On the Mordell-Weil groups of elliptic surfaces associated with Frey curves of degree two

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1 Introduction

An elliptic curve is a smooth projective curve of genus 1. For points on an elliptic curve we can define an addition law, which makes the set of points on an elliptic curve into an abelian group with the identity element being the point at infinity. For an elliptic curve E defined over a field K, the Mordell-Weil group $E(K)$ is a group consisting of all K-rational points on E.

Theorem 1.1. (Mordell's Theorem) Let E be an elliptic curve defined over a number field K. Then the Mordell-Weil group $E(K)$ is a finitely generated abelian group.

By the structure theorem of finite abelian groups, the Mordell-Weil group can be decomposed into a free part and a torsion part:

$$E(K) \cong \mathbb{Z}^{\oplus r} \oplus E(K)_{\mathrm{tors}}$$

where r is the rank of the Mordell-Weil group and $E(K)_{\mathrm{tors}}$ is the torsion subgroup of $E(K)$. The Mordell-Weil group is an important object in the study of elliptic curves. Especially, the rank of the Mordell-Weil group is important and difficult to determine.

In this paper, we consider elliptic curves in the form of the Frey curves for $n = 2$. In other words, let $(a, b, c) \in \mathbb{Z}^3$ be a Pythagorean triple and consider the elliptic curve defined by the Weierstrass equation

$$y^2 = x(x - a^2)(x + b^2). \tag{1}$$

We can parameterize Pythagorean triples (a, b, c) by $m, n \in \mathbb{Z}$ with $(m, n) = 1$ as $(a, b, c) = (2mn, m^2 - n^2, m^2 + n^2)$. Then the equation (1) can be written as $y^2 = x(x - 4m^2n^2)(x + (m^2 - n^2)^2)$. We replace x, y by n^2x, n^3y and put $s = m/n$. Then we get an elliptic curve

$$E_{1,s} : y^2 = x(x - 4s^2)(x + (s^2 - 1)^2). \tag{2}$$

We consider $E_{1,s}$ as an elliptic curve over a function field $\overline{\mathbb{Q}}(s)$. We associate an elliptic surface $\mathcal{E}_{1,s} \to \mathbb{P}^1$ to $E_{1,s}$.

2 Main Theorem

Theorem 2.1. The Mordell-Weil group of $E_{1,s}$ over $\overline{\mathbb{Q}}(s)$ satisfies

$$E_{1,s}(\overline{\mathbb{Q}}(s)) \cong \mathbb{Z}/4\mathbb{Z} \oplus \mathbb{Z}/4\mathbb{Z},$$

especially the rank is 0. The torsion subgroup is generated by

$$T_1 := (2s(s+1)^2, 2s(s+1)^2(s^2+1)),$$
$$T_2 := (2\sqrt{-1}s(s^2-1), 2\sqrt{-1}s(s+\sqrt{-1})^2(s^2-1)).$$

The following is our main result.

Theorem 2.2. The Mordell-Weil group of $E_{2,t}$ over $\overline{\mathbb{Q}}(t)$ satisfies

$$E_{2,t}(\overline{\mathbb{Q}}(t)) \cong \mathbb{Z} \oplus \mathbb{Z}/4\mathbb{Z} \oplus \mathbb{Z}/4\mathbb{Z},$$

especially the rank is 1. We denote $s = \frac{2t}{t^2-3}$. The torsion subgroup is generated by T_1 and T_2 in Theorem 2.1 and the free part is generated by

$$\left(s^2 - 1,\ \sqrt{-1}s(s^2-1)\frac{t^2+3}{t^2-3}\right).$$

The important point is that we prove that the generic rank of $E_{2,t}$ is exactly 1, not only the existence of a point of infinite order. Our proof is based on the method of Naskręcki in [1].

3 Preliminaries

In order to get the lower bound of the rank of the Mordell-Weil group, finding points of infinite order is enough. It is quite difficult to get a good upper bound of the rank. The following theorem behaves a key role in the proof of the main theorem.

Theorem 3.1. (Shioda-Tate formula, [2, Corollary 5.3]) Let $\mathcal{E} \to C$ be an elliptic surface over a smooth projective curve C over an algebraically closed field k. Let $R \subset C$ be the set of points where the special fiber of $\mathcal{E}$ is singular. For each $v \in R$, let m_v be the number of components of the special fiber of $\mathcal{E}$ at v. Let $\rho(\mathcal{E})$ denote the rank of the Néron-Severi group of $\mathcal{E}$. Then, we have

$$\rho(\mathcal{E}) = 2 + \sum_{v \in R}(m_v - 1) + \mathrm{rank}(E(k(C))).$$

4 Reductions

Let A be a discrete valuation ring with maximal ideal $\mathfrak{m}$ and fraction field K. Assume that the residue field $k = A/\mathfrak{m}$ has $q = p^r$ elements with p prime. Let S be an integral scheme with a morphism $S \to \operatorname{Spec} A$ that is projective and smooth of relative dimension 2. Then the projective surface $\overline{S} = S_{\overline{\mathbb{Q}}}$ and $\tilde{S} = S_{\overline{k}}$ are smooth over the algebraically closed field $\overline{\mathbb{Q}}$ and $\overline{k}$, respectively. We will assume that $\overline{S}$ and $\tilde{S}$ are integrals, i.e., they are irreducible, nonsingular, projective surfaces.

For a prime number $l \neq p$, we denote by $H^2_{\text{ét}}(\tilde{S}, \mathbb{Q}_l)$ the l-adic étale cohomology group of X and by $H^2_{\text{ét}}(\tilde{S}, \mathbb{Q}_l)(1)$ its Tate twist.

Let $F : S_k \to S_k$ denote the absolute Frobenius, which acts as the identity on the points and by $f \mapsto f^p$ on the structure sheaf. Set $\varphi := F^r$ and let $\varphi^{(i)}$ denote the automorphism on $H^i_{\text{ét}}(\tilde{S}, \mathbb{Q}_l)$ induced by $\varphi \times 1$ acting on $S_k \times_{\operatorname{Spec} k} \operatorname{Spec} \overline{k} \cong \tilde{S}$.

Theorem 4.1. ([3, Corollary 6.4.]) The ranks of $\mathrm{NS}(\overline{S})$ and $\mathrm{NS}(\tilde{S})$ are bounded from above by the number of eigenvalues λ of $\varphi^{(2)}$ for which λ/q is a root of unity, counted with multiplicity.

$$\begin{aligned} \mathrm{rank}\, E_{2,t}(\overline{\mathbb{Q}}(t)) = {} & \mathrm{rank}\, E_{1,s}(\overline{\mathbb{Q}}(s)) \\ & + \mathrm{rank}\, E_{0,u}^{(1+3u)}(\overline{\mathbb{Q}}(u)) \\ & + \mathrm{rank}\, E_{0,u}^{(u(1+3u))}(\overline{\mathbb{Q}}(u)). \end{aligned} \tag{3}$$

$$\mathrm{char}(\varphi^{(2)}) = (x-5)^{19}(x^3 + x^2 + 11x - 77).$$

By Corollary 4.1, $\rho(\mathcal{E}_{0,u}^{(1+3u)}) \leq 19$. Then by Theorem 3.1, we have

$$\mathrm{rank}\, E_{0,u}^{(1+3u)}(\overline{\mathbb{Q}}(u)) \leq 19 - (2 + (2-1) + (4-1) \times 2 + (5-1) + (7-1)) = 0.$$

References

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