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Algebraic independence results for Ramanujan $q$-series

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1 Introduction

In 1916, Ramanujan [8] defined the function

$$S_{2j+1}(x) = \frac{1}{2} \zeta(-2j-1) + \sum_{n=1}^{\infty} \frac{n^{2j+1}x^n}{1-x^n} \quad (j=0,1,2,\ldots),$$

where $\zeta(s)$ is the Riemann zeta function, in particular

$$P(x) = -24S_1(x), \quad Q(x) = 240S_3(x), \quad R(x) = -540S_6(x),$$

and proved various formulas for these functions.

Nesterenko [7] proved that, for an algebraic number $x$ with $0 < |x| < 1$, the three numbers $P(x), Q(x), R(x)$ are algebraically independent.

In this paper we study, for a given algebraic number $x$ with $0 < |x| < 1$, the algebraic independence of the numbers $S_{2j+1}(x)$ $(j=0,1,2,\ldots)$, or equivalently that of the numbers

$$A_{2j+1} = A_{2j+1}(q) = \sum_{n=1}^{\infty} \frac{n^{2j+1}q^{2n}}{1-q^{2n}} \quad (j=0,1,2,\ldots) \quad (1)$$

for $q^2 = x$ (using the symbol in [10]). We remark that the $q$-series identity

$$A_7(q) = A_3(q) + 120A_3(q)^2 \quad (2)$$

follows from Table I in [8]. Our result is stated as follows:

**Theorem 1.** The $q$-series $A_{2i+1}(q)$ and $A_{2j+1}(q)$ with $1 \leq i < j$ are algebraically dependent over $\overline{\mathbb{Q}}(q)$ if and only if $(i,j) = (1,3)$.

**Theorem 2.** Let $q$ be an algebraic number with $0 < |q| < 1$. Then the three numbers $A_1(q), A_{2i+1}(q)$ and $A_{2j+1}(q)$ with $1 \leq i < j$ and $(i,j) \neq (1,3)$ are algebraically independent.

As an immediate corollary of Theorem 2 we have

**Corollary 1.** The $q$-series $A_1(q), A_{2i+1}(q)$ and $A_{2j+1}(q)$ with $1 \leq i < j$ and $(i,j) \neq (1,3)$ are algebraically independent over $\overline{\mathbb{Q}}(q)$.

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It is easy to see that, for any positive integers $i, j, l$, the q-series $A_{2i+1}(q), A_{2j+1}(q), A_{2l+1}(q)$ are algebraically dependent over $\mathbb{Q}$ (cf. Lemmas 2 and 3 in Section 2). Our proof of the theorem depends on three basic tools; namely, a corollary of Nesterenko's theorem (see Lemma 1), expressions of $A_{2j+1}(q)$ in terms of $K/\pi, E/\pi$ and $k$ given by Ramanujan [8], Zucker [10] and the authors [2], where $K$ and $E$ are the complete elliptic integrals of the first and second kind with the modulus $k$ (see Lemmas 2 and 3), and an algebraic independence criterion (see Lemma 6). Our method of this paper can be applied to certain sequences of q-series studied by Zucker [10] and the authors [2], [3], [4].

2 Lemmas

Let $K$ and $E$ denote the complete elliptic integrals of the first and second kind

$$K = K(k) = \int_{0}^{1} \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}}, \quad E = E(k) = \int_{0}^{1} \sqrt{\frac{1-k^2t^2}{1-t^2}} dt,$$

with the modulus $k$ such that $k^2 \in \mathbb{C} \setminus (\{0\} \cup [1, +\infty))$. The branch of each integrand is chosen so that it tends to 1 as $t \to 0$. Moreover set $K' = K(k'), k^2 + (k')^2 = 1$. For any $q \in \mathbb{C}$ with $0 < |q| < 1$, choose $K'(k)/K(k)$ so that $q = e^{-\pi K'/K}$. Then by Nesterenko's theorem ([7], see also [2, §3]) we have

Lemma 1. If $q \in \overline{\mathbb{Q}}$ with $0 < |q| < 1$, then $k$, $K/\pi$, and $E/\pi$ are algebraically independent.

The Jacobian elliptic function $w = sn z = sn(z, k)$ may be defined by

$$z = \int_{0}^{w} \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}},$$

and we write

$$ns z = ns(z, k) = \frac{1}{sn(z, k)}, \quad cs z = cs(z, k) = \frac{cn(z, k)}{sn(z, k)}, \quad cn(z, k) = \sqrt{1-sn^2(z,k)}.$$

Let $a_j$ and $c_j = c_j(k)$ ($j \geq 0$) denote the coefficients of the series expansions

$$\csc^2 z = z^{-2} + \sum_{j=0}^{\infty} a_j z^{2j}, \quad \ns^2(z, k) = z^{-2} + \sum_{j=0}^{\infty} c_j(k) z^{2j}, \quad (3)$$

respectively; in particular

$$a_j := \frac{(-1)^j(2j + 1)2^{2j+2}B_{2j+2}}{(2j+2)!} \quad (j \geq 0) \quad (4)$$

with the Bernoulli numbers $B_2 = 1/6, B_4 = -1/30, B_6 = 1/42, B_8 = -1/30, \ldots$ etc. The following evaluations of $A_{2j+1}(q)$ in terms of $k$, $K/\pi$ and $E/\pi$ were given by Ramanujan [8] for $j = 1, 2, \ldots, 15$ and completed by Zucker [10].

Lemma 2. For $q = e^{-\pi K'/K}$, the q-series $A_{2j+1}(q)$ is expressed in the form

$$A_1(q) = \frac{1}{24} - \frac{1}{24} \left( \frac{2K}{\pi} \right)^2 \left( \frac{3E}{K} - 2 + k^2 \right),$$

$$A_{2j+1}(q) = (-1)^j \frac{(2j)!}{2^{2j+3}} \left( a_j - \left( \frac{2K}{\pi} \right)^{2j+2} c_j(k) \right) \quad (j \geq 1).$$

The coefficients of the series for $\ns^2(z, k)$ are determined recursively ([2, Lemma 2]):
Lemma 3. The coefficients $c_j = c_j(k)$ are given by
\[
c_0 = \frac{1}{3} (1 + k^2), \quad c_1 = \frac{1}{15} (1 - k^2 + k^4), \quad c_2 = \frac{1}{189} (1 + k^2)(1 - 2k^2)(2 - k^2),
\]
\[(j - 2)(2j + 3)c_j = 3 \sum_{i=1}^{j-2} c_i c_{j-i-1} \quad (j \geq 3).
\]

It follows from this lemma that $c_j = c_j(k) \in \mathbb{Q}[k^2]$ with deg $c_j(k) = 2(j + 1)$. Put
\[
c_j(k) = \alpha_{j,0} + \alpha_{j,1} k^2 + \cdots + \alpha_{j,j+1} k^{2j+2} \quad (j \geq 1).
\]

It is easy to see that $z^2 \text{nc}^2(z, k)$ is analytic around $(z, k) = (0, 0)$, and that $z^2 \text{nc}^2(z, k) = 1 + O(|z|^2 + |k|^2)$. The following lemma gives a detailed expression.

Lemma 4. Around $(z, k) = (0, 0)$ we have
\[
\text{nc}^2(z, k) = \text{cosec}^2 z + f(z)k^2 + g(z)k^4 + O(k^6),
\]
with
\[
f(z) = \frac{z}{4} (\cot z)'' + \frac{1}{2} (\cot z)' + \frac{1}{2} = \frac{1}{2} - \sum_{j=0}^{\infty} \frac{(-1)^{j+1} 2^{2j} B_{2j+2}}{(2j)!} z^{2j},
\]
\[
g(z) = -\frac{z^2}{32} (\cot z)^{(3)} - \frac{3z}{64} (\cot z)'' + \frac{3}{32} (\cot z)' + \frac{1}{16} - \frac{1}{32} \cos 2z
\]
\[= \frac{1}{16} + \sum_{j=0}^{\infty} \frac{(-1)^{j} 2^{2j-5}}{(2j)!} (2(4j - 3)B_{2j+2} - 1) z^{2j}.
\]

From (3), (4), (5) and Lemma 4 we deduce the following corollary.

Corollary 2. For $j \geq 1$ we have
\[
\alpha_{j,0} = \frac{(-1)^{j} (2j + 1) 2^{2j+2} B_{2j+2}}{(2j + 2)!} \quad (2j + 2)!
\]
\[
\alpha_{j,1} = \frac{(-1)^{j+1} 2^{2j} B_{2j+2}}{(2j)!} \quad (j \geq 1), \quad \alpha_{0,1} = \frac{1}{3},
\]
\[
\alpha_{j,2} = \frac{(-1)^{j} 2^{2j-5} B_{2j+2}}{(2j)!} (2(4j - 3)B_{2j+2} - 1) \quad (j \geq 1), \quad \alpha_{0,2} = 0.
\]

Lemma 5. All Bernoulli numbers $B_{2n}$ are distinct with the only exception $B_4 = B_8 = -1/30$.

Lemma 6. (cf. [5]) Let $x_1, \ldots, x_n \in \mathbb{C}$ be algebraically independent and let $y_j := U_j(x_1, \ldots, x_n)$, where $U_j(X_1, \ldots, X_n) \in \mathbb{Q}[X_1, \ldots, X_n] \quad (j = 1, \ldots, n)$. Assume that
\[
\det \left( \frac{\partial U_j}{\partial X_i}(x_1, \ldots, x_n) \right) \neq 0.
\]

Then the numbers $y_1, \ldots, y_n$ are algebraically independent.
3 Sketch of the proof of Theorem 1

We assume that two q-series $A_{2i+1}(q)$ and $A_{2j+1}(q)$ with $1 \leq i < j$ are algebraically dependent over $\overline{\mathbb{Q}}(q)$ and deduce the case $(i,j) = (1,3)$. There exists an algebraic number $q_0$ with $0 < |q_0| < 1$ such that the two numbers $A_{2i+1}(q_0)$ and $A_{2j+1}(q_0)$ are algebraically dependent. Choose $k$ so that $q_0 = e^{-\pi K'(k)/K(k)}$. We apply Lemma 6 with Lemma 1 and 2 by putting $x_1 = k$, $x_2 = K'/\pi$, $y_\nu = U_\nu(x_1, x_2)$ ($\nu = 1, 2$), where $U_1(X_1, X_2) = X_2^{2i+2}c_i(X_1)$, $U_2(X_1, X_2) = X_2^{2j+2}c_j(X_1)$. Then the vanishing of the determinant implies

$$(j + 1)c_j'(k)c_j(k) - (i + 1)c_i'(k)q(k) = 0$$

as a polynomial of $k$, or equivalently $c_j(k)^{i+1} = rc_i(k)^{j+1}$ for some $r \in \mathbb{Q} \setminus \{0\}$. Substituting (5) into both sides of the last identity and comparing the coefficients of $k^2$ and $k^4$, we get

$$\frac{2\alpha_{j,0}\alpha_{j,2} + i\alpha_{j,1}^2}{\alpha_{j,0}\alpha_{j,1}} = \frac{2\alpha_{i,0}\alpha_{i,2} + j\alpha_{i,1}^2}{\alpha_{i,0}\alpha_{i,1}}.$$

This with the explicit values of $\alpha_{i,j}$ given in Corollary 2 leads to

$$2(4j - 3) - 1/B_{2j+2} + 8i(j + 1) = 2(4i - 3) - 1/B_{2i+2} + 8j(i + 1),$$

that is $B_{2i+2} = B_{2j+2}$. By Lemma 5, we see that $(i, j) = (1, 3)$. The 'if part' follows from the formula (2), and the proof is completed.

Similarly, we can prove Theorem 2, from which Corollary 1 follows.

References