THE KORTEWEG-DE VRIES EQUATION AND A DIOPHANTINE PROBLEM RELATED TO BERNOULLI POLYNOMIALS

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Dedicated to Professor Hari Srivastava

Abstract. Some diophantine equations related to the soliton solutions of the Korteweg-de Vries equation are resolved. The main tools are the connection with Bernoulli polynomials and the application of certain computational number-theoretical results.

1. introduction

In the paper [12] Fairlie and Veselov obtained a relation of the Bernoulli polynomials with the theory of the Korteweg-de Vries (KdV) equation

$$u_t - 6uu_x + u_{xxx} = 0.$$

This equation has infinitely many conservation laws of the form

$$I_m[u] = \int_{-\infty}^{\infty} P_m(u, u_x, u_{xx}, \ldots, u_m)dx,$$

where P_m are some polynomials of the function u and its x-derivatives up to order m, see [18]. For example,

$$I_{-1}[u] = \int_{-\infty}^{\infty} udx, I_0[u] = \int_{-\infty}^{\infty} u^2dx, I_1[u] = \int_{-\infty}^{\infty} (u_x^2 + 2u^3)dx$$

and

$$I_2[u] = \int_{-\infty}^{\infty} (u_{xx}^2 + 10uu_x^2 + 5u^4)dx.$$

The KdV equation possesses a remarkable family of so-called n-soliton solutions corresponding to the initial profile $u_n(x,0) = -2n(n+1)\mathrm{sech}^2 x$. For some recent generalizations and applications of the Korteweg-de Vries equation we refer to [15], [14] and [22] and the references given therein.

Using the spectral theory of Schrödinger operators, see [30], Fairlie and Veselov [12] proved that

$$I_k[u_n] = \frac{(-1)^k 4^{k+2}}{2k+3} \sum_{i=1}^{n} i^{2k+3}$$

for $k = -1, 0, 1, \ldots$.

Now let $k \neq l$ be fixed integers with $k, l \in \{-1, 0, 1, 2, \ldots\}$ and suppose that

$$|I_k[u_n]| = |I_l[u_m]|.$$

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One can ask that for given k and l, how often can these integrals be equal? In other words, what is the cardinality of the set of solutions m, n to the equation

$$\frac{4^k}{2k+3}\sum_{i=1}^{n} i^{2k+3} = \frac{4^l}{2l+3}\sum_{i=1}^{m} i^{2l+3}, \tag{1}$$

where k and l are fixed distinct integers?

Applying some recent results by Rakaczki, see [23] and [24], it is not too hard to give some ineffective and effective finiteness statements for the solutions m and n to equation (1). However, the purpose of this note is to resolve (1) for certain values of m and n including an infinite family of the parameters.

Theorem 1. *For $k = -1$ and $l \in \{0, 1, 2, 3\}$, equation (1) has only one solution, namely $(l, m, n) = (0, 24, 5)$.*

Theorem 2. *Assume that $k = 0$ and l is a positive integer such that $2l + 3$ is prime. Then (1) has no solution in positive integers m and n.*

2. Auxiliary results

In our first lemma we summarize some classical properties of Bernoulli polynomials. For the proofs of these results we refer to [21].

Lemma 1. *Let $B_j(X)$ denote the jth Bernoulli polynomial and $B_j = B_j(0), j = 1, 2, \ldots$. Further, let D_j be the denominator of B_j. Then we have*
(A) $B_j(X) = X^n + \sum_{i=1}^{j}\binom{j}{i}B_i X^{j-i}$,
(B) $S_j(x) = 1^j + 2^j + \ldots + (x-1)^j = \frac{1}{j+1}(B_{j+1}(x) - B_{j+1})$,
(C) $B_1 = -\frac{1}{2}, B_{2j+1} = 0, j = 1, 2, \ldots$
(D) (von Staudt-Clausen) $D_{2j} = \prod_{p-1|2j, p \text{ prime}} p$
(E) $X^2(X-1)^2 | B_{2j}(X) - B_{2j}$ *(in* $\mathbb{Q}[X]$*).*
(F) $B_j(X) = (-1)^j B_j(1-X)$.

Consider the hyperelliptic curve

$$\mathcal{C}: \quad y^2 = F(x) := x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0, \tag{2}$$

where $b_i \in \mathbb{Z}$. Let α be a root of F and $J(\mathbb{Q})$ be the Jacobian of the curve $\mathcal{C}$. We have that

$$x - \alpha = \kappa\xi^2$$

where $\kappa, \xi \in K = \mathbb{Q}(\alpha)$ and κ comes from a finite set. By knowing the Mordell-Weil group of the curve $\mathcal{C}$ it is possible to provide a method to compute such a finite set. To each coset representative $\sum_{i=1}^{m}(P_i - \infty)$ of $J(\mathbb{Q})/2J(\mathbb{Q})$ we associate

$$\kappa = \prod_{i=1}^{m}\left(\gamma_i - \alpha d_i^2\right),$$

where the set $\{P_1, \ldots, P_m\}$ is stable under the action of Galois, all $y(P_i)$ are nonzero and $x(P_i) = \gamma_i/d_i^2$ where γ_i is an algebraic integer and $d_i \in \mathbb{Z}_{\geq 1}$. If P_i, P_j are conjugate then we may suppose that $d_i = d_j$ and so γ_i, γ_j are conjugate. We have the following lemma (Lemma 3.1 in [8]).

Lemma 2. *Let $\mathcal{K}$ be a set of κ values associated as above to a complete set of coset representatives of $J(\mathbb{Q})/2J(\mathbb{Q})$. Then $\mathcal{K}$ is a finite subset of $\mathcal{O}_K$ and if (x, y) is an integral point on the curve (2) then $x - \alpha = \kappa\xi^2$ for some $\kappa \in \mathcal{K}$ and $\xi \in K$.*

As an application of his theory of lower bounds for linear forms in logarithms, Baker [1] gave an explicit upper bound for the size of integral solutions of hyperelliptic curves. This result has been improved by many authors (see e.g. [2], [3], [4], [9], [20], [26], [27] and [29]).

In [8] an improved completely explicit upper bound were proved combining ideas from [9], [10], [11], [16], [17], [19], [29], [28]. Now we will state the theorem which gives the improved bound. We introduce some notation. Let K be a number field of degree d and let r be its unit rank and R its regulator. For $\alpha \in K$ we denote by $\mathrm{h}(\alpha)$ the logarithmic height of the element α. Let

$$\partial_K = \begin{cases} \frac{\log 2}{d} & \text{if } d = 1,\, 2, \\ \frac{1}{4}\left(\frac{\log\log d}{\log d}\right)^3 & \text{if } d \geq 3 \end{cases}$$

and

$$\partial'_K = \left(1 + \frac{\pi^2}{\partial_K^2}\right)^{1/2}.$$

Define the constants

$$c_1(K) = \frac{(r\,!)^2}{2^{r-1}d^r}, \qquad c_2(K) = c_1(K)\left(\frac{d}{\partial_K}\right)^{r-1},$$
$$c_3(K) = c_1(K)\frac{d^r}{\partial_K}, \qquad c_4(K) = rdc_3(K),$$
$$c_5(K) = \frac{r^{r+1}}{2\partial_K^{r-1}}.$$

Let

$$\partial_{L/K} = \max\left\{[L:\mathbb{Q}]\ ,\ [K:\mathbb{Q}]\partial'_K\ ,\ \frac{0.16[K:\mathbb{Q}]}{\partial_K}\right\},$$

where $K \subseteq L$ are number fields. Define

$$C(K,n) := 3 \cdot 30^{n+4} \cdot (n+1)^{5.5}\, d^2\,(1+\log d).$$

The following result will be used to get an upper bound for the size of the integral solutions of our equations. It is Theorem 3 in [8].

Lemma 3. *Let α be an algebraic integer of degree at least 3 and κ be an integer belonging to K. Denote by α_1, α_2, α_3 distinct conjugates of α and by κ_1, κ_2, κ_3 the corresponding conjugates of κ. Let*

$$K_1 = \mathbb{Q}(\alpha_1, \alpha_2, \sqrt{\kappa_1\kappa_2}), \quad K_2 = \mathbb{Q}(\alpha_1, \alpha_3, \sqrt{\kappa_1\kappa_3}), \quad K_3 = \mathbb{Q}(\alpha_2, \alpha_3, \sqrt{\kappa_2\kappa_3}),$$

and

$$L = \mathbb{Q}(\alpha_1, \alpha_2, \alpha_3, \sqrt{\kappa_1\kappa_2}, \sqrt{\kappa_1\kappa_3}).$$

In what follows R stands for an upper bound for the regulators of K_1, K_2 and K_3 and r denotes the maximum of the unit ranks of K_1, K_2, K_3. Let

$$c_j^* = \max_{1\leq i\leq 3} c_j(K_i)$$

and

$$N = \max_{1\leq i,j\leq 3} \left|\mathrm{Norm}_{\mathbb{Q}(\alpha_i,\alpha_j)/\mathbb{Q}}(\kappa_i(\alpha_i - \alpha_j))\right|^2$$

and

$$H^* = c_5^* R + \frac{\log N}{\min_{1\leq i\leq 3}[K_i:\mathbb{Q}]} + \mathrm{h}(\kappa).$$

Define

$$A_1^* = 2H^* \cdot C(L, 2r+1) \cdot (c_1^*)^2 \partial_{L/L} \cdot \left(\max_{1\leq i\leq 3} \partial_{L/K_i}\right)^{2r} \cdot R^2,$$

and

$$A_2^* = 2H^* + A_1^* + A_1^* \log\{(2r+1)\cdot \max\{c_4^*, 1\}\}.$$

If $x \in \mathbb{Z}\backslash\{0\}$ *satisfies* $x - \alpha = \kappa\xi^2$ *for some* $\xi \in K$ *then*

$$\log|x| \leq 8A_1^* \log(4A_1^*) + 8A_2^* + H^* + 20\log 2 + 13\,\mathrm{h}(\kappa) + 19\,\mathrm{h}(\alpha).$$

To obtain a lower bound for the possible unknown integer solutions we are going to use the so-called Mordell-Weil sieve. The Mordell-Weil sieve has been successfully applied to prove the non-existence of rational points on curves (see e.g. [5], [7], [13] and [25]).

Let $C/\mathbb{Q}$ be a smooth projective curve (in our case a hyperelliptic curve) of genus $g \geq 2$. Let J be its Jacobian. We assume the knowledge of some rational point on C, so let D be a fixed rational point on C and let $\jmath$ be the corresponding Abel-Jacobi map:

$$\jmath : C \to J, \qquad P \mapsto [P - D].$$

Let W be the image in J of the known rational points on C and $D_1, \ldots, D_r$ generators for the free part of $J(\mathbb{Q})$. By using the Mordell–Weil sieve we are going to obtain a very large and smooth integer B such that

$$\jmath(C(\mathbb{Q})) \subseteq W + BJ(\mathbb{Q}).$$

Let

$$\phi : \mathbb{Z}^r \to J(\mathbb{Q}), \qquad \phi(a_1, \ldots, a_r) = \sum a_i D_i,$$

so that the image of ϕ is the free part of $J(\mathbb{Q})$. The variant of the Mordell-Weil sieve explained in [8] provides a method to obtain a very long decreasing sequence of lattices in $\mathbb{Z}^r$

$$B\mathbb{Z}^r = L_0 \supsetneq L_1 \supsetneq L_2 \supsetneq \cdots \supsetneq L_k$$

such that

$$\jmath(C(\mathbb{Q})) \subset W + \phi(L_j)$$

for $j = 1, \ldots, k$.

The next lemma [8, Lemma 12.1] gives a lower bound for the size of rational points whose image are not in the set W.

Lemma 4. *Let* W *be a finite subset of* $J(\mathbb{Q})$ *and* L *be a sublattice of* $\mathbb{Z}^r$. *Suppose that* $\jmath(C(\mathbb{Q})) \subset W + \phi(L)$. *Let* μ_1 *be a lower bound for* $h - \hat{h}$ *and*

$$\mu_2 = \max\left\{ \sqrt{\hat{h}(w)} \ : \ w \in W \right\}.$$

Denote by M *the height-pairing matrix for the Mordell–Weil basis* $D_1, \ldots, D_r$ *and let* $\lambda_1, \ldots, \lambda_r$ *be its eigenvalues. Let*

$$\mu_3 = \min\left\{ \sqrt{\lambda_j} \ : \ j = 1, \ldots, r \right\}$$

and $m(L)$ *the Euclidean norm of the shortest non-zero vector of* L. *Then, for any* $P \in C(\mathbb{Q})$, *either* $\jmath(P) \in W$ *or*

$$h(\jmath(P)) \geq (\mu_3 m(L) - \mu_2)^2 + \mu_1.$$

The following lemma plays a crucial role in the proof of Theorem 1

Lemma 5. *The integral solutions of the equation*

$$\mathcal{C} : Y^2 = X(X+20)^2(X^2+10X+400) + 140625 \tag{3}$$

are

$$(X, Y) \in \{(0, \pm 375), (-20, \pm 375)\}.$$

Proof of Lemma 5. Let $J(\mathbb{Q})$ be the Jacobian of the genus two curve (3). Using MAGMA we determine a Mordell-Weil basis which is given by

$$D_1 = (0,375) - \infty,$$
$$D_2 = (-20,375) - \infty.$$

Let $f = x(x+20)^2(x^2+10x+400)+140625$ and α be a root of f. We will choose for coset representatives of $J(\mathbb{Q})/2J(\mathbb{Q})$ the linear combinations $\sum_{i=1}^{2} n_i D_i$, where $n_i \in \{0,1\}$. Then

$$x - \alpha = \kappa\xi^2,$$

where $\kappa \in \mathcal{K}$ and $\mathcal{K}$ is constructed as described in Lemma 2. We have that $\mathcal{K} = \{1, -\alpha, -20-\alpha, \alpha(\alpha+20)\}$. By local arguments it is possible to restrict the set $\mathcal{K}$ further (see e.g. [5], [6]). In our case one can eliminate

$$\alpha(\alpha+20)$$

by local computations in $\mathbb{Q}_3$. We apply Lemma 3 to get a large upper bound for $\log|x|$ in the remaining cases. A MAGMA code were written to obtain the bounds appeared in [8], it can be found at
`http://www.warwick.ac.uk/~maseap/progs/intpoint/bounds.m`. We obtain that these bounds are as follows

κ	bound for $\log\lvert x\rvert$
1	$6.27 \cdot 10^{307}$
$-\alpha$	$4.48 \cdot 10^{668}$
$-20-\alpha$	$1.89 \cdot 10^{612}$

The set of known rational points on the curve (3) is $\{\infty, (0,\pm 375), (-20,\pm 375)\}$. Let W be the image of this set in $J(\mathbb{Q})$. Applying the Mordell-Weil implemented by Bruin and Stoll and explained in [8] we obtain that $\jmath(C(\mathbb{Q})) \subseteq W + BJ(\mathbb{Q})$, where

$$B = 2^8 \cdot 5^3 \cdot 7^2 \cdot 11^2 \cdot 13^2 \cdot 17^2 \cdot 19 \cdot 31 \cdot 37 \cdot 41 \cdot 43 \cdot 53 \cdot 59 \cdot 71 \cdot 79 \cdot 83 \cdot 89$$

that is

$$B = 461282233060001882034358973120000.$$

Now we use an extension of the Mordell-Weil sieve due to Samir Siksek to obtain a very long decreasing sequence of lattices in $\mathbb{Z}^2$. After that we apply Lemma 4 to obtain a lower bound for possible unknown rational points. We get that if (x,y) is an unknown integral point, then

$$\log|x| \geq 2.216448 \times 10^{782}.$$

This contradicts the bound for $\log|x|$ we obtained by Baker's method. □

3. Proofs of the Theorems

Proof of Theorem 1. For $k=-1$ and $l \in \{0,1,2,3\}$ we have the diophantine equations

$$\frac{n(n+1)}{2} = \frac{m^2(m+1)^2}{3}, \tag{4}$$

$$\frac{n(n+1)}{8} = \frac{1}{15}z^2(2z-1) \text{ with } z = m(m+1), \tag{5}$$

$$\frac{n(n+1}{8} = \frac{2}{21}z^2(3z^2-4z+2) \text{ with } z = m(m+1), \tag{6}$$

and

$$\frac{1}{4}\sum_{i=1}^{n} i = \frac{64}{9}\sum_{i=1}^{m} i^9, \tag{7}$$

respectively. One can see that the first three equations are elliptic diophatine equations, thus using the program package MAGMA, subroutines `IntegralPoints` or `IntegralQuarticPoints` is just a straightforward calculation to solve them. In these cases the unique solution is $(l, m, n) = (0, 24, 5)$. The forth equation can be written as follows

$$(2n+1)^2 = \frac{128}{45}(m^2+m-1)(m^2+m)^2(2m^4+4m^3-m^2-3m+3)+1.$$

So we easily obtain a hyperelliptic curve

$$Y^2 = X(X+20)^2(X^2+10X+400)+140625,$$

where $Y = 375(2n+1)$ and $X = 20m^2+20m-20$. By Lemma 5 we have that $X = 0$ or -20. Therefore we have that $m \in \{-1, 0\}$, a contradiction and there is no solution in positive integers of (7). □

Proof of Theorem 2. Now $k = 0$ and $p = 2l + 3 \geq 3$ is a prime. From (1) we get

$$p \cdot n^2(n+1)^2 = 3 \cdot 4^{l+1}(1^p + 2^p + \ldots + m^p).$$

Let m and n be an arbitrary but fixed solution. An elementary numbertheoretical argument and Lemma 1 yield that $p|m(m+1)$ and

$$\mathrm{ord}_p\left(\frac{1^p + 2^p + \ldots + m^p}{m^2(m+1)^2}\right) = \mathrm{ord}_p\frac{B_{p+1}(m+1) - B_{p+1}}{m^2(m+1)^2} \neq 0.$$

Suppose that $p|m$ and let d the smallest positive integer such that $B_{p+1}(m+1) - B_{p+1} = \frac{1}{d}f(m)m^2(m+1)^2$, and $f(X) \in \mathbb{Z}[X]$. Since $\binom{p+1}{k}$ is divisible by p for $k = 2, \ldots, p-1$ and $B_1 = -1/2$ we have that p is not a divisor of d. The constant term of the polynomial $f(X)$ is $d\binom{p+1}{p-1}B_{p-1}$ and, by von Staudt-Clausen theorem, it is not divisible by p. On the other hand, p is a divisor of m and $f(m)$, we have a contradiction. If $p|m+1$ the we can repeat the previous argument using the fact $f(X) = f(-X-1)$, cf. Lemma 1.

□

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