 166$) $41242^2 - 166 \cdot 3201^2 = -2$.

For $m = 161$, we need to check whether $x^2 - 4my^2 = -7$ has a solution in $\mathcal{O}_{K_m}$, and we can get $203^2 - 4 \cdot 161 \cdot 8^2 = -7$.

Remark 2.9. In fact, [2] proved that the number of $g$-admissible elliptic curves over $K_m$ (up to isomorphism) for $m = 118, 134, 166$ is 2 if $x^2 - my^2 = -2$ is solvable and $m \neq 6$. Thus we conclude that the number of admissible elliptic curves over $K_m$ for $m = 118, 134, 166$ is greater than or equal to 2. Note that it is not true in general that all admissible curves defined over $K_m$ are $g$-admissible. However, assume the class number of $K_m$ is odd, it is true except some cases (see [2]).

2.5 Computation II: Non-admissible curves for real quadratic case

Proposition 2.10. If $m = 43, 46, 59, 62, 67, 71, 107, 127, 139, 151$ and $163$, there are no elliptic curves with everywhere good reduction over $K_m$.

Proof. A basis of $E^+_n(K_m)$ and the set of integral points $E_n^+(\mathcal{O}_{K_m})$ are as follows:

1. (Case $m = 43$)
   - (a) $E^+_0(K_{43}) \simeq \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{43}, P_{43A}\}$ where $T_{43} = (-12, 0)$ is 2-torsion and $P_{43A} = (-\frac{104}{9}, -\frac{56}{3} \sqrt{43})$ is a generator of the free-part.
   - (b) $E^+_2(K_{43}) \simeq \mathbb{Z}$ and a basis is $\{P_{43B}\}$ where $P_{43B} = (3200 - 488\sqrt{43}, 294088 - 44848\sqrt{43})$.
   - (c) $E^+_4(K_{43}) \simeq \mathbb{Z}$ and a basis is $\{P_{43C}\}$ where $P_{43C} = (-727456 + 110936\sqrt{43}, 496115392 - 75656888\sqrt{43})$.
The sets of integral points $E_n^\pm(\mathcal{O}_{K_m})$ are

(a) $E_0^+(\mathcal{O}_{K_{46}}) = \{O, T_{34}, T_{43} \pm P_{33A}\}$,

(b) $E_2^+(\mathcal{O}_{K_{46}}) = \{O, \pm P_{43B}, \pm 2P_{43B}\}$,

(c) $E_4^+(\mathcal{O}_{K_{46}}) = \{O, \pm P_{43C}, \pm 2P_{43C}\}$.

2. (Case $m = 46$) $E_3^+(K_{46})$ is isomorphic to $\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ with a basis $\{T_{36}, P_{46}\}$ where $T_{46} = (-12\varepsilon, 0)$ ($\varepsilon = 24335 + 3588\sqrt{46}$) is 2-torsion and $P_{46} = (\frac{1044832225}{6084} + \frac{947505}{39}\sqrt{46}, \frac{11617709481217}{47452} + \frac{7302442649}{2028}\sqrt{46})$ is a generator of the free-part. The set of integral points $E_3^+(\mathcal{O}_{K_{46}})$ is $E_3^+(\mathcal{O}_{K_{46}}) = \{O, T_{46}\}$.

3. (Case $m = 59$)

(a) $E_0^+(K_{59}) \cong \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{59A}, P_{59A}\}$ where $T_{59A} = (-12, 0)$ is 2-torsion and $P_{59A} = (-\frac{133}{16}, -\frac{283}{16}\sqrt{59})$ is a generator of the free-part.

(b) $E_3^+(K_{59}) \cong \mathbb{Z}^{\oplus 2} \oplus \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{59B}, P_{59B}, P_{59C}\}$ where $T_{59B} = (12\varepsilon, 0)$ ($\varepsilon = -530 + 69\sqrt{59}$) is 2-torsion and $P_{59B} = (9275 - \frac{2415}{2}\sqrt{59}, -\frac{581073}{4} + \frac{756493}{4}\sqrt{59})$ and $P_{59C} = (-\frac{90000200}{59}, -\frac{650460}{59} - \frac{6504772968}{59} - \frac{50000243752}{3481}\sqrt{59})$ are generators of the free-part.

The sets of integral points $E_n^+(\mathcal{O}_{K_{m}})$ are

(a) $E_0^+(\mathcal{O}_{K_{59}}) = \{O, T_{59A}\}$,

(b) $E_3^+(\mathcal{O}_{K_{59}}) = \{O, T_{59B}\}$.

4. (Case $m = 62$)

(a) $E_1^+(K_{62}) \cong \mathbb{Z}$ and a basis is $\{P_{62A}\}$ where $P_{62A} = (-\frac{1239444}{9409} - \frac{150258}{9409} + \frac{65}{2}\sqrt{62}, -\frac{189073396}{912673} - \frac{241863264}{912673}\sqrt{62})$.

(b) $E_3^+(K_{62}) \cong \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{62}, P_{62B}\}$ where $T_{62} = (12\varepsilon, 0)$ ($\varepsilon = -63 + 8\sqrt{62}$) is 2-torsion and $P_{62B} = (\frac{30492}{25} - \frac{3872}{25}\sqrt{62}, -\frac{8477936}{125} + 8512\sqrt{62})$ is a generator of the free-part.

(c) $E_5^+(K_{62}) \cong \mathbb{Z}$ and a basis is $\{P_{62C}\}$ where $P_{62C} = (-\frac{45066180}{9409}, -\frac{56523096}{9409} - \frac{13702098109968}{912673} - \frac{1740168200376}{912673}\sqrt{62})$.

The sets of integral points $E_n^+(\mathcal{O}_{K_{m}})$ are
(a) $E_1^+ (O_{K_{67}}) = \{O\}$,
(b) $E_3^- (O_{K_{67}}) = \{O, T_{62}\}$,
(c) $E_5^- (O_{K_{67}}) = \{O\}.$

5. (Case $m = 67$)

(a) $E_2^+ (K_{67}) \simeq \mathbb{Z}$ and a basis is $\{P_{67A}\}$ where

$P_{67A} = (−5304 + 648\sqrt{67}, 1955448 − 238896\sqrt{67})$.

(b) $E_4^+ (K_{67}) \simeq \mathbb{Z}$ and a basis is $\{P_{67B}\}$ where

$P_{67B} = (518121240 − 6329584\sqrt{67}, −16679875123872 + 2037771075816\sqrt{67})$.

The sets of integral points $E_i^\pm (O_{K_{67}})$ are

(a) $E_2^+ (O_{K_{67}}) = \{O, \pm P_{67A}\}$,
(b) $E_4^+ (O_{K_{67}}) = \{O, \pm P_{67B}\}$.

6. (Case $m = 71$)

(a) $E_1^+ (K_{71}) \simeq \mathbb{Z}^{3}$ and a basis is $\{P_{71A}, P_{71B}, P_{71C}\}$ where

$P_{71A} = (304 + 36\sqrt{71}, 7280 + 864\sqrt{71})$,

$P_{71B} = (128 + 12\sqrt{71}, −72 + 8\sqrt{71})$, and

$P_{71C} = \left(\frac{3139}{4} + 93\sqrt{71}, \frac{124933}{4} + \frac{29439}{8}\sqrt{71}\right)$.

(b) $E_3^+ (K_{71})$ is isomorphic to $\mathbb{Z}^{52} \oplus \mathbb{Z}/2\mathbb{Z}$ with a basis $\{T_1, P_{71D}, P_{71E}\}$ where $T_1 = (12\varepsilon, 0)$ ($\varepsilon = 3480 + 413\sqrt{71}$) is 2-torsion and

$P_{71D} = (165300 + \frac{39235}{2}\sqrt{71}, \frac{377998253}{4} + \frac{44753329}{4}\sqrt{71})$ and

$P_{71E} = \left(\frac{1569462848}{3025} + \frac{18192868}{3025} \sqrt{71}, −87152513410872 + 10344100438152\sqrt{71}\right)$

are generators of the free-part.

(c) $E_5^+ (K_{71}) \simeq \mathbb{Z}^{3}$ and a basis is $\{P_{71F}, P_{71G}, P_{71H}\}$ where

$P_{71F} = (15952016 + 1893156\sqrt{71}, −32603423328 − 3869314480\sqrt{71})$,

$P_{71G} = (651205312 + 77283852\sqrt{71}, 23501150604136 + 2789073448344\sqrt{71})$, and

$P_{71H} = \left(\frac{2038074336}{49} + \frac{241874924}{49} \sqrt{71}, \frac{126780558251720}{343} + \frac{1565913871312}{343}\sqrt{71}\right)$.

The sets of integral points $E_i^\pm (O_{K_{71}})$ are

(a) $E_1^+ (O_{K_{71}}) = \{O, \pm P_{71A}, \pm P_{71B}, \pm P_{71C}\}$,
(b) $E_3^- (O_{K_{71}}) = \{O, T_{71}, \pm P_{71D} \mp P_{71E}, T_{71} \pm P_{71D} \mp P_{71E}\}$,
(c) $E_5^- (O_{K_{71}}) = \{O, \pm P_{71F}, \pm P_{71G}, \pm P_{71F} \mp P_{71H}\}$.
7. (Case \( m = 107 \))

(a) \( E_0^+ (K_{107}) \cong \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} \) and a basis is \( \{ T_{107A}, P_{107A} \} \) where \( T_{107A} = (-12, 0) \) is 2-torsion and
\[
P_{107A} = \left( \frac{19415435}{12497107}, \frac{827056739}{12497107}, \sqrt{107} \right)
\]is a generator of the free-part.

(b) \( E_3^+ (K_{107}) \cong \mathbb{Z}^2 \oplus \mathbb{Z}/2\mathbb{Z} \) and a basis is \( \{ T_{107B}, P_{107B}, P_{107C} \} \) where
\[
T_{107B} = (-12, 0) \ (\varepsilon = 962 + 93\sqrt{107}) \text{ is 2-torsion and}
\[
P_{107B} = \left( \frac{3291}{4} + \frac{1024}{8}, \frac{56172733}{32} + \frac{2430425}{32}, \sqrt{107} \right)
\]and
\[
P_{107C} = \left( \frac{13900698150670419032}{982587075600025} + \frac{1265524873193709948}{982587075600025}, \frac{-6808441920591906566125}{3890011520559190566125} \right)
\]are generators of the free-part.

The sets of integral points \( E_n^+(\mathcal{O}_m) \) are

(a) \( E_0^+(\mathcal{O}_{K_{107}}) = \{ O, T_{107A} \} \),

(b) \( E_3^+(\mathcal{O}_{K_{107}}) = \{ O, T_{107B} \} \).

8. (Case \( m = 127 \)) \( E_3^- (K_{127}) \cong \mathbb{Z}/2\mathbb{Z} \) and a basis is \( \{ T_{127} \} \) where \( T_{127} = (12, 0) \ (\varepsilon = -4730624 + 419775\sqrt{127}) \) is 2-torsion. The set of integral points \( E_3^- (\mathcal{O}_m) \) is
\[
E_3^- (\mathcal{O}_{K_{127}}) = \{ O, T_{127} \}.
\]

9. (Case \( m = 139 \))

(a) \( E_0^+ (K_{139}) \) is isomorphic to \( \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} \) with a basis \( \{ T_{139}, P_{139A} \} \) where
\[
T_{139} = (-12, 0) \text{ is 2-torsion and}
\[
P_{139A} = \left( \frac{-21}{4}, \frac{-27}{8}, \sqrt{139} \right)
\]is a generator of the free-part.

(b) \( E_2^+ (K_{139}) \) is isomorphic to \( \mathbb{Z} \) with a basis \( \{ P_{139B} \} \) where
\[
P_{139B} = \left( \frac{-1457812 + 123650\sqrt{139}}{2049248038}, \frac{4930624 + 419775\sqrt{139}}{29877920529400} \right)
\]is a generator of the free-part.

(c) \( E_4^+ (K_{139}) \) is isomorphic to \( \mathbb{Z} \) with a basis \( \{ P_{139C} \} \) where
\[
P_{139C} = \left( \frac{643776432812}{54604404350\sqrt{139}}, \frac{-8853188743456929250 + 75091766845674998\sqrt{139}}{54604404350\sqrt{139}} \right)
\]is a generator of the free-part.

The sets of integral points \( E_n^+(\mathcal{O}_m) \) are

(a) \( E_0^+(\mathcal{O}_{K_{139}}) = \{ O, T_{139}, T_{139} \pm P_{139A} \} \),

(b) \( E_2^+(\mathcal{O}_{K_{139}}) = \{ O, \pm P_{139B} \} \),

(c) \( E_4^+(\mathcal{O}_{K_{139}}) = \{ O, \pm P_{139C} \} \).
10. (Case $m = 151$)

(a) $E_1^+(K_{151}) \simeq \mathbb{Z}^{\oplus 2}$ and a basis is $\{P_{151A}, P_{151B}\}$ where

$$P_{151A} = (-7520 + 612\sqrt{151}, 801584 - 65232\sqrt{151}),$$

and

$$P_{151B} = \frac{21766816}{2601} + \frac{1766476}{2601}\sqrt{151}, \frac{7227351880}{132651} - \frac{620655978}{132651}\sqrt{151}.$$

(b) $E_3^+(K_{151})$ is isomorphic to $\mathbb{Z}/2\mathbb{Z}$ with a basis $\{T_{151}\}$ where $T_{151} = (12\varepsilon, 0)$ ($\varepsilon = -1728148040 + 140634693\sqrt{151}$) is 2-torsion.

(c) $E_5^+(K_{151}) \simeq \mathbb{Z}^{\oplus 2}$ and a basis is $\{P_{151C}, P_{151D}\}$ where

$$P_{151C} = \frac{26882043940407709056}{146338222190683107499120032} - \frac{218762649245278968}{132651}\sqrt{151},$$

and

$$P_{151D} = \frac{2281116411955040800 - 185634620916248988\sqrt{151}, 4872345992082302805265708304 - 396505893549649303115433072\sqrt{151}}{281952144 - 220841940\sqrt{151}}.$$

The sets of integral points $E_n^+(\mathcal{O}_{K_m})$ are

(a) $E_1^-(\mathcal{O}_{K_{151}}) = \{O, \pm P_{151A}, \pm P_{151B}\}$,

(b) $E_3^-(\mathcal{O}_{K_{151}}) = \{O, T_{151}\}$,

(c) $E_5^-(\mathcal{O}_{K_{151}}) = \{O, \pm P_{151D}\}$.

11. (Case $m = 163$)

(a) $E_1^+(K_{163})$ is isomorphic to $\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ with a basis $\{T_{163A}, P_{163A}\}$ where $T_{163A} = (-12, 0)$ is 2-torsion and

$$P_{163A} = (640320, 40133016\sqrt{163})$$

is a generator of the free-part.

(b) $E_3^+(K_{163}) \simeq \mathbb{Z}^{\oplus 2}$ and a basis is $\{P_{163B}, P_{163C}, P_{163D}\}$ where

$$P_{163B} = \frac{91976}{9} + \frac{7204}{9}\sqrt{163}, \frac{18902744}{27} - \frac{269448}{27}\sqrt{163},$$

$$P_{163C} = \frac{283688}{81} - \frac{22220}{81}\sqrt{163}, \frac{12742368}{729} - \frac{989960}{729}\sqrt{163},$$

and

$$P_{163D} = \frac{2578555676}{81} - \frac{20204634}{81}\sqrt{163}, \frac{5859858412314}{185183} - \frac{45899019278}{185183}\sqrt{163}.$$

(c) $E_2^+(K_{163}) \simeq \mathbb{Z}^{\oplus 2}$ and a basis is $\{P_{163E}, P_{163F}\}$ where

$$P_{163E} = (-825064 + 64624\sqrt{163}, -2443830376 + 191415568\sqrt{163},$$

and

$$P_{163F} = \frac{16981860179}{81} - \frac{2669244829}{162}\sqrt{163}, \frac{12518525954485901}{2916} - \frac{90526627229655}{2916}\sqrt{163}.$$

(d) $E_3^+(K_{163}) \simeq \mathbb{Z}^{\oplus 2} \oplus \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{163B}, P_{163G}, P_{163H}\}$ where

$$T_{163B} = (12\varepsilon, 0)$$

is 2-torsion and

$$P_{163G} = (2819521144 - 220841940\sqrt{163}, 209569365956016 - 16414739588240\sqrt{163})$$

are generators of the free-part.
(e) $E^+_4(K_{163}) \simeq \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{P_{163I}, P_{163J}\}$ where
\[
P_{163I} = \left(\frac{24872060322049}{49} - \frac{1948130116049}{49} \sqrt{163}, \frac{918193764879785320}{443}\right)
\]
and
\[
P_{163J} = \left(955562172776 - 7484505744\sqrt{163}, 1364401359500472544 - 106868162280652088\sqrt{163}\right).
\]

(f) $E^+_5(K_{163}) \simeq \mathbb{Z}/3\mathbb{Z}$ and a basis is $\{P_{163K}, P_{163L}, P_{163M}\}$ where
\[
P_{163K} = \left(\frac{16676799596285288}{81} - \frac{13062277556144540}{81} \sqrt{163}, \frac{906121368782125104080}{729}\right)
\]
and
\[
P_{163L} = \left(23381186696204 - 18313558791786 \sqrt{163}, 3260001277150148593738 - 255343006730194102206\sqrt{163}\right).
\]

The sets of integral points $E^+_n(O_{K_m})$ are:

(a) $E^+_0(O_{K_{163}}) = \{O, T_{163A}, \pm P_{163A}\}$,
(b) $E^+_1(O_{K_{163}}) = \{O, \pm P_{163C}\}$,
(c) $E^+_2(O_{K_{163}}) = \{O, \pm P_{163E}\}$,
(d) $E^+_3(O_{K_{163}}) = \{O, T_{163B}, \pm P_{163G}, \pm P_{163G} \mp P_{163H}, T_{163B} \pm P_{163G} \mp P_{163H}\}$,
(e) $E^+_4(O_{K_{163}}) = \{O, \pm P_{163J}\}$,
(f) $E^+_5(O_{K_{163}}) = \{O\}$.

Moreover, there are no pairs $(c_4, c_6) \in E^+_n(O_{K_m})$ for which the elliptic curve $E_C$ has trivial conductor.

For the case $m = 109$, we can find $(c_4, c_6)$ (that gives the elliptic curve with everywhere good reduction appearing in Theorem A.1) from $E^+_4(O_{K_{109}})$.

**Proposition 2.11.** The elliptic curves with everywhere good reduction over $K_m$ are determined completely for $m = 109$.

**Proof.**

1. $E^+_0(K_{109}) \simeq \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{T_{109}\}$ where $T_{109} = (-12, 0)$ is 2-torsion.

2. $E^+_2(K_{109}) \simeq \mathbb{Z}/2\mathbb{Z}$ and a basis is $\{P_{109A}, P_{109B}\}$ where
\[
P_{109A} = \left(-\frac{5668}{29} - \frac{544}{29} \sqrt{109}, -\frac{30744}{129} - \frac{20432}{129} \sqrt{109}\right)
\]
and
\[
P_{109B} = \left(\frac{2026}{9} + \frac{290}{9} \sqrt{109}, -\frac{277340}{29} - \frac{26564}{29} \sqrt{109}\right).
\]
3. \( E_4^+ (K_{109}) \simeq \mathbb{Z}^{\oplus 2} \) and a basis is \( \{ P_{109C}, P_{109D} \} \) where
\[
P_{109C} = (-5596 - 536\sqrt{109}, -1286204 - 123196\sqrt{109})
\]
and
\[
P_{109D} = \left( \frac{916346}{81} + \frac{87770}{81} \sqrt{109}, \frac{1013792}{729} \sqrt{109} - \frac{154573276}{729} \right)
\]
are generators of the free-part.

The sets of integral points \( E_n^+ (\mathcal{O}_K) \) are
1. \( E_0^+ (\mathcal{O}_{K_{109}}) = \{ O, T_{109} \} \),
2. \( E_2^+ (\mathcal{O}_{K_{109}}) = \{ O, \pm P_{109A} \mp P_{109B}, \pm 2P_{109A} \mp 2P_{109B} \} \),
3. \( E_4^+ (\mathcal{O}_{K_{109}}) = \{ O, \pm P_{109C}, \pm 3P_{109C} \pm P_{109D} \} \).

From \( 2P_{109C} \) in \( E_4^+ (\mathcal{O}_{K_{109}}) \), we can construct the elliptic curve having everywhere good reduction over \( K_{109} \) as follows:
\[
y^2 + \frac{1 + \sqrt{109}}{2} xy = x^3 - \frac{3 + \sqrt{109}}{2} x^2 - (274 + 29\sqrt{109}) x - (3259 + 315\sqrt{109}).
\]

According to [30], there are no elliptic curves having good reduction everywhere and no \( K_{109} \)-rational point of order 2 (= not admissible) except the above up to isogenies. 

For the case \( m = 158 \), the class number of \( K_m \) is 2 so our strategy cannot apply. However, we can find one elliptic curve with everywhere good reduction over \( K_m \) with computing \( E_3^- (\mathcal{O}_{K_{158}}) \).

**Proposition 2.12.** There is an elliptic curve \( E \) having everywhere good reduction over \( K_{158} \). \( E \) is given by \( y^2 + xy + \sqrt{158} y = x^3 - x^2 + Ax + B \) where
\[
A = -361817559192191668851 - 28784659475803145415\sqrt{158},
B = 3691288333191863812738417681108
+ 293663132146367649175848062813\sqrt{158}.
\]

For the case \( m = 161 \), we can find \( (c_4, c_6) \) (that gives the elliptic curve with everywhere good reduction appearing in Theorem A.1) from \( E_3^- (\mathcal{O}_{K_{161}}) \).

**Proposition 2.13.** There is an elliptic curve \( E \) having everywhere good reduction over \( K_{161} \). \( E \) is given by
\[
y^2 + xy + y = x^3 - x^2 + (-3680 + 290\sqrt{161}) x + (-148482 + 11702\sqrt{161}).
\]
2.6 Computation III: Non-admissible curves for pure cubic case

Proposition 2.14. If \( m = 23, 44, 45, 75 \) and 87, there are no elliptic curves with everywhere good reduction over \( L_m \) which have no \( L_m \)-rational point of order 2 (not admissible) and cubic discriminant.

Proof. In this case, it is enough to determine \( E_0^+(\mathcal{O}_{L_{23}}), E_0^+(\mathcal{O}_{L_{44}}), E_3^+(\mathcal{O}_{L_{45}}), E_3^+(\mathcal{O}_{L_{75}}) \) and \( E_3^-(\mathcal{O}_{L_{87}}) \). Here is the result of computing Mordell-Weil groups and sets of integral points:

1. \( E_0^+(\mathcal{O}_{L_{23}}) \) is isomorphic to \( \mathbb{Z} \oplus \mathbb{Z} = \mathbb{Z} \) with a basis \( \{ T_{23}, P_{23} \} \) where \( T_{23} = (-12, 0) \) is 2-torsion and \( P_{23} = (-4\sqrt[3]{23}, 16) \) is a generator of the free-part. The set of integral points is
   \[
   E_0^+(\mathcal{O}_{L_{23}}) = \{ O, T_{23}, \pm P_{23}, T_{23} \pm P_{23} \}.
   \]

2. \( E_0^+(\mathcal{O}_{L_{44}}) \) is isomorphic to \( \mathbb{Z} \oplus \mathbb{Z} = \mathbb{Z} \) with a basis \( \{ T_{44}, P_{44A}, P_{44B} \} \) where \( T_{44} = (-12, 0) \) is 2-torsion and
   \[
   P_{44A} = \left( \frac{10\sqrt[3]{44}+14\sqrt[3]{11}+272}{3}, \frac{104\sqrt[3]{44}+320\sqrt[3]{11}+3256}{3} \right)
   \]
   and
   \[
   P_{44B} = \left( \frac{4\sqrt[3]{44}-16\sqrt[3]{11}+28}{3}, \frac{32\sqrt[3]{44}-56\sqrt[3]{11}+64}{3} \right)
   \]
   are generators of the free-part. The set of integral points is
   \[
   E_0^+(\mathcal{O}_{L_{44}}) = \{ O, T_{44}, T_{44} \pm P_{44B}, P_{44A} \pm P_{44B} \}
   \]
   (double sign in the same order).

3. \( E_3^+(\mathcal{O}_{L_{45}}) \) is isomorphic to \( \mathbb{Z} / 2\mathbb{Z} \) with a basis \( \{ T_{45} \} \) where \( T_{45} = (12\xi, 0) \)
   \( (\xi = 104\sqrt[3]{45} - 66\sqrt[3]{15} - 1081) \) is 2-torsion. The set of integral points is
   \[
   E_3^+(\mathcal{O}_{L_{45}}) = \{ O, T_{45} \}.
   \]

4. \( E_3^+(\mathcal{O}_{L_{75}}) \) is isomorphic to \( \mathbb{Z} / 2\mathbb{Z} \) with a basis \( \{ T_{75} \} \) where \( T_{75} = (-12\xi, 0) \)
   \( (\xi = 66\sqrt[3]{75} / 5 - 312\sqrt[3]{75} + 1081) \) is 2-torsion. The set of integral points is
   \[
   E_3^+(\mathcal{O}_{L_{75}}) = \{ O, T_{75} \}.
   \]

5. \( E_3^-(\mathcal{O}_{L_{87}}) \) is isomorphic to \( \mathbb{Z} / 2\mathbb{Z} \) with a basis \( \{ T_{87} \} \) where \( T_{87} = (12\xi, 0) \)
   \( (\xi = 414906405399771342\sqrt[3]{87}^2 - 2295582499903407744\sqrt[3]{87} + 2025487074437153495) \) is 2-torsion. The set of integral points is
   \[
   E_3^-(\mathcal{O}_{L_{87}}) = \{ O, T_{87} \}.
   \]

There are no pairs \( (c_4, c_6) \in E_n^+(\mathcal{O}_{L_m}) \) for which \( E_C \) has trivial conductor.

Finally, to complete the proof of Theorem 1.5, we show the following.
Proposition 2.15. The elliptic curve $E$ as follows is having everywhere good reduction and not admissible over $L_{46}$:

$$y^2 + \sqrt[3]{46}xy + \frac{\sqrt[3]{46^2} + \sqrt[3]{46} + 1}{3}y = x^3 + (\sqrt[3]{46} + 1)x^2 + \frac{C_1\sqrt[3]{46^2} + C_2\sqrt[3]{46} + C_3}{3}x + \frac{C_4\sqrt[3]{46^2} + C_5\sqrt[3]{46} + C_6}{3}$$

where $C_k's$ $(1 \leq k \leq 6)$ are as follows:

- $C_1 = 9421950375743390681493864706,$
- $C_2 = 1081334709186632184731947617604,$
- $C_3 = 5084087035543830437128808550119,$
- $C_4 = 2325842334479295709473275474986025640457867,$
- $C_5 = 8278921164629266750494613377875990377913857,$
- $C_6 = 32649741211533344905526205920140161442668175.$

Proof. $E^+_0(L_{46})$ is isomorphic to $\mathbb{Z}/2^2 \oplus \mathbb{Z}/2\mathbb{Z}$ with a basis $\{T_{46}, P_{46A}, P_{46B}\}$ where $T_{46} = (-12, 0)$ is 2-torsion and

$$P_{46A} = \left(\sqrt[3]{46^2}, 62\right)$$

and

$$P_{46B} = \left(\frac{4\sqrt[3]{46^2} - 8\sqrt[3]{46} - 20}{3}, -\frac{16\sqrt[3]{46^2} + 40\sqrt[3]{46} - 224}{3}\right)$$

are generators of the free-part. The set of integral points is

$$E^+_0(\mathcal{O}_{L_{46}}) = \{O, T_{46}, \pm P_{46A}, T_{46} \pm P_{46B}\}.$$

Finally, we can get $(c_4, c_6) = T_{46} + P_{46B}$ and find the curve $E$. We can also check that

$$\Delta(E) = -3793984397734581700890517196178912938805063879701109688859069841240872146001465208442236960\sqrt[3]{46^2}$$

$$+ 382663735102397023759478346534560753180134696061871746640223232761012926066508928658642440\sqrt[3]{46}$$

$$- 88402196060375965791126700381485837764341711498964900463229074317241483287536740383170905601$$

$$= -\epsilon^{24}$$

where $\epsilon = 309\sqrt[3]{46^2} + 48\sqrt[3]{46} - 4139$ is a fundamental unit of $L_{46}$. 

\[\square\]
3 Tables

We give tables showing the existence or non-existence of elliptic curves with everywhere good reduction defined over certain number fields. We note that

\begin{itemize}
  \item \textbf{DET} — Determined
  \item \textbf{NEX} — Non-existence
  \item \textbf{PEX} — Partly existence
  \item \textbf{PNEX} — Partly non-existence
  \item \textbf{UNDET} — Undetermined
\end{itemize}

and \( a \) is a generator of each base field, given by Magma’s setup

\[
K<a>:=\text{NumberField}(f)
\]

where \( f \) is defining polynomial of \( K \).

We remark that precise version of the following tables are available from the author’s website. These contain data of fundamental units and references.

### 3.1 The case of real quadratic fields

| \( m \) | fundamental unit | adm | n-adm | progress | reference |
|-------|-----------------|-----|-------|----------|-----------|
| 2     | \( a + 1 \)     | No  | No    | NEX      | [15]      |
| 3     | \( a + 2 \)     | No  | No    | NEX      | [15]      |
| 5     | \( 1/2 \times a + 1/2 \) | No  | No    | NEX      | [15]      |
| 6     | \( 2 \times a - 5 \) | Yes | No    | DET      | [2]       |
| 7     | \( 3 \times a + 8 \) | Yes | No    | DET      | [2]       |
| 10    | \( a + 3 \)     | No  | No    | NEX      | [16]      |
| 11    | \( 3 \times a - 10 \) | No  | No    | NEX      | [9]       |
| 13    | \( 1/2 \times a + 3/2 \) | No  | No    | NEX      | [5],[17]  |
| 14    | \( 4 \times a + 15 \) | Yes | No    | DET      | [2]       |
| 15    | \( a + 4 \)     | No  | No    | NEX      | [16]      |
| 17    | \( a - 4 \)     | No  | No    | NEX      | [17]      |
| 19    | \( 39 \times a - 170 \) | No  | No    | NEX      | [9]       |
| 21    | \( 1/2 \times a + 5/2 \) | No  | No    | NEX      | [17]      |
| 22    | \( 42 \times a - 197 \) | Yes | No    | DET      | [16]      |
| 23    | \( 5 \times a + 24 \) | No  | No    | NEX      | [9]       |
| 26    | \( a + 5 \)     | No  | Yes   | PEX/UNDET| [16]      |
| 29    | \( 1/2 \times a + 5/2 \) | No  | Yes   | DET      | [13]      |
| 30    | \( 2 \times a - 11 \) | No  | No    | NEX      | [16]      |
| 31    | \( 273 \times a + 1520 \) | No  | No    | NEX      | [9]       |
| 33    | \( 4 \times a - 23 \) | No  | Yes   | DET      | [14]      |
| $n$ | fundamental unit | adm | n-adm | progress | reference |
|-----|------------------|-----|-------|----------|-----------|
| 34  | $6a - 35$        | No  | No    | NEX      | [16]      |
| 35  | $a - 6$          | No  | No    | NEX      | [16]      |
| 37  | $a - 6$          | No  | No    | NEX      | [13], [6] |
| 38  | $6a - 37$        | Yes | Yes   | DET      | [2], [29] |
| 39  | $4a + 25$        | No  | No    | NEX      | [16]      |
| 41  | $5a - 32$        | Yes | No    | DET      | [2], [29] |
| 42  | $2a + 13$        | No  | No    | NEX      | [16]      |
| 43  | $531a - 3482$    | No  | No    | NEX      | 32        |
| 46  | $3588a + 24335$  | No  | No    | NEX      | 32        |
| 47  | $7a + 48$        | No  | No    | NEX      | [16]      |
| 51  | $7a + 50$        | No  | —     | PNEX/UNDET| —        |
| 53  | $1/2a - 7/2$     | No  | No    | NEX      | [9]       |
| 55  | $12a + 89$       | No  | No    | NEX      | 29        |
| 57  | $20a - 151$      | No  | No    | NEX      | [8]       |
| 58  | $13a + 99$       | No  | No    | NEX      | [16]      |
| 59  | $69a - 530$      | No  | No    | NEX      | 32        |
| 61  | $5/2a - 39/2$    | No  | No    | NEX      | [9]       |
| 62  | $8a - 63$        | No  | No    | NEX      | 32, [31]  |
| 65  | $a - 8$          | Yes | No    | DET      | [2], [29] |
| 66  | $8a + 65$        | No  | No    | NEX      | [16]      |
| 67  | $5967a - 48842$  | No  | No    | NEX      | 32, [31]  |
| 69  | $3/2a - 25/2$    | No  | No    | NEX      | [8]       |
| 70  | $30a - 251$      | No  | No    | NEX      | [16]      |
| 71  | $413a + 3480$    | No  | No    | NEX      | 32, [31]  |
| 73  | $125a + 1068$    | No  | No    | NEX      | [17]      |
| 74  | $5a - 43$        | No  | No    | NEX      | [16]      |
| 77  | $1/2a + 9/2$     | Yes | Yes   | DET      | [2], [16] |
| 78  | $6a + 53$        | No  | No    | NEX      | [29]      |
| 79  | $9a - 80$        | No  | Yes   | PEX/UNDET| 16        |
| 82  | $a - 9$          | No  | No    | NEX      | 16        |
| 83  | $9a - 82$        | No  | No    | NEX      | 9         |
| 85  | $1/2a + 9/2$     | No  | No    | NEX      | 16        |
| 86  | $1122a - 10405$  | Yes | Yes   | PEX/UNDET| 16        |
| 87  | $3a - 28$        | No  | —     | PNEX/UNDET| —        |
| 89  | $53a + 500$      | No  | No    | NEX      | [9]       |
| 91  | $165a - 1574$    | No  | —     | PNEX/UNDET| —        |
| 93  | $3/2a + 29/2$    | No  | No    | NEX      | [8]       |
| 94  | $221064a - 2143295$| No | No    | NEX      | 16        |
| 95  | $4a - 39$        | No  | No    | NEX      | 29        |
| 97  | $569a + 5604$    | No  | No    | NEX      | 17        |
| $m$ | fundamental unit | adm | n-adm | progress | reference |
|-----|------------------|-----|-------|----------|-----------|
| 101 | $a - 10$         | No  | No    | NEX      | [9]       |
| 103 | $22419*a + 227528$ | No  | No    | NEX      | [31]      |
| 107 | $93*a + 962$     | No  | No    | NEX      | [31]      |
| 109 | $25/2*a + 261/2$ | No  | Yes   | DET      | [30],[31] |
| 113 | $73*a + 776$     | No  | No    | NEX      | [9]       |
| 118 | $28254*a + 306917$ | Yes | No    | PEX/UNDET | [31]      |
| 127 | $419775*a - 4730624$ | No  | No    | NEX      | [31]      |
| 129 | $1484*a + 16855$ | No  | No    | NEX      | [9]       |
| 131 | $927*a - 10610$ | No  | —     | PNEX/UNDET | [31]      |
| 133 | $15/2*a - 173/2$ | No  | Yes   | DET      | [9]       |
| 134 | $12606*a - 145925$ | Yes | —     | PEX/UNDET | [31]      |
| 137 | $149*a - 1744$   | No  | No    | NEX      | [31]      |
| 139 | $657829*a - 77563250$ | No  | No    | NEX      | [31]      |
| 141 | $8*a - 95$       | No  | No    | NEX      | [9]       |
| 149 | $5/2*a - 61/2$   | No  | No    | NEX      | [9]       |
| 151 | $140634693*a - 1728148040$ | No  | No    | NEX      | [31]      |
| 157 | $17/2*a - 213/2$ | No  | Yes   | DET      | [9]       |
| 158 | $616*a + 7743$   | No  | Yes   | PEX/UNDET | [31]      |
| 161 | $928*a + 11775$  | Yes | Yes   | PEX/UNDET | [30],[31] |
| 163 | $5019135*a - 64080026$ | No  | No    | NEX      | [31]      |
| 166 | $132015642*a - 1709902565$ | Yes | —     | PEX/UNDET | [31]      |
| 167 | $13*a + 168$     | No  | No    | NEX      | [9]       |
| 173 | $1/2*a + 13/2$   | No  | No    | NEX      | [9]       |
| 177 | $4692*a + 62423$ | No  | No    | NEX      | [9]       |
| 179 | $313191*a + 4190210$ | No  | —     | PNEX/UNDET | [31]      |
| 181 | $97/2*a - 1305/2$ | No  | No    | NEX      | [9]       |
| 191 | $650783*a + 8994000$ | No  | No    | NEX      | [9]       |
| 193 | $126985*a - 1764132$ | —   | No    | PNEX/UNDET | [31]      |
| 197 | $a - 14$         | No  | No    | NEX      | [9]       |
| 199 | $1153080099*a - 16266196520$ | No  | —     | PNEX/UNDET | [31]      |
3.2 The case of pure cubic fields

We only consider the pure cubic field $L_m$ whose class number is 1.

| $m$   | adm | n-adm | progress   | reference  |
|-------|-----|-------|------------|-----------|
| $m_1 \in S_1$ | No  | No    | NEX        | [1], [28], [31] |
| $m_2 \in S_2$ | No  | —     | PNEX/UNDET | [28], [31] |
| 46    | No  | Yes   | PEX/UNDET  | [28], [31] |
| 107   | —   | —     | UNDET      | —         |

where

- $S_1 = \{2, 3, 5, 6, 10, 12, 17, 18, 29, 116, 137, 173, 197\}$,
- $S_2 = \{23, 33, 41, 44, 45, 53, 55, 59, 69, 71, 75, 82, 87, 99, 145, 167, 177, 179, 188\}$.

Please note that fundamental units are omitted in the table because the size of them becomes too large.

4 Conclusion

In this paper we proved the (non-)existence of elliptic curves having everywhere good reduction over certain real quadratic fields for 14 cases and partly determined the (non-)existence for 9 cases. We also proved such results over certain pure cubic fields for 12 cases and partially proved for 6 cases.

It seems extremely difficult to extend these results using same approach because of some limitations of computational tools and equipments. To improve these results, we need to discover efficient algorithms or new mathematical tools.

Acknowledgments The author likes to express his gratitude to Takaaki Kagawa, Masanari Kida and Yuichiro Taguchi who guided him to the theory of elliptic curves. Their advice during the preparation of his papers on elliptic curves was very helpful.

The author would like to thank John Cremona and Denis Simon for making their programs available to him and for initially guiding him through the intricacies of the codes. He also would like to thank Iwao Kimura, Kazuo Matsuno, Yu Shimasaki and Yukihiro Uchida who gave him some useful advice and information.

This work was supported by Grant-in-Aid for JSPS fellows.

References

[1] M. Bertolini and G. Canuto, Good reduction of elliptic curves defined over $\mathbb{Q}(\sqrt[3]{2})$, Arch. Math., 50 (1988), 42-50.

[2] S. Comalada, Elliptic curves with trivial conductor over quadratic fields, Pacific J. Math. 144 (1990), 233-258.
[3] J. Cremona and M. Lingham, *Finding all elliptic curves with good reduction outside a given set of primes*, Exp. Math. 16 No.3 (2007), 303-312.

[4] J. Cremona (compiled), *Elliptic Curves with Everywhere Good Reduction over Quadratic Fields*, available from his website: http://www.warwick.ac.uk/staff/J.E.Cremona//ecegr/ecegrqf.html.

[5] H. Ishii, *The non-existence of elliptic curves with everywhere good reduction over certain quadratic fields*, Japan. J. Math. 12 (1986), 45-52.

[6] T. Kagawa, *Determination of elliptic curves with everywhere good reduction over \( \mathbb{Q}(\sqrt{37}) \)*, Acta Arith. 83 (1998), 253-269.

[7] T. Kagawa, *Determination of elliptic curves with everywhere good reduction over real quadratic fields*, Arch. Math. 73 (1999), 25-32.

[8] T. Kagawa, *Determination of elliptic curves with everywhere good reduction over real quadratic fields \( \mathbb{Q}(\sqrt{37}) \)*, Acta. Arith. 96 (2001), 231-245.

[9] T. Kagawa, *Determination of elliptic curves with everywhere good reduction over real quadratic fields, II*, preprint.

[10] T. Kagawa, *Elliptic curves with everywhere good reduction over real quadratic fields*, Ph. D. Thesis, Waseda University (1998).

[11] T. Kagawa, *Computing integral points of elliptic curves over real quadratic fields, and determination of elliptic curves having trivial conductor* (in Japanese), available online: http://www.ritsumei.ac.jp/se/~kagawa/waseda.pdf.

[12] KANT/KASH, *Computational Algebraic Number Theory*, http://www.math.tu-berlin.de/~kant/kash.html.

[13] M. Kida, *On a characterization of Shimura’s elliptic curve over \( \mathbb{Q}(\sqrt{37}) \)*, Acta Arith., 77-(2) (1996), 157-171.

[14] M. Kida and T. Kagawa, *Nonexistence of elliptic curves with good reduction everywhere over real quadratic fields*, J. Number Theory, 66-(2) (1997), 201-210.

[15] M. Kida, *Reduction of elliptic curves over certain real quadratic number fields*, Math. Comp. 68 (1999), 1679-1685.

[16] M. Kida, *Nonexistence of elliptic curves having good reduction everywhere over certain quadratic fields*, Arch. Math. 76 (2001), 436-440.

[17] M. Kida and T. Kagawa, *Nonexistence of elliptic curves with good reduction everywhere over real quadratic fields*, J. Number Theory 66 (1997), 201-210.

[18] Magma, *Computational Algebra System*, http://magma.maths.usyd.edu.au/magma/.
H. Müller, H. Ströher and H. Zimmer, Torsion groups of elliptic curves with integral $j$-invariant over quadratic fields, J. Reine. Angew. Math. 397 (1989), 100-161.

Pari(-GP), A computer algebra system designed for fast computations in number theory, http://pari.math.u-bordeaux.fr/.

R. G. E. Pinch, Elliptic curves over number fields, Ph. D. thesis, Oxford (1982).

Sage, Open Source Mathematics Software, http://www.sagemath.org/.

B. Setzer, Elliptic curves over complex quadratic fields, Pacific J. Math. 74 (1978), no. 1, 235-250.

S. Siksek, Infinite descent on elliptic curves, Rocky Mountain J. Math. 25 (1995), 1501-1538.

J. H. Silverman, The Arithmetic of Elliptic Curves, 2nd edition, Graduate Texts in Mathematics 106, Springer-Verlag (2009).

D. Simon, Computing the rank of elliptic curves over number fields, LMS JCM, vol 5 (2002), 7-17.

N. P. Smart, The algorithmic resolution of Diophantine equations, London Mathematical Society Student Text 41 (1998).

N. Takeshi, On elliptic curves having everywhere good reduction over cubic fields, Master’s Thesis (2012), Tsuda College (in Japanese).

T. Thongjunthug, Heights on elliptic curves over number fields, period lattices, and complex elliptic logarithms, Ph. D. Thesis, The University of Warwick (2011).

A. Umegaki, A construction of everywhere good $Q$-curves with $p$-isogeny, Tokyo J. Math. 21 (1998), no. 1, 183-200.

S. Yokoyama, On elliptic curves with everywhere good reduction over certain number fields, preprint.

S. Yokoyama and Y. Shimasaki, Non-existence of elliptic curves with everywhere good reduction over some real quadratic fields, J. Math-for-Industry, vol.3 (2011B-4), 113-117.

Shun’ichi Yokoyama
Faculty of Mathematics, Kyushu University
744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan
E-mail address:
s-yokoyama@math.kyushu-u.ac.jp